Protection Devices and Systems for High-Voltage Applications

Vladimir Gurevich

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Series Introduction

Power engineering is the oldest and most traditional of the various areas within electrical engineering, yet no other facet of modern technology is currently undergoing a more dramatic revolution in both technology and industry structure. Certainly protection engineering, one of the fundamental areas of power engineering, is no exception. While the goals of protection engineering – public and employee safety, equipment protection, and power supply reliability – have never changed, both the needs for and methods to achieve power system protection have changed dramatically in the last decades and will continue to evolve as electrical appliances and digital equipment become ever smarter, faster, and more integrated into the fundamental infrastructures of our society.

Protection Devices and Systems for High-Voltage Applications presents several interested new switching technologies – reed switch contacts, hybrid reed-transistors and hybrid reed-thyristors – that have heretofore received little comprehensive coverage in references and textbooks. Vladimir Gurevich's focus is on the switching technologies and the devices themselves. His book comprehensively reviews these new devices, the concepts behind their operation, their design, and their construction and usage. As is often the case with high-speed, high-power switching devices, these switching devices have applications in both RF and power protection equipment. The author highlights both the similarities and the differences in these two application areas and shows how these new technologies are applied to each. Industrial and power equipment engineers will find the book interesting and thought-provoking, whether these devices are directly applicable to their areas of engineering, or merely of interest from a professional and technical development standpoint.

Like all the volumes in the Series, *Protection Devices* puts modern technology in a context of practical application; useful as a reference book as well as for self-study and advanced classroom use. The series includes books covering the entire field of power engineering, in all its specialties and subgenres, all aimed at providing practicing power engineers with the knowledge and techniques they need to meet the electric industry's challenges in the 21st century.

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Preface

This book describes a family of new devices (protection relays, contactors, automatic circuit breakers, etc.) based on reed switch contacts, hybrid (reed-transistors and reed-thyristors) technology, and various automatic device–based components intended for use in high-voltage (5 to 100 kV) power supplies, power on these lasers and radar, RF-generators, and also in protection systems for 6 to 24 kV distribution networks.

This volume is a product of my professional experience accumulated over many years of work in research laboratories and industrial companies in the former Soviet Union and Israel.

The book consists of seven chapters and six appendices.

The **first chapter** discusses general problems related to the generation of current overload protection systems of high-voltage electrical installations.

The **second chapter** describes different designs of the new high-voltage interfaces presented by the author for the first time. Dozens of patents have been registered for different variations of these devices, but the book includes only the novel devices developed by the author, the descriptions of which have not been published before.

The **third chapter** describes the high-voltage semiconductor and reed switch–based hybrid switching devices.

The **fourth chapter** describes novel low-voltage switching devices used for high-voltage power supplies, including semiconductor, hybrid, soft-start and others.

The **fifth chapter** includes descriptions of different automation devices developed by the author, designated for use in high-voltage power networks in the power industry.

The **sixth chapter** describes automatic overload protection systems for powerful high-voltage radio electronic devices: radar, lasers, RF-generators, etc.

The **seventh chapter** describes different technological high-voltage devices.

Appendices include various reference data: recommended materials for production, the most suitable electronic components (reed switches, thyristors, transistors, HV cables, solid-state modules, relays, etc.).

The described devices and systems were first mentioned in the author's previous book: "High-Voltage Devices with Reed Switch" - 2000 (in Russian). This previous book contains further information about the author's work in the field. For the readers' convenience, **Appendix A** lists some other author publications in English, which are available internationally and a list of libraries and institutions that have this book.

All the described devices and systems were constructed by the author and successfully tested. Some of them have been successfully used in different power installations. Moreover, in some cases the devices were put to use in industry beyond their intended scope. For example, some RG-series relays were used for transmission of discrete control commands from ground potential to electronic modules, with high voltage applied to them. Another example: high-voltage HVTS-5 switching devices were used for generation of strong high-voltage pulses in a special transformer bench-test.

The author will be pleased to reply to the readers' questions and will appreciate any constructive criticism. Send your comments to:

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Acronyms

AC – Alternating Current

ACB – Automatic Circuit Breaker
APD – Arc Protection Device
CT – Current Transformer
DC – Direct Current
DFL – Device for Forming Loops
EMI – Electro-Magnetic Interference

EPI – Electro-Physical Installation
ET – Electronic Tube (vacuum)
FET – Field-Effect Transistor
GCFI – Ground Circuit Fault Indicator
GFD – Ground Fault Detector
HPR – Hybrid Power Relay
HVTS – High Voltage-Thyristor Switch
IC – Integrated Circuit
IEC – International Electrotechnical Commission
IGBT – Isolated Gate Bipolar Transistor
LED – Light-Emitting Diode
LPU – Load-per-Unit Ratio
LR – Latching Relay
LV – Low Voltage
M - Modulator
MOSFET – Metal Oxide Semiconductor Field-Effect Transistor
MU – Mobile Unit
PCB – Printed Circuit Board
PS – Power Supply
RF – Radio Frequency
RB – Rectifier Bridge
REPS – Remote Electric Power Supply
RG – Relay of Gurevich

RG-PLS – Impulse Action RG Relay
RL-load – Load, Contained Resistance and Inductance

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SAPT – Switch, Based on Anti-Parallel Thyristors
SCI – Short Circuit Indicator
SCR – Silicon Controlled Rectifier
SPST-NO – Single Pole Single Throw Normally Open Contact
SSA – Special Switching Apparatus
SSLS – Series Shared Load System
SU – Stationary Unit
TC-soft – Thyristor Contactor with Soft-Start
TDGC – Temperature Dependence of Gate Current (static)
TCDS – Thyristor Contactor with Direct Start
TSDC – Thyristor Switch with Direct Connection
UBS – Unattended Booster Station
VAC – Volt-Ampere Characteristics
VT – Voltage Transformer

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1

Problems of Overload and Spark Protection Systems for High Power RF Generators, Lasers, and Radar

1.1 COMMON PROBLEMS OF HV EQUIPMENT

High voltage (HV) equipment (10-100 kV) has become very popular over the last few years. It is utilized in military and civil radar stations, powerful signal transmitters for communication, broadcasting and TV systems, technological lasers, X-ray devices, powerful electronic and ion devices, devices for inductive heating and melting of metals, technological electron accelerators for materials irradiation, electro-physical and medical equipment, and industrial microwave ovens, among others.

Despite considerable success in each of these fields, the problem of current overload protection (level current trip) of such devices, caused by HV circuit insulation breakdowns or breakdowns in the high voltage devices, still remains acute. The first is related to unfavorable conditions that cause moisture and dust penetration into the equipment, and the second to unpredictable internal breakdowns in high voltage vacuum electronic elements (klystrons, tetrodes, etc.) or semiconductor elements (HV rectifier).

Current overload protection in such devices is usually resolved by inclusion of current sensors and electronic relays into the low voltage (LV) or grounded circuits. However, such protection is not necessarily efficient and implies some problems:

1. Complicated devices include more than one HV circuit, often having different potential relative to ground, as well as different internal resistance and operational currents. This produces difficulties in adjustment of the

sensor connected to the common ground circuit and is not appropriate for equal protection efficiency of all these circuits.

2. The possibility of connecting to an emergency current sensor located only in the common ground circuit imposes certain restrictions on the system design, forcing the designers to use more complex and expensive devices.

3. In this matter, sensitivity of the current sensor is dependent on grounding circuit quality, which is particularly severe in mobile equipment. However, this connection enables high voltage overpass to a low voltage circuit in emergency mode. All this has an effect on the equipment and maintenance personnel.

4. Internal high voltage power supplies (PS) have a powerful filter with reactive elements used for leveling the high voltage rectifier pulsations. If such power supplies are disconnected from the low voltage power supply net (220, 380, 440 V), the reactive filter elements will still replenish the arc in the breakdown point up to their complete discharge. On the other hand, a "crowbar" connecting to the HV source at the high voltage side, rather than disconnection at the LV side, will cause a heavy overload of the high voltage rectifier and the feeding transformer elements. In this way, their risk of failure will drastically increase.

5. The use of protective shorting by gas discharge thyratrons or vacuum-triggered spark gaps yields more problems because of the extremely short time (a few microseconds) during which discharge current flow is permitted via such devices. In continuous operation, very small currents are permitted in such devices. For example, in a HY-3201 device with parameter values as high as U_{anode} =32kV and I_{anode} = 20kA, the permitted average anode current is only 0.5A. On the one hand, it is quite difficult to enable discharge of such powerful filter elements within fractions of microseconds. On the other hand, considerable discharge currents are not permitted via standard high-capacity filter condensers. They can be discharged only via limiting resistance, namely within time intervals longer than a few microseconds. Moreover, the filament circuit of the thyratrons must be permanently powered, similar to standard high-power electronic tubes (6.3 V, 18A).

6. When a PS with a powerful step-up transformer, rectifier and high capacity ripple filter at the output is connected to equipment, a strong current spike occurs, causing the overloading of all the above elements.

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This generates a need for selective tuning-out of the emergency current sensor, which considerably lowers protection efficiency.

This book describes a new generation of universal HV equipment protection systems to deal with overcurrent situations and internal breakdowns. A set of units comprises a series of High Voltage Interface Relays or RG (**"Relay of Gurevich"**), a series of low voltage solid state contactors and a series of HV thyristor short circuiting devices, and other devices.

We offer system designers a set of universal units from which a variety of highly efficient protection systems, customized to specific needs, can be assembled.

1.2 INTERFACE RELAYS

Technical difficulties caused by the presence of functional components isolated from each other, not permitting direct connection owing to a high difference of potentials, are encountered when designing systems for control and protection against emergency conditions (over current, sparks) in modern power HV equipment. To guarantee information and electrical compatibility as well as to implement the required algorithms for interaction of functional components of equipment, special control instruments are required that have been called "interface relays" or "insulating interfaces" in the technical literature. The general principle of design of these instruments is the presence of a special galvanic decoupling unit between the receiving and final controlling systems of the relay.

Interface relays with a working voltage of more than 10 kV have the greatest interest for these areas of engineering, to which the present study is devoted.

In the design of devices classified as interface relays, some of the widely-used physical principles may not be used in electrical relays of other types.

It is well-known that any electromagnetic relay has a specific level of isolation of the output circuits from the input circuits, i.e., it functions secondarily as an interface relay. However, in ordinary relays, this function is not decisive and is not at all considered in the existing system of classification. In the interface relay, the property of galvanic decoupling of the circuits has been repeatedly intensified, and the parameters of the galvanic decoupling unit are decisive from the standpoint of the function performed by this relay. On the other hand, the parameters associated with switching capacity are secondary and, significantly, can be interface relays with the same level of galvanic decoupling. In this regard, an artificial assignment of interface relays to existing classes does not seem to be expedient. Rather, it seems more appropriate to classify them as a separate type of electrical equipment having an intrinsic structure based mostly on classification according to characteristics of the galvanic decoupling unit. For example, according to the decoupling voltage level:

- low level (to 10 kV);
- medium level (10 to 100 kV);
- high level (above 100 kV).

According to principle of action:

- opto-electronic,
- pneumatic,
- radio-frequency,
- electrohydraulic,
- transformer,
- ultrasonic,
- electromagnetic, and with mechanical transmission.

According to speed:

- super fast (up to 100 μsec);
- fast (100 μsec to 2 ms);
- inertial (above 2 ms).

Although such classification may seem arbitrary, it fully reflects the most important properties of interface relays that have a decisive effect on the functions performed by them.

The simplest interface relays of the opto-electronic type typically consists of a light-emitting element (LED) built into the semiconductor structure (power SCR, triac) or LED and matching low power photothyristor or phototransistor in switching mode, mounted close together and optically coupled within a light-excluding package having a galvanic decoupling voltage up to 4 kV.

Some companies (EAC Electronics, Aleph, Crydom, Magnecraft) are producing high voltage reed relays for commutation voltage up to 10 - 12 kV DC, and therefore, have a galvanic decoupling voltage on the same level. All these relays are intended for use only in DC circuits under normal climatic conditions and have no reserves for withstanding voltage.

In order to significantly increase the galvanic decoupling level of interface relays of the opto-electronic type, a fiber optic cable of appropriate length is installed between the LED and photo-receiving elements. These relays are also equipped with an electronic pulse shaper and an electronic amplifier. At a length of about 1 to 3 meters of fiber optic cable connecting the transmitting and receiving units, the galvanic decoupling voltage ensured by the interface relay can reach 40 kV and more.

Interface relays of the opto-electronic type have also found application in electrical power configurations in which the transmitting and receiving units are connected by hollow porcelain insulators of fairly large dimensions that are equipped with a built-in optical system. Such interfaces are used in 110 – 330 kV power networks to control the drives of high voltage circuit breakers as a device for protecting shunt capacitor batteries, etc.

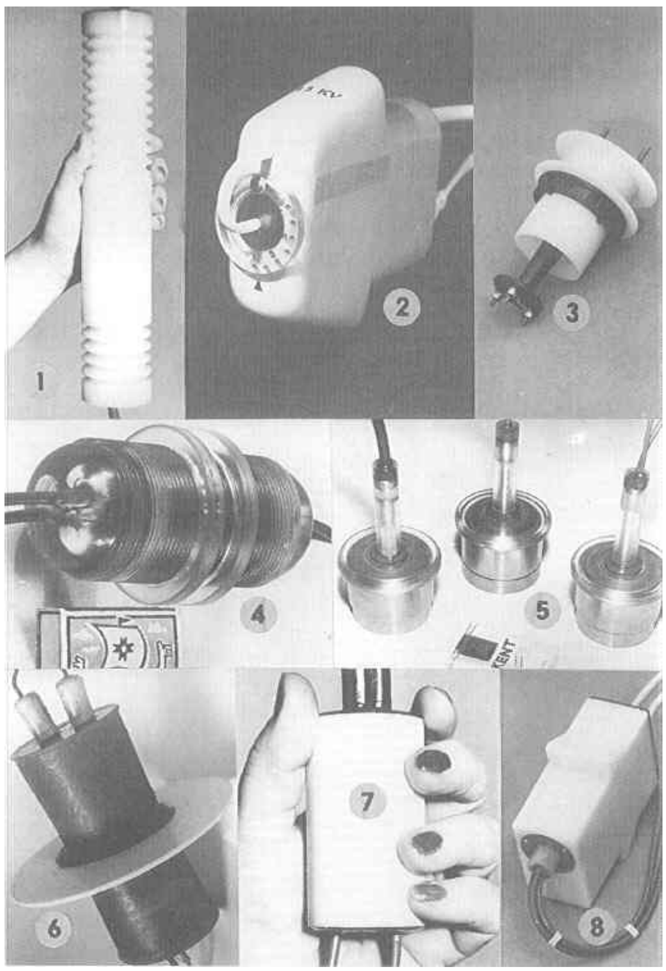

Figure 1.1 Some reed switch-based HV interfaces developed by the author in the years 1977-1994.

The developmental trends of interface relay technology suggest the use of opto-electronic systems as the prevailing design principle for galvanic decoupling units. It is agreed that the most important characteristic feature of opto-electronic systems is their noise immunity and insensitivity to electromagnetic fields. However, what is not considered here is that, in additional to the fiber optic line itself and the output actuator, such a system includes shaper of light pulses on the transmitting and electronic amplifier with triggering units on the receiving end that are generally based on microcircuitry.

It is precisely these elements, which have low activation levels, that are damaged by pulse noise on the side of high voltage power equipment (interferences, spikes and high voltage discharges), which negates the main advantage of opto-electronic systems.

Moreover, the optical fibers themselves are subject to a severe negative effect of ionizing radiation and external mechanical influence (it is a very important for military applications).

The arrangement of input and output circuits of such systems should be widely spaced (optical fiber length is 1 – 2 meters for voltage 40 – 150 kV), and it is this factor that determines the overall dimensions of interface unit.

Figure 1.2 Patents and certificates of authorship pertaining to the HV reed switch-based interfaces.

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All this indicates that the preferred use of an opto-electronic galvanic decoupling unit in interface relays is not always warranted, and it sometimes is merely the consequence of stereotypical thinking of developers or a peculiar technical style.

In 1985, the Brown Bowery Co. started a special program for development of the "Sigma-Switch" interface relays. The development and introduction of essentially new interface relays were contemplated together with the usual opto-electronic system, especially with a galvanic decoupling unit of the electromagnetic type. However, we should mention that BBC does not have priority in the creation of interface relays that function on this principle. As early as 1977, such relay interfaces (based on the reed switch). were proposed by the author of this book. By the time the "Sigma-Switch" program was published, there had been already a number of varieties protected by dozens of certificates of authorship (in ex-USSR). These instruments greatly surpassed proto-types of the BBC and other companies in terms of their parameters. Analysis of the characteristics of the new type reed switch-based HV interface relays developed by author ("Relay of Gurevich" or "*RG-relay*"), as well as experience in creating and using them, shows that they have a definite area of use within which they enjoy distinct advantages over other types of interface relays. These parameters include transmission of discrete control commands, protection and binary warning transfered by a frequency up to 50 – 100 Hz and an admissible speed 0.8 – 1.5 msec, between parts of equipment under a potential difference to 100 kV. Within these values of the parameters, the RG-interfaces are characterized by the highest degree of simplicity and reliability and possess broad functional capabilities. Particularly attractive are such RG-relay properties as a large overload capacity of the control circuit and a large power output circuit, insensibility to pulse noise, mechanical strength of the design, preservation of serviceability over a wide range of temperatures, pressure and humidity. The relatively low cost of RG-relays is also of no small importance in a number of cases. These properties of RG-relays are responsible for their widespread use for industrial and military applications in on-board, mobile and stationary powerful radio-electronic equipment, in relay protection and automation systems of electrical networks of the 6 – 24 class, in electro-physical installation, in power converter technology, etc.

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2

High-Voltage Interface RG-series Relays

2.1 HV INTERFACE RELAYS FOR DC CIRCUITS

RG interface relays are a new type of high-voltage device designed for automation systems for overload protection, fault indicating, interlocking of HV equipment as well as for transfer of control signals from ground potential to HV potential (reverse connection).

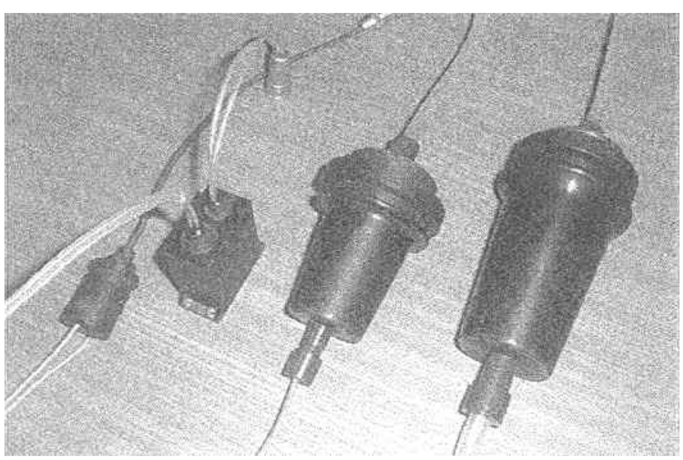

Figure 2.1 High voltage interface RG series relays for industrial and military applications.

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The series consists of the following devices: RG-15, RG-25, RG-50, RG-75, which are designed to operate under voltages of 15, 25, 50 and 75 kV DC, respectively (refer to Fig.2.1).

The operation of these devices is based on the separation between the electric and magnetic electromagnetic field components. Each device is based on a magnetic field source (coil), connected in a high potential current circuit, a reed switch and a layer of high voltage insulation, transparent for the magnetic component of the field and completely insulating the reed switch from the electric field component, Fig. 2.2 – 2.5. The current trip levels can be adjusted up to 50% (for each subtype).

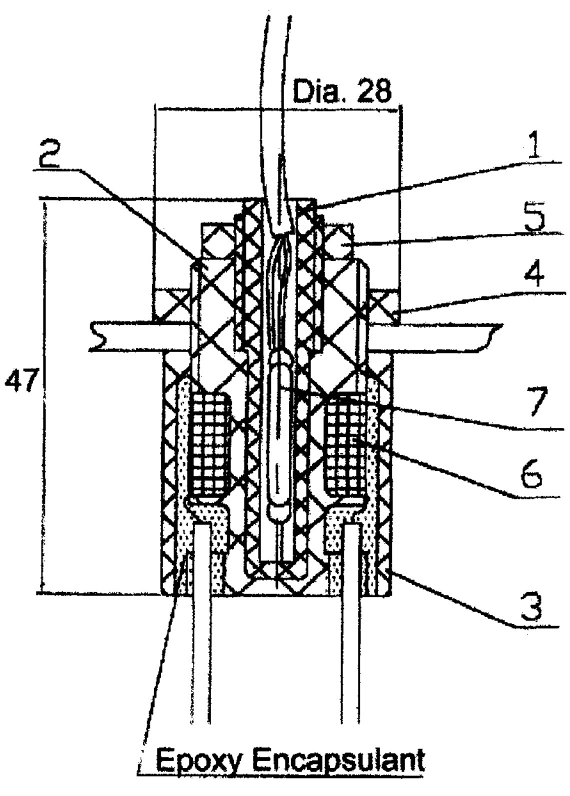

Figure 2.2 RG-15 series design for compact HV power supplies.

1 – moving insert; 2 – main insulator; 3 – external bushing; 4, 5 – nuts; 6 – coil; 7 – reed switch.

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Material for all construction elements is “Ultem-1000”. Leads – HV Teflon cable (etched) 178-8195 type.

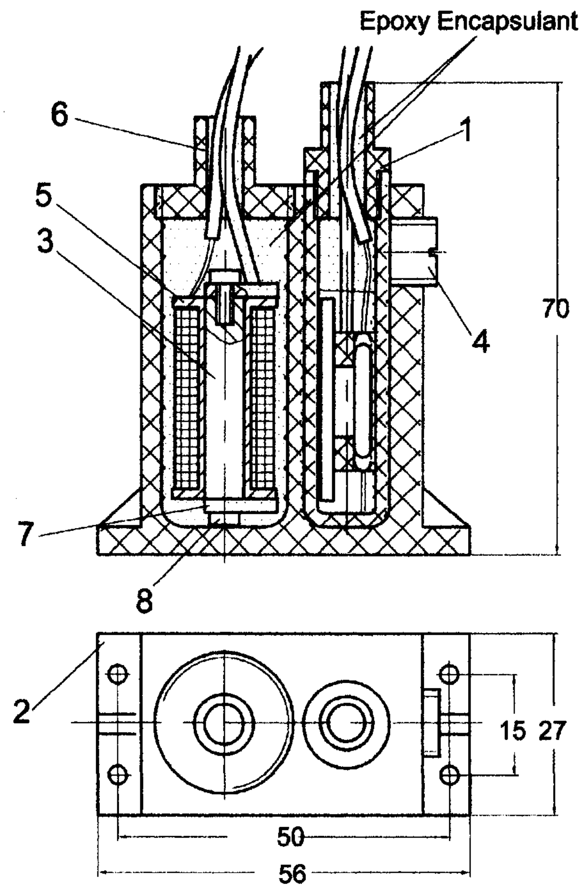

Figure 2.3 RG-25 series design for power lasers, industrial microwave ovens, medium power radar.

1, 6 – bushing; 2 – main insulator; 3 – ferromagnetic core; 4 – plastic screw; 5 – coil, 7 – polus

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The RG-75 (and RG-50) relay (Fig. 2.5) is comprised of the main insulator 1 formed as a dielectric glass, whose cylindrical part is extended beyond flange 2.

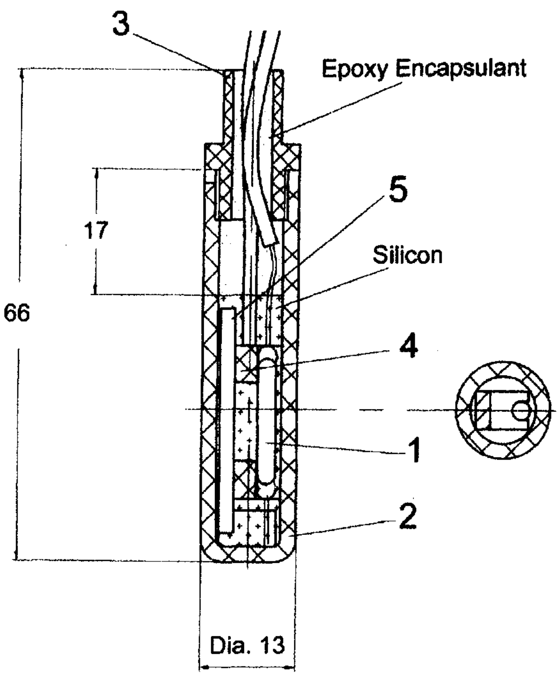

Figure 2.4 Revolving Assembly Part of RG-25.

1 – reed switch; 2 – insulator; 3 – bushing; 4 – support; 5 – ferromagnetic plate.

The flat external surface of bottom 3 of this glass smoothly mates with the extended cylindrical part 4 having threaded internal 5 and external 6 surfaces. The relay also includes control coil 7 with a Π-shaped ferro-magnetic core 8 located inside the main insulator and reed switch 9 located in an element for reed switch rotation through 90° 10. This element 10 is formed as an additional thin-walled dielectric glass with walls grading into the bottom and mating with the

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inner surface of cylindrical part 4. These mated surfaces are coated with conducting material 11. Reed switch outputs 9 are conveyed through additional insulator 12 formed as a tube extending beyond reed rotation element body 10. The lower end of this tube is graded into oval plate 13 covering the reed formed with the conducting external coating. Control coil 7 outputs are also conveyed through tube-shaped insulator 14 extending beyond the main insulator. The reed switch position fixation element is formed as disk 15 with a threaded side surface and a central hole with insulator 12 conveyed through it. External attachment of the device is effected with dielectric nut 16. Lower layer 17 of epoxy compound filling the main insulator to the control winding performs conduction by the addition of copper powder (60-70% of the volume). The rest of the filling compound 18 has been made dielectric. Element space 10 is filled with the same dielectric epoxy compound.

The shape of the main insulator and the reed switch rotation element are chosen so that their mating surfaces, which contact with the conducting coating, do not form sharp edges emerging on the main insulator surface and, at the same time, provide for safe shunting of the air layer between them and removing the thin conducting sharp-edged layer from the design.

Significantly reducing the field intensity generated by the sharp outputs of the reed switch is achieved by adding one more tube-shaped insulator extending beyond the main insulator used to convey the reed switch outputs and executing the inner end of this tube as a plate with conducting coatings covering the reed switch.

Applying the lower layer of epoxy compound, which fills the main insulator conducting space (holding the control coil with a ferromagnetic core), thus reduces the intensity of the field generated by the winding outputs and neutralizes the action of the air bubbles remaining between the coil windings.

Implementing the reed fixation element as a simple threaded disk, which is threaded into the respective part of the main insulator, forces the reed rotation element. Use is made of an additional dielectric nut threaded on the appropriate part of the main insulator as an element of the relay external attachment assembly, and the main insulator flange is used as a stop for this attachment assembly.

Device operation is based on the action of the magnetic field of the control coil (penetrating through bottom 3 of high voltage insulator 1) to reed switch 9. When the reed switch threshold magnetic flux value is attained, it becomes engaged and appropriately switches the external circuits of the installation.

The reed switch engagement threshold value is adjusted by changing its position relative to the magnetic field source. This change is effected by rotation of element 10 with reed switch 9 by an angle of 90° relative to the poles of Π-shaped ferromagnetic core 8. The position of element 10 with the reed is fixed by forcing element 10 as disk 15 is screwed in.

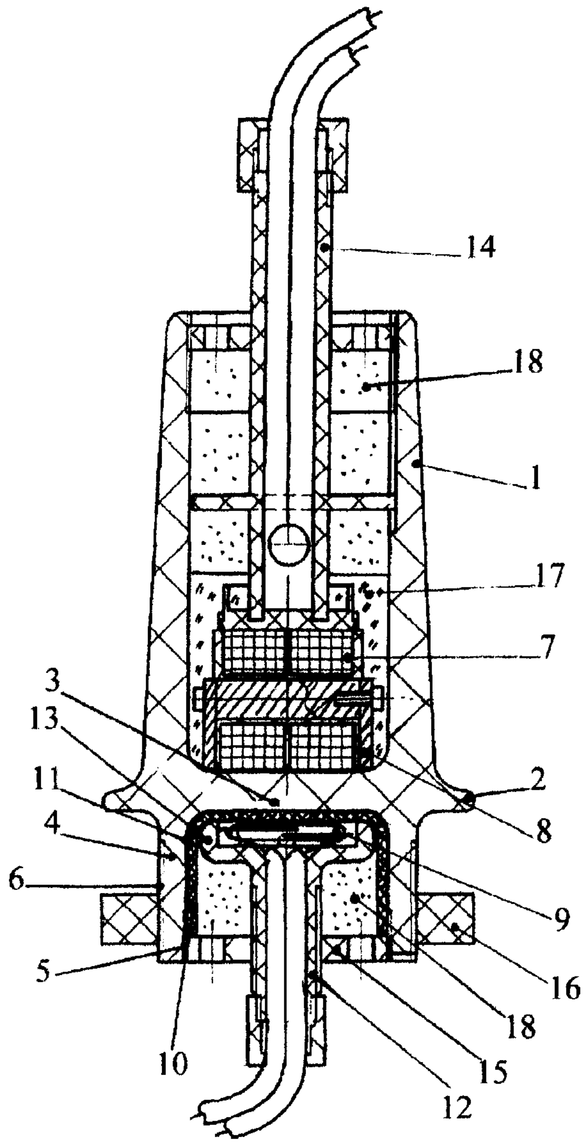

Figure 2.5 RG-75 and RG-50 series relay design.

Each device from this series functions as four separate devices:

- ***current level meter in an HV circuit***
- ***trip level adjustment unit***
- ***galvanic isolation assembly between the HV and LV circuits***
- ***fast response output relay in LV circuit***

Table 2.1 Main parameters of the RG devices

RG Relays	**RG-15** (Subtypes **A – G**)	**RG-25** (Subtypes **A – G**)	**RG-50** (Subtypes **A – D**)	**RG-75** (Subtypes **A – D**)
Nominal voltage, kV	15	25	50	75
Test DC voltage 1 min, kV	20	35	70	90
Response currents range for subtypes, A	**A**: 0.01…0.02 **B**: 0.02…0.03 **C**: 0.03…0.05 **D**: 0.05…0.10 **E**: 0.10…0.20 **F**: 0.20…0.50 **G**: 0.50…1.00	**A**: 0.025…0.05 **B**: 0.05…0.10 **C**: 0.10…0.25 **D**: 0.25…0.50 **E**: 0.50….1.00 **F**: 1.00…2.50 **G**: 2.50…5.00	**A**: 0.25…0.5 **B**: 0.5… 1.0 **C**: 1.0… 3.00 **D**: 2.0… 5.0	**A**: 0.05…0.03 **B**: 0.15… 0.5 **C**: 0.25… 2.5 **D**: 1.0…. 5.0
Limit current in control circuit with 1 s duration	Ten-fold value of the maximal response current for each version			
Control signal power, W	0.2… 0.4	0.2…0.5	0.5	0.9

Maximal switching voltage in the output circuit, V: DC AC	600 400			
Maximal switching output circuit current, A	0.5			
Maximal switching output circuit power, W	25			
Maximal response frequency, Hz	100			
Maximal response time, ms	0.5...0.8			
Control circuit parameters for different versions: R, Ohm, L, mGH	15...1300 23...400	1...600 0.12...900	0.8...50 0.26...70	0.8...50 0.26...70
Maximal dimensions, mm	∅26×47	56×27×70	∅75×150	∅75×190
Weight, g	45	130	370	620

The devices withstand the action of external environmental factors according to MIL-STD-202 requirements:

- Operation temperatures range –55 to +85°C
- Cyclical temperature change in range –55 to +85°C
- Air humidity 87% at a temperature of 40°C
- Low air pressure with high voltage applied – 87 mmHg
- Vibrations resistance 10g at an oscillation amplitude frequency in range 10-500 Hz
- Repeated shock: 55 g, duration 2 ms, 10,000 impacts
- Single mechanical impacts: 30 g/s, ½ sinusoid with duration 11 msec.

The tests were carried out in the Environmental Engineering Center of RAFAEL (Haifa, Israel), appendix 3.

The overload protection system based on RG devices was tested at Optomic Lasers (Israel) as a part of powerful industrial CO_2 type laser with the output beam power equal to 1600W.

The total time of the protection system operation was 240 hours. During this time reoccurring emergency cases were simulated. The developed protection system proved to be reliable and effective.

In additional, a protection system was built and passed over to Elta Electronics Industries (Israel) for testing as a part of a powerful ship radar system.

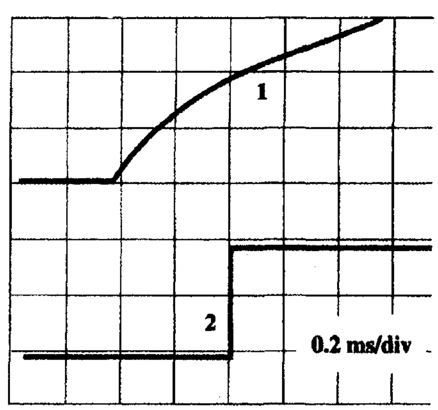

Figure 2.6 Time/Current Characteristics of RG-relay.
1 - current in a control coil;
2 - current in an output circuit.

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In current overload protection systems, the RG Relays are usually connected to the open circuit of the HV power supply between the rectifier bridge and filter capacitor, when the acting current does not exceed 10 A (pulsating current amplitude up to 30 A).

However, when the current is above 10A, they are connected to the shunt. The LV interface output is usually connected to the direct start low voltage power semi-conductor (TCDS) or "soft" start (TC-soft) contactor. The RG Relay is triggered when the current in the HV circuit exceeds the trip level, Fig. 2.6.

The RG response time depends, to a large degree, on the overload-to-nominal current ratio (I/I_{NOM}).

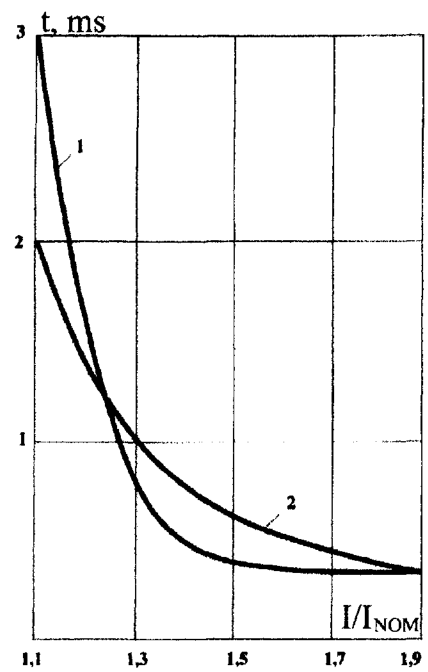

Figure 2.7 Dependence of operating time of the RG from current in the control coil.

I – operating current, I_{NOM} – nominal operating current
1 – RG for I_{NOM} = 0.25 A;
2 – RG for I_{NOM} = 3A

2.2 THE IMPULSE ACTION DEVICE

RG-PLS type devices (Fig. 2.8, 2.9) are based on impulse action, and unlike the RG devices are insensitive to the DC current value flowing through them. An RG-PLS device is operated by a drastic current change: di/dt. Moreover, a built-in filter in the RG-PLS device prevents its operation through short modulation current pulses occurring in the controlled circuit. This type of device can be adapted to different response current ranges (from fractions of amperes to tens of amperes) and have a built-in trip level controller.

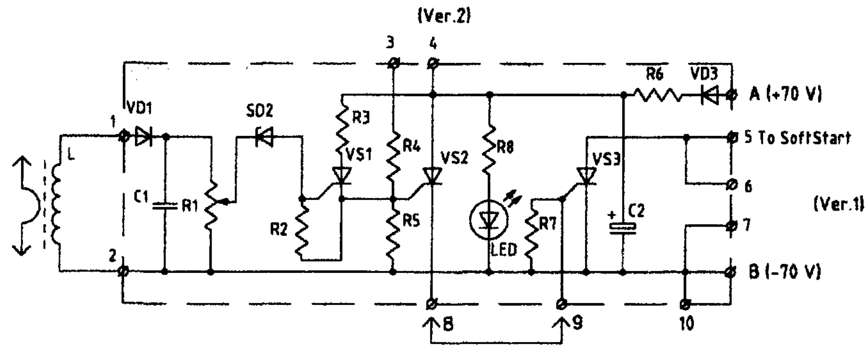

Figure 2.8 RG-PLS device circuit diagram.

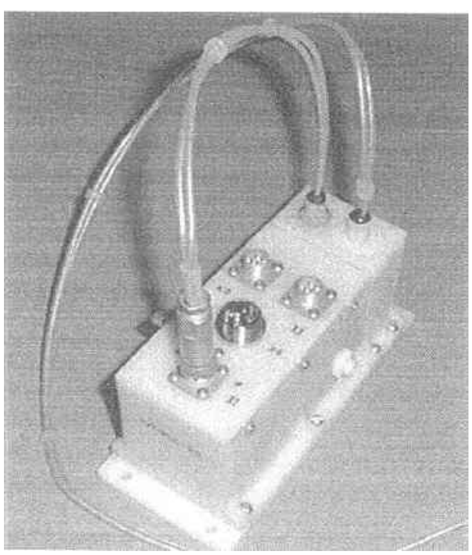

Figure 2.9 The impulse action RG-PLS-25 type device on common base plate with RG-25 device.

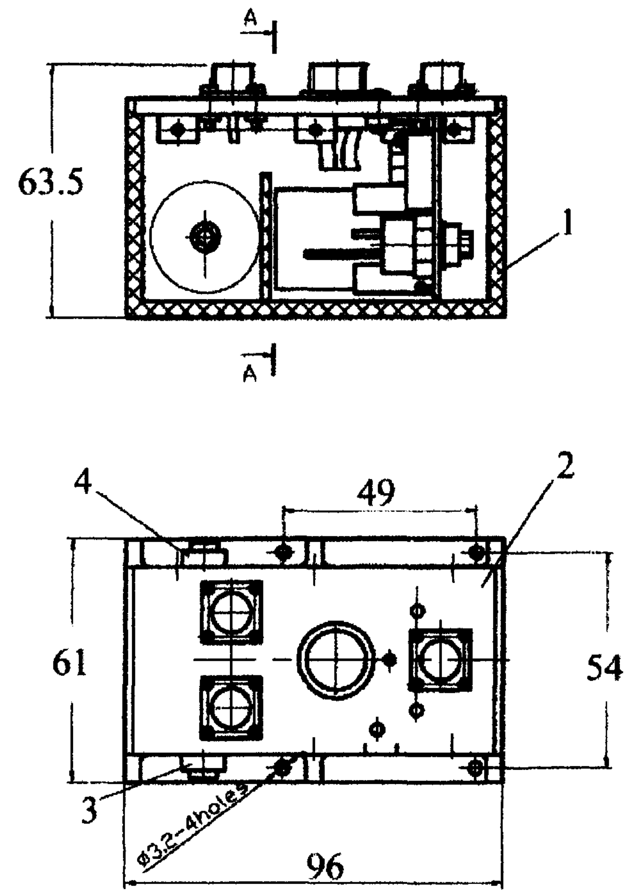

Figure 2.10 RG-PLC-25 type device drawing.
1 – insulated box; 2 – upper panel;
3, 4 – bushing for HV wire.

An RG-PLS interface can be connected to any other RG type relay (to RG-25, for example, as shown in Fig. 2.9) and either share a common output circuit that generates a strong current pulse on operation of any interface part, or have two separate outputs (an external RG relay can be connected to 3 – 4 input or 5 – 6 inputs, see Fig. 2.8).

Table 2.2 Main parameters of the RG-PLC devices

RG-PLS-_______	SUBTYPE	
	25	**50**
Nominal Voltage, kV DC	25	50
Test Voltage, kV DC	35	70
Max. Continuous Operating Current, A (rms)	10	
Over Current in Operating Circuit for 1 sec, A	50	
Maximal Time Delay, Microsecond	10	
External Power Supply: voltage, V DC current, A DC	 70...120 0.01	
Internal Resistance of Operating Circuit, Ohm	≈ 0	
Internal Inductance of Operating Circuit, mH	≈ 0	
Dimensions, mm	95 x 60 x 70	

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In the latter case, the output reed switch of the RG controls the thyristor contactor in the LV circuit, whereas the pulse RG-PLS output controls both the LV thyristor contactor and the HV thyristor short circuiting device. As a relatively slow current increases in the controlled circuit, the RG is activated and disconnects the low voltage thyristor contactor, whereas at fast current jumps with a steep front edge (typical for internal breakdowns), RG-PLS is operated and simultaneously triggers control signals to the LV contactor and the HV short circuiting device.

2.3 HV RG-SERIES INTERFACES FOR POWER ENGINEERING

The RG-24-bus device, Fig. 2.11, is designed to be used in overload protection units for 3 – 24 kV AC power networks, powerful electric motors, etc.

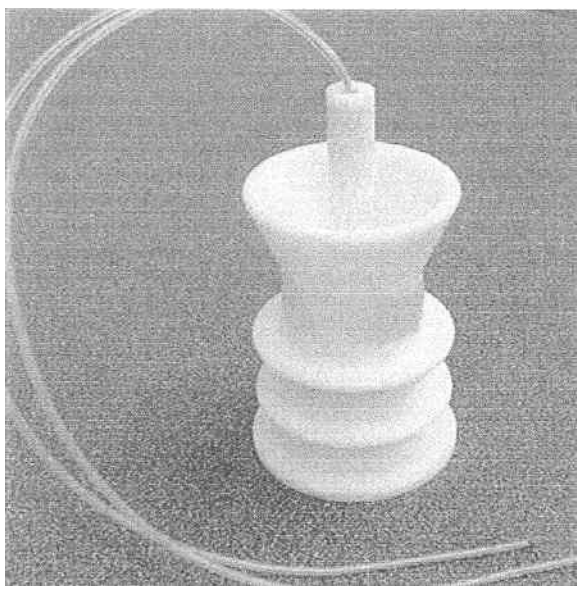

Figure 2.11 RG-24-bus device.

The device output is a 100 Hz signal with 100 – 150 V DC or a standard "on-off" type relay protection signal.

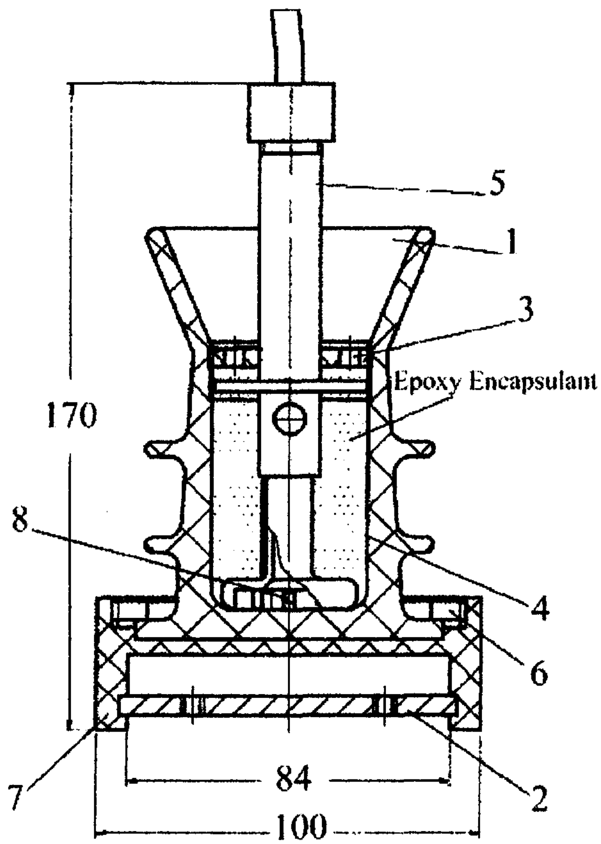

Figure 2.12 Construction of RG-24-bus device.

1 – main insulator; 2 – fixative plate; 3 – inside nut; 4 – semi-conductive cover; 5 – bushing; 6 – fixative nut; 7 – fastener; 8 – reed switch.

The device design envisages its installation directly on a high voltage current-carrying bus or cable, as well as allows for the possibility of wide range variations of the operation threshold (5 – 5000 A).

Operate time – 1 ms.

The main advantage of these devices, as compared to those available on the market, is their possible direct installation on HV buses and output connection to low voltage automatic circuits. Medium voltage compact switchboard and switchgear cubicle systems (including SF_6 filled) can be significantly improved by using these devices.

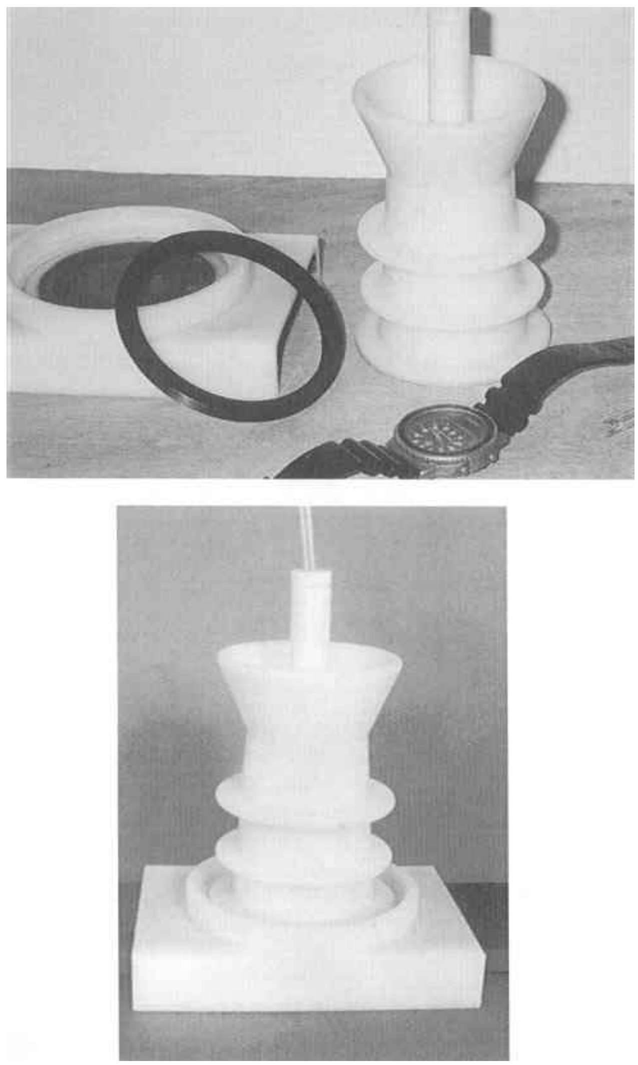

Figure 2.13 Installation of RG-24-bus device on a high voltage bus bar.

Built-in fault detectors and other automatic systems can now be produced as factory-standard equipment and at affordable prices and are obtained without any alteration whatsoever of the HV equipment design.

A high voltage analog output current transducer can be made based on an RG-24-bus device (by using a coil instead of a reed switch) and is intended for direct measurement of current in HV bus bar or wiring. The output signal (voltage or current is linear and directly proportional to bus bar current, see Fig. 2.14).

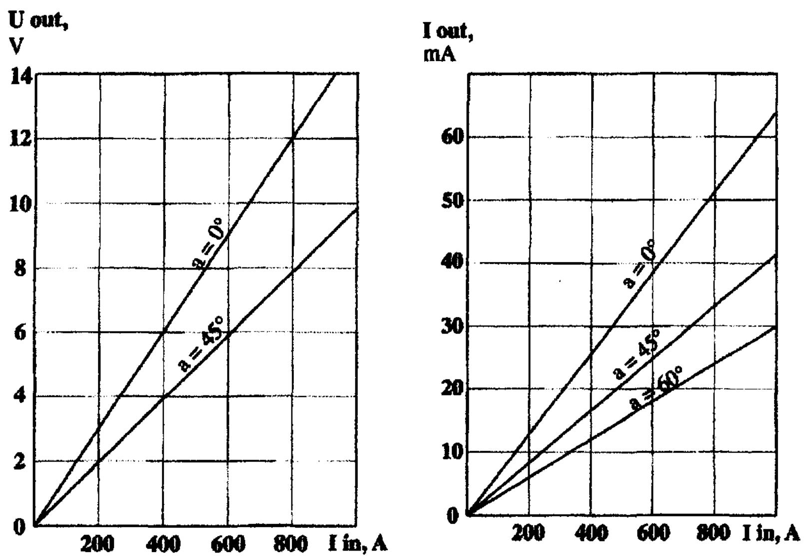

Figure 2.14 Typical characteristics of the analog output current transducer on an RG-24-bus device base.

The linear function slope is proportional to the transducer's relative angle position (angle "a") on the bus bar.

The transducer output may be connected to any electronic measurement device.

2.4 SPECIAL RG-RELAY-BASED DEVICES

2.4.1 Relay Responding to the Current Change Rate

In circuits with load varying in a wide range a need in protection devices distinguishing between emergency and load increase regime is generated. For this purpose high voltage RG-relay with additional winding 3 and additional RC-circuit (4 and 5) can be used (Fig. 2.15).

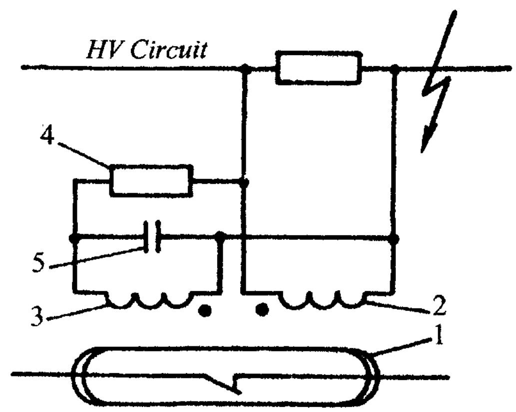

Figure 2.15 Circuit diagram for RG-relay responding to the current change rate.

In this device the magnetic fluxes generated in windings 2 and 3 are opposing and compensate for each other, moreover, all the changes in magnetic flux generated by winding 3 are delayed in time relative to the magnetic flux of main winding 2. When the current increase in the device input circuit is relatively slow, magnetic flux of additional winding 3 has the opportunity to compensate for the magnetic flux of main winding 2, thus reed switch 1 is not operated even if considerable current increase occurs.

Upon fast current jumps in the input circuit the magnetic flux in the main winding remains uncompensated and the reed switch has the time for a short-term switching before the magnetic fluxes in the both windings become balanced. In order to provide for steady balance the reed switch can be connected to a thyristor or latching relay circuit.

2. 4.2 Differential RG-relay

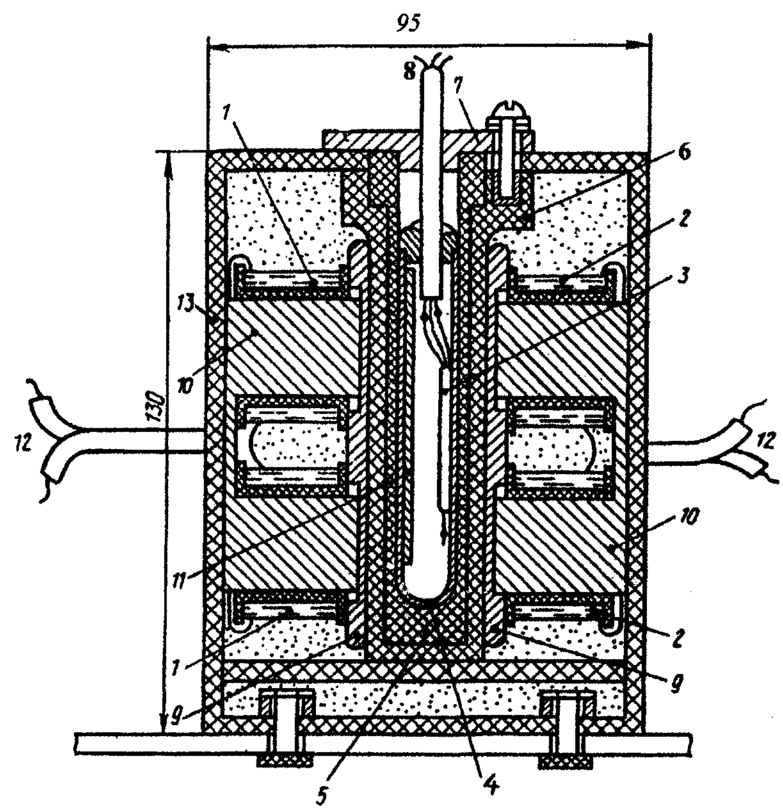

Figure 2.16 Differential RG-relay.

1, 2 – differential windings, 3 – reed switch; 4 – aluminum capsule; 5 – internal insulator; 6 – immovable insulator; 7 – limb with fixing unit; 8 – reed switch leads; 9 – aluminum shields; 10 – ferromagnetic cores; 11 – ferromagnetic shield; 12 – differential inputs (HV cables); 13 – insulated body frame, filling with epoxy compound.

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The reed switch used as a final control output element in this device (Fig. 2.16), is switched when a difference in the magnetic fluxes generated by the two differential windings occurs.

When internal insulator 5 is turned together with asymmetrically mounted reed switch 3, the relative position of the reed switch to the windings is changed: it is drawn to one of them and withdrawn from the other. As a result the reed switch sensitivity to the signals of either one of the inputs becomes different.

The device can be used also for summation of signals from two inputs.

2.4.3 RG-relay-based Device for Current Measurement in High Potential Circuits

In this device (Fig.2.17) reed switch is switched under the sum of magnetic fluxes generated by the current measured in high potential circuit (winding 2) and the magnetic flux in winding 3, which is smoothly increased when source 6 is activated.

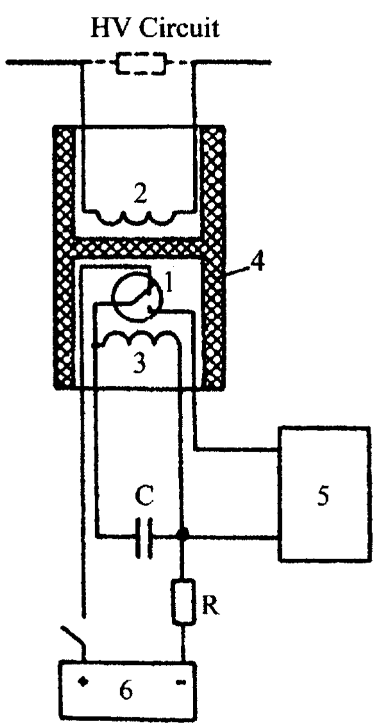

Figure 2.17 RG-relay based device for current measurement in high potential circuits.

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When the sum of these magnetic fluxes becomes equal to the magnetomotive force of the reed switch operation, it is switched and connects capacitor C to voltmeter 5.

Given the reed switch operation magnetomotive force, which is stable in time, the voltage measured with voltmeter 5 provides a quite unique current value in the high potential circuit. In order to revert the device to its initial position power supply 6 must be disconnected.

For continuous current monitoring in the high potential circuit a second type of device containing a low frequency saw-tooth voltage generator (6) as a power supply is used (Fig. 2.18)

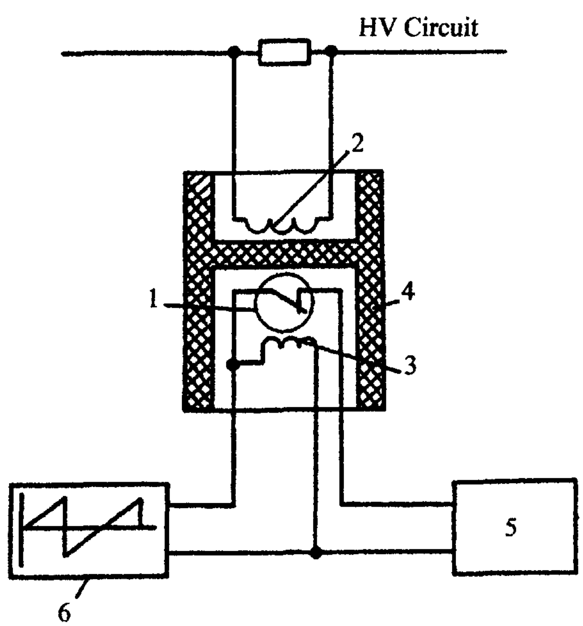

Figure 2.18 RG-based device for continuous current monitoring in high potential circuit.

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2.4.4 The Use of Spark-Arresting Circuits for Reed Switches in DC Circuits

Without going into detailed classification of the principles of spark-arresting circuits designed for low voltage low-powered DC contacts (according to switching type, composition of bypass circuit, the use of auxiliary switching contacts etc.), two groups can be pointed out: active and passive spark-arresting (arc - arresting). The first group contains devices having active electronic elements such as transistors and thyristors. The other group offers the contacts shunting (bypassing) with spark-arresting circuit containing a capacitor and a resistor (linear, non-linear or a combination of both).

The simplest way of passive arc arresting on contacts switching a DC circuit with inductance is to bypass them with an active linear resistance R, Fig. 2.19a.

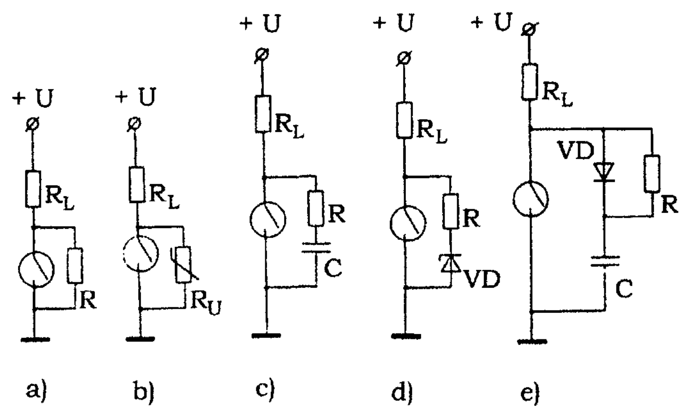

Figure 2.19 Embodiments of passive arc-arresting circuits for the DC circuit contacts.

In order to limit over-voltage at switching the R-value must meet the requirement:

$$R \leq \frac{U_{BR} R_L}{U}, \tag{2.1}$$

where U_{BR} - minimal value of breakdown voltage between contacts.

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If control winding of electro-magnetic devices (relays, contactors) is used as the discussed contacts load (e.g. power amplifier), the following condition must be preserved for safe release of this device:

$$R \geq \frac{K_R R_L (1 - K_S)}{K_S}, \tag{2.2}$$

where K_R - return coefficient of electromagnetic device used as a load;
K_S - device release safety factor.

Substitution of standard coefficient values $K_R = 3$ and $K_S = 2$ to (2.2) will yield $R \approx 5\ R_L$. With lower resistance value the mentioned electro-magnetic device is not switched off upon contacts breaking, moreover the arc arresting becomes inefficient as the resistance is increased. In this case it is very advantageous to use a non-linear resistor - varistor (Fig. 2.19b), or Zener doide included in this circuit and acting in a similar way (Fig. 2.19d), featuring high resistance in the initial state which is automatically reduced with the increase of the voltage applied to them.

Often the scheme with resistor-capacitor circuit shown in Fig. 2.19c provides for adequate arc-arresting only for low values of R:

$$R < \frac{R_L U_{BR}}{U}$$

However, in this case the switching contacts will be subjected to overload caused by the capacitance discharge current at the instant of contacting and are due to be welded.

The circuit illustrated in Fig. 2.19e is the most advantageous in the discussed group of circuits. At contact breaking capacitor C is rapidly discharged via very low resistance of direct diode junction VD, bypassing the contacts and preventing generation of electric arc over them. In contacting process the charged capacitor is discharged via resistance R that limits the discharge current to the value safe for the contacts. The use of film-type capacitors with capacity of 1-2 μF and working voltage of 630 V and resistor of about 500 Ohm allows for the use reed switches for controlling of intermediate relay windings, contactors with nominal voltage up to 220 V DC.

Experimental study of this circuit with high-inductivity big electromagnetic coils used as a load showed that quick and efficient arresting of the arc process across the contacts at the instant of contact breaking results in considerable overloads across the load, (in this case 440 V at power supply voltage of 75 V), Fig. 2.20.

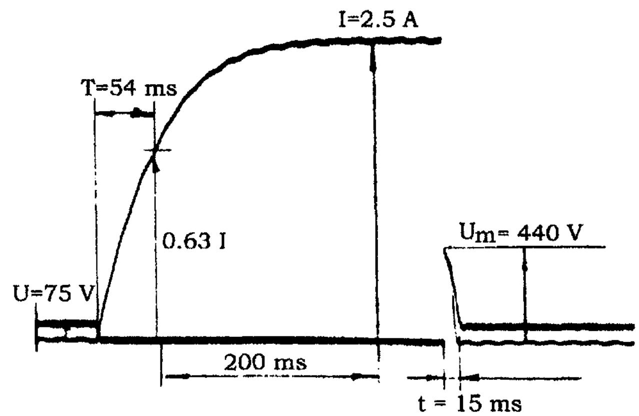

Figure 2.20 Switching process oscillogram in control coil circuit of powerful electromagnetic coil with arc-arresting circuit shown in Fig, 2.19b. Nominal supply voltage U = 75 V. Nominal current I = 2.5 A. Time constant of the switched circuit T = 54 sec.

Therefore in this case one varistor is to be connected in parallel to the load and the other one - in parallel to the capacitor, Fig. 2.21.

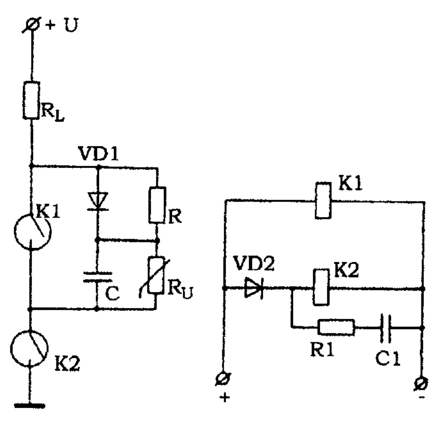

Figure 2.21 Arc-arresting device circuit for switching of high-power inductance loads.

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If for some reason (say for safety reasons) varistor cannot be left permanently connected in parallel to the contacts, an auxiliary relay K2 can be connected in the device, engaged with a certain delay relative to switching contacts K1. This delay is provided with the standard R1C1 circuit.

If necessary, additional relay R2 with an RC-circuit must be connected in the active arc-arresting device for safe galvanic decoupling of load circuit (Fig, 2.22).

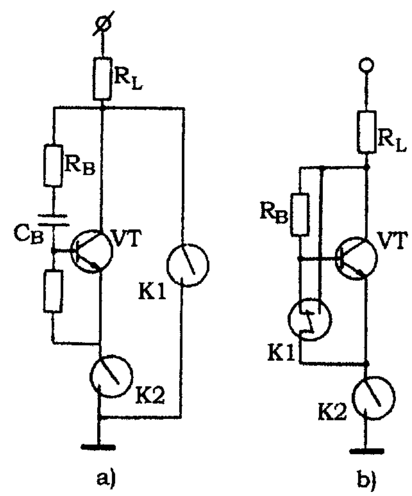

Figure 2.22 Active type arc-arresting device circuits.

In the device illustrated in Fig. 2.22a at contact K1 breaking the VT transistor collector-emitter junction is bypassed along with capacitor C_B charging circuit, which provides for current flow in the transistor base, hence it becomes opened till saturation is reached shunting the contact during switching. After the capacitor is charged the transistor is cut off (since the base current flow ceases) and contact K2 can be cut off without current.

Circuit illustrated in Fig. 2.22b does not have a capacitor. When a control signal is generated, contact K2 is closed and then contact K1 is switched, allowing for current flow in the load. During this time period the transistor is cut off because of collector-emitter junction shunting. As signal to control coil K1 is removed the contact is returned to its initial state in which the transistor is also cut off, then contact K2 is disconnected with very low current (limited with high resistance resistor R_B) de-energizing the load. In this device the transistor is activated only during contact K1 switching, providing for arcless commutation.

In both the examined circuits the transistors are activated in single short pulses regimes and at low commutation frequency can be operated without radiators, however, when working voltages are increased to 250 V, transistors with allowed collector-emitter voltage of 500-800 V shall be used; moreover at switching of high inductivity load it must be bypassed by a varistor.

3

High-Voltage Switching Devices

3.1 HV RELAY "GOLIATH" SERIES

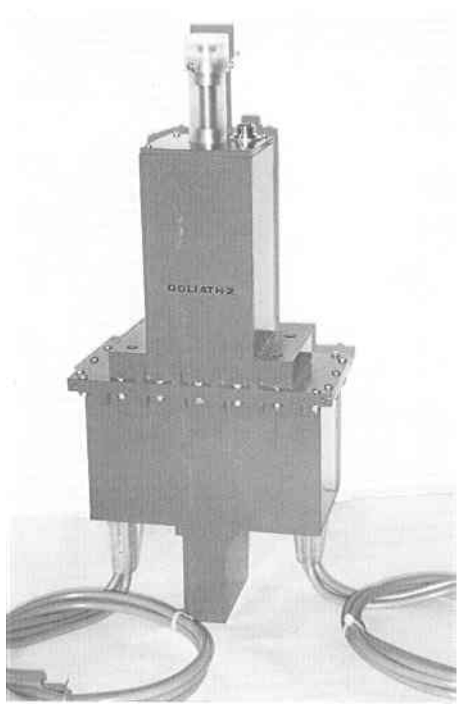

Figure 3.1 HV relay "Goliath" series.

"Goliath" is a new type of high performance commutation device with the following unique characteristics : high voltage, low cost and small size (see below).

"Goliath" design includes a minimal number of components with no need for vacuum technology, while assuring reliable operation at low cost.

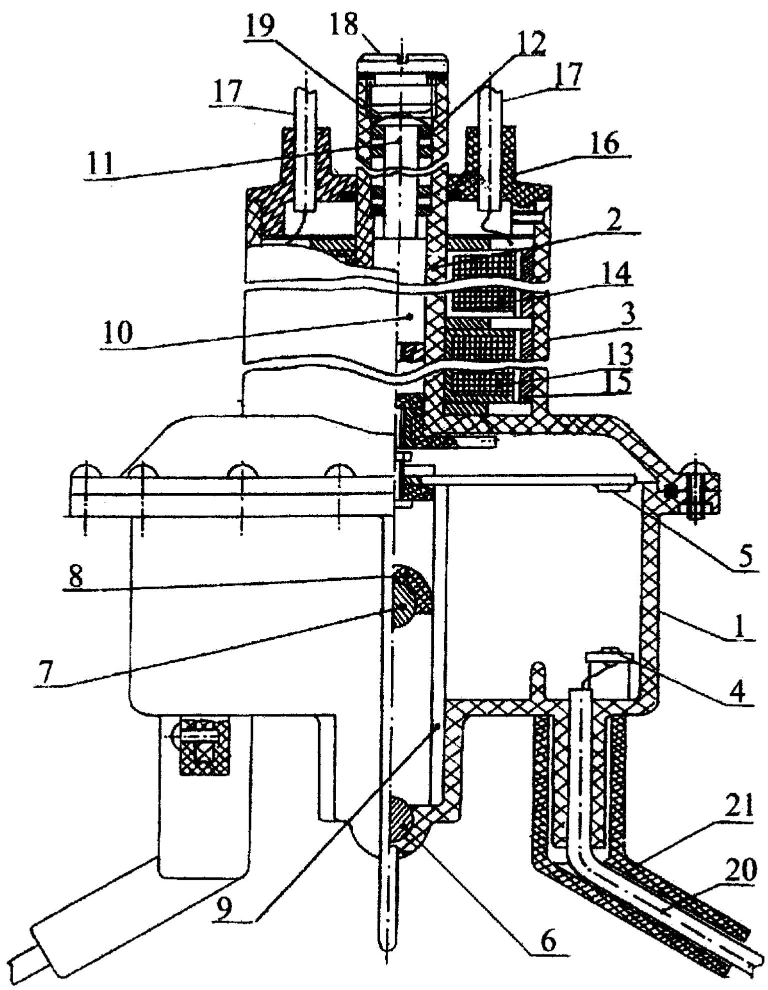

Figure 3.2 "Goliath" device design.

"Goliath" can be switched ON or OFF (fixed position) by control signals and consumer energy only during transition time. Actual position of the switch may be indicated by a LED on the operator's control console.

The "Goliath" high voltage relay consists of a dielectric body formed with two isolated compartments: big compartment 1 for contact systems and small compartment 2 for magnetic systems, and one more insulated open compartment 3, which is concentric with small compartment 2. In big compartment 1, symmetrically positioned are two fixed contacts 4, mobile bridge-type contact 5, fixed magnet 6 and mobile magnet 7 fixed in housing 8, which is connected to the central part of bridge-type contact 5. This housing 8 enters special guides 9 that limit the degrees of freedom of housing 8. From the other side of the central area of bridge-type contact 5, a dielectric rod is attached (having a certain clearance) with ferromagnetic core 10 fixed to its other end. Permanent magnet 11 with steel bushings 12 is located in small compartment 2, which is free to move in the upper part of compartment 2 along its longitudinal axis by 1-1.5 cm. Two control coils 13 (the lower) and 14 (the upper) mounted in compartment 3 and provided with magnetic circuits 15 are located in open concentric cavity 3. With the control coils mounted in compartment 3, it is filled with epoxy compound and covered with cover 16 having partition insulators with outputs 17 formed as wires with high voltage insulation drawn through them.

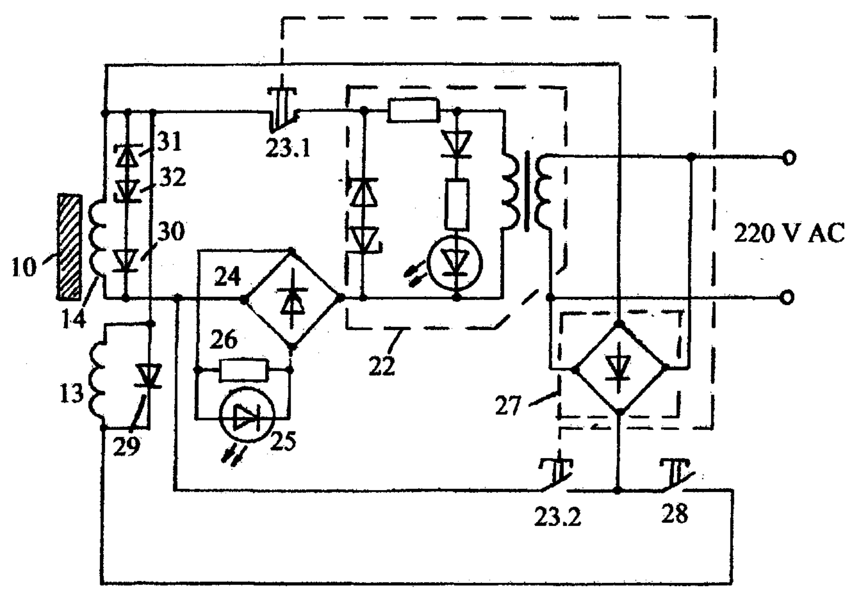

Figure 3.3 Circuit diagram of "Goliath" control unit.

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The ferromagnetic core 10 is 20-30% longer than the control coils. Small cavity 2 is closed with threaded plug 18. Buffer 19 such as a disk spring is placed between this plug and magnet 11. The outputs of the fixed contacts are formed as high voltage wires 20 drawn through partition insulators 21.

Upper control coil 14 is connected to the first stabilized AC power supply 22 via break contact 23.1 of the "STOP" button and rectifying bridge 24. The light diode is connected at the bridge output 25 shunted with resistor 26. The same control coil 14 is connected to the second DC power supply 27 via closing contact 23/2 of the same "STOP" button. Lower control winding 13 is connected to DC power supply 27 via closing contact 28 of the "START" button.

Both control windings have spark-protecting circuits. In winding 13, this circuit is formed with diode 29. In winding 14, a circuit is formed with diode 30 connected in series with Zener diodes 31 and 32, whose stabilization voltage exceeds the voltage of stabilized AC power supply 22.

The device operation is as follows:

With external power supply cut off, the relay can be in one of its extreme positions: (a) either engaged when core 10 with contacts 5 are in their lower position and magnet 7 being attracted to magnet 6 fixes this position and generates the required contact pressure, or (b) disengaged when core 10 with contacts 5 and magnet 7 are in their upper position, which is fixed owing to core 10 attraction to permanent magnet 11.

When the switch is disengaged, a small alternating voltage from stabilized power supply 22 is applied to upper winding 14. The current in this coil is very small owing to the high inductive reactance of winding 14 with core 10 enclosed in it. Voltage drop on resistor 26 is insufficient to illuminate light diode 25.

The device is started by pressing and releasing "START" button 28. As a result, lower winding 13 is momentarily connected to DC power supply (rectifier) 27. The magnetic field generated by this winding detaches core 10 from permanent magnet 11 and imparts a motion pulse to the core. As a result, the core quickly moves downward, carrying away contacts 5 and magnet 7 coupled with it. As fixed contacts 4 are attained and the velocity is reduced by the elasticity of the spring located at the center of the bridge that interconnects contacts 5, core 11 and all the mobile elements connected to it are stopped in the lower position so that a few millimeters gap is left between magnets 6 and 7. Mutual attraction between magnets 6 and 7 prevents the springing back of contacts 5 from contacts 4 at their initial touch, providing for the required contact pressure and fixation of the mobile device elements in the lower position. As core 10 leaves upper winding 14, its inductive reactance is considerably reduced, and the current is increased, illuminating light diode 25, which induces the device activation.

The device is switched off by pressing and releasing "STOP" button 23. As a result, upper winding 14 is disconnected from AC power supply 22 (contact 23.1) and is connected to DC power supply 27 (contact 23.2).

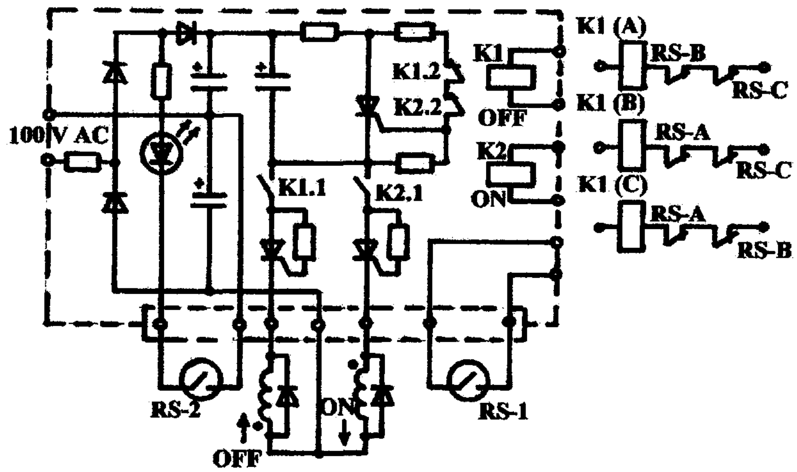

Figure 3.4 Circuit diagram of single "Goliath" control unit when three-channel (**A, B, C**) switch-gear is assembled from separate "Goliath" units.

K1 – control relay for inside command "OFF";
K2 – control relay for inside command "ON";
RS-1 (blocking) and RS-2 (indication) – inside reed switch contacts sensitive to "Goliath" ferromagnetic core position.

As the movement pulse is damped, the mobile relay elements together with magnet 11 are lowered under gravity and, owing to spring 19 elasticity through magnet 11, allowed clearance. It remains in this position waiting for the relay engagement command.

Spark-protection circuits formed with components 29-32 protect the contacts of buttons 23 and 28 from electric erosion resulting from switching windings 13 and 14, characterized by considerable inductivity.

The magnetic field generated in this winding acts on core 10 and imparts a motion pulse owing to which magnet 7 is detached from magnet 6 and, together with contacts 5, quickly moves upward until core 10 reaches permanent magnet 11. Since the magnet is not fixed permanently and can move along the axis, inelastic impact of core 10 on magnet 11 is prevented, so that after they come in touch, their joint movement is preceded and damped by spring 19 elasticity.

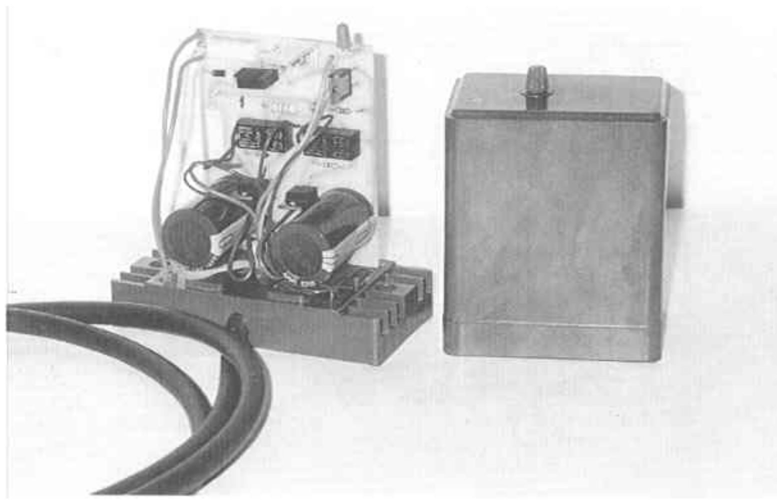

Figure 3.5 Single (one channel) "Goliath" control unit for three-channel switch-gear.

"Goliath" Main Parameters:

Max. Switched Voltage, kV AC (rms)	60
Dielectric Strength, kV AC (rms)	120
Max. Continuous current through closed contacts, A (rms)	100
Current Spike (for 20 ms duration), A	1500
Control Voltage, V DC	12, 24, 110
Control Power, W	5
Min. Control Pulse Wight (duration), sec	0.5
Operate Time, ms	50

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Temperature Range, °C	-10 +55
Dimensions, mm	235 x 95 x 435
Weight, kg	5.2

"Goliath" can be used in various applications where low cost, reliability and small dimensions are needed (for example, in power distribution networks for single-phase ground fault detection, as a component of a portable laboratory for carrying out field testing of HV power networks and other HV installations).

A 100 kV "Goliath" test specimen has been manufactured. The specimen has successfully passed testing as a component of a traveling HV laboratory (in a motor car) and also can be used in powerful radio transmitters, electro-physical units, in test beds and HV technological applications.

3.2 HV SOLID-STATE SWITCHING DEVICES HVTS SERIES

HVTS-series devices are used for protection of HV power supplies in cases of insulation breakdown in high voltage circuits. It is a fast-response single-pole switch, providing fast energy evacuation from the reactive filter elements of a HV power supply.

They are designed for operation with nominal voltages in the range of 5 to 25 kV and maximum discharge currents up to 10 kA (for 10 ms duration).

HVTS series devices can be operated with RG-PLS-25 type devices (Fig.2.10) or with RG-series devices (Fig. 3.9) or with a separate control unit.

HVTS-type devices are designed for fast energy removal from the reactive filter elements mounted at the HV side of the power supply and can also be used for generation of high power pulses.

The HVTS is connected in parallel to the HV power source output, Fig. 3.11.

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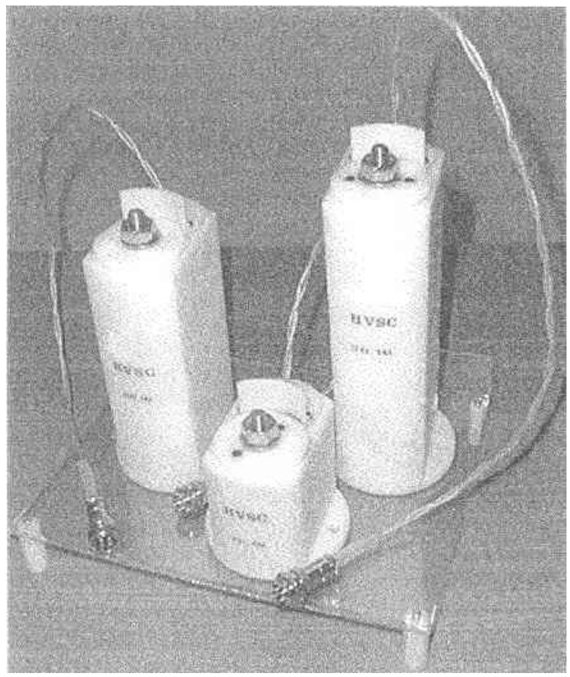

Figure 3.6 High voltage switching devices HVTS-15, HVTS-5 and HVTS-25 for voltages 15, 5 and 25 kV, respectively, and switching current up to 5 kA.

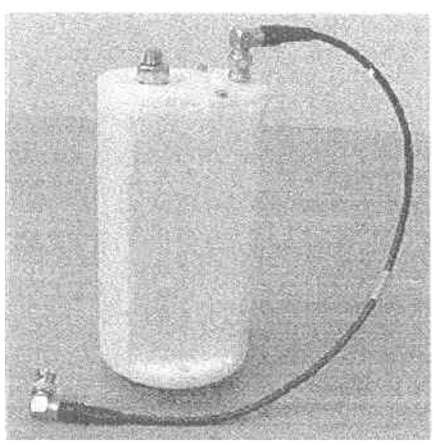

Figure 3.7 HVTS-2-15 series device for 15 kV and switching current up to 10 kA.

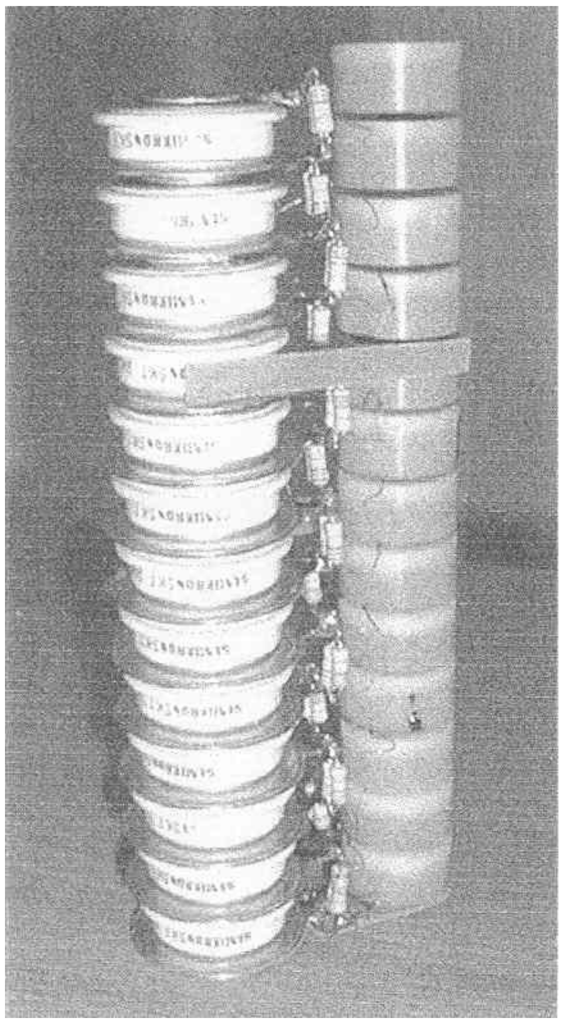

Figure 3.8a Internal design of the HVTS-series devices.

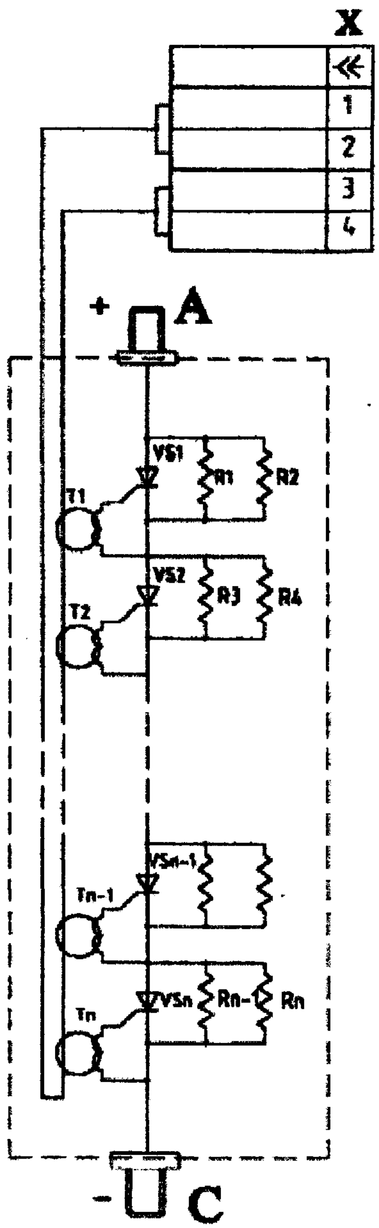

Figure 3.8b Circuit diagram of the HVTS-series devices.

R1 to R_N – special high voltage high ohmic resistors;
T1 to T_N – epoxy encapsulated HV pulse transformers.

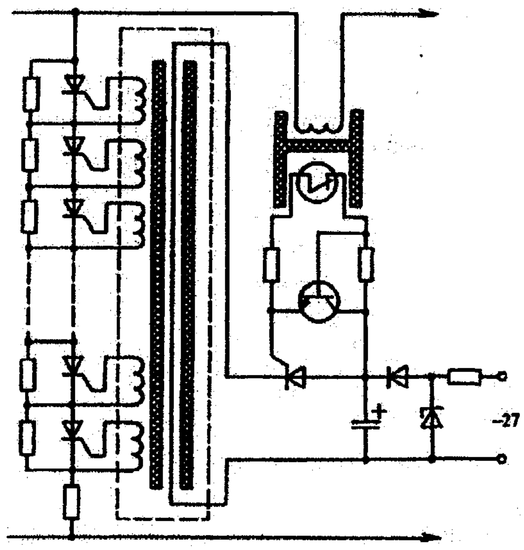

Figure 3.9 Circuit diagram of HVTS device, operated with RG-series relay.

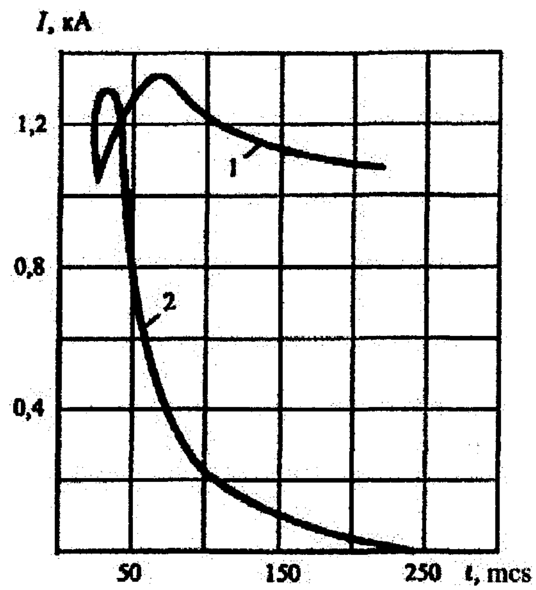

Figure 3.10 Discharge characteristic of HVTS device:

1 – current in a control circuit;
2 – discharge current

(capacitor 5 μF, voltage 15 kV, ballast resistor 10 Ω).

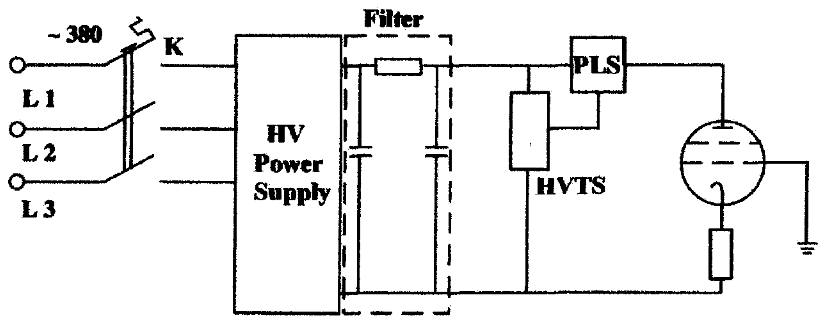

Figure 3.11 HVTS connection to HV power supply.

Table 3.1 Main parameters of the HVTS-series devices

HVTS________	SUBTYPE						
	5	**8**	**11**	**15**	**17**	**22**	**25**
Nominal Voltage, kV DC	5	8	11	15	17	22	25
Test Voltage, kV DC	7	10	15	18	20	25	27
Breakdown Voltage, not less, KV DC	9	13	18	22	22	29	31
Maximal Current, kA	5.0 (for 10 ms)						
Turn-ON Time, μs	10						
Dimensions, mm	90x60 x100	90x60 x130	90x60 x160	90x60 x200	90x60 x215	90x60 x230	90x60 x245
Weight, kg	0.9	1.15	1.3	1.6	1.95	2.3	2.5

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Energy removed by these devices is higher than the energy of the known gas discharge and vacuum switch.

The total response time of short circuiting HVTS-type devices driven by RG-PLS interfaces does not exceed 30 microseconds.

3.3 HV REED SWITCH BASED COMMUTATION DEVICES

With high-voltage (5 kV) vacuum reed switch contacts available in the market, a low cost commutation device for 25 - 30 kV and current up to 3 A can be constructed.

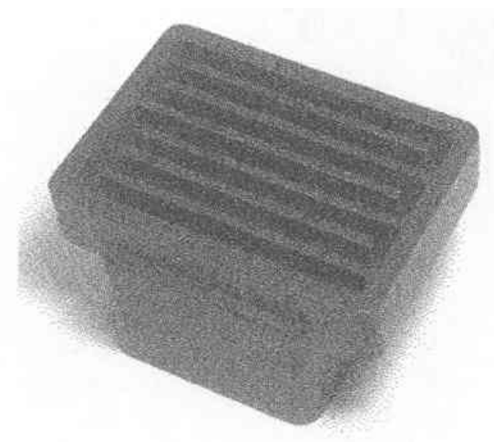


Figure 3.12 Insulation body with individual cells for each reed switch connected in serial.

All reed switch contacts in this device are connected in series. Each of these contacts is located in a special cell in the insulation body, Fig. 3.12, filled with an epoxy compound.

The control unit of the device provides current-free commutation of a high-voltage circuit: disconnected HV power supply (2, 3) from a low voltage network before commutation HV load 1, and restored low voltage circuit after commutation of HV load.

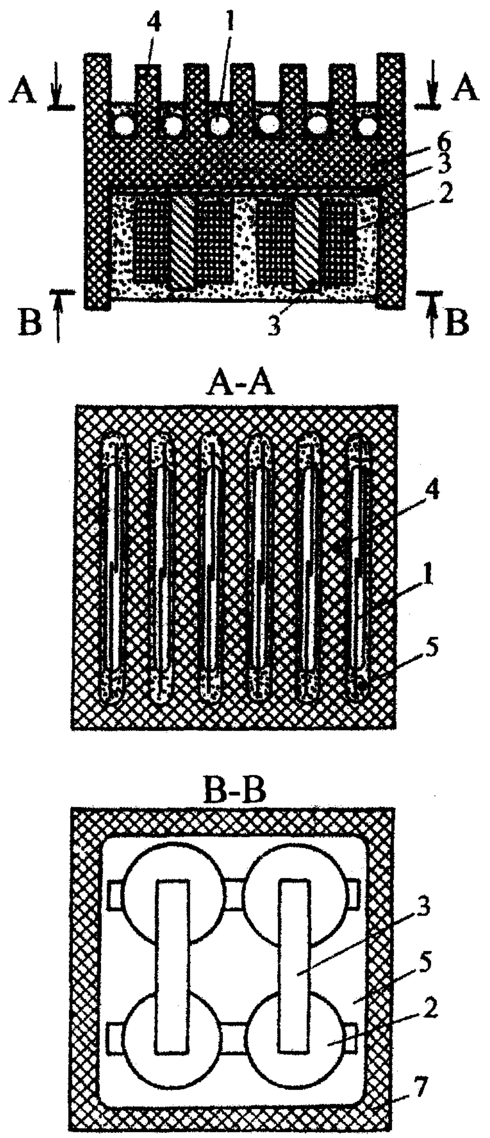


Figure 3.13 HV reed switch based commutation device.

1 – HV reed switches;
2 – operation coils;
3 – ferromagnetic core;
4 – insulation walls between cells;
5 – epoxy compound;
6 – insulation wall between reed switches and coil;
7 – insulation body.

The control unit of the device, Fig. 3.14, provides current-free commutation of a high-voltage circuit: disconnected HV power supply (2, 3) from low voltage network before commutation HV load 1 and restored low voltage circuit after commutation of HV load.

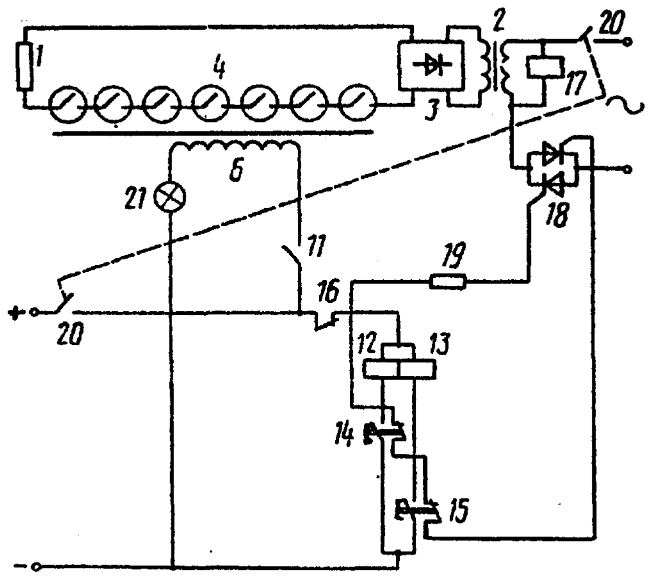


Figure 3.14 Circuit diagram of control unit for reed switch based commutation device.

The problem of the switching capacity increase can be generally solved also by reed switch synchronous commutation – for the AC application, and by putting the reed switch into the control circuit of the solid-state (amplifying) key – for the DC and AC applications.

3.4 HYBRID HV COMMUTATION DEVICES

The arc-free high voltage commutation device, Fig. 3.15, consists of the synchronizer SYN; two RG-relays H1 and H2, based on HV reed switches (5 kV); and diode chain VD3. The output reed switch in the RG-relay can be either of the NO or NC type. In the first case, arc-free commutation is realized through the following sequence:

H1 is closed when the VD3 cathode potential is positive. The reed switch conducting only the reverse current of the diode. H2 closes when VD3 cathode potential is negative, the reed switch being shunted by VD3.

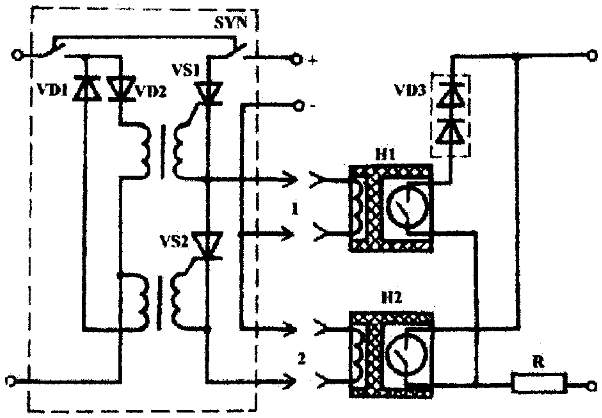


Figure 3.15 The arc-free hybrid high voltage commutation device.

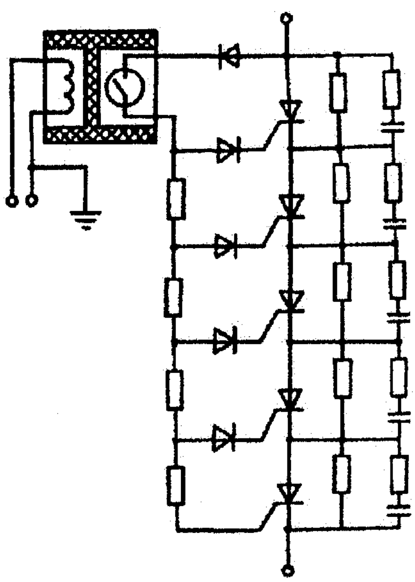


Figure 3.16a Hybrid HV commutation devices for AC applications.

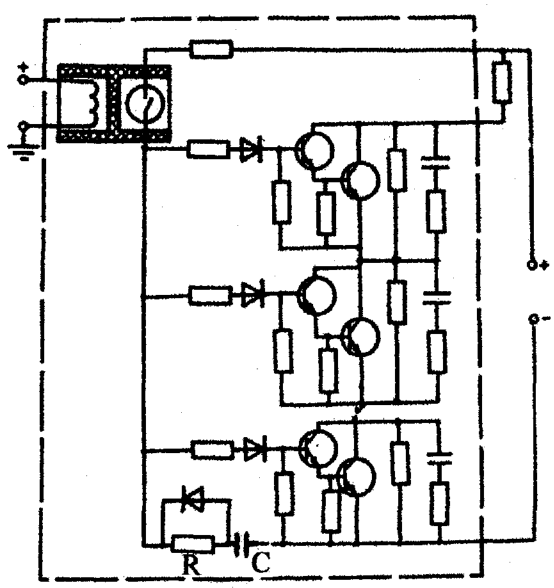


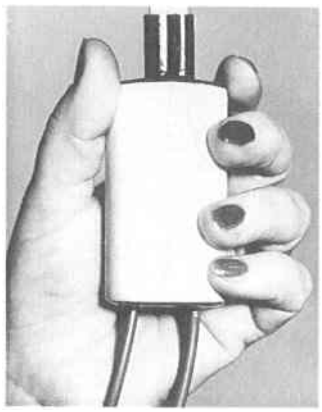
Figure 3.16b Hybrid HV commutation devices for DC applications.

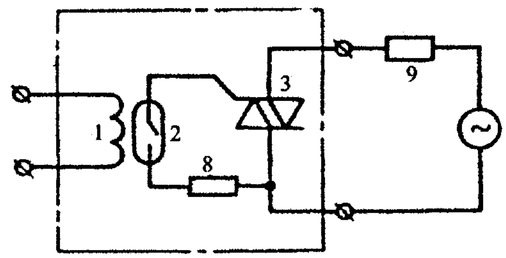
R and C - the additional RC-chain for current pulsations prevention, caused by the reed switch transient bounce (and amplified by transistor) to the output (load) signal.

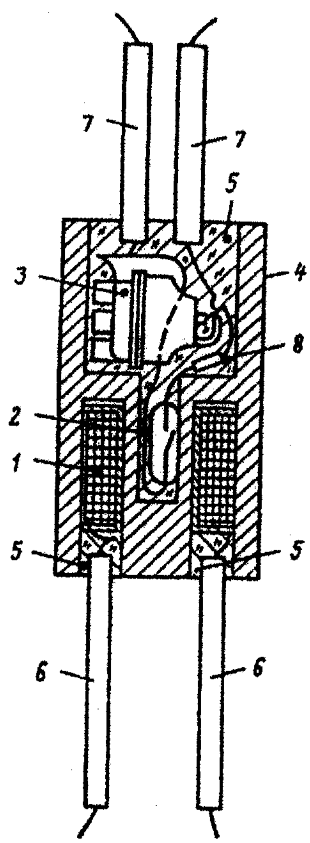
In the second case, the synchronization sequence of H1 and H2 is reversed. The synchronization is provided by the synchronizer, which includes the AC half-wave polarity identification module based on VD1 and VD2 diodes and the sequence synchronization module based on VS1 and VS2 thyristors. The sequence synchronization module provides that the signal to output 1 is applied prior to output 2. The switching capacity of the device is 0.5 A at 10 kV. The dimensions are 130 x 95 mm.

The hybrid (reed – solid-state) HV commutation devices can be designed for AC applications (with thyristors), Fig.3.16a, and DC applications (with transistors), Fig. 3.16b.

A very simple hybrid device with HV galvanic decoupling (10 – 25 kV) can be made on a triac, reed switch and special form insulator, Fig. 3.17. This device can be use for loads up to 500 – 800 W.







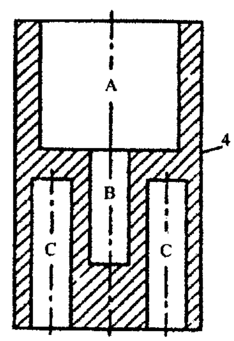


Figure 3.17 A simple hybrid commutation device with HV insulation:

1 – control coil;
2 – reed switch; 3 – SCR or triac;
4 – HV insulator (plastic or ceramic) with three cavities;
5 – epoxy compound;
6, 7 – HV wires;
8 – resistor;
9 – load.

The powerful hybrid reed – thyristor commutation devices can be based on the anti-parallel thyristor couple, Fig. 3.18.

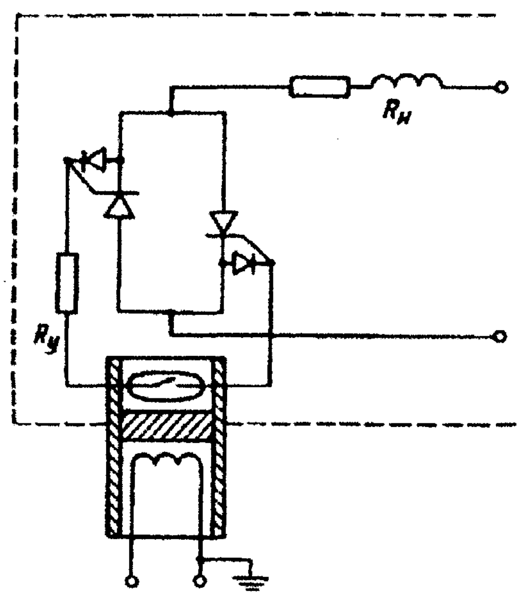


Figure 3.18a The powerful commutation device based on the anti-parallel thyristor couple.

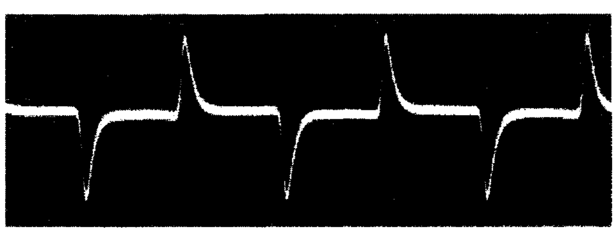


Figure 3.18b Current form through reed switch in powerful commutation device.

In this case, the current through the reed switch is a short duration triangular pulse series, which appears at the beginning of each positive half-wave, Fig. 3.18b.

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Therefore, the switching capacity of the reed switch can not be based on the nominal value of the control thyristors current, but rather on the integral equivalent intermittent current defined by the following expression:

$$I_R = 0.5 I_i \sqrt{\frac{1 - \exp\left(\frac{tp}{\tau}\right)}{1 - \exp\left(\frac{-(tp + ts)}{\tau}\right)}} \qquad (3.1)$$

where

I_i – max value of the intermittent current;
tp, ts – duration of the I_i pulse and space;
τ - reed switch heating time constant.

The above mentioned equivalent current can be represented by:

$$I_E = \sqrt{\frac{1}{n}\frac{\sum t}{\sum_1 t}\int_0 i^2 dt}$$

assuming that the pulse current is linear with respect to time, i.e.,

$$I_p = \alpha t$$

Where $\alpha = I_{OP}/t = const$ and I_{OP} – is the nominal opening current of the thyristor, the following is obtained:

$$I_E = \sqrt{\frac{\int_0^t a^2 t^2 dx}{t}} \qquad (3.2)$$

This later expression evaluates to $3^{1/2}\, I_{OP}$. By plugging (3.2) into (3.1), the following is obtained:

$$I_R = I_{OP} / 2\sqrt{3},$$

which states that the calculated current trough reed switch is less than the thyristor nominal opening (control) current by a factor of almost 3.5. Besides, it should be noted that the thyristor SDS gives not the actual value of the opening current but rather the maximum possible limit. Our statistical analysis of the opening current distribution for the high power thyristors has shown that the average actual value of the opening current is usually less than the nominal value by a factor of 1.5...2. The above considerations prove that the reed switch parameters are very compatible with those of the medium and high power thyristors.

Reed-transistor commutation devices have the highest potential from the standpoint of communication equipment applications. Their usage, however, has a number of peculiarities, which are discussed below.

The design of the high voltage solid-state commutation devices are traditionally focused on the HV transistors. However, the gain properties of ordinary bipolar HV transistors are so low ($h_{FE} = 2\ldots5$) that for many parameter-demanding applications their usage becomes questionable. In reed-transistor devices that contain more than two serially connected transistors, their total control current (which is equal to the sum of the all base currents) becomes practically comparable to a power amplifier which, in this case, is nonsense. That is why the mentioned transistors can only be used for the simplest one-component applications.

One can obtain much better results (in terms of switching power) by compromising the operating voltage (e.g. $U_{CE} = 0.8 \ldots 1.0$ kV) to much better gain ($h_{FE} = 20\ldots50$): BUP34, 2SC3456M, 2SC3150M, 2T506A, and others. The increase in the number of the serial components is now compensated by a high gain. Besides, low dimensions and weight of these transistors with TO-220 package style (even, if there are twice as many as compared to the previously mentioned type) reduce the total dimension and weight indices of the commutation system. For these transistors in a HV commutation device involving more than 5 serially-connected high gain units, the total base current still exceeds the maximum switching capacity of a HV reed switch. The only remaining possibility to decrease the total base current is the cascade transistor circuitry (Darlington circuit).

New types of powerful MOSFET and IGBT transistors are very appropriate for usage in HV commutation devices. These transistors (even at high power) have a very small gate current and voltage up to 1200 V.

The base circuit diodes eliminate the mutual interference of the serially-connected devices and provide for the uniform distribution of the collector voltage in the static mode. The individual diode voltage is distributed according to the equation:

$$U_{D.i} = U_P (N - j) N^{-1}, \tag{3.3}$$

where:

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U_P – the power supply voltage;
N – number of transistors in a serial chain;
$j = 1 \ldots (N-1)$ –the ordinal numbers of transistors from a positive terminal.

Maximum reverse voltage of an individual triode should either be based on (3.3) or on the quantity of

$$U_P(1-N^{1})$$

Another issue that has to be addressed in relation to the HV reed-transistor commutation devices is the effect of the current pulsations caused by the reed switch transient bounce (and amplified by transistor) to the output (load) signal. The additional RC-chain (see Fig. 3.16b) is one of the possible solutions. It is assumed that the capacitor gets charged during the first contact impact and provides a positive potential at the transistor bases during the first bounce. It then gets additionally charged during the second impact, etc. Thus, the compensating capacitor eliminates the effect of the reed switch bounce on the transistor output circuit and increases the time response of device.

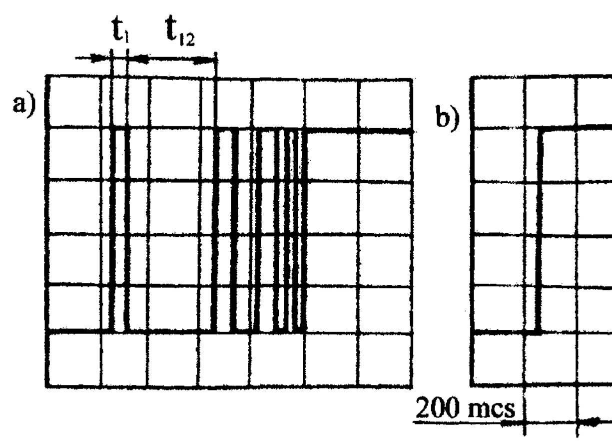

Figure 3.19 Oscillograma of collector (load) current with (b) and without (a) the compensating capacitor.

The parameter vector derivation of the RC-chain becomes somewhat specific.
First, the capacitor has to be fully charged during the first impact of the reed switch t_1 :

$$T_1 \geq \pi RC \tag{3.4}$$

Second, the power dissipated at the intercontact resistance of the reed switch during the charge of the capacitor can not exceed reed switch maximum switching capacity P_R, i.e.,

$$P_R \geq \frac{R_R}{t_1}\int_0^{t_1} i_C^2(t)dt \tag{3.5}$$

where
R_R – intercontact reed switch resistance;
$i_c(t)$ – free component of the capacitor charge current.

Third, during the discharge of C over t_{12} (the first bounce duration), the free component attenuation of the voltage drop across the base resistors should not exceed the maximum acceptable voltage drop at the collector load, i.e.,

$$\frac{U_{L\min}}{U_P} \geq \exp\left(-\frac{t_{12}}{R_b C}\right) \tag{3.6}$$

where

$$R_b = \left(\sum_{i=1}^{N} \frac{1}{R_{bi}}\right)^{-1}$$

represents the equivalent resistance of the transistor base circuit.

Integrating (3.5) and solving the result based on (3.4) defines the value of the compensating capacitor:

$$C = \frac{t_1}{U_P}\sqrt{2\frac{P_R}{\pi R_R}} \tag{3.7}$$

After a simple transformation of (3.6), one can get minimal resistance of an individual base resistor:

$$R_{b\min} = \frac{t_{12}}{NC\left(\dfrac{-\ln U_{L\min}}{U_P}\right)} \tag{3.8}$$

The time response of the described device (with the HV reed switch MKA-52141 type) is about 0.3 msec.

3.5 RELIABILITY OF THE HV COMMUTATION DEVICES BASED ON SERIALLY CONNECTED ELEMENTS *

It is interesting that many investigators associate a shared load system only with a parallel system whose units equally share the system function. Incidentally, a series-connected system of electrical elements having finite resistance also represents a shared load system with respect to overall voltage applied to the chain. The load-per-unit ratio (LPU) in this case – voltage drop across a component – will be the same for each element and inversely proportional to their number (assuming equal resistances for individual elements and neglecting deviations owing to technological reasons):

$$LPU = K_V = V_{OV}/(V_C\, N) = V'N^{-1}, \tag{3.9}$$

where

V_{OV} - the overall voltage, applied to the system (which in many practical instances is associated with the voltage of a power source);

* ***V. V. Krivtsov, V. I. Gurevich****: An Optimization Method for Serially Connected Electronic Components .- "Electronic Engineering. Ser. 4. Electrovacuum and Gas Discharge Instruments", vol. 1(132), 1991.*

V_C - rated voltage of a system element;
$V' = V_{OV}/V_C$.

If a major failure mode for a particular type of elements is a short-circuit, then the series share load system will basically be no different from a parallel one, and the same model for the system reliability, which in the case of two units looks like

$$R_S(t)=[R_h(t)]^2 + 2\int_0^1 f_h(t_1)\, R_h(t_1) R_f(t-t_1)\, dt_1, \qquad (3.10)$$

where

$f_h(t), f_f(t), R_f(t), R_h(t)$ – *pdf's* and reliability functions for the full-load operation and half-load operation, respectively, will hold. However, if the main failure mode is open-circuit, then the above equation becomes no longer valid, as $f_h(t)$ can not be defined (notably, $f_f(t)$ takes a form of the extreme value distribution in this case).

However, in a parallel shared load system, the number of elements that share the system's functioning affects system reliability in a directly proportional way (the more elements – the higher reliability), and their role in a series shared load system (SSLS), becomes two-fold.

On the one hand, one is interested in increasing number N, as it, in compliance with (3.9), diminishes the LPU and according to the inverse power relationship or even simple life-stress considerations, increases element reliability.

On the other hand, SSLS is effectively a series system, whose reliability depends on the number of elements in an inversely proportional manner.

By analyzing the two relationships, it becomes obvious that a compromise exists in terms of N.

Therefore, the problem is to determine an optimal numbers of elements in series, which provides the highest possible reliability for both a single element and SSLS as a whole. In other words, we are looking for the situation when the decrease in the system's reliability will be compensated by an increase of the element's reliability

$$|\Delta R'| = |\Delta R''|,$$

where:

$|\Delta R'|$ - scaler change of the SSLS reliability, caused by the LPU reduction;

$|\Delta R''|$ - scaler change of the SSLS reliability, caused by the increased number of elements in series.

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Since we are speaking about the LPUs being less than one, this problem can theoretically be interpreted as a problem of hot standby. However, we choose to proceed with the concept of SSLS, as the term "series standby" seems to be contradictory in its essence.

Although it has been mentioned that the only issue relevant to the present discussion is the failure mode of the SSLS is an open circuit, for the sake of completeness, it is probably worth allowing for the other mode, too. The system reliability model in this case can be written in the form of (3.11):

$$R = 1 - P_S{}^n + (1 - P_O)^n, \tag{3.11}$$

where P_O , P_S - probability of failure due to open-circuit and short-circuit, respectively.

It is obvious that the SSLS model that accounts for only one failure mode is a particular case of (3.11) with P_S being equal to one.

The element reliability is assumed to be distributed exponentially, as this is often the case for many technical applications in general, and electronic elements in particular.

Ignoring the burn-in period and assuming $d\lambda / dt = const$, one can say that the failure rate of a single element depends on the application stress factor (which in our interpretation is expressed by (3.9)) and the ambient temperature (T). The generic version is:

$$\lambda_c = \lambda_b \Pi_A \Pi_Q \Pi_E \ldots \tag{3.12}$$

where λ_b is the base failure rate related to temperature, and Π_A, Π_Q, $\Pi_E \ldots$ are factors that take account of application stress, element quality level, equipment environment, etc.

For the convenience of our case, it is better to represent (3.12) in another (Bardin-1978, Petuhov-1988) popular form:

$$\lambda_c = (\lambda_b / AA')\exp(BK_v + B'T), \tag{3.13}$$

where:

A, B, A', B' – empiric factors, defining the relationships $\lambda_b = f(K_v)$ and $\lambda_b = f(T)$, respectively.

Particular values of the factors are normally available from technical handbooks; if not, they can be easily obtained by statistical testing methods.

To simplify the analysis further and keeping in mind that the failure rate as a function of temperature is now not of interest, we can transform (3.13) into:

$$\lambda_c = (\lambda / A)\exp(BK_v), \tag{3.14}$$

where $\lambda = (\lambda_b' / A)\exp(B' T)$.

Thus, the reliability function of SSLS, accounting for (3.9), (3.10) and (3.14), becomes:

$$R = \exp[-(\lambda t N / A)\exp(BV' / N)] - [1 - \exp[-\lambda t A \exp(BV'/N)]]^N . \tag{3.15}$$

Here, t stands for time.

Designating the first term of (3.15) as R_1 we will first find the optimum N_O for the SSLS having one failure mode (namely, we assume that the increase of LPU causes the open circuit of a component).

By solving

$$\partial(R_{so}) / \partial N = [\exp(-(\lambda t N / A)\exp(BV'/N))].\ [(\lambda t / A)\exp(BV'/N))].\ [(BV'/N) - 1] = 0$$

with respect to N, the optimum value of N is obtained:

$$N_O = BV' \tag{3.16}$$

Computing N_O for the SSLS that has two failure modes becomes much more involved, as the derivative of (3.15) takes a non-trivial form:

$$\partial(R_s)/\partial N = [\exp(-(\lambda t N / A)\exp(BV'/N))].[\exp(BV'/N - N^{-1}\exp(BV'/N)] + [\lambda t/(NA)]\exp(-\lambda/A + \exp(BV'/N))\ \exp(BV'/N)].\ [1 - \exp(-\lambda t/A \exp(BV'/N))]^{N-1} .$$

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However, after a number of consecutive transformations, it can be reduced to

$$\partial(R_s)/\partial N = XY \tag{3.17}$$

where

$$X = [\lambda t/(NA)].[\exp((1-\lambda t/A)BV'/N)],$$
$$Y = [N-1].[\exp(-\lambda t/A\exp(BV'//N)(N-1))].$$
$$[1-\exp(-\lambda t/A\exp(BV'/N))].$$

It is still impossible to resolve (3.17) explicitly with respect to N.
One can define the condition of extreme existence in the form:

$$\lim_{N\text{-}No} |\partial(R_s)/\partial N| \rightarrow min \tag{3.18}$$

Analysis of (3.17) from the standpoint of (3.18) has shown that while Y is a monotonous function of N, X – is not! It implies that it is X that makes (3.18) possible. As such, by differentiating X with respect to N, and equating the function obtained to zero, we arrive at the expression for N_{opt}.

$$N_O = BV'(1+A^{-1}\lambda t) \tag{3.19}$$

It is interesting to observe that (3.19) looks very much like (3.16), except for quantity in parentheses.
Let us consider a thyristor switching device, operating in a stationary regime. The failure rate of a thyristor as a function of the overstress rate can be approximated (Petuhov-1988) by:

$$\lambda = (\lambda_b/8.196)\exp(2.179K_v).$$

If we pick a thyristor of the T-132-25-18 type (which shows $\lambda_b = 1.6 \times 10^{-6}\,hr^{-1}$) and assume that the power source voltage exceeds the rated voltage of the thyristor by a factor of 5, then according to (3.19), their optimum number for a mission of 10^5 hours will amount to:

$$N_O = 5 \times 2.179(1 + (1.6 \times 10^{-6} \times 10^5 / 8.196)) \approx 11.$$

Analysis of a Series Shared Load System shows that:

• The optimum numbers of SSLS elements, where the major failure mode is an open circuit, is completely defined by a power-source-to-elements voltage ratio and the exponential term in a generic relationship, which is described by the failure rate model of the element under consideration.

• If SSLS elements are characterized by both open-circuit and short-circuit failure modes, then the optimum number of elements is modified by the factor that involves the linear term of the mentioned relationship along with the base failure rate and mission time - as shown by (3.19).

• For practical applications, it is preferable to keep the power-source-to-element voltage ratio as low as possible, since it drastically decreases the reliability of the system.

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4

Low-Voltage Switching Devices for High-Voltage Power Supply

4.1 SOFT-START THYRISTOR CONTACTOR

The simplest device of this type is a TSDC (Thyristor Switch of Direct Connection), which is formed with a three-phase thyristor module and a simple semiconductor control system designated for joint operation with the RG devices. The contactor is designated to control a three-phase load with nominal voltage of up to 440 V, nominal current up to 80 A and frequency of 50-400.

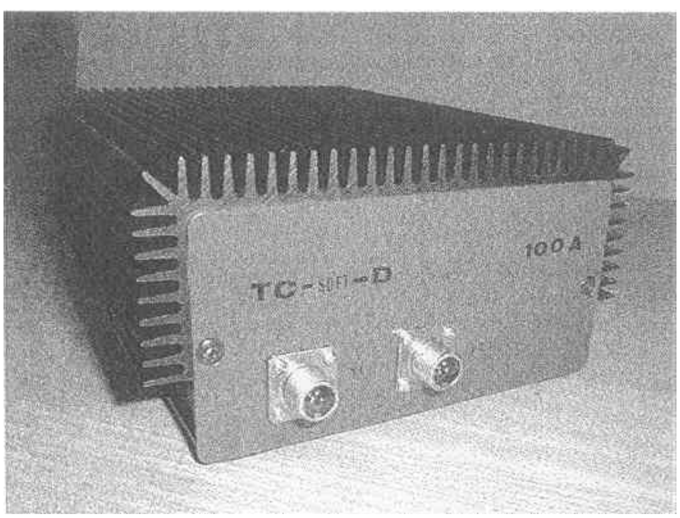

Figure 4.1 Thyristor "TC-soft" series contactor.

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The load is applied by the command of any external control device, and the emergency disconnection by the command of any of the RG series devices.
The thyristor "TC-soft" series contactor enables smooth connection of power supplies, preventing deflections of power transformer magnetizing current in the LV circuit and deflections of filters charging current in the HV circuit. The only difference between this device and the TSDC contactor is the special control circuit that provides for smooth change of the triggering angle of the power thyristors during the contactor activation.

Table 4.1 Main parameters of LV thyristor contactors

TSDC-_____ TC-soft-_____	SUBTYPE	
	25	**80**
Nominal Voltage, V AC	440	
Phase Number	3	
Nominal Current (rms), A	25	80
Maximum Non-Repetitive Surge Current (1/2 cycle), A	250	1000
Time switch to On-state (soft start), s	2...20	
Maximum Operate (disconnecting) Time	½ cycle of AC power supply	
Dimensions (Cooling Case), mm	250 x 175 x 90	
Weight, kg	3.0	

The idle mode of a three-phase transformer in a power supply is very widespread for power RF-generators, radar, industrial lasers, etc.

This mode is very specific and the ordinary soft-start devices with thyristors do not work correctly in this mode. SOFCON is a new one soft-start contactor intended for use in this case.

4.2 SOFT-START CONTACTOR ON IGBT TRANSISTOR

A new soft-start solution is used in SOFCON device: operation on over frequency, IGBT transistors used for power switching elements, as well as built-in fast overload protection, damage mode (overload) locking, and additional input for an outside current sensor.

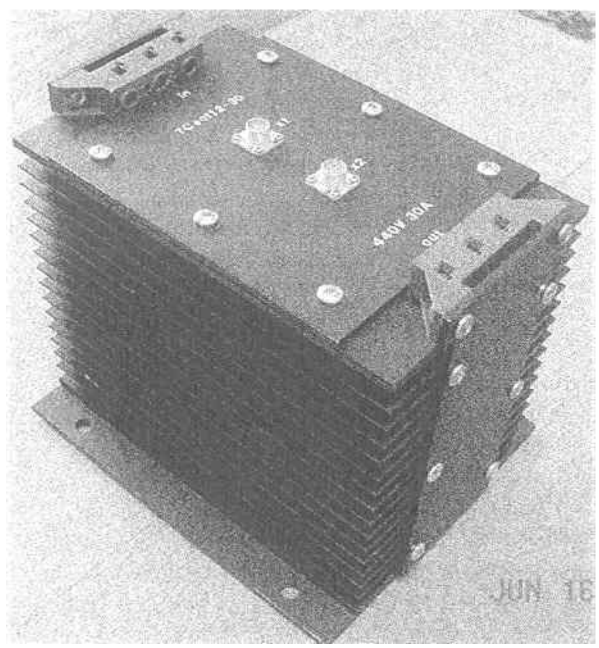

Figure 4.2a Soft-start contactor "SOFCON" series (outside).

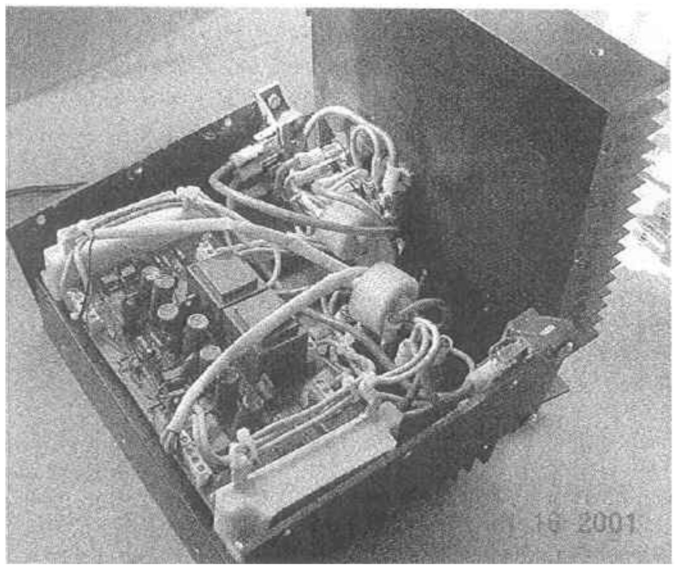

Figure 4.2b Soft-start contactor "SOFCON" series (inside).

Main parameters of SOFCON type contactor:

Nominal Voltage, V AC	440
Nominal Current, A	35
Maximal Over current, A (3 sec)	70
Current Level Trip (Overload Protection), A	50
Max. Non Repetitive Surge Current, A (1 ms)	200
Insulation Voltage, V AC	2500
Time Switch to ON-state (soft start), s	1.0
Heating	Built-in Heat Sink
Dimensions, mm	220x140x200

4.3 POWER-COMBINED DEVICE

The "Barracuda" is a revolutionary new type of power-combined device intended for use as a three-phase commutation device, which combines the functions of a contactor, a soft-start and fast overload protection module, *which does not produce heat.*

The soft-start module can be used for an ordinary three-phase load as well as for a special load such as a transformer in idle mode.

The overload protection module is formed by a three-phase thyristor switch connected in parallel from the power source directly to the current buses, Fig.4.3.

The thyristor switch 2 is momentarily triggered (6 to 10 microsecond) by an RG signal switch. Artificial short circuit is generated on the current buses thus shunting the protected electric installation (HV power supply 6). The short circuit remains during the time needed to engage the standard built-in automatic circuit breaker 1.

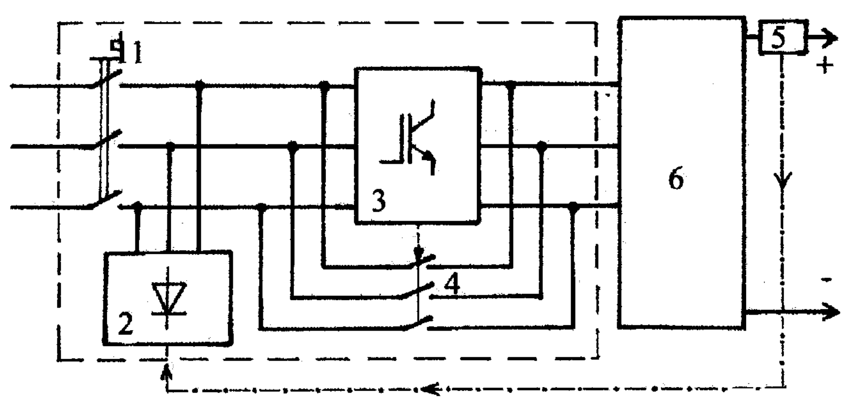

Figure 4.3 Block-diagram of "Barracuda" combined protection device
1 - automatic circuit breaker; 2 – thyristor short-circuit switch; 3 – soft-start contactor on IGBT transistors; 4 – electromagnetic power relay; 5 – RG; 6 – HV power supply.

The "Barracuda" protection device:

- A revolutionary principle for very fast overload protection.

- Combines a power thyristors, power IGBT transistors and power electro magnetic relays as active components.

- Free heating and heat sink.

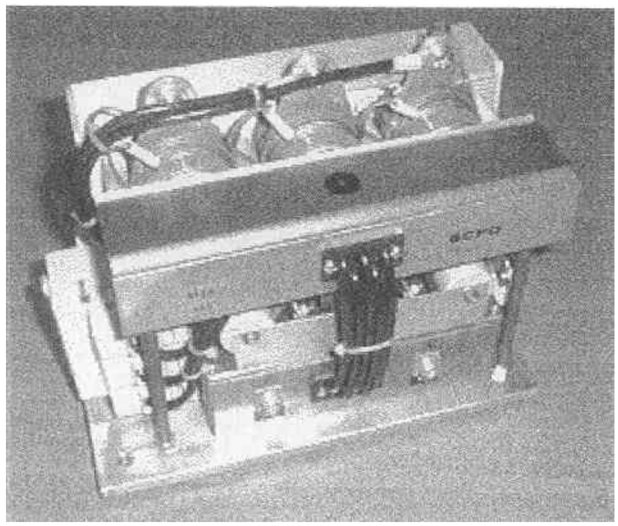

Figure 4.4 "Barracuda" protection device (outside).

The "Barracuda" applications are: HV power supply, power radar, industrial lasers, power RF-generators, etc.

The "Barracuda" main parameters:

Nominal Voltage, V AC	440
Nominal Current, A (rms)	30
Time Switch to ON-state (soft-start), sec	1.5
Own Response Time, μsec	10
Maximal Short Circuit Current, A (1/2 cycle)	2,000
Maximal Disconnected Current, A	12,000
Dimensions, mm	260x160x200

4.4 HYBRID POWER RELAY

Low voltage commutation devices, such as relays and contactors are among the most popular kinds of electro-technical equipment and are manufactured by dozens of companies including Omron, Magnecraft, Potter & Brumfeld, Deltrol, Midtex, Klockner-Mouller, Matsushita, Hartman, Finder, Schrack. These companies produce hundreds of millions of items per year.

Some 25 years ago, most of these devices were fitted with mechanical contacts that connected and disconnected electric circuits.

The main drawback of these devices was electric arc that struck across the contacts at the moment of commutation and significantly lowered the service life of the devices by destroying the contacts. The powerful interference caused the electronic devices to work irregularly. For instance, the amount of operations pickup a modern electro-mechanical relay can withstand (without current commutation, i.e., without arc interference) is 10 million operations, while with current commutation (i.e., under the interference of an electric arc), it is 50-70 thousand only.

Currently, 20-25% of the commutation device market between 3-10 kW is occupied by non-contact (semiconductor) devices that connect and disconnect the load without electric arc. These devices are manufactured by many companies including Crydom, Teledyne Relays, Carlo Gavazzi, Celduc and Crouzet (Fig. 4.5).

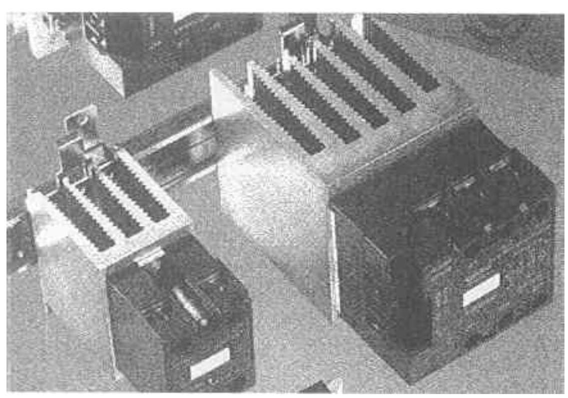

Figure 4.5 Non-contact (solid-state) relays mounted on heat sinks.

Despite all their advantages, these devices occupy only a small segment of the market due to one very serious drawback: they become hot during operation. This makes it necessary to install miniature semiconductor blocks on huge aluminum heat sinks, which are 2 - 5 times larger in volume and 5 – 20 times larger in weight.

In addition, it is often necessary to use forced air-cooling of these radiators by special ventilators, or water circulation. In many cases, the additional intensive heat produced inside a device is prohibitive, making it impossible to use with semiconductors.

There are combined (hybrid) devices that use both semiconductor elements (diodes, thyristors) and electromechanical contactors. Incorporating hybrid switching devices in electric device design has been known for a long time. Extensive work in this field was conducted in the FSU at the following research institutes: VNIIElectroapparat (Kharkov), VNIIR (Cheboksari), VNIIVE (Donetsk). Production of hybrid contactors series KT64, KTP64, KT65, and KTP65 was established for currents of up to 630 A. Similar devices were manufactured by a number of other companies (Klochner-Moeller, CEM, etc.). These were clumsy and heavy devices, in which semiconductor devices were used as arc-carrying systems providing for powerful arc extinction on diverging contacts. Novel types of arc extinction chambers for powerful switching devices, in particular vacuum devices, completely replaced the complicated and unreliable hybrid devices in the market. Notwithstanding a great number of patents registered during the last 20 years in this field, at present such devices are not manufactured at all.

A completely novel elements base that entered the market in recent years includes: compact single and three-phase semiconductor switching modules for currents in range 25-100 A (the size of a cigarette package!) with opto-electronic elements for control and synchronization with the mains built into the semiconductor structure (turn-ON at zero voltage, turn-OFF at zero current), small size electromagnetic relays with nominal contact currents of 25-30 A, enabled the author to set up and define some new concepts in constructing hybrid devices:

1. Modern elementary base enables extending the field of use of hybrid devices to the most popular range of power switching devices with nominal currents of 10-50 A (95% all power relays, available in the market).

2. New generation hybrid devices must be constructed from mass-produced semiconductor units with a built-in control system and mass-produced modern electromagnetic-free relays. The only unit to be tailored is the electronic synchronization circuit consisting of a minimal electronic components number, designed in the form of a small PCB. In this way, a device comparable in price with semiconductor relays (with a big and quite expensive radiator) can be made available in the market.

3. The use of electromagnetic relay contacts for arc-less switching operation enables the use of a contacts array connected in parallel in order to increase the device power without accounting for non-simultaneity of switching processes on the parallel contacts. A relatively small and cheap electromagnetic relay can be incorporated in this quite high-powered device.

4. Synchronization of circuit design should not be based only on the time lag between the elements response (the principle described in numerous patents), since small time delays are due to cause non-synchronous elements operation, whereas high time delays impairs the very important fast response capability of the switching device.

5. A synchronization circuit should not contain current sensors, assemblies for detecting specific points of the current sinusoid or amplification and data processing integral circuits (offered in some patents), since in actual practice, in an environment of spikes, harmonicas etc., such designs turn out to be extremely unreliable and expensive.

6. Synchronization circuit implementation must be based on the principle of events tracking, namely a certain element response to another element's signal, enabling such response. In this way, minimization of the amount of simple elements is achieved along with their dependable operation, circuit operation independent of time-related changes (or temperature related changes) in the element parameters, minimal response and return time of the device.

7. For switching powerful DC circuits in a hybrid device, the thyristor module is replaced by an IGBT-transistor (Isolated Gate Bipolar Transistor) module with a powerful varistor and miniature gas spark-gapes for spikes protection.

8. The next step in further development of this trend should be a control circuit consisting of mass-production small-size latching relays and a thyristor module with a built-in soft-start circuit, which is currently available in the market.

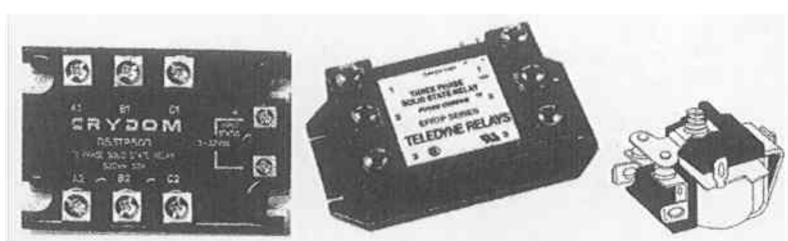

Figure 4.6 "Crydom" and "Teledyne" solid-state relays combined with built-in opto-electronic control circuit and miniature power electromagnetic relay "Magnecraft" are very suitable components for the hybrid relay.

The fundamentals of this concept were successfully applied by the author in specific designs of different types of powerful hybrid relays: one-phase, three phase, with protective functions, with soft-start functions, etc.

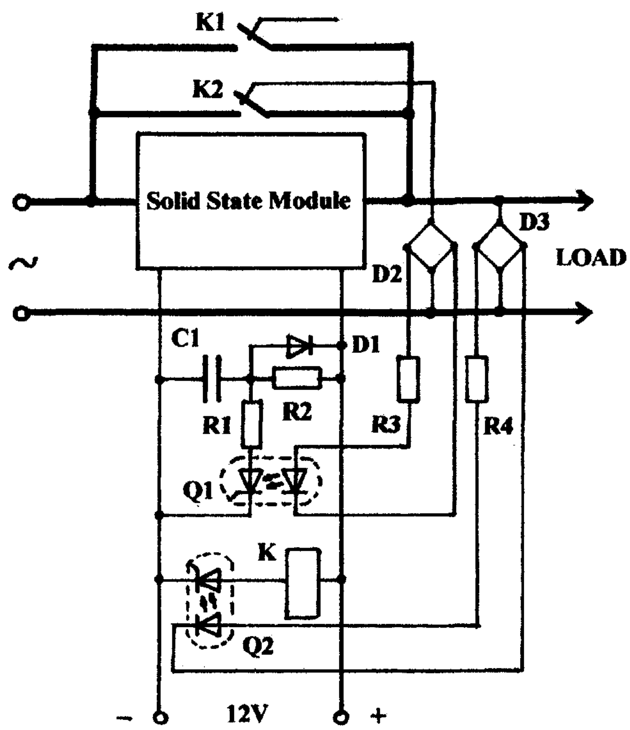

Figure 4.7 Circuit diagram of the one-phase hybrid relay.

C1- capacitor; Q1, Q2 – opto-couplers (diode-SCR); D2, D3 – rectifier bridges; K – power electromagnetic relay with contacts K1, K2.

Our Hybrid Power Relays (HPR) represent a new generation of power relays for industrial and military applications, combining positive properties of both relays (contact and solid state) in one relay.

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HPR are intended for a nominal current of up to 50 A, nominal voltage up to 440 VAC and 250 VDC, 1PST-NO and 3PST-NO contact configuration, zero cross turn-ON and zero cross turn-OFF, arc-free switching and heat-free.

HPR series relays have longer switching life due to the "contactless" system and high switching reliability due to low resistance in ON-mode and heat-free. They do not require a heat sink for heat dissipation, do not generate voltage spikes in a power network and are not an EMI source for electronic devices.

HPR can be used in all cases, as ordinary power relays (contactors) with an increased reliability and service life, and also in exceptional cases, when the additional heat production in equipment is not allowed or the electric arc on contacts and the effects associated with it are not allowed; when it is required to power up and to turn out a load in zero; and for reducing RF interference that is usually generated when switching reactive loads.

All relay models emit in two types of plastic enclosures (E1, E3) with standard terminals for one- and three-phase relays, Fig. 4.8.

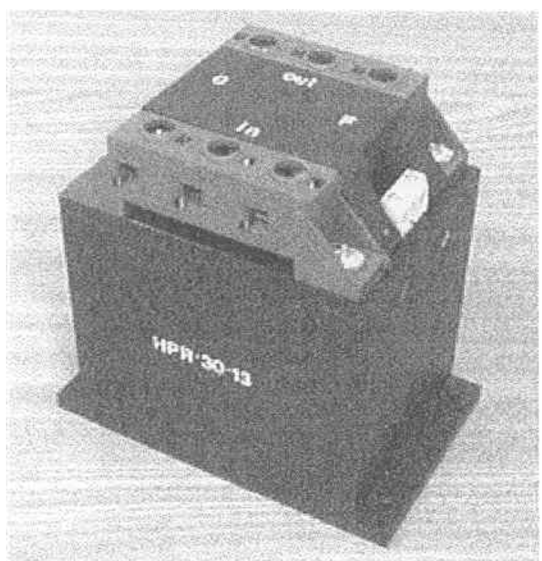

Figure 4.8a Power hybrid relays for one phase.
E1 (90 x 70 x 110 mm)

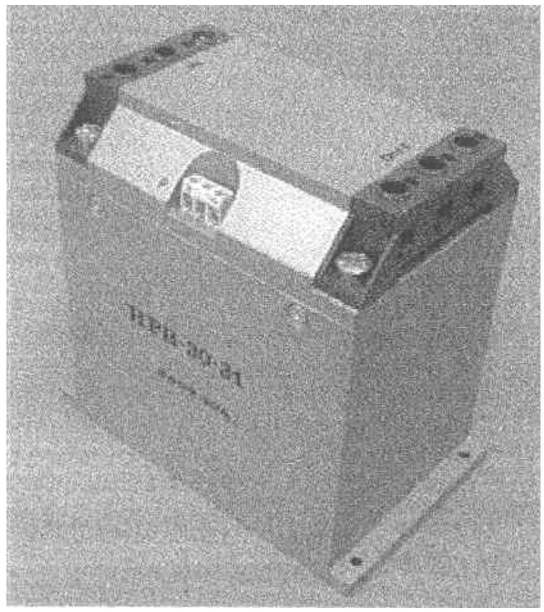

Figure 4.8b Power hybrid relays for three phase.
E3 (115 x 80 x 135 mm)

Table 4.2 Main specifications of three-phase hybrid power relays

Output (Load) Specifications	***HPR-30-33***	***HPR-30-31***	***HPR-30-21***
Contact Configuration	3 Form A (3PST-NO)		2 Form A (2PST-NO)
Load Voltage Range, VAC (rms)	48 – 440		
Over Voltage, V (peak)	1200		

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Nominal Load Current Range (per phase), A (rms)	0.05 – 30		
Maximal Starting Current, A, rms (for time <3 sec)	180 (AC3)	70 (AC1)	70 (AC1)
Turn-ON	Zero cross		
Turn-OFF	Zero cross		
Power Factor (Cos φ)	1 – 0.5		
Contact Resistance, Ohm	0.05		
Current (OFF-state), mA	1		
Supply Frequency Range, Hz	47 – 60		
Input (Control) Specifications	***HPR-30-33***	***HPR-30-31***	***HPR-30-21***
Input Voltage, VDC	12		
Control Power, W	5.0		
Maximal Response Time, ms Open Close	10 20		
Other Characteristics:	***HPR-30-33***	***HPR-30-31***	***HPR-30-21***

Operating Temperature, °C	-20 + 60
Input-to-Output Insulation Voltage, VAC (rms)	2500
Life Expectancy, operation, min	5,000,000
Mechanical: Vibration Resistance Shock Resistance	5 g's 10 to 55 Hz 5 g's 11 ms
Enclosure Type	E3

Table 4.3 Main specifications of one-phase hybrid power relays

Output (Load) Specifications	HPR-30-13	HPR-75-11	HPR-30-11-L
Contact Configuration	1 Form A (1PST-NO)		
Load Voltage Range, VAC (rms)	48 – 440	24 - 260	
Over Voltage, V (peak)	1200		
Nominal Load Current Range (per phase), A (rms)	30	75	30

Maximal Starting Current, A, rms (for time <3 sec)	120	75	30
Turn-ON	Zero cross		
Turn-OFF	Zero cross		
Power Factor (Cos φ), range	1 – 0.5		
Contact Resistance, Ohm	0.05		0.1
Leakage Current (OFF-state), mA	1		Without Leakage
Supply Frequency Range, Hz	47 - 60		
Input (Control) Specifications	HPR-30-13	HPR-75-11	HPR-30-11-L
Input Voltage, VDC	12		
Control Power, W	5		
Maximal Response Time, ms Open Close	 10 20		 20 20

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Other Characteristics	HPR-30-13	HPR-75-11	HPR-30-11-L
Operating Temperature, °C	-20 + 60		
Input-to-Output Insulation Voltage, VAC (rms)	2500		
Life Expectancy, operation, min	5,000,000		
Mechanical: Vibration Resistance Shock Resistance	5 g's 10 to 55 Hz 5 g's 11 ms		
Enclosure Type	E1		

Table 4.4 Main specifications of DC hybrid power relays

Output (Load) Specifications	*HPRD-25-15*	*HPRD-50-11*	*HPRD-25-11L*
Contact Configuration	1 Form A (1PST-NO)		
Load Voltage Range, VDC	24 - 350		
Over Voltage, V (peak)	1200		
Nominal Load Current Range, A	0.01 - 25	0.01 - 50	0.01 - 25

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Maximal Starting Current, A, (for time <3 sec)	50	75	25
Time Constant for Inductive Load, ms	50	10	10
Contact Resistance, Ohm	0.05		0.1
dv/dt, V/μs	500		
Leakage Current (OFF-state), mA	1		Without Leakage
Input (Control) Specifications	***HPRD-25-15***	***HPRD-50-11***	***HPRD-25-11L***
Input Voltage, VDC	12		
Control Power, W	5		
Maximal Response Time, ms Open Close	 20 20		 30 30
Other Characteristics	**HPRD-25-15**	**HPRD-50-11**	**HPRD-25-11L**
Operating Temperature, °C	-20 + 60		
Input-to-Output Insulation Voltage, VAC (rms)	2,500		
Life Expectancy, operation, min	5,000,000		

Mechanical: Vibration Resistance Shock Resistance	5 g's 10 to 55 Hz 5 g's 11 ms	
Enclosure Type	E3	E1

Table 4.5 Main specifications of "soft-start" hybrid power relays

Specifications	HPR-30-13-S
Contact Configuration	1 Form A (1PST-NO)
Load Voltage Range, VDC	24 - 250
Over Voltage, V (peak)	1200
Maximal Load Current Range, A	25
Maximal Peak Single Cycle Surge Current, A	250
Contact Resistance, Ohm	0.05
Leakage Current (OFF-state), mA	1
Soft-Start Ramp-Up, sec	2
Input Voltage, VDC	12
Control Power, W	5

Operating Temperature, °C	-20 + 60
Input-to-Output Insulation Voltage, VAC (rms)	2500
Mechanical: Vibration Resistance Shock Resistance	 5 g's 10 to 55 Hz 5 g's 11 ms
Enclosure Type	E3

4.5 HYBRID SWITCH, BASED ON ANTI-PARALLEL CONNECTED THYRISTORS (SAPT)

One of the relevant components for many protection devices, both low voltage and high voltage (see Fig. 3.18, for example), is the anti-parallel connected thyristor switch using a reed switch in the control circuit (SAPT), Fig. 4.9.

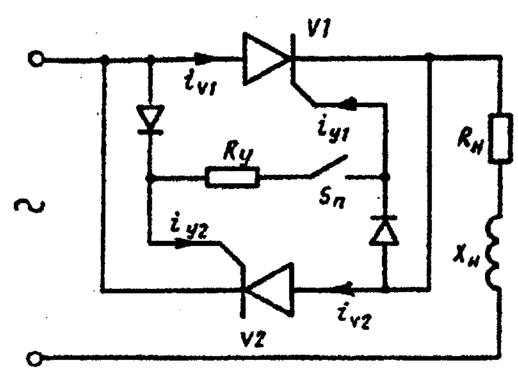

Figure 4.9 Circuit diagram for hybrid switch based on anti-parallel connected thyristors (V1, V2) using a reed switch (S_n) as the starting element.

It is very simple, effective and works well with a reed switch and RG-relay (which can be used as a control element in HV applications).

The important feature of this device is its high noise immunity because control pulses to thyristors are not transmitted from the outside and are shaped directly inside the scheme. An additional, but no less important feature of the device, is automatic synchronizing of the control pulse with a phase of a load current.

At the same time, the SAPT has some special functions, which are considered below.

At the applied voltage, the connected load and closed contact S_n, the control current of SAPT, is determined by expression:

$$i_y = \frac{U_m}{Z_y}\sin\left(t\omega - \varphi_y\right), \tag{4.1}$$

where

$$Z_y = \sqrt{\left(R_H + R + R_y\right)^2 + X_H^2},$$

R_H and X_H – resistance and inductance of load;
R – impedance of thyristor's junction "gate-cathode";

$\varphi_y = \arcsin\dfrac{X_H}{Z_H}$ - phase of current relative to voltage.

Thyristor will be open at the moment that $i_y \geq I_y$ (I_y – gate trigger current).
The phase of triggering for the first (V1) thyristor:

$$\alpha_1 = \arcsin\frac{X_H}{Z_{y1}} + \arcsin\frac{I_{y1}Z_{y1}}{U_m}, \tag{4.2}$$

and for second (V2) thyristor:

$$\alpha_2 = \arcsin\frac{X_H}{Z_{y2}} + \arcsin\frac{I_{y2}Z_{y2}}{U_m}. \tag{4.3}$$

Thyristors will switch off at the moment when the current through the "anode-cathode" circuit will be equal to i_v (off-state current)

$$i_v = \frac{U_m}{Z_H}\sin(\omega t - \varphi_H) \le I_{yg}, \tag{4.4}$$

where $\varphi_H = \arcsin(X_H / Z_H)$ – phase of load current relative to voltage (resistance of "anode-cathode" junction is not taken into account because its value is very low).

Therefore, the switching off phases of thyristors will be equal:

$$\beta_1 = \arcsin\varphi_H - \arcsin\frac{I_{yg1}Z_H}{U_m} + \pi,$$
$$\beta_2 = \arcsin\varphi_H - \arcsin\frac{I_{yg2}Z_H}{U_m} + \pi. \tag{4.5}$$

In an ordinary (pulsed) control circuit in moment $\omega t = \beta + \pi$, current through the thyristor will be smaller than off state current (I_v), and the thyristor switches off. However, voltage does disappear and varies according to the following equation:

$$u = U_m \sin\beta \exp\left(-\frac{\omega t - \beta}{C_\tau}\right), \tag{4.6}$$

where $C_\tau = \omega L_H / R_H$ – load time constant.

For a thyristor in ON-state mode, the equation (4.7) is:

$$u = \omega L\frac{di_T}{d\omega t} + R_H i_H, \tag{4.7}$$

and from this, one thyristor's current can be expressed as:

$$i_T = \frac{U_m}{R_H}\cos\varphi\left[\sin(\omega t-\varphi)-\sin(\alpha-\varphi)\exp\left(-\frac{\omega t-\alpha}{C_\tau}\right)\right], \qquad (4.8)$$

here φ =arctg C_τ - phase angle of load.

In (4.8), inserting off-state current of thyristors instead of i_T, we get (from 4.8):

$$\frac{I_y R_H}{U_m} = \left(1+C_\tau^2\right)\cos\left[\sin(\pi+\beta-\varphi)-\sin(\alpha-\varphi)\exp\left(-\frac{\pi+\beta-\alpha}{C_\tau}\right)\right] \qquad (4.9)$$

Even if $\alpha_1 = \alpha_2$, in an ordinary (pulsed) control circuit, off-switching angles of thyristors (β_1 and β_2) are not alike because of differences in off-state currents.
In a SAPT device, the control circuit is permanently connected in series with a load, but it bypasses after the thyristors open.
At moment $\omega t = \beta$ (terms for switching to off state), the control circuit will de-short. Therefore, load circuit does not break and current through load will permanently be:

$$i_H = i_y = \frac{U_m}{Z_y}\sin\omega t, \qquad \text{where } \beta < \omega t \geq \pi + \varphi \qquad (4.10)$$

In this period, after the closing of the thyristors, the load current saving has a value similar to an ideal switch. Therefore SAPT is not sensitive to differences of off-state currents, and it is possible not to consider angles β. It is an additional feature of the SAPT device.

Then, deducting (4.3) from (4.2), we obtain the equation for switch-on angles imbalance:

$$\Delta\alpha = \arcsin\frac{X_H}{Z_{y1}} - \arcsin\frac{X_H}{Z_{y2}} + \arcsin\frac{I_{y1}Z_{y1}}{U_m} - \arcsin\frac{I_{y2}Z_{y2}}{U_m}. \qquad (4.11)$$

Analysis of this equation shows that completely symmetrical thyristor work is possible only for terms:

$$I_{y1} = I_{y2} \ \ and \ \ Z_{y1} = Z_{y2}. \tag{4.12}$$

If $R_y << R + R_H$, it can be written, that $Z_{y1} = Z_{y2} = Z_y$. With provision for it, we can transform (4.11) into:

$$\Delta\alpha = \arcsin\frac{I_{y1}Z_y}{U_m} - \arcsin\frac{I_{y2}Z_y}{U_m}. \tag{4.13}$$

If we neglect voltage drop on an open thyristor, we get:
$U_m = I_m Z_m = \sqrt{2}\, I_H Z_H$, where I_H – load current (rms), which will be for interval angles $\gamma = \pi$, corresponding to an open state of the thyristor.

Hence,

$$\Delta\alpha = \arcsin\frac{I_{y1}Z_y}{\sqrt{2}I_H Z_H} - \arcsin\frac{I_{y2}Z_y}{\sqrt{2}I_H Z_H}. \tag{4.14}$$

Using an equation for the conversion difference of two arcsines and using a binomial theorem for replacing a square root, we obtain for two first numbers of the binomial series:

$$\Delta\alpha = \arcsin K_Z \frac{\Delta I_y}{\sqrt{2}I_H}\left(1 + \frac{1}{4}K_Z^2 \frac{I_{y1}I_{y2}}{I_H^2}\right), \tag{4.15}$$

where:

$$\Delta I_y = I_{y1} - I_{y2} \ \ \text{and} \ \ K_z = \frac{Z_y}{Z_H} = \sqrt{\frac{(R + R_H)^2 + X_H}{R_H^2 + X_H^2}}.$$

Analysis of equation (4.15) reveals some peculiarities of the SAPT device:

1. The angle of an imbalance ($\Delta\alpha$) of anti-parallel connected thyristors in a SAPT device increases when load current decreases (Fig. 4.10).

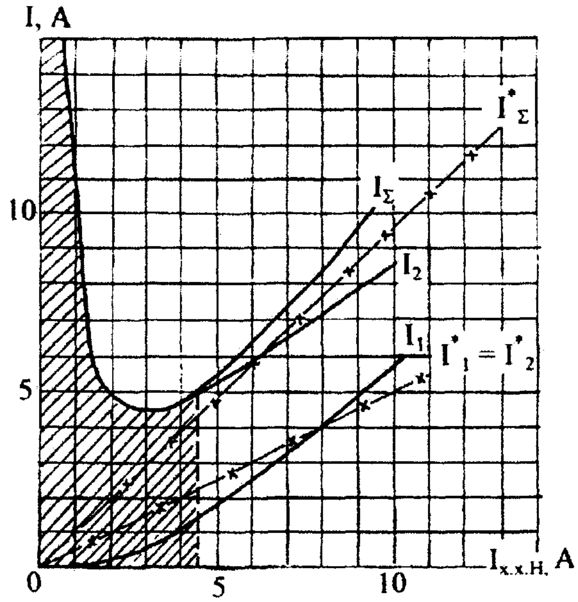

Figure 4.10 Experimental graph for dependency of the thyristors anode currents (I_1, I_2) and its sum (I_Σ) from idle mode current ($I_{X.X.H}$) of RL-load. For RL-load with current in idle mode – 0.84 A.

When load current is commensurable to gate trigger current, imbalance becomes especially great. For example, if
I_{y1} = 0.2 A, I_{y2} = 0.1 A, we obtain (from 4.15) for I_{H1} = 6 A and I_{H2} = 0.5 A angles of imbalance — 1° and 8°, respectively.

2. A great imbalance can occur even if $I_H >> I_y$, provided that load impedance (Z_H) is commensurable to a resistance of the R_y resistor (see circuit diagram of SAPT device), Fig. 4.11.

In this case, a coefficient K_Z will be more than 1, and its influence on the angle of imbalance shall be increasing. This is a reason for the choice of $R_y << Z_H$, when $K_Z \to 1$.

For practical engineering, it is interesting to calculate such a load current range when the imbalance value is not more than 1° (resolved value).

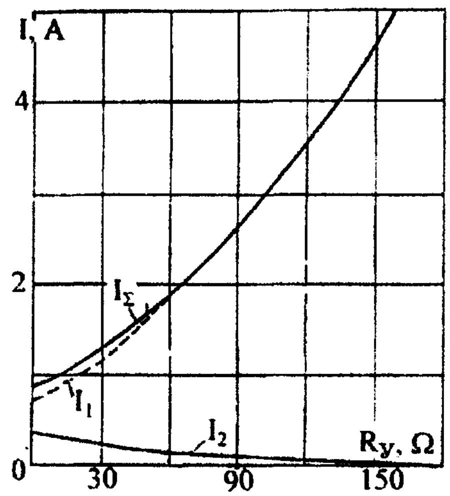

Figure 4.11 Experimental graph for dependency currents of the thyristors (I_1, I_2) with gate trigger currents I_{y1} = 0.11 A I_{y2} = 0.16 A, respectively, and total current (I_Σ) from value of R_y resistance.

In this case and for K_Z = 1, we obtain (from 4.15):

$$\frac{\Delta I_y}{\sqrt{2}\, I_H}\left(1+\frac{1}{4}\frac{I_{y2}I_{y1}}{I_H^2}\right)=0.0175 \tag{4.16}$$

After several series transformations, we obtain a cubic equation:

$$0.0175 I_H^2-\frac{\Delta I_y}{\sqrt{2}}I_H^2-\frac{1}{4}I_{y1}I_{y2}\Delta I_y, \tag{4.17}$$

This equation can be solved and simplified as:

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$$I_{H.CR} \approx 28.57\Delta I_y \tag{4.18}$$

where $I_{H.CR}$ – is a critical (minimal) load current, which guarantees normal conditions (without imbalance) for the functioning of the SAPT device.

The special mode of SAPT functioning is occurring under the following conditions:

- SAPT is connected to a primary winding of the transformer;
- transformer is operating in an idle mode;
- primary transformer current in this mode is not more than gate trigger currents.

Under these conditions SAPT together with the unloaded transformer will compose a dynamic automatic control system with feedback, fig. 4.12.

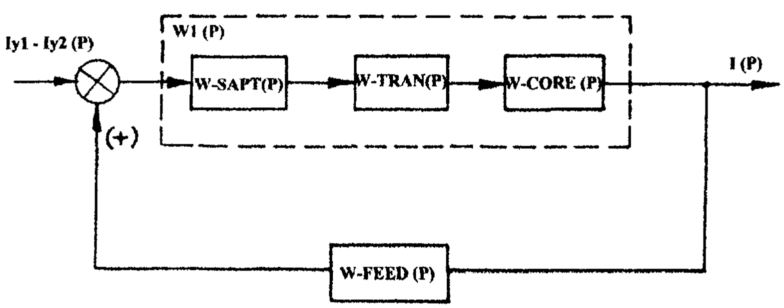

Figure 4.12 SAPT together with the unloaded transformer will compose a dynamic automatic control system with feedback

W-SAPT (P) - transfer function of object of regulation (SAPT);

W-TRAN (P) - transfer function of an nonperiodic unit (transformer without a magnetic core);

W-CORE (P) - transfer function of an integration unit (core of the transformer in an idling);

W-CORE (P) = K_i/P, K_i – time constant of integration;

W-FEED (P) – Feedback (the current of a primary winding of the unloaded transformer is a control current of SAPT);

$I_{y1} - I_{y2} = \Delta I_y$ - disturbing effect (difference of gate trigger currents for SAPT);

P = d/dt - differential operator.

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Equations for separate units will:

$$I(P)=W1(P)\Delta F(P)=[W-SAPT(P)]\cdot[W-TRAN(P)]\frac{K_I}{P}\Delta F(P); \quad (4.19)$$

$$\Delta F(P)=\Delta I_y(P)+F_{FEED}(P); \quad (4.20)$$

$$F_{FEED}(P)=[W-FEED(P)]\Delta I_y(P), \quad (4.21)$$

where: $F_{FEED}(P)$ – factor of feedback.

Substitution of (4.20) and (4.21) to (4.19) will yield:

$$I(P)=[W-SAPT(P)]\cdot[W-TRAN(P)]\frac{K_I}{P}$$

$$\text{x } \{\Delta I_Y(P)+[W-FEED(P)]\Delta I_Y(P)\}$$

whence, using standard conversion, one gets:

$$I(P)=\frac{[W-SAPT(P)]\cdot[W-TRAN(P)]K_I/P}{1-[W-SAPT(P)]\cdot[W-TRAN(P)]\cdot[W-FEED(P)]K_I/P}\Delta I_Y$$

(4.22)

As in this system the current of a primary winding of transformer is a control current of SAPT, hence [*W-FEED*(*P*)] = 1 and factor of feedback will be equivalent to transfer coefficient:

$$F_{FEED}=[W-SAPT(P)]\cdot[W-TRAN(P)]\frac{K_I}{P}[W-FEED(P)]=W_1(P)$$

(4.23)

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If $W_1(P) < 1$, system transfer coefficient $W(P)$ is increasing;
if $W_1(P) \to 1$, that $W(P) \to \infty$;
if $W_1(P) > 1$, denominator of (4.22) will negative and our system will be in self-excitation mode.

The stability condition of a system is defaulted because the separate components of the left part of an inequality (under the mentioned above conditions) already are more than 1.
Physically it means that even the very small own asymmetrical operating current of thyristors is memorizing in an iron core of the transformer; reverting to a control circuit of thyristors in the next halfcycle; summarizing with operation current; amplifying an asymmetry of currents in control circuit of thyristors; and so on to complete saturation of the transformer core, Fig. 4.13.

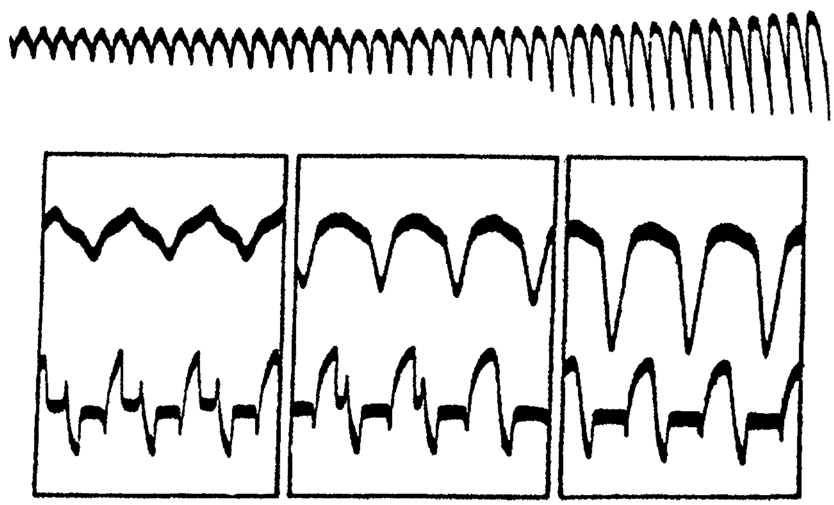

Figure 4.13 Oscillograms of core saturation process for very small value ΔI_y.

At the bottom of the oscillogram is shown fragments of current in unloaded transformer and fragments of thyristor's gate trigger currents.

Since for an integrating unit the speed of output value change is proportional to input value, it means that time delay to full core saturation will be reduced, with increasing of an asymmetry of currents in control circuit of thyristors.
And it also can be watched in actual experiment, Fig. 4.14.

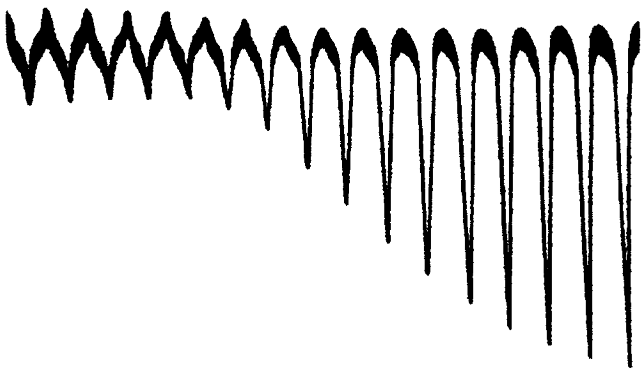

Figure 4.14 Oscillogram of core saturation process for great value ΔI_y.

As in real conditions the core of the unloaded transformer can be magnetized by inrush current at transformer actuation, it means that sometimes a process resulting in full saturation can develop even at a full symmetry of thyristors. However, when SAPT works in normal conditions, instead of in those which is an are considered above, it is unconditionally reliable and convenient device.

4.6 TEMPERATURE INFLUENCE ON SAPT OPERATION

The relationships derived above describe SAPT operation without considering the temperature effect. However, in real conditions, ambient temperature variations over a wide range are quite possible, especially for on-board and carried equipment operation. Therefore, the pattern of thyristors static control current variation under temperature should be revealed, and the relationship describing the degree of asymmetry and minimal allowed (critical) SAPT load current should be refined. Experimental study of the temperature dependence of the static gate currents (TDGC) for various types of thyristors was conducted using a thermostat; the control (gate) currents were monitored using an instrument that we developed (Fig. 4.15).

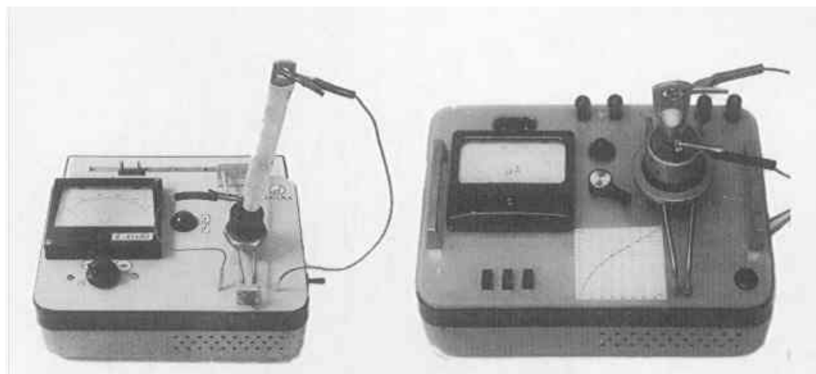

Figure 4.15 Simple instruments for mass measurements of thyristors gate currents.

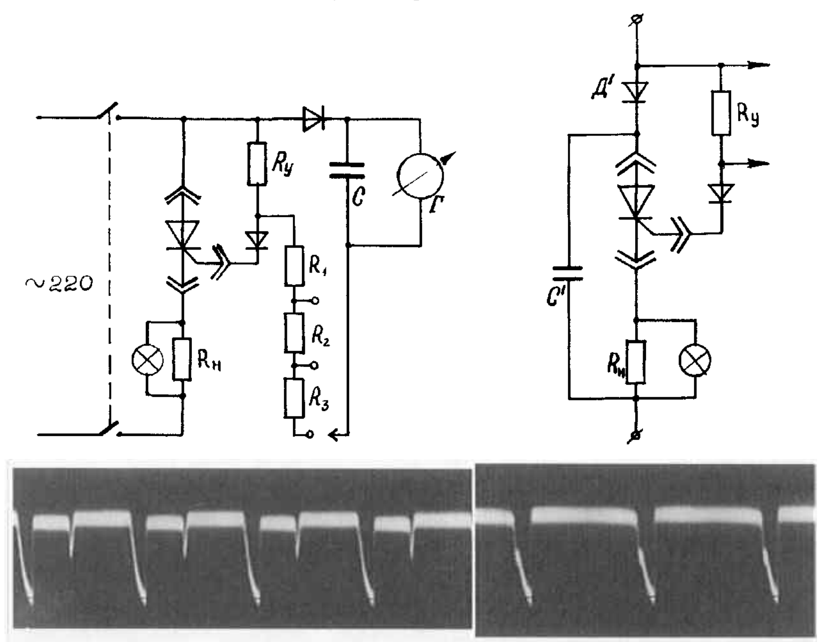

Figure 4.16 Circuit diagrams of gate current measurement instruments and oscillograms in measurement circuit.

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In the first variant (on the left), one can observe two pulses: gate current (big pulse) and off current (small pulse). In the advanced variant (on the right) – only the gate current pulse is presented. Current in a galvanometer G circuit: $G = 0.039I_y^2$ (I_y^2 – static gate current). Instrument accuracy is ± 5% for static the gate currents interval 20 mA to 500 mA.

Power thyristors of each type with maximal, minimal and average static gate currents from the sampling under study were tested. In this way, adequate information about the TDGC was gained from a small body of experimental data.
The examination of TDGC of some types of thyristors revealed the following:

1. The relationship $I_y = f\ (t^o)$ was found to be linear in the entire investigated temperature range (Fig. 4.17). Therefore, in general, just two measurements must be taken for a graphical representation of TDGC.

2. The TDGC slope (tangent α of the slope angle) is different even for the same type of thyristor.

3. Thyristors with a large initial value of I_y (for example at 0°C) always features a steep temperature dependence slope, namely, if

$$I_{y1} > Iy2, \text{ then } \mathrm{tg}\alpha_1 > \mathrm{tg}\alpha_2$$

4. The initial value I_y varies in direct proportion to the TDGC slope:

$$\mathrm{tg}\alpha = kI_y,\ k \text{ – coefficient of proportion}$$

Prior to the practical use of the TDGC, its parameters are evaluated as follows:

- Samples with maximal, average and minimal values of static gate current are selected from the lot of the thyistors of interest (by means of the instrument mentioned above).

- $I_y = f\,(t^o)$ curves are plotted using two points that correspond to the initial and the final temperature of the experiment (for example 20°C and 100°C respectively).

- From $I_y = f\,(t^o)$ curves, calculating angular factor (slope), $\gamma = \mathrm{tg}\ \alpha$ of TDGT.

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• The temperature coefficient k of TDGT for the initial temperature of the selected thyristors: $k = \gamma / I_y$ is determined, and then $M(k)$ is calculated using the formula:

$$(M)k = \frac{1}{n}\sum_{i=1}^{n} k_i \tag{4.24}$$

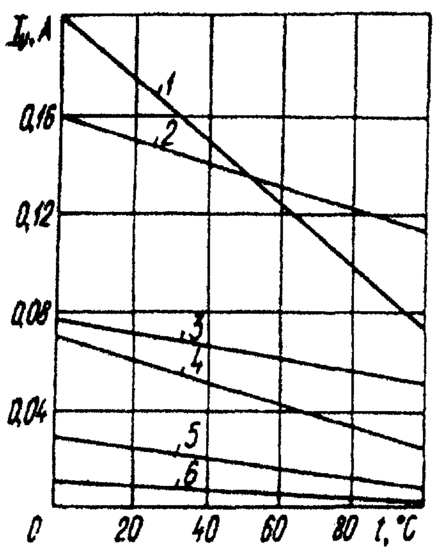

Figure 4.17 Static gate currents of the T160 type (1,4,5) and TD250 (2,3,6) thyristors with minimal, average and maximal values versus temperature.

With the known value of (M)k, TDGC can be plotted ***for any thyristor of a given type without the need for temperature measurement.*** To do this would require measuring the thyristor control current at any temperature and calculating the slope of the future TDGC using the formula:

$$\alpha = \mathrm{arctg}\,[\,I_y\, k(M)\,], \tag{4.25}$$

then obtaining TDGC by plotting a straight line through the point corresponding to the measured temperature at the angle of α.

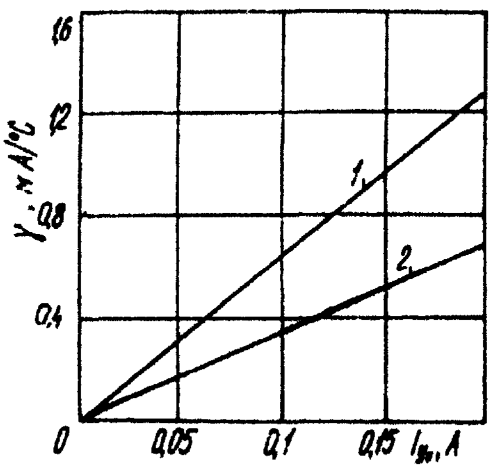

Figure 4.18 TDGC slope ($\gamma = \text{tg}\,\alpha$) versus the initial value of the gate current (I_y) of T160 (1) and TD250 (2) type thyristors.

In principle, the temperature coefficient values of k can be rated in advance as reference values for different types of thyristors.

As an example, the rated values of this parameter for some types of thyristors are contained in the table.

Table 4.6 Rated values of temperature coefficient for some thyristors

Thyristor Type	Nominal Current, A	(M)k, mA/°C
T50	50	8.64
T160	160	6.15
TD250	250	3.96

In general, the thyristor gate current versus temperature shown in fig. 4.17 can be approximated by a straight line:

$$I_y = I_{y0} - \gamma t = I_{y0}(1 - kt), \qquad (4.26)$$

where I_{y0} - thyristors static gate current for $t = 0°C$; $\gamma = kI_{y0}$ - the TDGC slope.

However, in practice, the I_{y0} value is necessarily obtainable by available means. At the same time, according to (4.26), the following can be stated:

$$I_{y0} = I_y / (1 - kt) \tag{4.27}$$

Substitution of (4.27) to (4.26) will yield:

$$I_y^{ti} = \frac{I_y^{tn}}{1 - kt_n}(1 - kt_i), \tag{4.28}$$

where t_i - preset temperature value used for the calculation of I_y^{ti};
t_n - temperature at which the thyristor I_y^{tn} gate current was measured.

The obtained expression allows for rating thyristor gate current at any preset temperature according to merely one I_y measurement result at any other temperature, as well as for obtaining the difference between static gate currents of two coupled thyristors (SAPT device), taking into consideration the temperature effect:

$$\Delta I_y^t = I_{y1}^{tn}\frac{1 - kt_i}{1 - kt_n} - I_{y2}^{tn}\frac{1 - kt_i}{1 - kt_n} = \Delta I_y^{tn}\frac{1 - kt_i}{1 - kt_n}. \tag{4.29}$$

By substituting the found values into (4.14), the expression for imbalance of thyristor control angles SAPT can be derived, taking into consideration temperature influence. Moreover, substituting these values to (4.18) yields the adjusted value of the critical load current:

$$I_{H.CR} = 28.75\Delta I_y^{tn}\frac{1 - kt_i}{1 - kt_n} \tag{4.30}$$

In the same way the opposite problem can be solved: finding the thyristors p-n junction temperature from the measured gate current value.

The loading capacity of thyristors is limited by the maximum permissible temperature of the semiconductor structure (p-n-junction), which normally lies between 110 and 140°C. The temperature increase is due to result in irreversible impairment of thyristor parameters even to the point of its complete destruction (burn-through of the silicon plate, solder melting in the plate and the cupper substrate junction points, etc.)

In transient and emergency regimes the semiconductor structure temperature elevation is determined by the time constant $\tau=R_{TR}C_{TR}$, where R_{TR} - thermal resistance; C_{TR} - thermal capacity of the structure. Because of the small dimension of the semiconductor structure (35-7000 mm^3) its thermal capacity is also small and the time constant of the structure is 1-5 ms.

In practice, thyristor overload protection is usually provided with quick response fuses; operate current of these fuses must be determined by the maximum permissible temperature of the thyristor structure corresponding to this current value. However, in practice, constant ratio between current flowing in the thyristor and its temperature is not necessarily possible because of the influence of the thyristor cooling conditions, ambient temperature variations in a wide range, etc. For example, for naturally cooled thyristor T25 the allowed average value of maximal direct current is 10A, for forced air-cooled - it is 25A; for thyristor T800 these values are 170A and 400a respectively, and for water-cooled - 1000A. When using fuses it is impossible to consider the temperature change or rate of cooling agent, the ambient temperature change. Therefore often such protection becomes inadequate, especially for on-board and portable equipment.

At present thyristors overload protection is performed through thyristor body temperature control by means of thermo-resistors connected at the electronic relay input. However, temperature distribution over the thyristor structure elements is known to be non-uniform, and the thyristor body temperature might be substantially different from that of the internal structure, while the thyristor responds to overheating within short period as brief as a few milliseconds.

The thyristors overload prevention method is known based on the temperature dependence of direct voltage drop over the p-n-junction. However, this voltage drop depends not only on the structure temperature, but also on the thyristor activation angle, which must be taken into account in some way. Moreover, certain problems are faced in the realization of this method because of the need to register the temperature variations of the tenth of volts over the object (thyristor), whose voltage is changed during operation from fractions of a volt (in operative state) to hundreds or thousands of volts (in cut-off state). The thyristor overload protection system with the electron analog thermal model of gated block is known, which produces protection signals according to the current measured in the circuit. A thermal model is provided with a correction circuit having a thermo-sensitive element for balancing the ambient temperature influence.

Our protection device is based on the linear relation between the temperature thyristors control static current allowing for instant response, and the silicon structure overheating, Fig. 4.19.

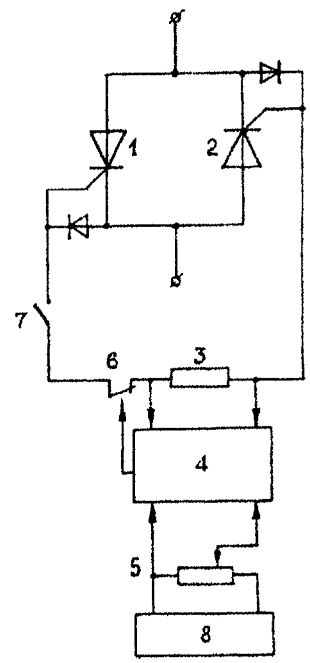

Figure 4.19 Circuit diagram of fast SAPT overload protection.
4 – balanced voltage comparator; 5 – adjustment element;
6 – working element of the protection circuit;
8 – reference voltage source.

The circuit adjustment procedure is as follows. Average current in thyristors 1 and 2 control electrodes circuit is measured, according to voltage drop on limiting resistor 3 when the thyristors are operated at nominal load and steady-state temperature. The control current is fixed during adjustment by balancing the comparator 4 with potentiometer 5. In the normal operation mode the average value of control current is continuously measured by comparator 4 and compared to the average value of this current at nominal load. When the difference between these currents is positive and exceed the preset value of comparator 4, a command is generated to disconnect contact 6 or activate contact 7, which cuts off the thyristors control circuit.

Substitution of the permitted structure temperature to (4.29), for example 125°C, will yield equation for the preset value Y of comparison circuit 4 activation (in amperes) for the selected thyristors type:

$$Y_{T160} = 0.188\frac{\Delta I_y^m}{1-61.5\cdot 10^{-4} t_n} \tag{4.31}$$

$$Y_{TD250} = 0.588\frac{\Delta I_y^m}{1-39.6\cdot 10^{-4} t_n} \tag{4.32}$$

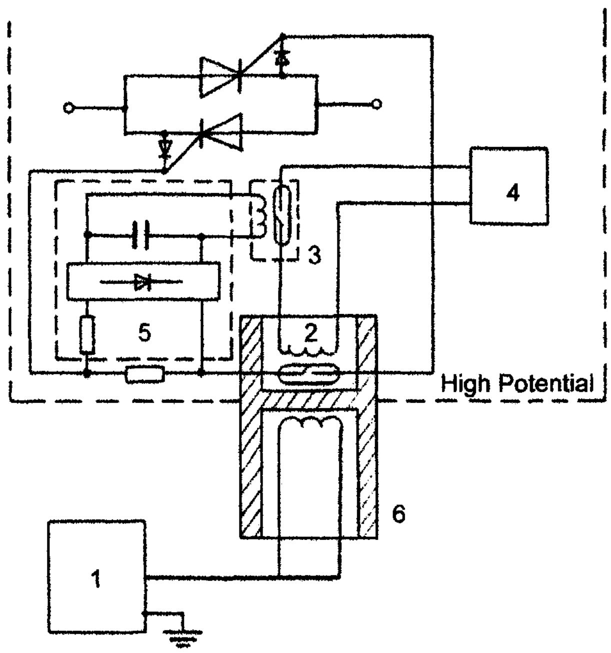

Figure 4.20 Overload protection system for SAPT with RG-relay. 1 – control unit; 2 – additional RG-relay winding; 3 – miniature reed switch relay; 4 – additional power supply; 5 – pulse stretcher.

Such a protection system is quite simple for implementation when the SAPT is operated from RG-relay, Fig. 4.20.

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4.7 HYBRID REED-TRANSISTOR SWITCHING DEVICE FOR DC CIRCUITS

One of the most efficient ways to increase the output power of RG-relays is to connect the reed switch to the input of transistor amplifier. Such a hybrid device is called a reed-transistor switch.

In general a transistor switch can be built around a bipolar or FET transistor; it should be mentioned that lately switching devices built around powerful FET transistors have become popular. A FET transistor is characterized by being controlled by an electric field, generated by the ***voltage*** applied to its "control gate", whereas a bipolar transistor is controlled by the ***current***, flowing in its "base" circuit. In spite of a great variety of FET transistor types, they can be generalized as *charge controlled devices*. Because of very high input resistance (10^{14}Ohm) and control current virtually equal to zero, these transistors are widely used in high-quality switching circuits. However, the use of bipolar transistor is advantageous in the effective area of high voltage strong electric fields.

It is known transistors used as switch circuits may be used in extreme conditions: closed (cut off) when the load current is virtually zero and the entire power supply voltage is applied to the collector-emitter junction of the transistor; or open (saturation state) when the entire voltage of the power supply is applied to the load and the current flowing in it is limited only by its resistance value.

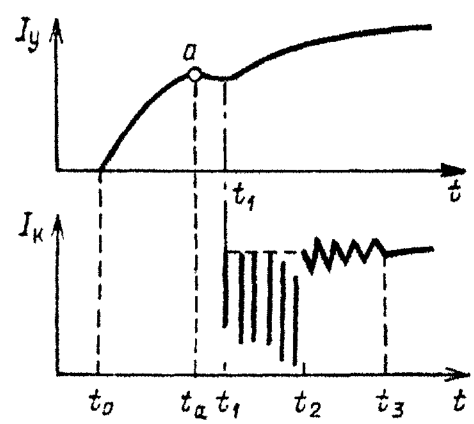

Figure 4.21 Oscillograms of current in control coil (I_Y) and in a contact (load) circuit (I_K) of reed switch relay during commutation process.

Owing to very quick response of transistors, the amplified output signal in the collector circuit of the transistor is modulated by the transient process, which occurs during circuit switching by the reed switch.

Reed switch operating process consists of a few phases. When control winding is activated at a time t_0, the current in it is increased to the point, marked a in which fast rapprochement of contact elements commences (Fig. 4.21).

The current increase rate is somewhat decreased because of the control winding inductivity increase. At a time t_1 collision and bouncing of contact elements moving with high speed occurs, followed by another collision and bouncing. The contact element vibration (called contact element rattling) continues until t_2. In the time interval between t_2 and t_3 the contact elements are not disconnected, however, small current oscillations still occur in their circuit because of the contact pressure change and contact element transient resistance oscillation induced by it.

Therefore such a device must necessarily include a compensating capacitance. This capacitance will energize only the transistor base circuit whose current consumption is very low when the amplification factor is adequately high (50 - 300 and even more for Darlington transistors), rather than the load, Fig. 4.22.

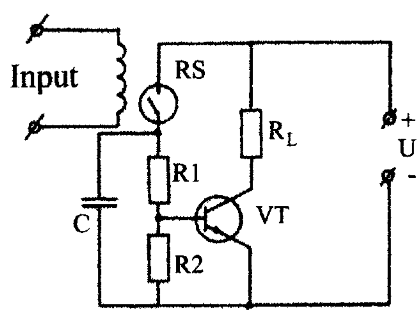

Figure 4.22 Circuit diagram for reed-transistor switching device.

Maximal C capacitance value for maximal power witch reed switch can dissipative for period t_1:

$$C_{\max} = \frac{t_1}{U}\sqrt{\frac{2P_R k}{r_R \pi}}\ , \qquad (4.33)$$

where P_R – maximal switching power of reed switch;

r_R – contact resistance of reed switch;

$k = 1\ldots3$

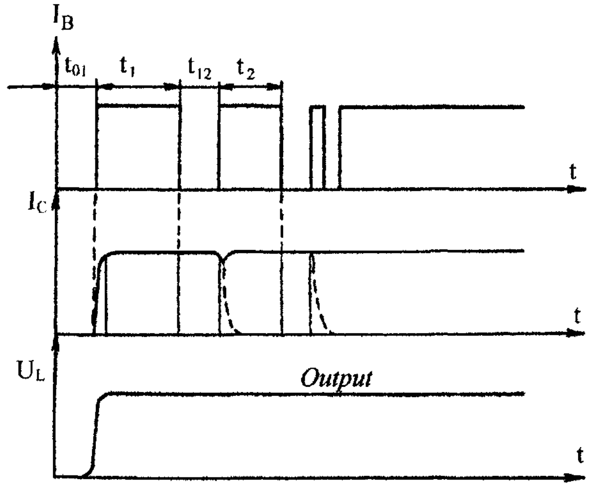

Figure 4.23 Currents in components of reed-transistor switch.

I_B – base current (equivalent to reed switch current); I_C – collector current; U_L – load voltage; t_1 – reed switch closed; t_{12} – reed switch opened; t_2 – reed switch closed.

$t_1 > t_2 > t_3 > t_N$; $t_1 \geq \pi r = \pi r_P C$; $t_{12} = -\tau' \ln \Delta U$; $\tau' = R_B C$
(r_P – internal resistance of power supply)

Minimal R_B value needed for good vibration compensation:

$$R_B = \frac{t_{12}}{C(-\ln \Delta U)}, \tag{4.34}$$

τ - time constant of capacitor charge

The minimal allowed load resistance for bipolar transistor is known to be determined by the equation:

$$R_L = \frac{U - U_S}{I_C} \approx \frac{U}{I_C}\ , \tag{4.35}$$

where U_S – saturation voltage of collector-emitter junction;
I_C – maximal collector current

Base current needed for transistor activation:

$$I_B = \frac{I_C}{\beta}, \tag{4.36}$$

Where β (β equivalent to h_{FE}) - static forward current transfer ratio (transistor current amplification coefficient)

The base circuit resistance corresponding to current I_B:

$$R_B = \frac{U - U_{BE}}{I_B} \approx \frac{U}{I_B} = R_L\beta \tag{4.37}$$

With taking into account our equations* the following method for reed-transistor switch parameters has been offered:

1. First, transistor type is selected according to the preset values of switching voltage U and current I_N and voltage and current safety factors:

$$U_{CE} \geq KU; \quad I_C \geq KI_L$$

where U_{CE} - maximal allowed collector-emitter voltage of the transistor;
I_K - maximal allowed collector current;
K- safety factor (normally 1.5… 2).

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* ***Krivtsov V., Gurevich V., Namitokov K., Savchenko P.*** Research of reed relays speed and development methods for increasing speed. – Informelektro (Moscow), 76 pp., Reg. Number 34-et90, 1990.

2. Then reed switch type is selected according to the preset values of switching voltage U and current I_N and voltage and current safety factors:

$$U_R \geq kU; \quad I_R \geq \frac{kI_L}{\beta_{\min}},$$

where U_R and I_R - maximal allowed voltage and current respectively, switched by the reed switch, according to the technical specification;

k- safety factor (normally 1.5... 2);

β_{min} - minimal amplification value of pre-selected transistor.

One should take into account that both in transistors and reed switched the product of maximal switched voltage and the maximal switched current is not equal to the maximal switched power. Hence, in addition, the following conditions shall be met:

$UI_L \leq P_R$ - for reed switch;

$U_{CE}I_C \leq P_C$ - for transistors,

where P_R - the maximal rated power switched by the reed switch;

P_C - maximal allowed power dissipated on the transistor collector in a preset operation regime.

Usually handbooks include maximal power values dissipated by a transistor collector in active mode (the most severe when dissipated power is considered). As mentioned above a transistor in a reed-transistor switch may be either in the cut-off or saturation (completely open) state. Subject to the condition that the transistor is an ideal switch, it is quite reasonable that the heat energy dissipated in the transistor in cut-off (with no current) and saturation state (with no direct voltage drop) is equal to zero. In this case the limitations put on the transistor would apply only to maximal collector-emitter voltage and maximal collector current. In practice, a transistor is far from being an ideal switch because of considerable heat energy produced at transition from one state to another and in a saturation regime because of residual resistance which is unequal to zero in the open state. While the power loss in the saturation regime can be easily rated using the saturation resistance r_S given in handbooks, the losses in a transient regime depend on the switching frequency, the duty factor of commutation current pulses, specific commutation loss, including the loss in control circuit (base), transistor switching time (which depends on the transistor features and the external circuit parameters), etc. At low commutation frequency the power dissipated in the collector junction in a saturation regime will apparently constitute the major loss power. The power can be obtained from the following formula:

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$$P_S \approx U_S\left(I_C + I_{BS}\right) = I_C\left(1 + \frac{1}{\beta}\right), \tag{4.38}$$

where $U_S = I_{CS} \cdot r_S$ - voltage drop on the open transistor with transient (contact) voltage equal to r_S (in saturation regime) with I_{CS} in it.

I_{BS} - base current maintaining the transistor in saturation regime.

According to the results of evaluation using equation (4.38) for some types of powerful transistors presented in the table below the power dissipated in a saturation regime usually does not exceed the maximal allowed dissipated power P_{Dmax}

Transistor	U_C, V	I_C, A	β_{min}	$P_{D max}$, W	R_S, Ω	P_{CS}, W	P_S, W
KT809A	400	5	15	40	0.75	20	700
KT827A	100	20	750	125	0.2	80	700
KT828A	800	5	2.25	50	0.66	24	1400
2N6284	100	20	750	150	0.2	80	700
2SC3061	850	10	10	200	0.38	42	2975
BUX25	500	20	15	250	0.12	51	3500

The power of tens of watts (which is the power of an electric solder!) dissipated in a small transistor body necessitates the use of radiators.

Hence, transistor in a reed-transistor switch can sustain the maximal allowed voltage in the cut-off regime and conduct maximal allowed current flow in a saturation regime (in an open state). Taking into account that in the reed-transistor switch the transistor can operate only in one of the above regimes, it may be thought of as providing commutation of power which is the product of maximal allowed voltage and maximal allowed current; moreover, taking into account the current and voltage safety factors used in practice (1,5...2 for every parameter), power commutation of a reed-transistor switch equal to $P_S \approx 0.35\ U_{CE}I_C$ might be considered.

3. Taking into account the time and switching characteristics of the selected reed switch, compensating capacitance C is determined from equation (4.33).

4. Resistance R_B is calculated from formula (4.37) (based on that now R_B is the discharge resistance for C).

5. The minimal allowed load resistance is evaluated from equation (4.35).

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In designing a reed-transistor switch, very low amplification factors β of standard powerful transistors with working voltages of 200-500 V and more should be borne in mind, which causes high base current to be switched by the reed switch. With limited reed switch power the use of powerful transistors in a reed-transistor switch becomes a problem. The solution is provided through the use of so-called composite transistors (Darlington, Shiclaee etc.), Fig. 4.24

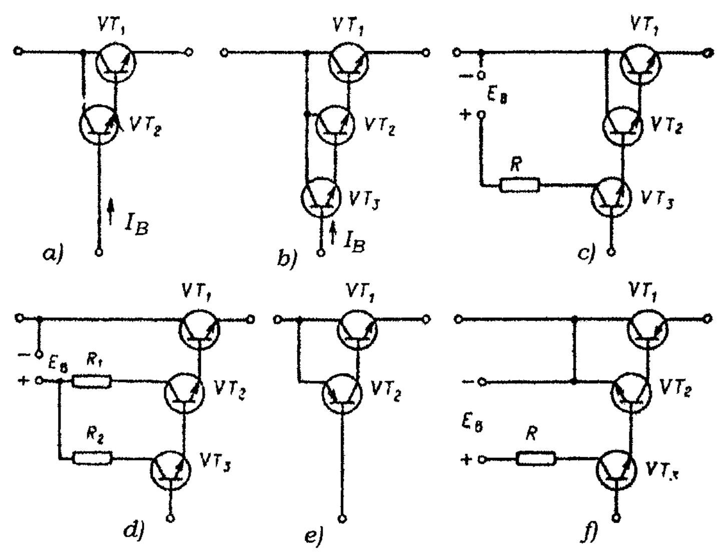

Figure 4.24 Composite transistors circuit diagrams.

a - two transistors; b - three transistors; c - with additional power supply for composite transistor; d - with additional power supply for main transistor; e- two transistors with different junction types; f - two transistors with different junction types and additional power supply.

Amplification coefficient of the circuit consisting of two transistors is:

$$\beta \approx \beta_{(VT1)} \cdot \beta_{(VT2)},$$

saturation voltage:

$$U_S = U_{S(VT2)} + U_{EB(VT1)}$$

For a composite circuit consisting of three transistors these values will be:

$$\beta \approx \beta_{(VT1)} \cdot \beta_{(VT2)} \cdot \beta_{(VT3)}$$

$$U_S = U_{S(VT3)} + U_{EB(VT2)} + U_{EB(VT1)}$$

respectively, where U_{EB} - the emitter-base voltage of the respective transistor.

Parameters of several types of power transistors, including Darlington (manufactured for standard transistor package styles), meeting virtually any design requirements are given in the Appendix.

However, in some cases (unavailability of the needed transistor type, an attempt to reduce the current load factor of the transistor and to provide easier thermal operation conditions, etc.) there is no escape from using several transistors connected in parallel, Fig. 4.25.

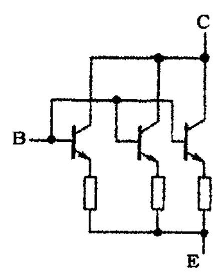

Figure 4.25 Power transistors connected in parallel.

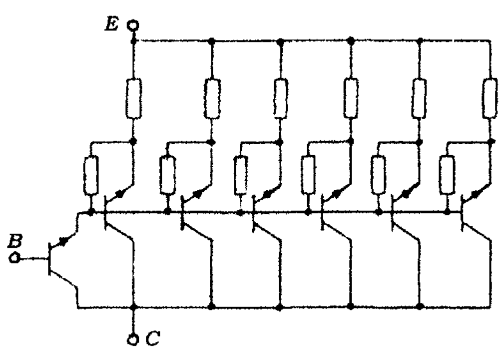

Figure 4.26 Powerful reed-transistor switch based on transistors connected in parallel with an additional control transistor.

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Moreover, because of the scattering of the U_{EB} values of the transistors connected in parallel, low resistant resistors must be connected in a series with each emitter in order to assist the current balancing in parallel branches. The resistance value R of the resistors is selected to provide for a voltage drop of about 0.2 V across each one of them.

The drawback of this circuit is that the current switched by the reed switch (equal to the sum of the base currents of all the transistors connected in parallel) is substantially increased. This puts considerable limitations on the practical usability of this circuit.

In order to clear up the trouble, an additional control transistor is added to the circuit shown in Fig. 4-26, the base circuits of transistors connected in parallel being its load. In this case the maximum allowed collector current of this transistor should be higher (taking into account the safety factor) than the sum of the base currents of transistors connected in parallel.

5

Applications for Power Engineering

5.1 NEW RELAY PROTECTION TECHNOLOGY

Maximum current protection relays are the basic components in a majority of types of powerful electrical and electronic devices and also have use in power engineering. Analysis of the trends in relay technology development shows that the major relay developers do not share a solid and consistent direction for simple current relay design improvement. For instance, some experts reason that certain families of electric-mechanical relays currently in mass production, need to be replaced by static IC relays. At the same time, they claim that regular electric-mechanical relays (including the simple maximum current relays) are most reliable and affordable for many electric utility companies, and will, therefore, be used in the majority of control and protection systems. It is important to note that the modern electric-mechanical relay is a high speed device, which is insensitive to pulse and high-frequency interference and surge voltage. It exhibits a very robust behavior in overload modes and has a satisfactory reset ratio. One has to agree, though, that electric-mechanical relays usually consist of many high precision expensive components, the production of which becomes inefficient for the relay manufacturer.

A dynamic measuring system with exposed contacts reduces the required relay reliability in a dust and gas intensive environment under a constant vibration factor. Besides, the need to clean and adjust the contacts contributes to increased labor intensive maintenance.

Static relays, however, have a lower complexity and a better assembly factor, since they consist of standard electronic components mounted on PCBs. They require zero maintenance and are decently robust when subjected to environmental and mechanical impact.

At the same time, the threshold components, such as IC triggers and comparators as well as the transformer by means of which ICs are connected to the high current circuits, cause an entirely new range of problems related to the interface immunity issue. The threshold components happen to be extremely sensitive to high-frequency signal interference, pulse peak interference coming through the feeding circuitry, etc. Therefore, it is difficult to filter out the useful signal in the wide spectrum noise background for these components.

In compliance with the recommendations of the IEC, static relays are to be subjected to obligatory special noise immunity tests. At the same time, manufacturers of such relays do not recommend to perform tests that include the application of electronic relay inputs having high-voltage pulses and powerful high frequency signals. Moreover, it is not recommended even to use megohmeter for insulation tests of such relays. Similar tests are resolved only for term, when all relay inputs are connected together. In this case, there is no sense in such tests!

The input relay transformer – an interface between the highly sensitive electronic module and the high current circuit – transforms the useful signal as well as the noise. Besides, in many cases, the transformer itself becomes a source of the interference. While this issue is very critical for static relays, the electric-mechanical relays are well compatible with transformers. In this way, the transformed-based interfaces have found a wide range of applications in relay protection engineering.

We have used the above considerations as a basis for the new methodology in current relay design to combine the advantages of the two relay concepts (electric-mechanical and static). The basic guidelines of the our methodology are as follows:

- the threshold element, which in principle is a measuring organ, has to have an electric-mechanical structure to ensure interference immunity;
- it is expedient to use a reed switch equipped with a special module to move the former relative to the control coil;
- to ensure the compatibility of the reed switch specifications with the output commutation component, an interface unit should be implemented with the discrete electronic components (not ICs!) having wide current and voltage margins; the number of these components has to be minimal and their schematics should not result in a threshold circuitry (such as a trigger, comparator, monostable vibrator, etc.).

Relay designers are well familiar with the technical characteristics of these reed switches: high level of protection from environmental impact, extreme reliability, a large communication resource, zero maintenance requirements. It is less known, however, that their reset ratio in the AC magnetic field is about 0.8…0.9, and the pickup ratio (not to be confused with its statistical variance) is relatively stable, and its adjustment function has been technologically resolved. The problem of the statistical variance of the magnetomotive force becomes irrelevant with the introduction of the reed switch adjustment module. The initial value of the relay can be defined at the manufacturing stage.

The mentioned principles have been implemented in a whole new family of relays including the universal maximum current relay, arc protection relay, short circuit indicator, current relay with the a non-transformer HV interface, etc. Some these developments are described below.

5.2 HYBRID OVER-CURRENT PROTECTION RELAY "QUASITRON" SERIES

The "Quasitron" is a multipurpose protection relay, based on a hybrid (reed-electronic) technology, with very high noise immunity, Fig. 5.1a.

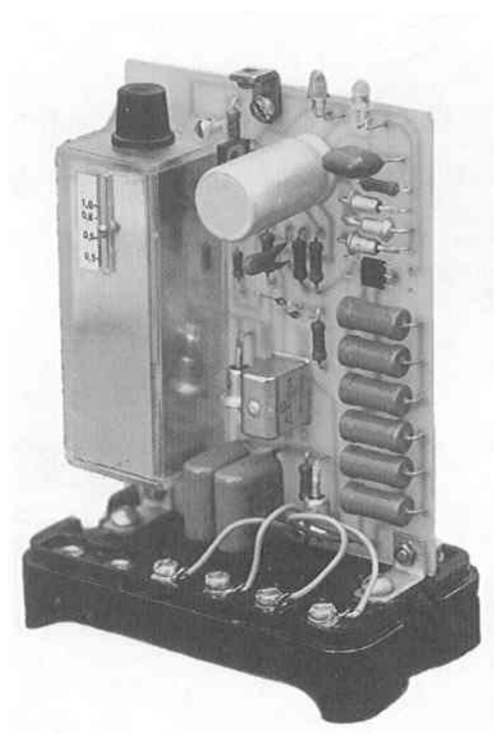

Figure 5.1a Hybrid over-current protection relay "Quasitron" series (without protection lid).

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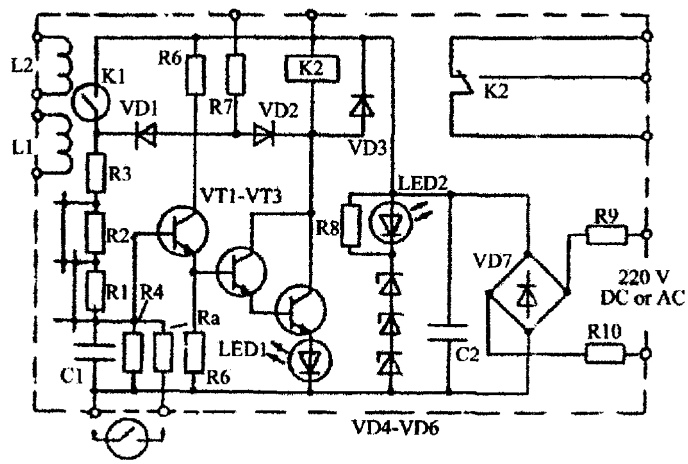

Figure 5.1b Circuit diagram of "Quasitron" relay.

K1 – reed switch; L1, L2 – input current coils; K2 – output auxiliary relay.

One relay unit may be used simultaneously with different current sensors: low voltage (above) and high voltage (Fig. 2.12), each of which has a different current trip value.

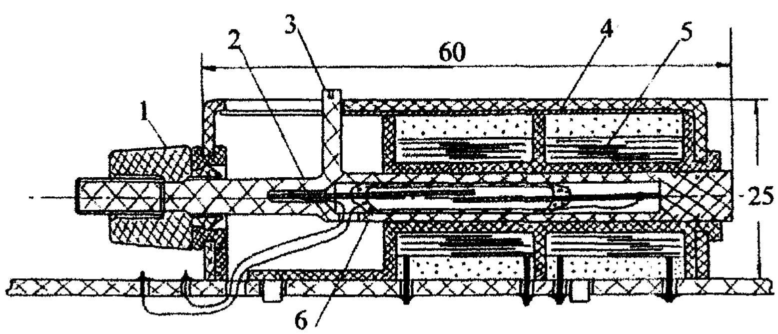

Figure 5.2 The "Quasitron" current sensor with adjustable current trip level.

1 – limb; 2 – movable dielectric capsule; 3 - level indicator of current trip; 4 – ferromagnetic screen; 5 – coil; 6 – reed switch.

A current sensor may be mounted into the relay unit (as shown in the Fig. 5.1) or mounted outside the relay unit on an additional plate (Fig. 5.3).

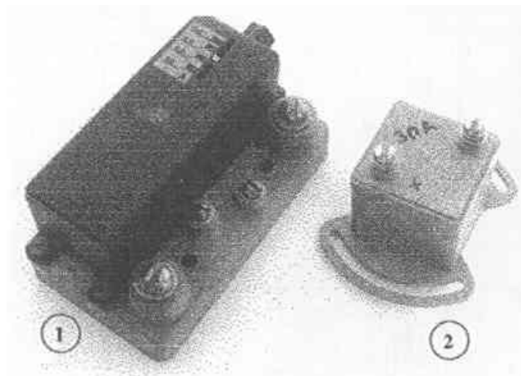

Figure 5.3a External low voltage current sensors to "Quasitron" relays.

1 – cutting-circuit sensor type "1" for current trip 0.01 to 100 A;
2 – sensor type "2" for bus bar and cable installation (30 to 10.000 A).

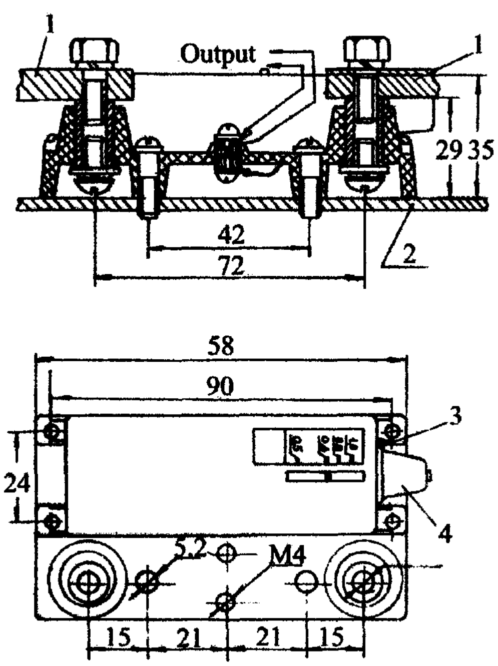

Figure 5.3b Outside dimensions of external low voltage current sensors.

1 – external wires of current circuit;
2 – plate;
3 – fixative element;
4 – limb;
"output" is connected to "Quasitron" relay.

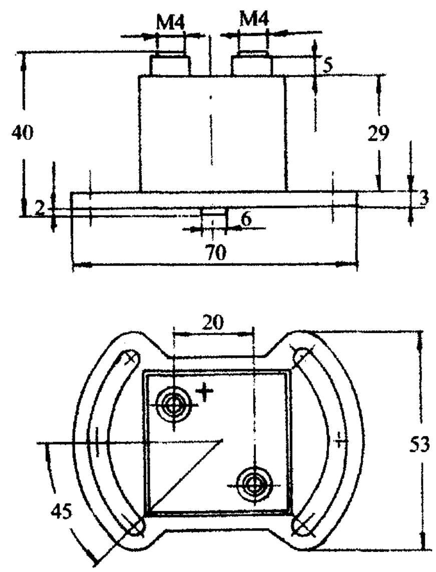

Figure 5.3c Outside dimensions of sensor type "2" for bus bar and cable installation.

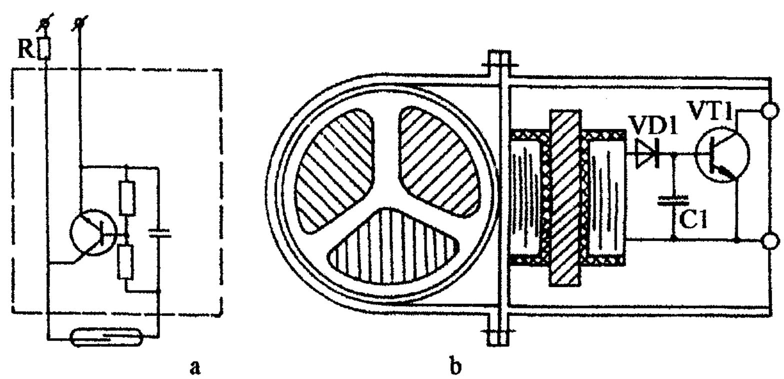

Figure 5.4 Circuit diagrams of type "2" sensors
a - for current level 100 A and more; b - for low current levels.

All sensor outputs are connected to the relay unit via low voltage wire.

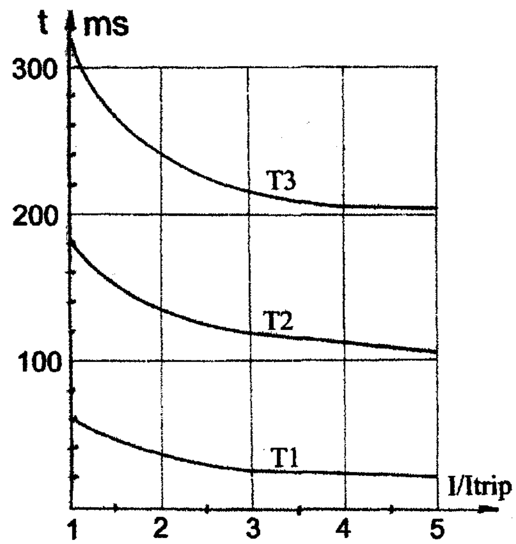

Figure 5. 5 Time/current characteristics of "Quasitron" relay.

The relay unit has three time/current characteristics (T1 – T3), Fig. 5.5, one of which can be selected by a customer by means of jumpers on resistors R1, R2 (see Fig. 5.1). For this purpose one (or two) jumper(s) can be cutting.
As the circuit configuration (Fig. 5.1) implies, it does not contain ICs; its active solid-state components (transistors) do not constitute a threshold element and are merely used as an amplifier. An interface between the electronic circuit and the outside network bus is implemented via an insulated interface, based on reed switch K1, which also plays the role of threshold elements and starts vibrating with the double network frequency when the relay trips. The contact erosion-free capacity of the reed switch (about $10^6 - 10^8$ operations) along with the short period of the maximum current relay's on-state, ensure the required commutation resource of the relay.

The amplifying module of the base circuit (Fig. 5.1) is nothing else than a compatibility link between the integrating couple L1-L2C1, and the output auxiliary relay K2 provides for the stability of the on-state of the relay under the K1 vibration conditions.

The feeding voltage of transistors (KT605BM, or similar series) does not exceed 50...70 V, the nominal operating range being 250 V. The control coil (K2) current under the tripping relay condition is as low as 15 mA, while the maximum collector current limit for these transistors is 100 mA. This magnitude of the current and voltage margins ensure a high level of the relay's operational reliability.

The high frequency and short pulse interference at the relay input cannot migrate to the electronic module, since K1, being the interface link, does not react to the high frequency control signals due to the inherent inertia. Neither does it respond to the transient interference from the power circuit commutation. Therefore, the whole relay becomes very robust to the power circuit pulse interference.

The effect of the magnetic component of the dissipation fields can be neutralized by introducing the ferromagnetic screen into the relay design (see Fig 5.2). The 1.5 mm screen shields the reed switch in the fields with an intensity much higher than that of the dissipation fields under the actual operation conditions.

For different applications of the "Quasitron" device, several types of output modules are available, Fig. 5.6.

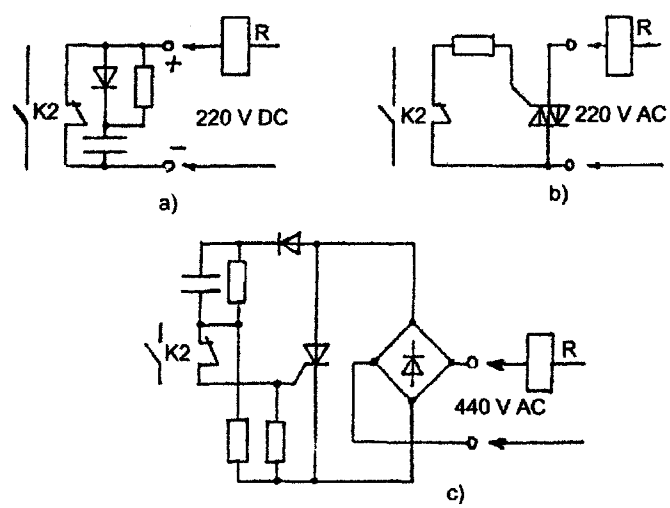

Figure 5.6 Output modules for "Quasitron" relays.

K2 – contact of output auxiliary relay, mounted on PCB in relay unit;
R – load of RL-type;
a – with spark protection, for DC load with large inductance;
b – with power amplifier, for power AC load (up to 500 VA);
c – for AC load, connected to power supply with voltage more than switching voltage of output auxiliary relay.

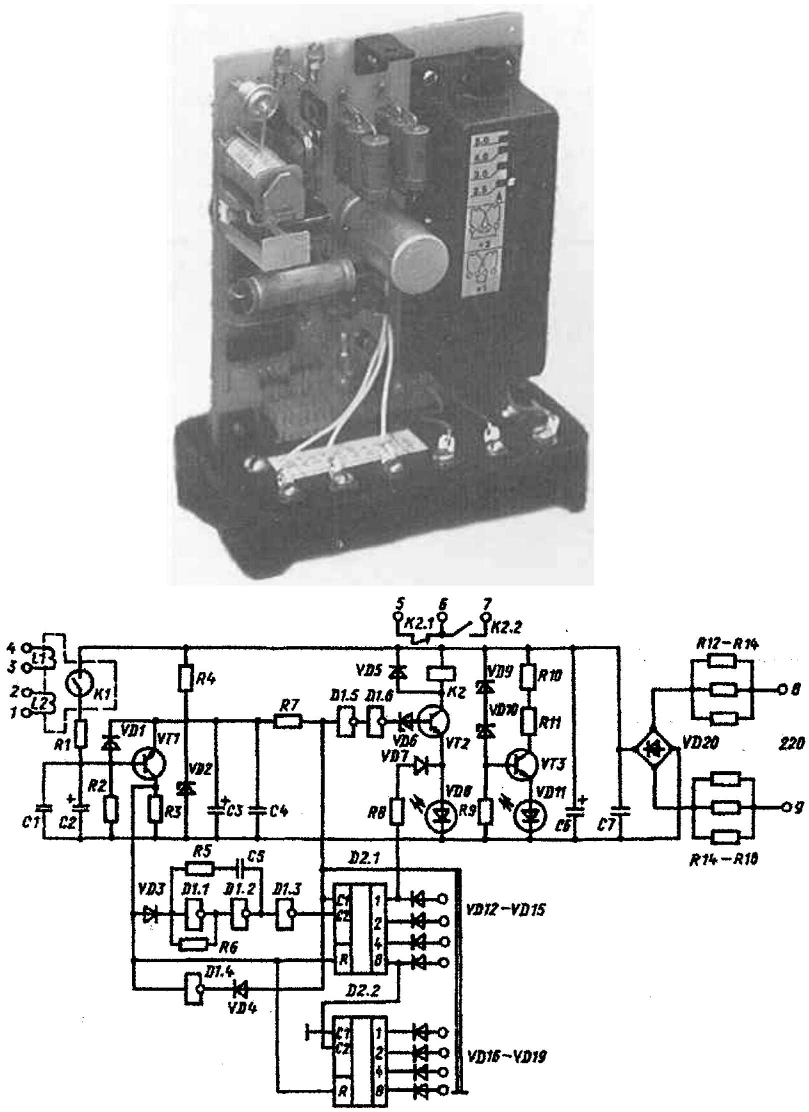

Figure 5.7 Over-load protection relay "Quasitron-T" type with the built-in timer.

Perspective improvement of this device is a current protection relay with the built-in timer, Fig. 5.7.

Time dial is adjustable in the range 0.1 to 25 (± 2.5 %) second with a grade of 0.1 s.
Dimensions of all modifications of relay units "Quasitron" and "Quasitron-T" device are 110 x 65 x 150 mm.
All types of relays were tested. Some oscillograms are shown in Fig. 5.8.

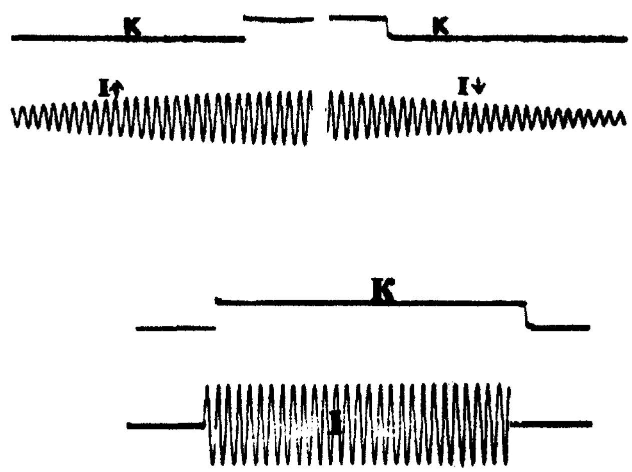

Figure 5.8a Some oscillograms, received during test process. Sudden increasing and decreasing of control current (I).
K – position of output contact; I↑ - slow increasing of control current; I↓ - slow decreasing of control current

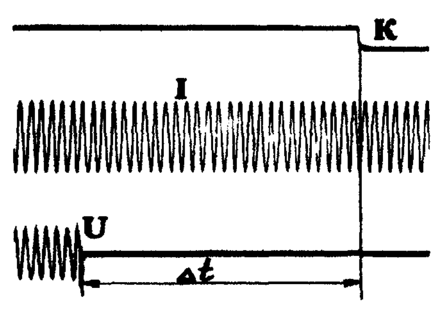

Figure 5.8b Some oscillograms, received during test process. Unset of relay after tripping in case of sudden disconnecting from power supply with voltage U ($U = U_{NOMINAL}$; frequency - 50 Hz).

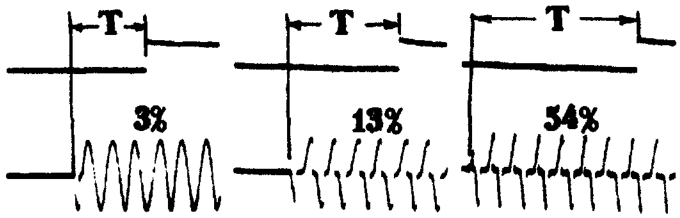

Figure 5.8c Some oscillograms, received during test process. Influence of distortion of the measured current in relay input (simulation of overload of current transformer) on a response time (T) of the relay.

5.3 ARC PROTECTION DEVICE FOR SWITCHBOARD 6 – 24 KV

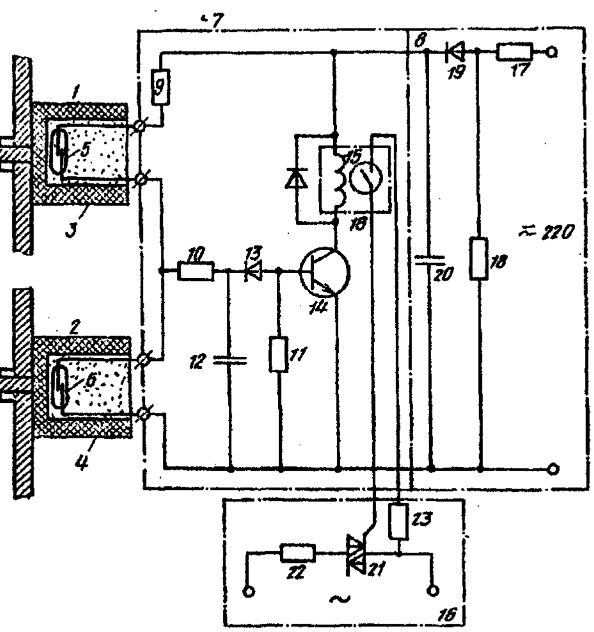

Figure 5.9 Basic circuit diagram for relay unit with the function of differential protection.
1, 2 – HV current sensors; 5, 6 – reed switches; 16 – output circuit.

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To ensure protection against an electric arc inside factory-assembled switchboard or switchgear (FAS) cubicles, units sensitive to arc luminous radiation are usually used. However, luminous radiation sensors become contaminated during operation, and for this reason sometimes do not operate, which results in complete FAS destruction.

A new arc protection relay has been developed that uses the basic technical ideas implemented in the relay "Quasitron" series.

As shown above, the current trip level of each sensor in a "Quasitron" device can be different. Therefore, a single relay unit may operate several current circuits in complex electric equipment.

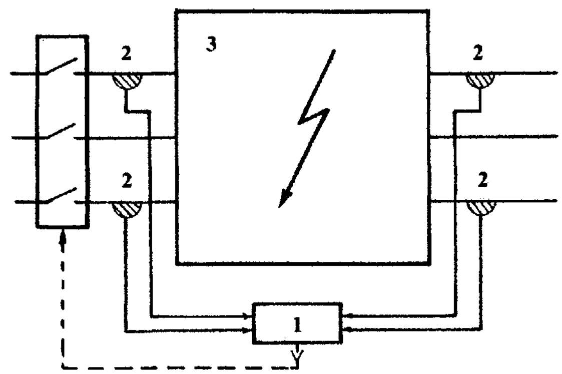

Figure 5.10 Arc protection device for switchboard 6 – 24 kV.

1 – relay unit; 2 – HV current sensors (RG-24-bus, see fig.2.12); 3 – object to be protected.

Moreover, the single relay unit can be supplied with the second (differential) input, Fig. 5.9, and can be used for differential protection of a power object, for example, for arc protection of switchboard 6 – 24 kV, Fig. 5.10.

The arc protection device (APD) monitors the current at switchboard inlets and outlets. When the current of any of the inlets exceeds the over-current limit, and at the same time, the outlets are absent (low level), then the APD immediately sends a signal to actuate the solenoid-operated HV circuit breaker. The APD is a standalone device and requires no further connection to HV current transformers or other intermediary systems.

The sensors are adjusted independently of each other for a pre-set operation current value in ranges of 300 to 10,000 A.

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To raise the stability of operation and tuning out of current inrush in case of powerful load connection, the APD is provided with an operation lag in the range of 0.2 s.

The device is fed from a 180 ... 250 V AC or DC network at the consumption current value about 5 mA. Safe operation of the APD is also ensured in case of deep voltage drops down to complete disappearance of voltage.

This principle can also be used to implement various applications (such as a simple differential protection).

5.4 AUTOMATIC RESET SHORT CIRCUIT INDICATOR FOR 6 – 24 KV BUS BARS

The Short Circuit Indicator (SCI) is intended to facilitate finding the line fault in 6 – 24 kV branched cable networks without circuit breakers on each line, to reduce significantly the power supply failure duration and to improve cost effectiveness.

The importance of this problem and the promising character of the use of such devices is confirmed by the fact that they are developed and used by leading companies, such as Pacific Power; Light Co. (USA); Nortroll AS (Norway); EM Elektromechanik GmbH (Germany); East Midlands Electricity Board (England), etc.

Our device is based on the use of new technical concepts, which enables a significant increase in its reliability and reduction of its cost.

The SCI consists of HV current sensors with an RG-24-bus (Fig. 2.12), installed directly on each current-curryiing bus bar, Fig. 5.11, and indicator units.

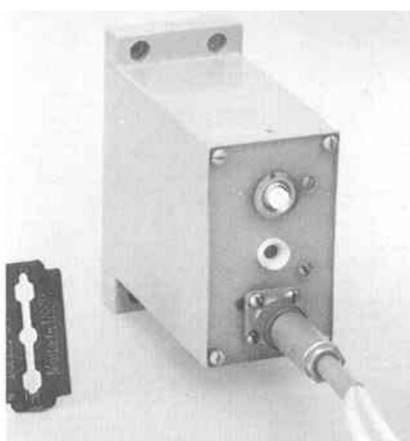

Figure 5.11a Short circuit indicator: indicator unit (dimensions is 90 x 70 x 40 mm).

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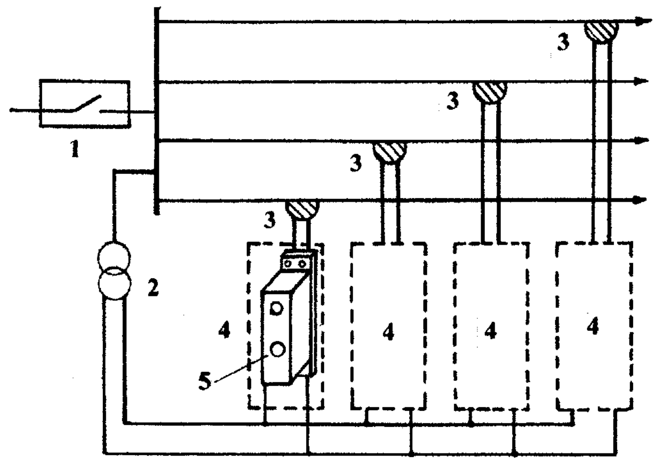


Figure 5.11b Short circuit indicator: connection diagram.

1 – main circuit breaker; 2 – original voltage transformer;
3 – HV current sensors; 4 – indicator units; 5 – button for manual check.

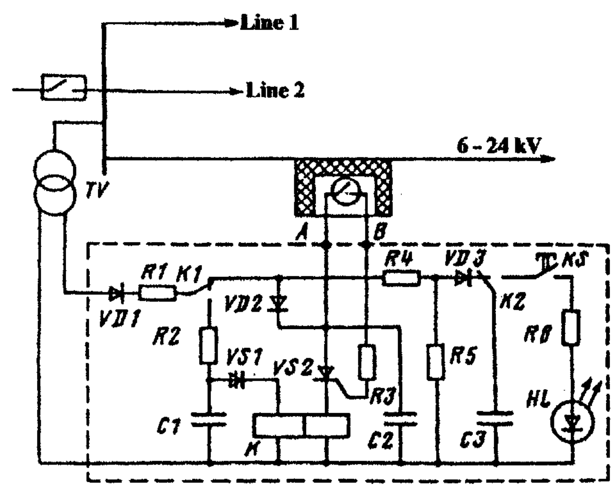


Figure 5.12 Circuit diagram of indicator unit.

K – two coils latching relay; HL – LED; KS – button for manual check.

The SCI automatically returns to its initial position as soon as the short circuit is eliminated, as well as under the effect of strong current inrushes after a powerful load connection.

The SCI stores phase-to-phase short circuits events even in the absence of external power supply up to 360 hours.

It is provided with the use of a special miniature latching relay K having two coils, and capacitor C3 with low leakage, Fig. 5.12.

The fault indicator can be displayed (LED) or sent to a remote system.

5.5 HIGH-VOLTAGE THRESHOLD CURRENT TRANSDUCER

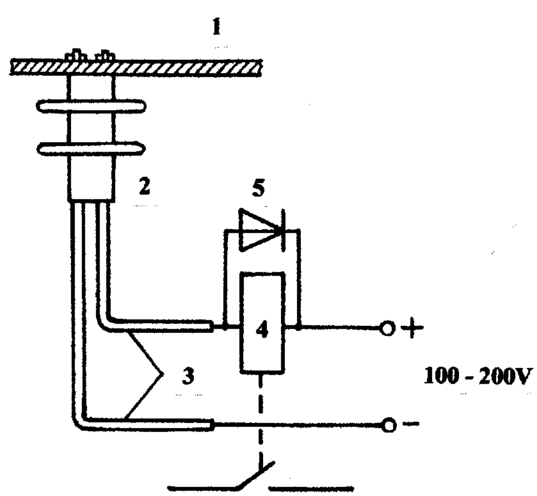


Figure 5.13 Connection diagram for HV threshold current transducer.

1 – HV AC bus bar; 2 – transducer, mounted in body of RG-24-bus interface (fig 2.12); 3 – HV wires; 4 – outside auxiliary relay; 5 – diode.

The transducer is designed to be used in overload protection units for 3 – 24 kV AC power networks, powerful electric motors, etc.

The transducer output is a standard "On – Off" type relay protection signal with 100 – 150 V DC, Fig. 5.13.

The transducer design, Fig. 5.14, envisages its installation directly on a high voltage current-currying bus bar or cable, as well as allowing the possibility for wide range variations of the operation threshold.

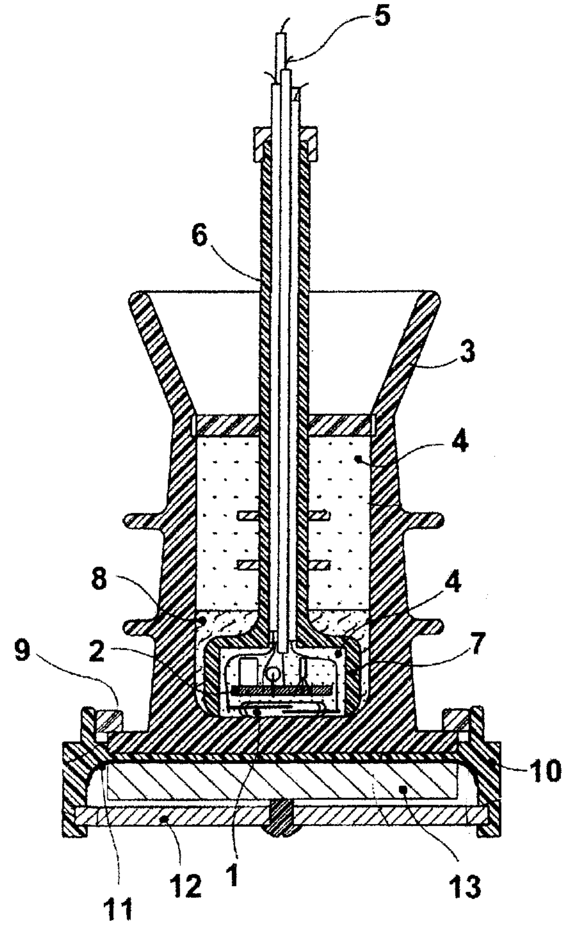
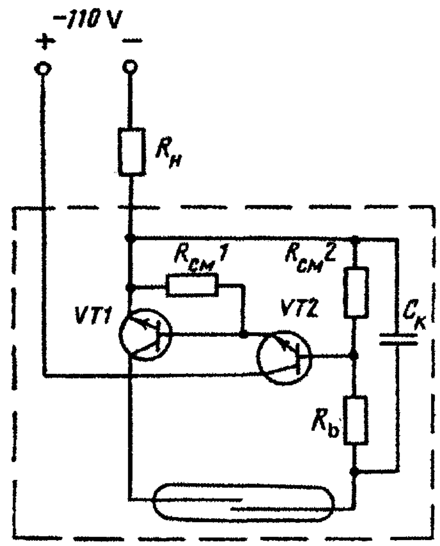


Figure 5.14 Design of the HV threshold current transducer.

1 – reed switch; 2 – PCB with electronic converter; 3 – main insulator; 4 – epoxy encapsulant; 5 – HV wires (device output); 6 – bushing; 7 – case for electronic-converter; 8 – conductive epoxy compound; 9 – fixative dielectric nut; 10 – dielectric fastener; 11 – semi-conductive cover; 12 – fastener (aluminum); 13 – HV bus bar.

The magnetic field of the current carrying bus excites the reed switch whose pulses are then converted into a standard binary signal compatible with the relay protection devices. Fig. 5.15 shows the solid-state converter circuitry with reed switch as a triggering component.



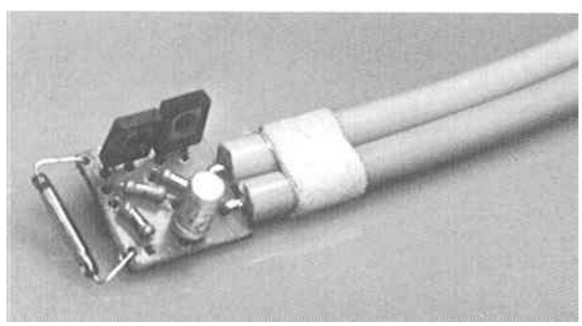


Figure 5.15 Circuit diagram and external view of the build in converter.

The sensitivity of this module is directly proportional to the sine of the angle α between the longitudinal axes of the reed switch and the HV bus, and is inversely proportional to the distance h between these axes. Keeping in mind that for a reed switch operating in the magnetic field of the current carrying bus, the operative (F_o) and the release (F_r) magneto-motive forces are respectively adequate to the operative and the release currents in the bus, one can say :

$$I_o = \frac{F_o}{K_h \sin\alpha};; \tag{5.1}$$

$$I_r = \frac{F_r}{K_h \sin\alpha} \tag{5.2}$$

where

I_o, I_r - are the values of the current in the bus causing the triggering and the release of the reed switch, respectively;

K_h – remoteness factor accounting for the distance between the longitudinal axes of the reed switch and the bus.

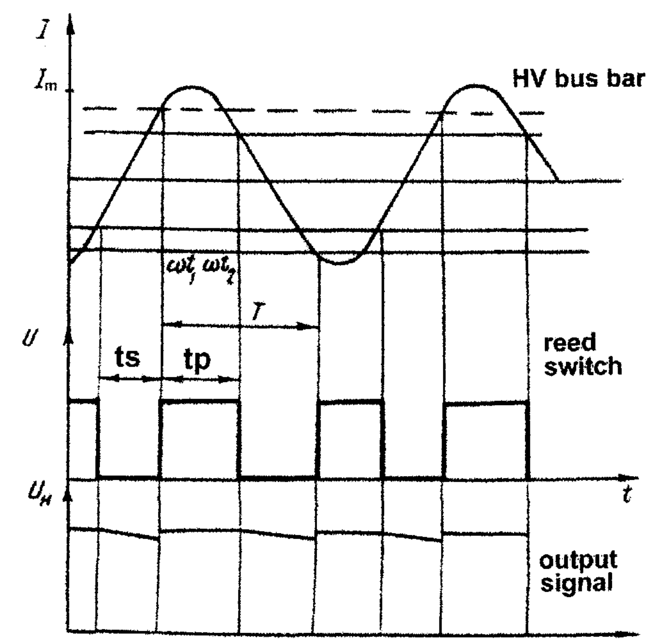


Figure 5.16 AC operational oscillogram.

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Therefore, by rotating the current transducer with respect to its longitudinal axis, one can set up the operative current at differential values.

The solid-state converter is based on a transistor filter with a peculiar parameter vector, which is explained below.

Excited by AC magneto-motive force, the reed switch generates rectangular pulses, Fig. 5.16, the duration of which is t_p and space is the t_s. Capacitor C_k is supposed to gain the full charge during period t_p, i.e., the full charge time must satisfy the following condition:

$$\pi R_H C_k < t_p \,,$$

which defines the capacity:

$$C_k \leq \frac{t_p}{\pi R_H} . \qquad (5.3)$$

During the discharge period of C_k, the transient voltage free component attenuation on the R_b resistor is not supposed to exceed a given load pulsation factor K_p:

$$K_p = U(t_s)/\,U,$$

where: U, $U\,(t_s\,)$ – nominal voltage and voltage drop on the load at the end of the pulse space, respectively. (If the load R_H is represented by a control coil of an auxiliary relay, then this pulsation factor can be expressed through the relay reset ratio).

The above requirement can formally be expressed as:

$$K_p \geq \exp\left(-\frac{t_s}{R_b C_k}\right), \qquad (5.4)$$

where $\tau = R_b C_k$ – the discharge time constant.

The resistance of R_b should, therefore, satisfy the condition:

$$R_b \geq \frac{t_s}{-\ln K_p C_k} . \qquad (5.5)$$

The oscillogram in Fig. 5.16 shows that the duration of pulses generated by the reed switch is:

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$$t_p = \omega^{-1} (\omega t_2 - \omega t_1) , \tag{5.6}$$

where the current phases ωt_2 and ωt_1 are, respectively, given by

$$\omega t_1 = \arcsin (I_o / I_m) \tag{5.7}$$

$$\omega t_2 = \pi - \arcsin (I_r / I_m) \tag{5.8}$$

where I_m – the current amplitude.

Based on (5.1), (5.2), (5.7) and (5.8), the reed switch pulse duration takes a form of:

$$t_p = \omega^{-1} [\pi - \arcsin (I_o / I_m) - \arcsin (I_r / I_m)]. \tag{5.9}$$

The pulse duration and space are related to each other by

$$t_p = T - t_s$$

where T is the pulse period, which under the sinusoidal form of the current in the bus bar is equal to π .

Taking in to account (5.9):

$$t_s = \omega^{-1} [\arcsin (I_o / I_m) + \arcsin (I_r / I_m)]. \tag{5.10}$$

By incorporating (5.9) and (5.10) into (5.3) and (5.5), we finally get:

$$\begin{aligned} C_k &\leq \frac{\pi - \arcsin(I_o / I_m) - \arcsin(I_r / I_m)}{\pi\omega R_H} \\ R_b &\geq \frac{\arcsin(I_o / I_m) - \arcsin(I_r / I_m)}{C_k\omega(-\ln K_p)} \end{aligned} \tag{5.11}$$

Thus, expressions (5.11) define the parameter vector for the above solid-state converter.

5.6 SINGLE-PHASE GROUND FAULTS PROTECTION

Single-phase ground faults account for roughly 80% of all power interruptions in medium-voltage electrical networks (6 to 36 kV).

In electrical networks with an insulated neutral position, the current level of a single-phase ground fault, as a rule, does not exceed 10...30 A. Therefore, instantaneous disconnection of such a line is not necessary. Furthermore, in some countries the activity power distribution line in a single-phase ground fault mode is admitted for many hours, which allows the continued supply of customers with electric power and avoids very heavy losses from interruptions of electric power.

In locations where there is ground fault with currents in the range of 10 to 30 A, voltage drops may create a hazard. Consequently, in countries with high population densities, continued operation of a line with such damage is not permitted. The line is immediately disconnected by relay protection.

· Use of the "Peterson Coil" can reduce current levels flowing through areas of ground fault. Peterson coils are adjustable so ground fault current does not exceed fractions of an ampere. This significantly reduces voltage drops in damage zones to reduce the hazard resulting from the ground fault.

At the same time, existing types of relay protection reacting to single-phase ground faults are based on measurements of zero-sequence and negative-sequence of fault current. These devices do not respond adequately to single-phase ground faults where the reduction of current is less than 5 to 8 A.

There is frequent application of automatic systems for searching for a damaged power network section. Such systems, for example, SIMAGIK, generate multiple cutting off and switching on of sections of a link until the damaged section is detected. Such multiple power commutation of sections of a link, causes accelerated wear-out of equipment and involves heavy emergency consequences for electric power consumers.

On the basis of the above, the following method for solving the problem of single-phase ground faults is offered:

Instead of disconnection of a power line, realizing a synthetic connection of a damaged phase to ground with the help of a special switching apparatus (SSA), can be established through each 2 - 3 kilometers of a power line. Thus, first canceling the unstable arc in a place of ground faults eliminates the necessity for usage of a Peterson coils. Secondly, the overvoltage of a tangency in a damaged area does not exceed 50 - 100 Volts and is not dangerous to people.

Full-time power supply of customers can be provided during search period and damage elimination.

After synthetic connection to ground of a damaged phase in a damaged area, the same conditions prevail as during the switching-off of a line and operation is similar to an automatic bulk-channel reclosing. In other words, disconnection from ground of a damaged phase by the SSA apparatus with a high probability of recovery of normal operational mode of a power network can be achieved within approximately ten seconds.

The implementation of this proposal is possible if the special switching apparatus satisfying to the following requirements is available:

- The apparatus should be single-phase
- The apparatus should be compact
- The apparatus should be intended to current switching 20 - 30 A
- The insulation characteristics of the apparatus should correspond to all requirements of standards for electrical equipment of the class 36 kV
- The apparatus should not contain the difficult mechanical drive, which may be left out of operation at repeated commutations
- The apparatus should be maintenance-free while in service
- The apparatus should have impulse control that consumes electric power on control only at the moment of changeover
- The apparatus should be known to be much cheaper than high voltage of switching breakers.

The analysis of parameters of high-voltage cutout switches issued by leading worldwide firms shows that there are no switching apparatus that satisfy all these requirements.

We developed such apparatus, i.e., "Goliath" (see Fig. 3.1, 3.2).

In addition, a device that detects a damaged phase with high reliability - "Ground Fault Detector" (GFD) - was also developed by us, Fig. 5.17.

An amplifying module (mounted on a small PCB) and an antenna are located in the main insulator of the RG-24-bus interface, similar to HV threshold current transducer, Fig. 5.14. Here conductive epoxy compound 8 is used as an antenna.

The GFD detects the electrical isolation between the HV bus bar or an aerial power lines and the ground and trips when isolation resistance is decreased.

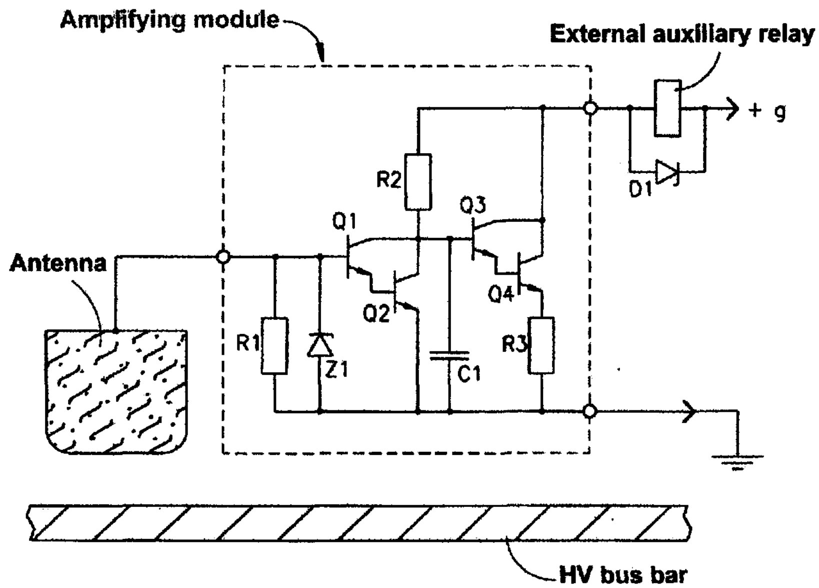

Figure 5.17 Ground Fault Detector (GFD).

Main parameters:

Nominal voltage, kV	10 to 24
Resistance trip, MOhm	0.5
Power supply, V DC	100 – 150
Dimension, mm	Diam. 80 x 125

The implementation of the solution allows continued power supply to customers during single-phase ground faults while reducing hazards caused by these faults to provide full safety against damage. It is possible to use a GFD device and GOLIATH apparatus together with existing automatic systems when single-phase ground faults occur.

5.7 GROUND CIRCUIT FAULT INDICATOR FOR UNDERGROUND HV CABLE NETWORK*

The Ground Circuit Fault Indicator for underground applications (GCFI) is designed to identify the location of emergency current percolations in circuits that have underground cable screens (161 kV) connected to the ground circuit bus. GCFI also defines these currents' percolation in the circuits.

Using GCFI provides the operating staff with valuable information regarding the behavior of a cable circuit in emergency mode and enables them to make appropriate technical decisions to ensure the circuit's safety.

GCFI consists of the following units:

- Stationary leak-less unit (SU) with memory elements installed in the underground well on the metallic Cross Bounding Link Box
- Current sensor made in the form of a circular current transformer (CT) including elements of outer fixation
- Mobile manual indication unit (MU) including elements of indication and monitoring

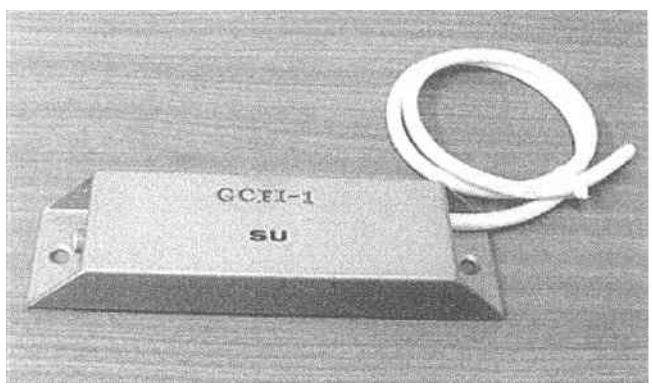

Figure 5.18 Stationary unit of GCFI system.

The Stationary Unit, Fig. 5.18, includes elements that change their state when the input current reaches the given threshold value, and remains in this new state after the input current ceases working.

* This problem was formulated by Dr. A. Shkolnik, IEC

Each SU has three thresholds functioning within the chosen range of emergency currents, which present approximately 30, 60 and 100 percent of the selected range of emergency currents.

The user can select one of the following ranges of emergency current: 0-10 kA, 0-20 kA and 0-30 kA. The current range should be chosen when the device is ordered. The SU is connected to CT by a piece of twin-core isolated cable not less than 0.5 meter in length, which is provided with leak-proof input into the body of the SU. The SU is connected to the MU by means of a connector.

Threshold elements and memory elements (latching relays K1...K3, Fig. 5.19) have high interference immunity and stability, enabling them to function efficiently in a powerful electromagnetic field and difficult environmental conditions. The SU does not require using a separate power source. Its body is made of steel and is coated on the outside with two layers of waterproof varnish. The SU's interior is filled with an epoxy compound. The unit has a leak-proof and non-separable design.

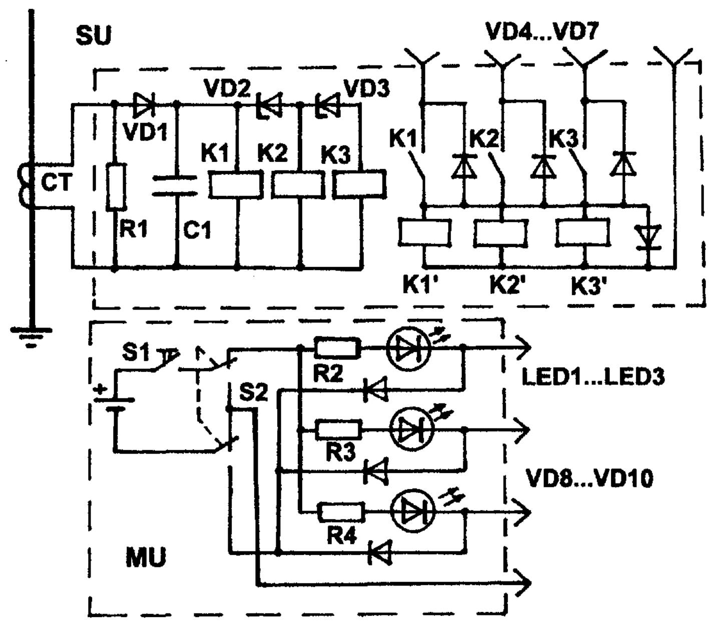

Figure 5. 19 Circuit diagram of GCFI system.

SU – stationary unit; MU – movable unit; CT – current transformer
K1...K2 – two coils miniature latching relays; S1 – "test" button;
S2 – "test – reset" toggle switch; VD2, VD3 – Zener diodes.

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The Current Transformer, Fig. 5.20, is designed to be installed on the isolated cable connecting the generic point of connection of the cable screens with the grounding circuit. The CT has a non-separable circular core and is filled with an epoxy compound.

The CT is attached to the vertical wall on the cable well or on the Cros Bounding Link Box by means of bolts.

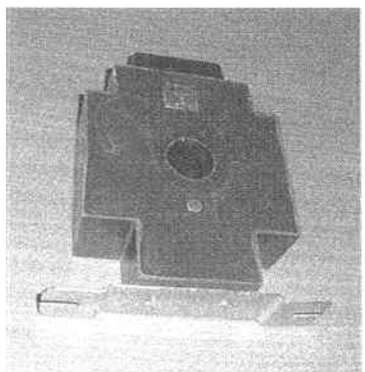

Figure 5.20 Encapsulated current transformer (2000/5A, 15P5) for GCFI system.

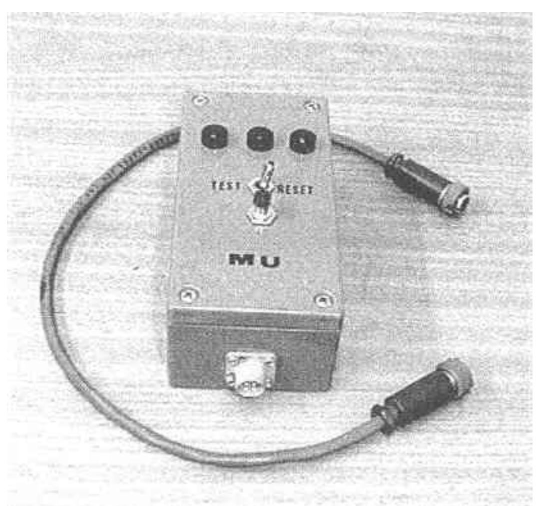

Figure 5.21 Manual unit of GCFI system.

The Manual Unit, Fig. 5.21, contains:

- A deciphering unit
- Three elements of indication (LED) which determine the state of the threshold elements of the SU
- A button and toggle switch that switches the Manual Unit into TEST and RESET modes
- A connector to connect with the SU
- A connector to check operating capacity of the device and battery status
- A built-in power source (standard 9V battery)
- A control wire with two connectors

The MU has a miniature, plastic rectangular body.

Table 5.1 Main parameters of ground circuit fault indicator

*GCFI-*_____	SUBTYPE		
	10	**20**	**30**
System rated voltage, кV		161 kV	
Frequency, Hz		50 - 60	
Rated operating current: - in normal mode, A (not a working area) - in damage mode, kA (working area)	 50 10	 50 20	 50 30
Thresholds of a pick-up current in damage mode (in percent of operating current range) 1 2 3		 30 % 60 % 100 %	
Fault sensing time, msec		10	
Duration of storage of emergency current information, hours		240	

Reset method	Manual
Power supply: - SU - MU	 not necessary 9 V battery
Maximal cable diameter, mm	30
Environmental conditions: - temperature range, °C - maximum relative humidity, % - atmospheric and industrial air pollution, coal dust, salt spray (for SU) - natural water (for SU)	 -10 to +55 98 steady steady
Dimensions, mm - SU - MU - CT	 150 x 50 x 25 110 x 55 x 42 220 x 150 x 60

Installation of the system, Fig. 5.22.

The standard unit (SU) is installed in the cable well (on the inner wall of the well or on the Cross Bounding Link Box) and is affixed by two 6-mm bolts. The location of the SU fixation must be as high as possible from the surface of the well's bottom and must be maximally remote from current-conducting parts.

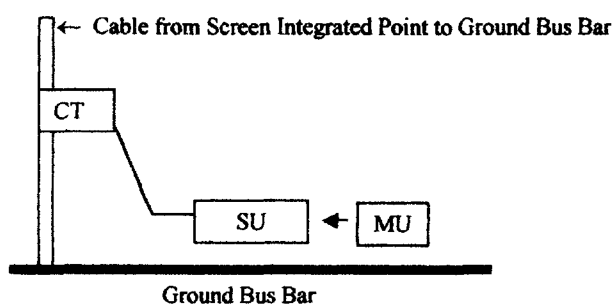

Figure 5. 22 Installation diagram of GCFI system.

The Current Transformer (CT) is installed in the cable well (on the inner wall of the well or on the Cross Bounding Link Box, at a distance of no more than 0.5 m from the SU). It is affixed by four 6-mm bolts. The piece of cable connecting the generic point of the monitors of high-voltage cables with the grounding circuit must be passed through the CT's opening. The polarity does not matter.

The twin-core flexible cable (0.5 m in length), coming out of the SU, is connected to CT cleats. The polarity does not matter. After connection of the cable, the CT's cleat box must be coated by silicone plastering to prevent the cleats' oxidation resulting contact with water.

Before using the device, it is necessary to check serviceability of the MU and the built-in battery. To do so, it is necessary to connect both connectors located on the MU's body, using a control wire with connectors that are part of the kit. Furthermore, it is necessary to put the toggle switch on TEST mode and press the button. In a completely serviceable MU, all three LEDs are brightly lit. Weak luminescence means that the battery is depleted. In this case, it is necessary to open the MU lid and replace the battery.

In order to define the status of SU's memory elements, it is necessary to connect it to the MU by means of the control wire with connectors.

The MU toggle switch is set on TEST mode, and the button is pressed.

If a short-circuit current of more than 10 kA surged through the location of the SU installation, LEDs must start glowing. The number of LEDs is proportional to the value of the short-circuit current.

One LED – 30% of rated operating current in damage mode.
Two LEDs – 60% of rated operating current in damage mode.
Three LEDs – 100% of rated operating current in damage mode.

After evaluation of the short-circuit current, the SU's memory must be cleared. To do so, it is necessary to set the tumbler on RESET mode and press the button.

When the clearing of the memory elements is completed, the control wire with connectors are disconnected from the SU, and the protecting plug is screwed on the connector of SU's body.

5.8 CURRENT TRANSFORMERS PROTECTION FROM SECONDARY CIRCUIT DISCONNECTION*

Current transformers (CT) should never be operated with the secondary circuit

* This problem was formulated by Dr. A. Shkolnik, IEC

open because hazardous crest voltages may result (ANSI/IEEE C57.13-1978). Occasionally, the CT secondary circuit might become disconnected for different reasons. In this case, high voltage (3...5 kV) is generated over the disconnected secondary winding resulting not only in CT's secondary winding failure but also in severe circuit damage (partial discharges in oil, fuming and detonating CT even).

We have offered a simple automatic protection device, Fig. 5.23, which forces the CT secondary winding shortage when the voltage over it becomes higher than 100V for metering burdens (fig. 5.23) and 600-800 V for relaying burdens (fig. 5.24). After the fault has been cleared the device is manually returned to its initial state (reset). A remote signal indicates that the device operation can be generated.

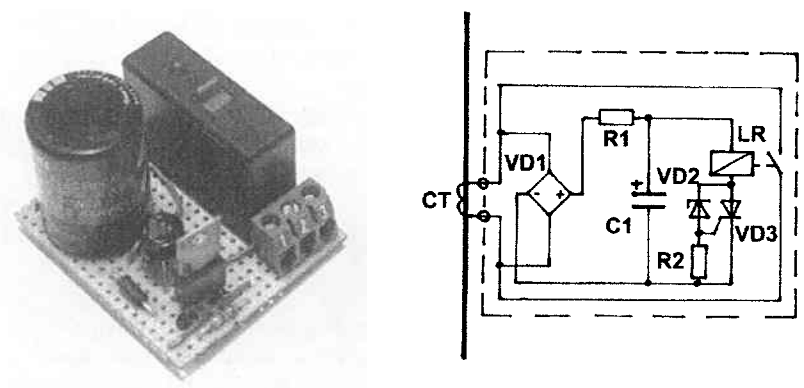

Figure 5.23 CT protection module for metering burdens.

The device circuit is it very simple and cheap. The price of the most expensive element – the latching relay (LR) with switching current of up to 20A and manual reset – is $9.

For a large-size high voltage CT with a number of separate secondary windings, the corresponding number of such protection modules is mounted inside a common protective jacket fixed on the CT body. The protection device is connected to the CT outputs with a simple clamp.

For extra sensitive CT burdens such as a some types of a high impedance differential relay with very small operating current, a miniature gas discharge surge arrestor (suppressor) with very high resistance (10^8 Ohm) in normal mode can be used as a threshold element instead of varistor (fig. 5.24).

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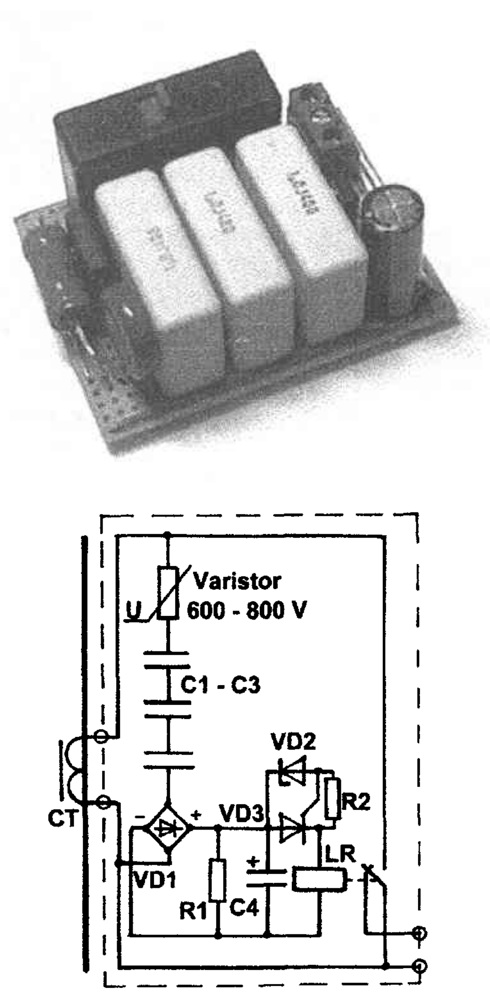

Figure 5.24 CT protection module for relaying burdens.

Tests have proved safe operation of this device. Operating time for 720 V is about 3 sec; for 800 V- 50 ms. The protection module was also tested successfully with a real CT ASEA 170/√3 kV, on core: 10P; 1200/5 A; 90 VA. At deliberate disconnection of a secondary circuit (with a primary current up to 1000 A) the protective module instantaneously short-circuited it.

5.9 PROTECTION AGAINST FERRORESONANCE IN VOLTAGE TRANSFORMERS

Ferroresonance is a non-linear resonance phenomenon that can affect power networks. The abnormal rates of harmonics and transient or steady state over voltage and overcurrents that it causes are often dangerous for electrical equipment.

Measurement voltage transformer (VT) operation failures in 6...24 kV distributing power circuits and in generator voltage circuits are quite common. On evidence derived from certain sources, about 10% of installed VTs fail to operate annually in circuits with short circuit current to earth equal to 10 A. The parent cause of this phenomenon is thermal destruction of the high voltage winding of the VT by large currents resulting in transformer core saturation and a drastic drop of its inductive resistance (the main component of the impedance).

Usually the core saturation occurs during oscillation in the circuit, formed by circuit capacitance and transformer non-linear inductivity. Such an oscillation process, Fig. 5.25, is initiated by unstable mono phase contacts to ground; partial phase operation of the VT itself results from the blow-out of fuses in high voltage circuits; VT operation on "idles" buses; partial phase operation of the power transformer accompanied by over voltages on the VT, etc.

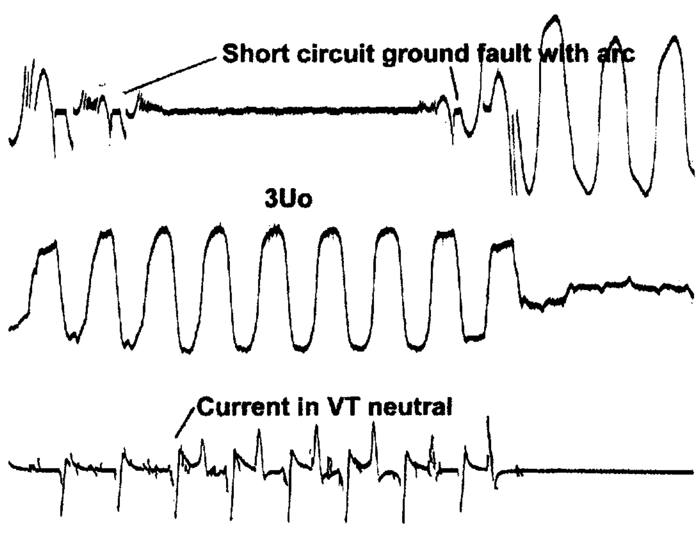

Figure 5.25 Oscillograms of current and voltage in VT during ferroresonance.

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The oscillations frequency may vary for different oscillation origins, parameters of the specific VT and specific circuits. In big VTs designed for 160...400 kV and more, the case in point is sub-harmonic frequencies 10; 12.5; 16.6; 25 Hz. In 6-10 kV distribution circuit VTs, the resonance frequency is due to attain 150 Hz.

It is worth mentioning that the processes occurring in the VT in these operation modes depends on a certain combination of the VT and the circuit parameters and their rating. Accounting for it is by no means easy (manufacturing variability of VT parameters; circuit parameters variation; undefined parameters in transient regimes that caused the oscillation process, etc.). Therefore, different hardware is used to protect the VT from those regimes that impede or disrupt resonance once it occurs. For example, some manufacturers offer special ferroresonance protecting devices for large VTs rated for 160...400 kV. The protecting device has an analyzer of the current spectrum in the VT circuit, which detects sub-harmonics emerging at low frequencies and subsequently generates an activation command in parallel with the secondary VT winding special throttle and active resistance of 0.3...0.7 Ohm, which disrupt the oscillation process. For medium-size VTs rated for 6...24 kV, simpler means are used. For example, for efficient protection against ferroresonance of transformers with an "open triangle" type winding, it is good practice to connect a 5...150 Ohm resistance in parallel to this winding.

Another common way of protection against ferroresonance is to include a 3...5 k Ohm resistor to the VT neutral terminal.

The author has not encountered reports that analyze the influence of such protection means on VT operation errors, yet experience shows that designers rating the VT loads (relay protection circuits, variations and registration of energy consumption) take into account the nominal power range of the VT for which its nominal accuracy level is preserved. Moreover some Western manufacturers supply VT with anti-ferroresonance resistors, which load the VTs to 60...80% of their nominal power. The result is overloaded voltage circuits, and consequently, VT operation error goes beyond the accuracy grade and power consumption registration circuits powered by VT result in heavy losses.

There is no doubt that resolution of this problem will be provided by simple automatic devices, which connect resistors to the VT circuits only in response to ferroresonance.

Practical implementation of some common techniques of ferroresonance suppression based on this principle requires a special component base. For example, according to simple calculations, even in the case of current limitation in the VT neutral terminal to 0.3A, voltage drop over a 3...5 Ohm resistor is likely to attain 1500V. This necessitates the use of a high voltage low current switching element for this resistor to de-shunt in the case of ferroresonance.

When current limiting resistors are included in the circuits of primary (high voltage) windings for VT protection in case of ferroresonance, more severe demands are imposed on switching devices.

A VT protecting device, shown in Fig. 5.26, in which a resistor added to the neutral terminal circuit, consists of threshold body 15 and high voltage operation unit 16 de-shunting the anti-ferroresonance resistor 4 in response to the increase of current flowing via the measurement shunt 2.

In normal operation of the VT, the voltage drop over shunt 2 is very small, threshold elements 11...13 are cut off, winding 14 of the reed switch relay is de-energized, reed switch relay 10 is short-circuited, and thyristor switch 5...6 is disconnected providing for the VT neutral terminal grounding.

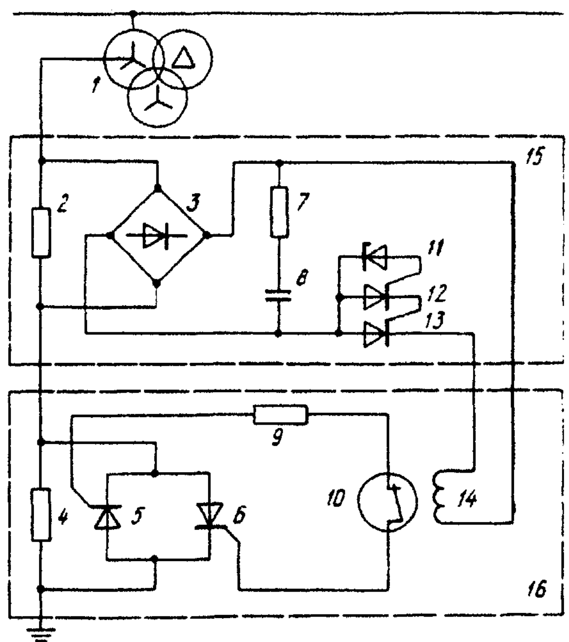

Figure 5.26 Circuit diagram of VT protecting device.

Following ferroresonance resulting in arc contact of one of the phases to ground, current spikes occur in the VT neutral terminal circuit and voltage pulses occur on shunt 2. After condenser 8 is charged into the trigger voltage of threshold elements 11...13, they are triggered and condenser 8 is discharged into the reed switch relay winding causing its safe operation. Thyristors 5 and 6 are turned-off, thus deshunting resistor 4, which limits the current in the neutral terminal.

Depending on the selected algorithm, winding 14 operation can be designed so that after the current in the neutral terminal is decreased, reed switch relay 10 can either revert to the initial state or remain turned off waiting for manual reset.

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For an improved anti-ferroresonance effect, one more switching element can be added to the device in order to connect the low resistance resistor to the "open triangle" circuit.

In cases when the neutral point of VT is not separated, a device automatically connecting current limiting resistors to the high voltage windings circuit can be used for its protection.

In essence, any of the high voltage low current switches mentioned above can be used.

In cases where a set of three single-phase VTs is used for control and each is provided with an individual and separate connection to the line, shunting of secondary windings of each VT with a low resistance resistor automatically engaged in response to the current increase in the high voltage winding circuit can be used for successful fighting of the ferroresonance. To do so, a resistor with resistance of several Ohms is added to the high voltage winding grounding circuit, which controls the voltage drop over it.

A "Quazitron" relay (Fig. 5.1), in which a reed switch with an additional amplification transistor cascade replaces the relay, can be used to control this voltage drop and to connect the anti-ferroresonance resistor. The "Quazitron" relay provided with this additional cascade is engaged when alternating voltage of about 0.7 V is applied to its input. Resistor K2 can be used to reduce the sensitivity of the amplification cascade. Diode MB1 provides for thermal stability of the device operation threshold. In a three-phase implementation, the outputs of all the three amplification cascades are connected in parallel and connected to the input of one "Quazitron " relay common to all the phases.

5.10 HV INDICATORS FOR SWITCHGEARS AND SWITCHBOARDS

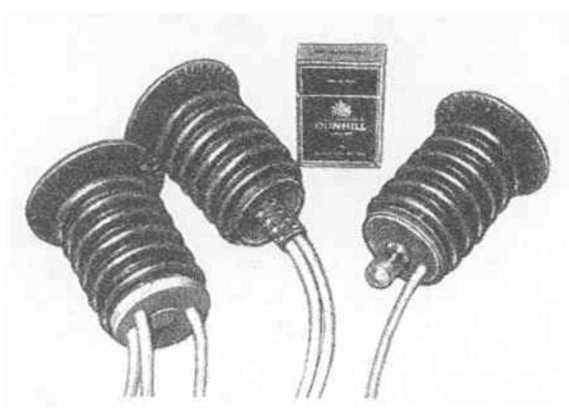


Figure 5.27a Portable HV indicators for direct installation on bus bars.

Many of the modern compact Switchgears and Switchboards, and in particular those filled with SF_6, are not operable with traditional portable high voltage indicators formed as long rods. In such devices built-in fixed voltage indicators with an indication unit based on neon lamps and a dedicated high-voltage sensor with a resistive and a capacitance voltage divider have been widely used.

We have proposed some novel designs of such devices (Russian Patents No. 1718129, 1821750, 2015516, 2020682).

The first group constitutes portable indicators, which can be temporarily assembled during maintenance works on high voltage bus bars of all types of high voltage equipment, Fig. 5.27.

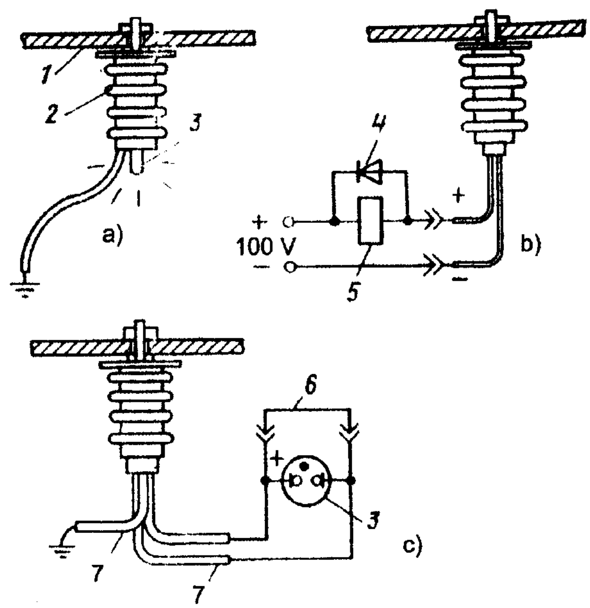


Figure 5.27b Connection versions for portables HV Indicators.

a – with local neon lamp; **b** – with relay output; **c** – with remote indication 1 – HV bus bar; 2 – HV plastic insulator with antenna and electronic components; 3 – neon lamp; 4 – diode; 5 – electromagnetic relay; 6 – removal jumper; 7 – HV wiring.

Such devices can be designed either in the form of a visual indicator with blinking neon lamp, fig. 29, or relay voltage sensor with an output contact (of electromagnetic relay K) used to connect indication or interlock circuit, Fig. 28.

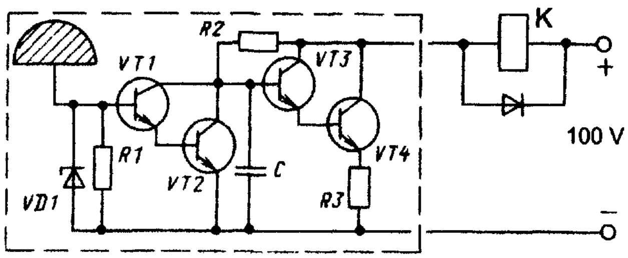


Figure 5.28 Circuit diagram for relay voltage sensor
K – outside electromagnetic relay

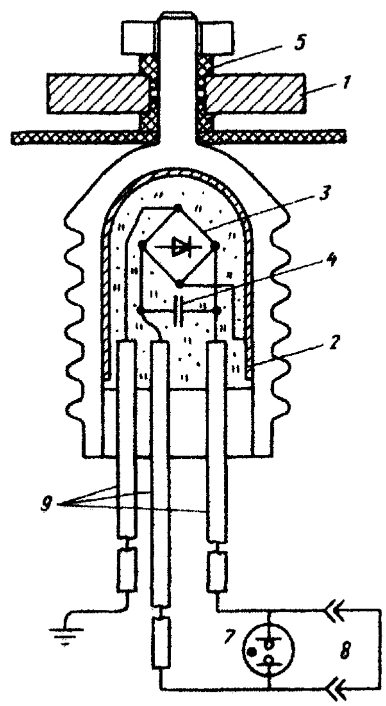


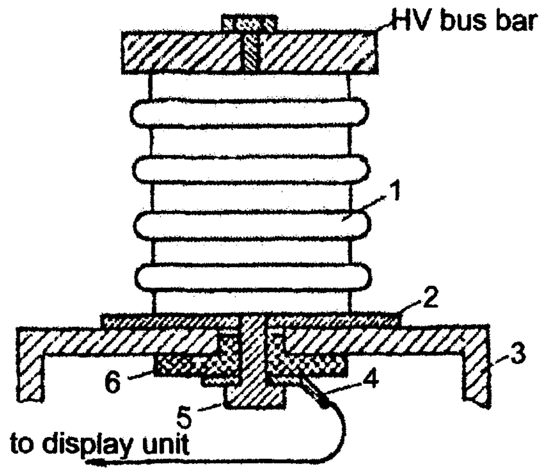
Figure 5. 29 Construction and circuit diagram for HV indicator with blinking neon lamp.

1 – HV bus bar; 2 – antenna (conductive coating); 3 – rectifier bridge; 4 – capacitor; 5 – thermostable insertion; 7 – neon lamp; 8 – removable jumper; 9 – HV wiring

Devices with output contact can also be used in addition to existing fixed indicators.

Materials used to manufacture such high voltage insulators and their production procedures are same as used for RG-series interface relays described above.

The other group comprises stationary devices, which are built-in to switchgears and switchboards.



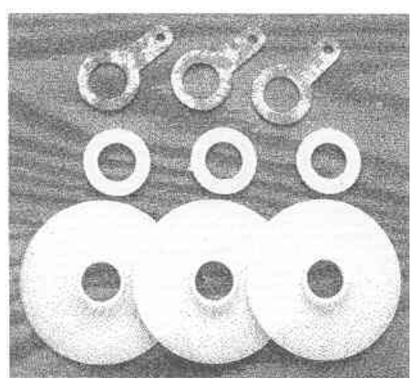


Figure 5.30a The stationary HV indicator: installation on bus bar and elements set.

1 - base permanent insulators; 2 – insulation washer; 3 – switchboard's console; 4 – conductive petal (output of sensor); 5 – bolt; 6 – insulation insert.

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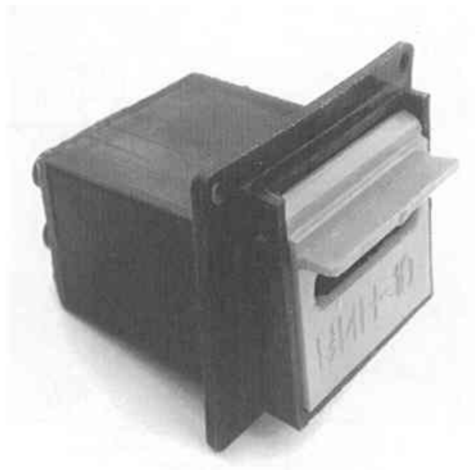

Figure 5.30b Display unit with neon lamps (65 x 65 x 75 mm).

All known HV indicators usually comprise a specially designed insulator installed on a switchboard's bus bar and connected to a display unit.

Our HV indicator does not require any special insulators and operates with base permanent insulators already installed on a switchboard. This enables the use of a HV indicators not only at switchboard manufacturing plants, but also to improve electric units of any types already in operation.

Our indicators use base permanent insulators included in switchgears and switchboards as capacitance voltage dividers, Fig. 5.30.

The display unit case has a hinged self-closing cover with an additional window, providing for viewing the neon lamps even with the cover closed. Permanent magnet mounted on the cover provides for connecting reed switch 13, Fig. 5.32, with the cover closed, and its disconnecting with the cover open.

When the display unit cover is open the switch side to which high voltage is applied can be validated. The device can be also used to verify the correctness of the line phasing.

After repair work in power system (6 – 24 kV) it is necessary to check the phase tangling of the electric cables to avoid unpredicted accidents. Our indicator has been developed to solve this problem.

With phased-in voltage at the both inputs of the display unit (from the side of assembled buses and from the side of the cable input) the indication lamps will not blink when the cover is closed. In cases of phase tangling, the indicator is capable of identifying the wrongly connected phases (the lamps corresponding to the wrong phases will blink indicating to the maintenance staff which Switchgear or Switchboard phases should be changed.

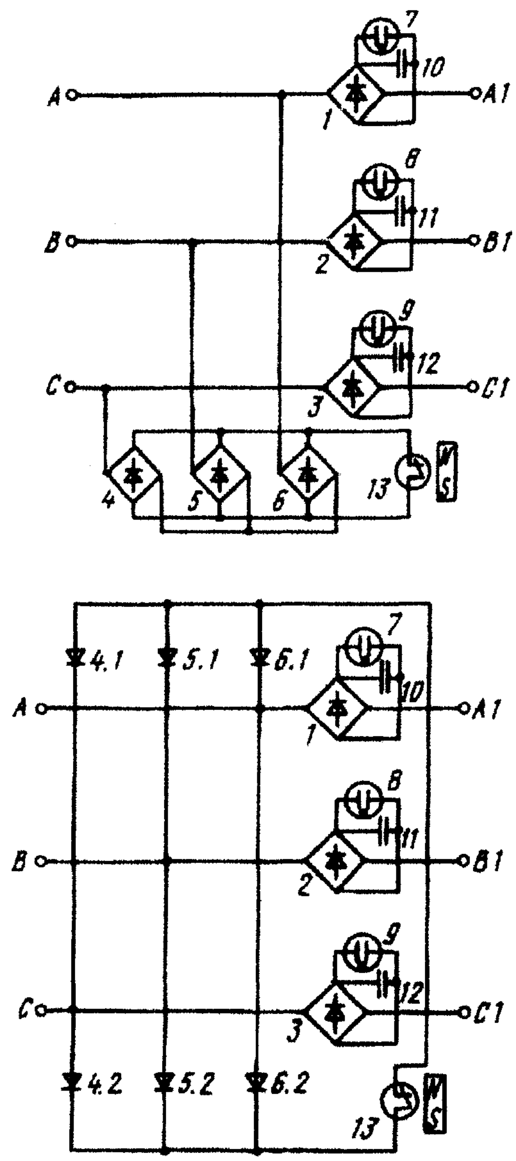

Figure 5.31 Variants of display unit circuit diagrams.

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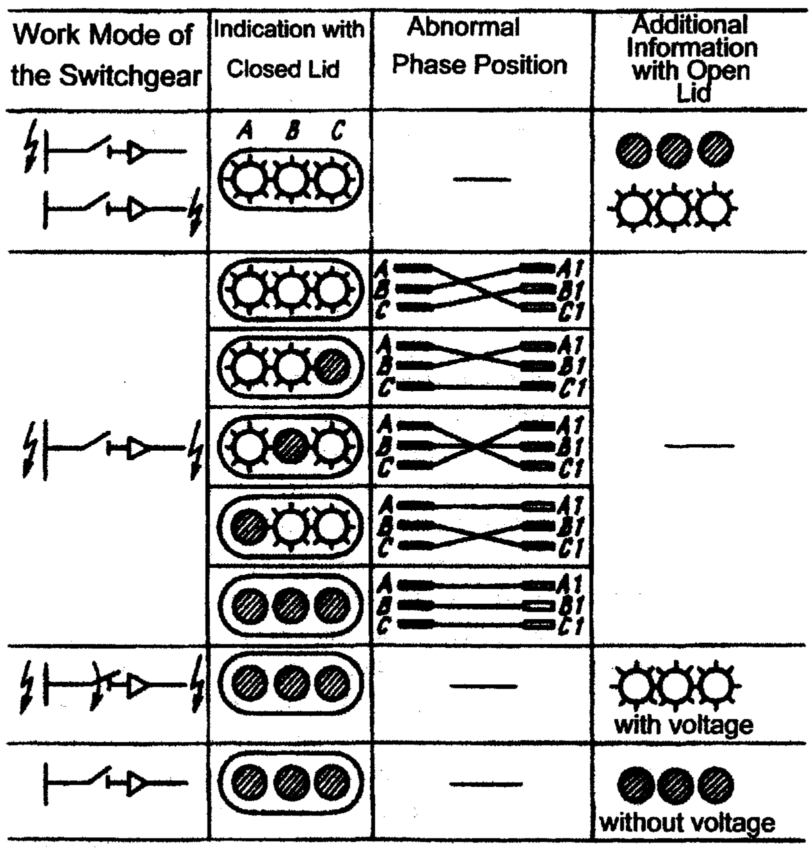

Figure 5. 32 Mnemonic diagram for abnormal modes identification.

This device can be also used to determine some other Switchgears or Switchboards operation modes, Fig. 5.32

The display unit was also subjected to fundamental upgrading and it can be connected via remote control or by a signal from the doors block-contact, Fig. 5.33.

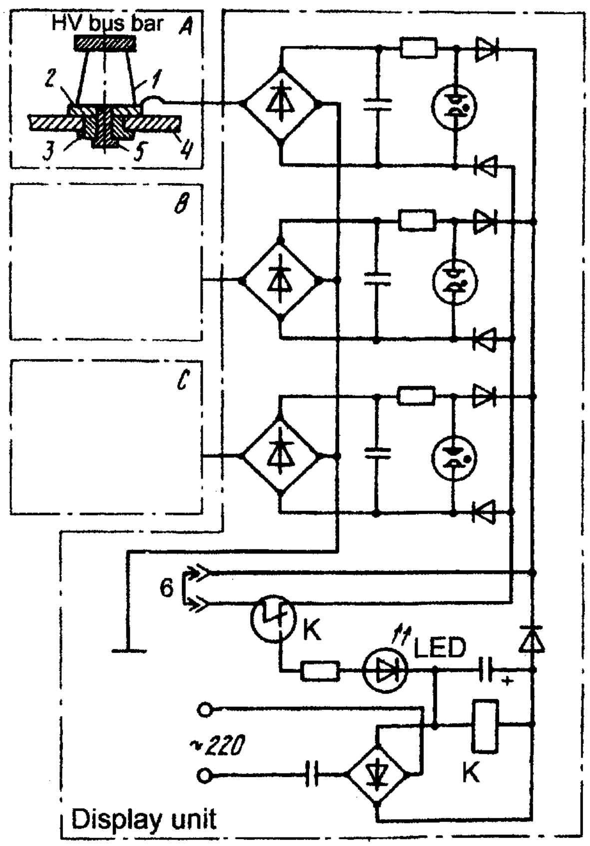

Figure 5.33 HV indicator with remote control.

1 – HV insulator; 2...5 – elements of HV indicator; 6 – removal jumper; K – electromagnetic relay.

5. 11 HIGH SPEED VOLTAGE UNBALANCE RELAY

Some types of industrial complex electronic power systems are quite sensitive to electrical energy quality. For example, repeated occurrence of emergency conditions with strong over-currents in 500 V power reversing thyristor drive of powerful coal lifting mechanism engine at thermal power stations have been quite common. The thermal power station staff found out the relation between these conditions and single-phase short circuits occurring in 161 kV powering circuit used to power the drive (via transformer). Highly distorted signal arriving at the drive elements sensitive to current and voltage angles cause failures in the drive control circuit and unpredictable power thyristors activation.

In order to prevent emergencies we have developed two versions of High Speed Voltage Unbalance Relays instantly acting on the trip coil of the power switch in case of voltage unbalance, Fig. 5.34, 5.35.

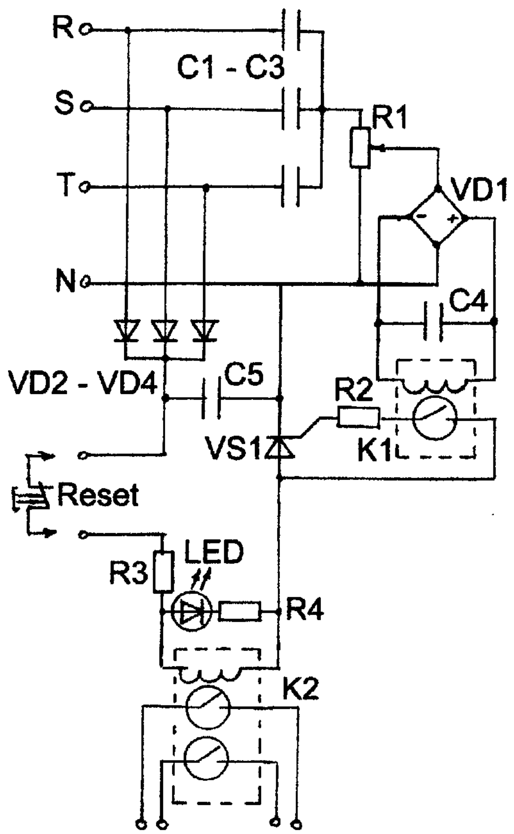

Figure 5.34a Circuit diagram of the high speed voltage unbalance relay (Ver. 1).

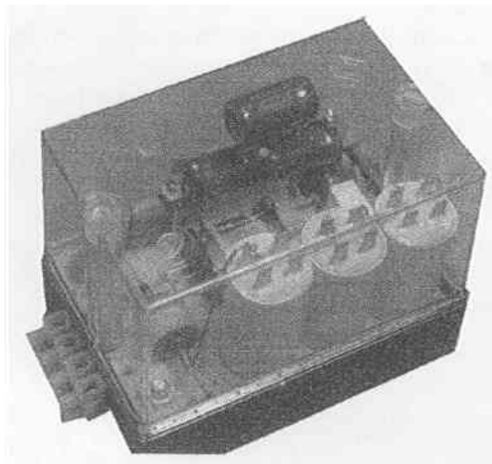

Figure 5.34b Experimental sampler of the high speed voltage unbalance relay (Ver. 1).

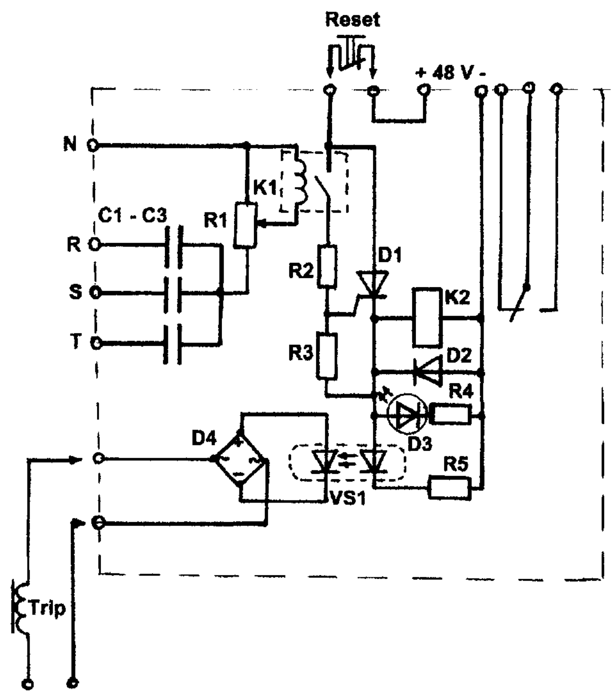

Figure 5.35a Circuit diagram of the high speed voltage unbalance relay (Ver. 2).

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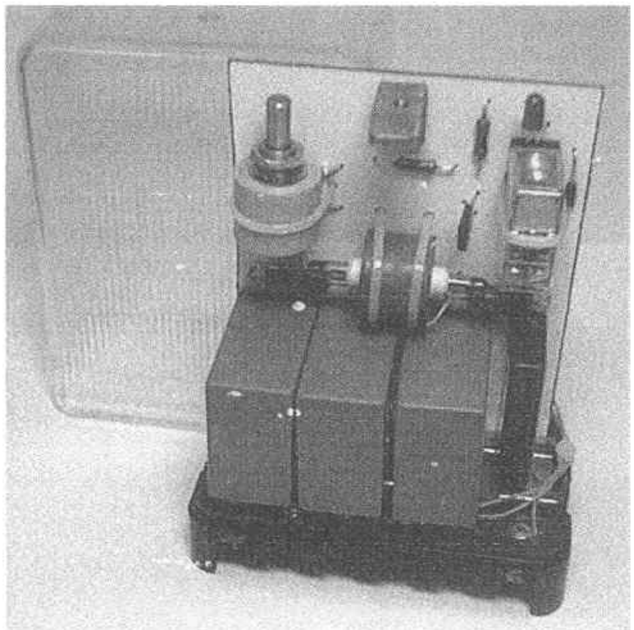

Figure 5.35b Experimental sampler of the high speed voltage unbalance relay (Ver. 2).

Dimension: 65 x 52 x 115 mm.

In both types of relays a zero sequence voltage filter on capacitors C1-C3 is used. Also, a high-speed reed switch relay K1 is used as a sensitive element at the filter output.

The two versions differ in the output switching elements (reed switch or thyristor in the first and the second version respectively) and in different powering circuits. The first version of the relay has a built-in diodes VD1-VD3 rectifier, which is insensitive to a phase loss.

The second version is more stable and quick, and has an external source of DC voltage and additional K2 auxiliary relay for remote indication.

Laboratory pilot tests for ver.2 Unbalance Relay on test-set EPOCH-10 (Multi-Amp Corp.) proved action time 0.0008 sec (0.8 ms) and minimal voltage unbalance – 15 %.

5.12 DEVICE FOR PROTECTION OF ELECTRICAL NETWORKS WITH INSULATED NEUTRAL FROM VOLTAGE SPIKES, PRODUCE BY COMMUTATION APPARATUS

Voltage spikes are quite common in electrical networks. The problem is especially vexed in networks with vacuum contactors, which are very powerful sources of the voltage spikes during switching. Yet vacuum switches offer certain advantages over other switches and are in general use, in particular in electric networks 6 kV in coalmines. Powerful non-linear resistors based of zinc oxide - varistors, which drastically reduce their resistance with the increase of the applied voltage, are used to protect such networks from voltage spikes. Yet, varistors are pulse-type elements which while effectively absorbing short voltage spikes, will be quickly destroying under sustained over voltage.

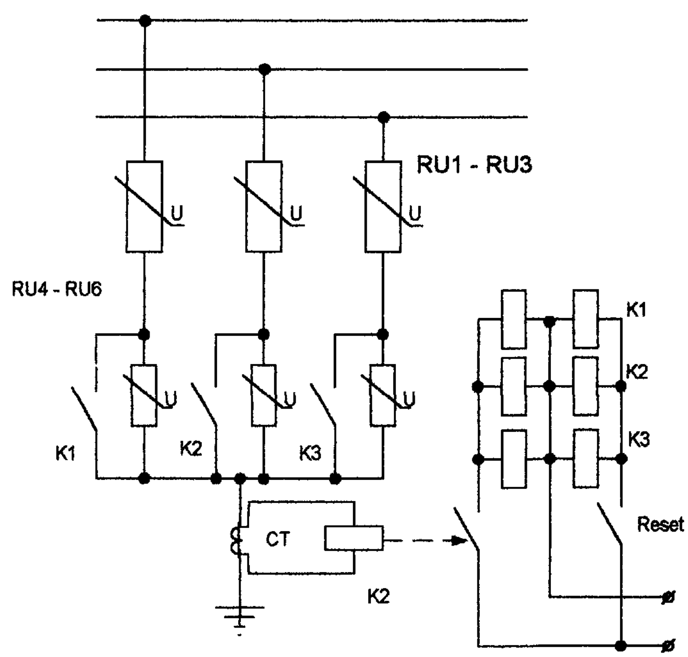

Figure 5.36 Device for protection of HV electrical networks with insulated neutral from voltage spikes.

RU1 – RU3 – main varistors; RU4 – RU6 – additional varistor; K1 – K3 – small HV Goliath relays, CT – current transformer, K2 – standard relay.

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Such a long time over voltage on varistors connected in two phases occurs when a third phase is grounded (ground fault in electrical network with insulated neutral). Overheating and destruction of two varistiors is a result of this regime in an electrical network.

The use of varistors with higher nominal voltage will inevitably lead to drastic deterioration of their performance in normal mode of the electric network operation.

In order to resolve this contradiction, connecting of an additional varistor with nominal voltage equal to 0.73 of the main varistor's voltage in series with every main varistor rated for nominal mains voltage, is hereby proposed. This additional varistor is shunted by a high voltage relay's contact in a normal operation mode of the network and it is automatically deshunted at ground fault, Fig. 5.36. Hence, the device provides for efficient network protection from voltage spikes both in normal mode and at ground fault. The small Goliath relay (see chapter 3) redesigned for appropriate voltage can be used in this device for control of an additional varistor.

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6

Applications for Powerful Radio-Electronic Equipment

6. 1 A SPECIAL COMMUTATION DEVICE FOR UNATTENDED BOOSTER STATIONS

Extended communications lines generally include remotely supplied unattended booster stations (UBS), located along a route at a distance of 5 – 10 km. A break in the remote electric power supply (REPS) at any point along the route disrupts operation of the entire transmission system; this may lead to serious consequences and is frequently intolerable. In this connection, it is advisable to provide the UBS electric power supply system with special means for forming loops (DFL), which represent two-position unistable relays.

Let us consider the operation of an electric power supply system with DFL units, Fig. 6.1.

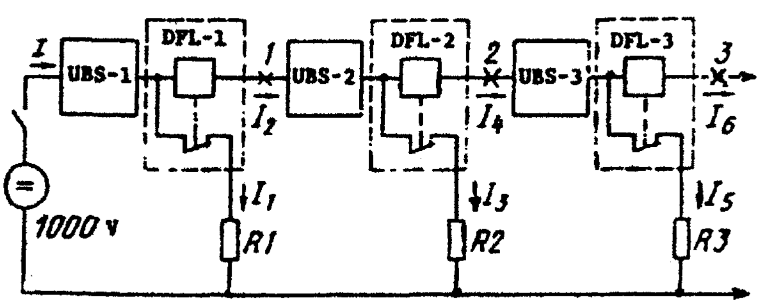

Figure 6.1 Power supply system of unattended booster stations.

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Under idle conditions, all the switching DFL contacts are closed. When the electric power supply is switched on, the working value of current is established only in the first UBS-1 from the supply source. This current then branches into two parts, one of which (I_2) is fed to UBS-2, while the other (I_1) flows through a ballast resistance R1. Beyond UBS-2, current I_2 again branches into components I_3 and I_4, etc. The ballast resistance decreases with distance from the supply source, and it is chosen according to the relation:

$$R_{bi} = R_{\Sigma} - R_{li}, \tag{6.1}$$

where
R_{Σ} - total line resistance;
R_{li} – resistance of the line section up to the point where the i – th ballast resistance is installed.

As the DFL operating current decreases, requirements are lowered for the exact satisfaction of equation (6.1). Moreover, the following relation is established between the currents in the line:

$$\begin{aligned} I_2 &= I - I_1; \\ I_4 &= I - I_1 - I_3; \\ I_6 &= I - I_1 - I_3 - I_5 \end{aligned} \tag{6.2}$$

Current I_2 is only sufficient for operating a DFL. When the contact opens in DFL-2, current in the DFL-3 circuit similarly increases, etc. Thus, successive connection of DFL units and successive entering of all system sections into a nominal regime occurs.
When the power supply circuit is disrupted, for example at point 3 (Fig. 6.1), all DFL units return to the initial state, and all UBSs, except the first, lose their electric power supply. In this case, the process described above – of successive operation of DFL units – begins, and it ends when the failure point is reached. As a result, only the system section that lies beyond the failure point remains without power supply, i.e., the failed section is cut-off from the system, having been replaced in terms of a power supply circuit by a loop (ballast resistance) of the triggered DFL.
A number of specific requirements are imposed on the loop formation devices. For example, in the example considered above, there is the need to switch voltages greater than 1 kV at a current of 0.1 A; sufficient isolation of the control circuit from the output circuit, capable of sustaining voltage of not less than 3 kV; small size for placing in UBS containers. The devices should also have a special volt-ampere characteristic that ensures their switching at small currents (10 – 20 mA) with a subsequent 5 – 10 fold rise in the working current. Moreover, for an indefinite period, the unit should maintain the effect of this current (until a break occurs

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on a line or during planned disconnection) and have a very small internal resistance (in order not to exert substantial influence on the general level of the UBS power supply voltage when there are many such devices connected in series).
Devices that are capable of functioning as DFL units are nonexistent among a long list of currently mass-produced relay devices. A possibility of implementing the described system of the UBS power supply has arisen in connection with development in recent years of electromagnetic devices of a new type, the so-called RG-relays (with HV reed switch). However, mass-produced vacuum HV reed switches have a highly limited value of allowable switched power: up to 50 W at voltages up to 1 kV, and 10 W at voltages above 1 kV, which is unsatisfactory for use in DFL units.

These reed switches at the same time permit switching of large currents (up to 3 – 4 A) within the indicated power value. Consequently, considerable increase in the switching current at high voltage is possible by connecting the reed switches in series. This substantially simplifies construction, since it is simpler to balance voltage distribution in series-connected elements than to balance current distribution for parallel elements.

A device that satisfies the DFL requirements and switches the 0,1 A current at voltage of 1 kV has been constructed on the basis of two series-connected MKA-52141 reed switches, each of which was furnished with a separate excitation coil, Fig. 6.2. Both coils are connected to each other with a common control winding.

To avoid breaking a closed reed switch, two small permanent magnets were used, placed with their magnetization axes perpendicular to the excitation coil field vector.

The HV divider consisted of two 25 MOhm 0.5 W resistors, connected in parallel with the reed switches. To compensate for the scatter of the reed switches and magnet parameters, magnetic shunts were placed directly on the magnets in the form of steel plates that could be moved freely for adjustment. The entire structure was mounted on a frame 90 x 55 x 28 mm, Fig. 6.2, and filled with epoxy compound. Internal connections were made with HV wires.

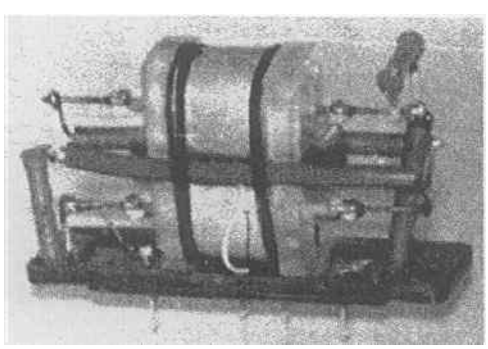

Figure 6.2 HV commutation unit (before epoxy encapsulation) based on two series-connected HV reed switches, each of which is furnished with a separate coil and is provided with an HV resistor divider. Internal connection is made with HV wire.

Since the remote power supply voltage in modern communications systems may reach 2 kV at current from 400 to 500 mA, further increase in commutation power is necessary; this allows the device to be used for any type of remotely supplied UBS. The unavailability of reed switches of required power has led to the construction of hybrid transistor-reed switch circuits (see above).
Development of a switch that satisfies the operating conditions in a DFL constitutes a solution of one of the problems. The second problem is that of giving the switch a special volt-ampere characteristic (VAC). This problem was solved by means of an electronic VAC converter, Fig. 6.3.

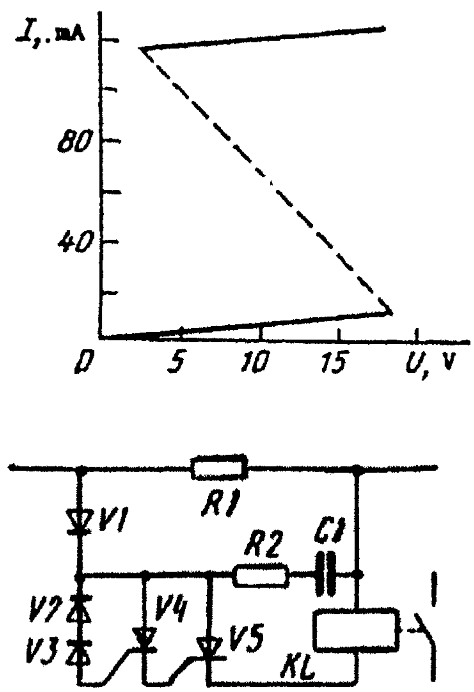

Figure 6.3 Electronic converter and its volt-ampere characteristic.

The device works as follows. When voltage is supplied to the line, a small current begins to flow in it, which produces a noticeable voltage drop in the high-resistance shunt R1. Capacitor C1 begins to be charged under the effect of this voltage by a current that flows through diode V1 and resistor R2. At this time, thyristor V4 and V5 are blocked, and the winding KL is practically de-energized. After capacitor C1 is charged to the breakdown voltage of Zener diode V2 and V3,

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their equivalent resistance is reduced, which leads to triggering of the thyristors, first V4 and then V5. In this case, capacitor C1 discharges through thyristor V5 and resistor R2 to the winding KL, generating a current pulse that is sufficient to fire the relay, Fig. 6.4.

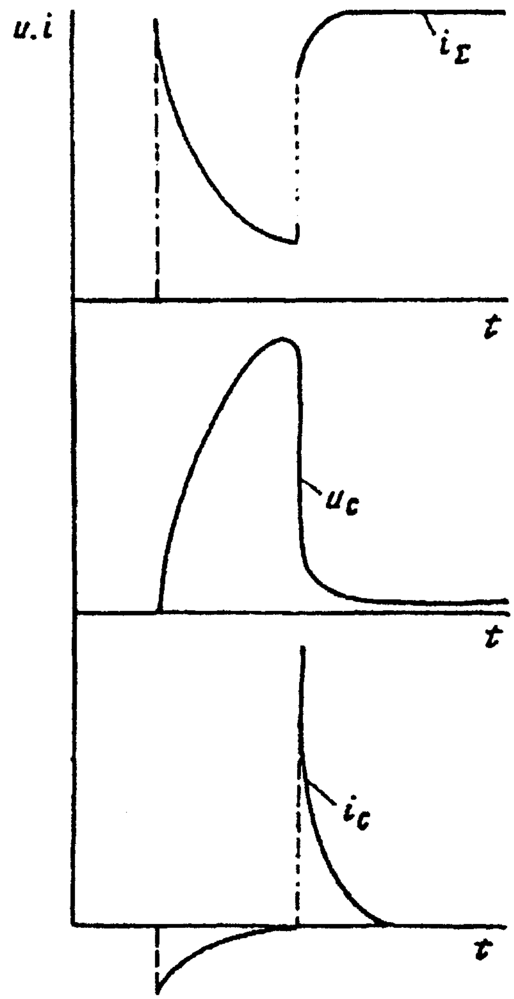

Figure 6.4 Oscillograms of current (I_c) and voltage (u_c) on capacitor C1, and common current (i_Σ).

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When the relay contacts are made, a low resistance winding KL becomes connected in parallel to the high-resistance shunt R1, which leads to a sharp reduction in the equivalent resistance of the device and voltage drop across it (although it remains sufficient to maintain the relay).

The presence of a low power thyristor V4 that has a rather large resistance of the gate junction compared to the resistance of the gate junction of thyristor V5, enables one to reduce substantially the leakage current of C1 during its charging and increase the efficiency of its utilization.

The use of Zener diodes jointly with a thyristor as a threshold triggering element ensures a stable and low firing threshold, in contrast with the dynistor (diac). Diode V1 prevents discharge of the condenser through the shunt R1.

An essential difference between ordinary relay-type devices and the previously described switching device having a converter consists in the specific dependence of firing current on voltage and its nature if there is variation of the equivalent resistance, which, until firing, remains high and the current very small; after firing, it drops sharply and current rises.

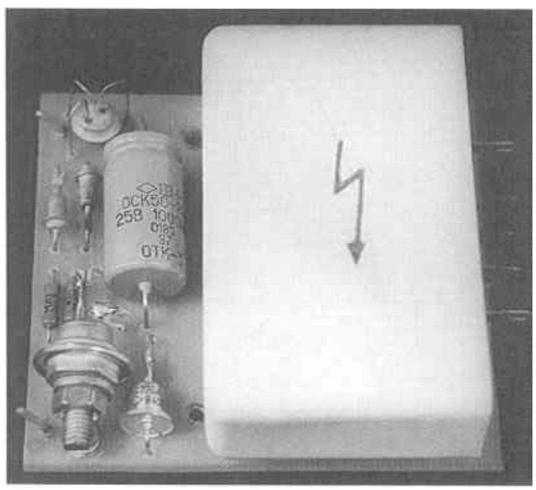

Figure 6.5 DFL units, mounted on small PCB:
electronic VAC converter with HV reed switch commutation unit.

The developed DFL units (Fig. 6.5) are assembled on small boards that are directly built into the equipment; they are reliable to operate and satisfy all the requirements imposed on them.

6.2 SYSTEM PROTECTION FOR POWERFUL RADAR

The decision about the construction principle of efficient ET (electronic vacuum tube) protection should be mainly based on the ET's power. For example, as a rule, low power ET (such as X-ray tubes) do not need any special current protection, since the discharge current limitation in the ET is provided by high internal resistance of the power supply.

For some higher power ET, serial connection of a non-linear current limiting element proved to be sufficient, while it has been possible to restrict the short circuit current ratio at a level of 3-4 fold of the nominal value.

As the order of magnitude of operating current in ET reaches several amperes, relay-type protection means should be used. The simplest and also sufficiently efficient devices of this type have a low voltage switching element in the low voltage power supply circuit, which is controlled by the commands originating from a sensor connected to the high voltage circuit.

When the ET and consequently the power supply capacity is increased, the latter incorporates reactive filter elements accumulating energy sufficient for damaging the ET in case of breakdown, even after the low voltage supply circuit is disconnected. In this case, a more sophisticated protection system is to be used having a quite expensive high voltage fast-response switching element (shorting device) with an autonomous control system, bypassing the ET in case of breakdown. In this case, in order to prevent overload and power supply system elements failure, such a shorting device can be used only in addition rather than in place of them.

Eventually, the most powerful radio electronic devices, such as those in transmitters of stationary and reciprocal radio location stations with the radiated power of an order of magnitude of several megawatt, pose another difficulty for selective disconnection of one of 10-15 ETs operating in parallel (for example modulators) in case of failure. This can be resolved by the use of special high voltage disconnecting devices.

ET protection systems related to disconnecting the power supply should have an automatically repeated connection for better "survivability" of the equipment.

In autonomous systems, all the mentioned problems become even more complicated because of the severe weight and dimension requirements, which necessitate special system solutions, alternative elementary bases, etc.

The use of the developed elementary basis offers higher efficiency of the protection system's operation.

The simplest single device is a current relay in the low voltage circuit of the power supply and a contactor, which disconnects the step-up transformer from the mains upon overload. Such a protection system is simple and inexpensive, however, it does not offer adequate ET protection (low speed of operation, inability to distinguish between the internal ET breakdowns and other damages in the power supply system, the operation current depends on the resistance of the grounding buses circuits, etc.). Apart from these, in high-voltage power circuits, current restriction elements (such as special throttles) are used.

Elements described in the book are designated for substantial improvement of ET protection.

Medium power ET protection device operation is as follows, Fig. 6.6.

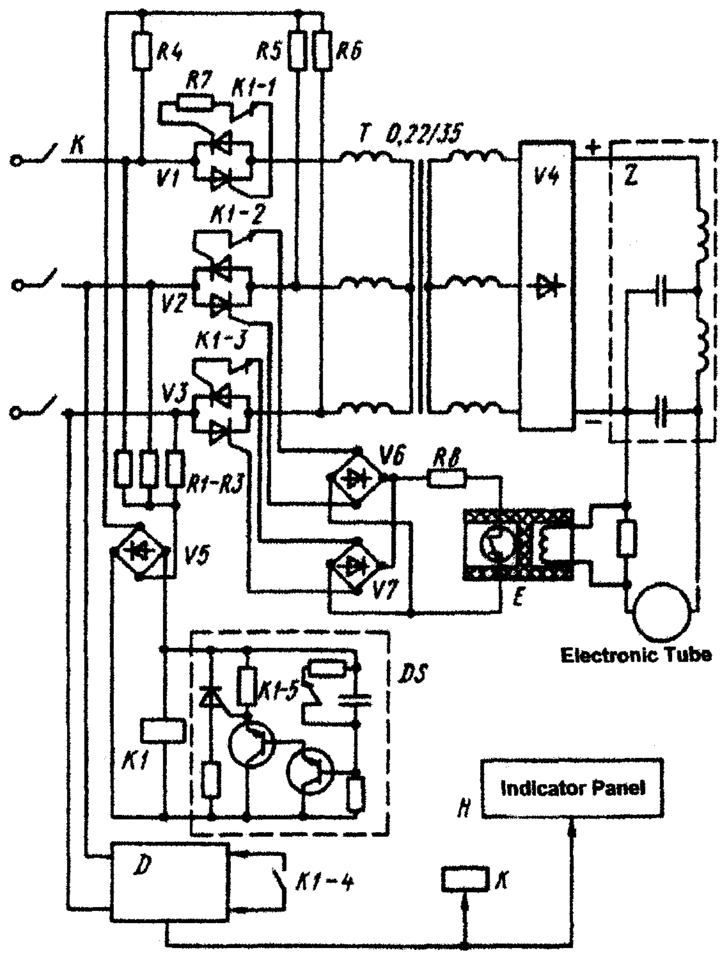

Figure 6.6 Circuit diagram of a simple medium power protection device.

In normal operation with closed contacts of low-voltage contactor K, the ET operating current in winding RG E generates a weak magnetic field, which is too

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low for the reed switch operation. Short spikes of operating current, which depend on the ET modulation regime, do not put reed switches into operation since their duration is 2-3 orders of magnitude lower than the reed switch operating time. The ET non-contact switch thyristors' control circuits V1-V3 are closed, the thyristors are open, and the voltage across the K1 relay winding is nearly zero.

Internal breakdowns in ET operate the RG E (the contacts become open), thus disconnecting the diode bridges V6 and V7 of the thyristor switches V2 and V3 control circuits. Once the sinusoidal alternating current first passes the zero point, the thyristors of the switches V2 and V3 are cut off causing de-energizing of the primary winding of transformer T. Hence, even under the most adverse conditions, the maximal time for complete power disconnection does not exceed a single half-period duration. Once thyristor switches V2 and V3 are cut off at the zero point of the star connected resistors R4-R6, phase voltage is generated, while the voltage at the zero point of the second "star" formed by resistors R1-R3 remains zero. The voltage difference causes K1 relay operation. Its contacts produce additional disconnection of the thyristor-switched control circuits Thus, renewed power supply after the discharge of filter Z elements is prevented, and the HV reed switch interface E returns to its initial state.

At the same time, the K1-4 contact of this relay is engaged, sending an input signal to the operations counter D; the contact R1-5 is broken, which disconnects the condenser of the time relay timing circuit DS. After an elapsed time of $\tau = RC$ sufficient for de-ionizing the vacuum gap generated in the ET and perfect reconstruction of its dielectric properties (about 0.5 c), the time relay thyristor DS is opened thus shunting the K1 relay winding. Once the K1 relay is disconnected, all its contacts are returned to their initial state, and the thyristors of switches V1-V3 are reconnected in order to power the transformer again. The circuit returns to its initial state, except for counter D.

If the first cut-off does not result in self-elimination of the ET failure, the protection mechanism is operated again in a similar way. Once a preset number of pulses are accumulated in the operation counter (say, three), a signal for electromagnetic contact K disconnection and the "ET failure" display is generated at the counter output.

For powerful radar, a device for selective disconnection of one of the modulators connected in parallel to the common load has been designed, Fig. 6.7.

In this device, a failure in one of the ETs connected in parallel, say in 1, causes a drastic increase of the current in the current sensor circuits (shunt) 10.1 and in the RG-interface 6 winding. Threshold element 11.1 is operated (reed switch), which activates the memory 12.1 element and acts on the switch element 13.1. The latter disconnects the control signals generation unit operation circuit 14.1 from output contact RG 6. Control pulses are supplied to thyristors 9.1, yet they remain open, since direct current flowing in the failed ET 1 keeps thyristors 9.1 open. After 1-2 ms has elapsed, RG 6 is operated, and consequently, the thyristor switch 7 control circuit is cut off by its contact. As a result, transformer 4 is disconnected from the power circuit. Within 20-30 msec after stopping the current flow in thyristors 9.1, 9.2, 9.3 circuit, they are cut off. RG 6 returns to its initial state, and its output contact is closed. Thyristor switch 7 is reconnected, restarting power supply. Consequently, control pulse generation units 14.2 and 14.3 are restarted, and thyristors 9.2 and 9.3 reconnected. Unit 14.1 remains disconnected as a result of emergency current flow via shunt 10.1 "recorded" in memory element 12.1, and the supply of the unit 14.1 operation signal is inhibited. Hence, within a few tens of milliseconds, the failed ET becomes disconnected from the other ETs, which are normally powered.

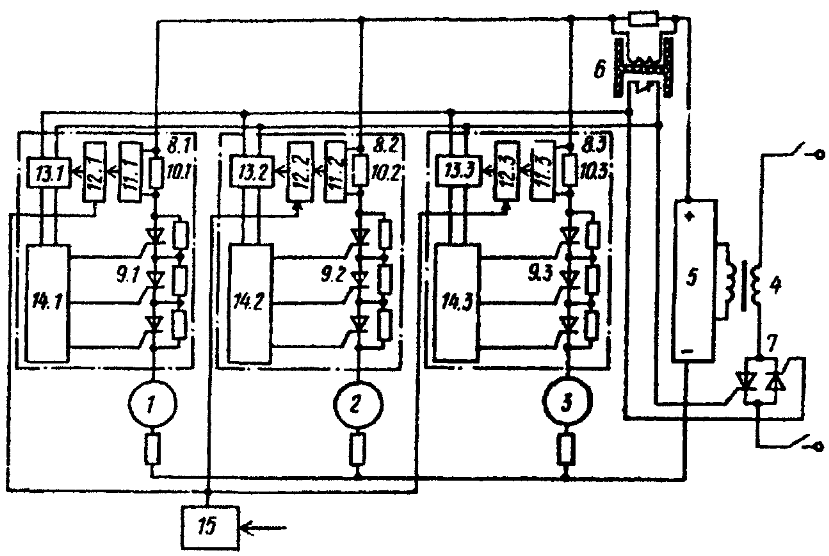

Figure 6.7 Circuit diagram for protection of high power radar with several modulators (1, 2, 3) connected in parallel.

Once the failed ET is replaced, the memory "inhibit" is removed by the operator via unit 15.

Normally in stationary and movable powerful radar, target unlock is allowed for a few hundreds of milliseconds and more. In such cases, instead of high-voltage thyristor switches 9.1 - 9.3, "Goliath"-type switching devices can be used, whose size is reduced relative to the voltage used in every specific system.

The universal set of elements and assemblies described in this book, enables the design of highly efficient, complex equipment protection from all types of damage of HV devices, which are different in their complexity, functional capabilities and price, Fig. 6.8.

The RG-relay interface usually fits into the HV circuit prior to connection to the filter capacitor point. The RG-PLS device is connected after the filter capacitor directly into the load circuit (see Fig. 6.8). In this case, the influence of the device's parameters on modulation characteristics must be ruled out.
In figure 6.8:

CP – built-in low voltage current protection (trip) elements;
TC-soft - soft-start thyristor contactor (or direct start thyristor contactor – TCDS);
T – HV transformer;
RB – HV rectifier bridge;
RG – HV reed switch interface RG-series;
C, R2 – elements of HV filter;
R1 – ballast resistor (2…4 Ohm);
HVTS – HV thyristor switch ("crowbar");
M – modulator;
RG-PLS – HV pulse-type interface RG-PLS-series
VT – HV vacuum tube (tetrode, klystron, etc.)

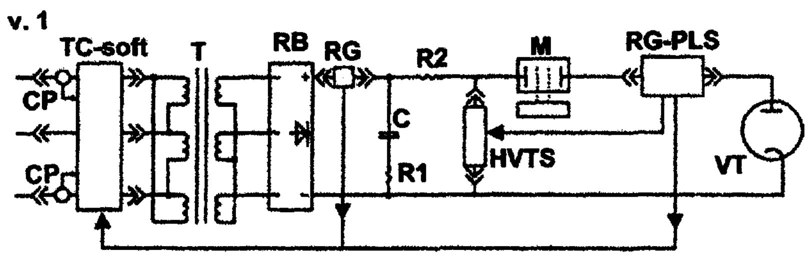

Figure 6.8a Version 1 of protection system.

Version 1.

A complete protection system, in which RG and RG-PLS devices are autonomously operated at internal insulation breakdowns (di/dt, 10 μsec) and level current trip (1/2 cycle). At internal insulation breakdown, only a high voltage thyristor switch (HVTS) is operated, which shortens the high voltage circuit. At current overload, the low voltage thyristor contactor (soft-start or direct-start), which cuts off the power supply, is disconnected.

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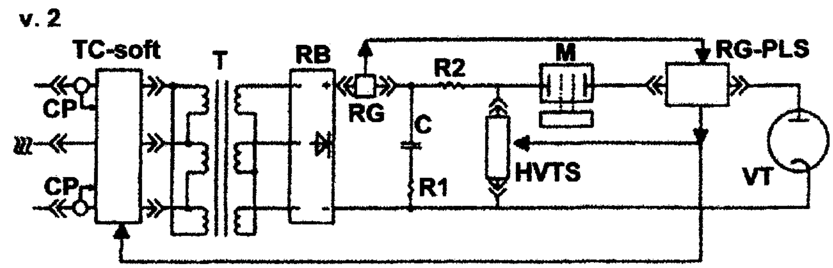

Figure 6.8b Version 2 of protection system.

Version 2.

A complete protection system with an "OR" type connection between RG and RG-PLS devices, which have a common output. An HV thyristor switch (HVTS) is operated simultaneously with the low voltage thyristor contactor (soft or direct start) disconnection either at internal insulation breakdown (di/dt), or upon exceeding the preset current value (level current trip).

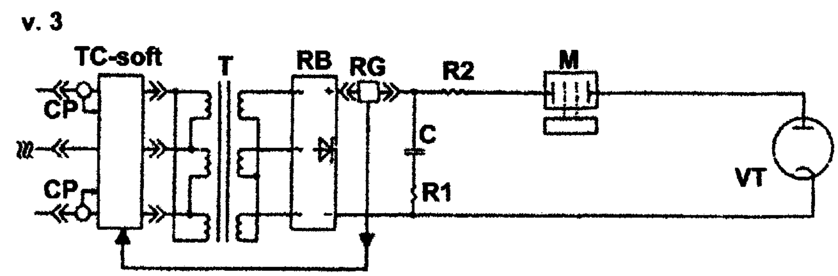

Figure 6.8c Version 3 of protection system.

Version 3.

The simplest and least expensive protection system that responds to current overload (produced level current trip) in high voltage circuits and disconnects low power circuit (1/2 cycle).

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v. 4

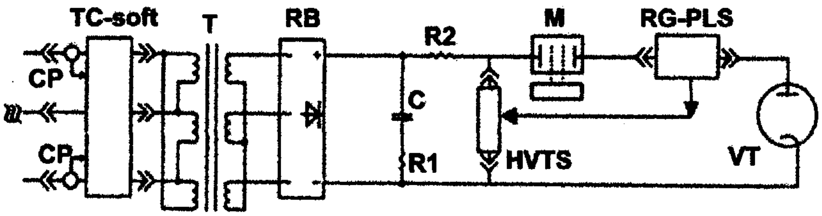

Figure 6.8d Version 4 of protection system.

Version 4.

A simplified protection system that responds only to internal breakdowns (di/dt) and shortens the HV circuits.

v. 5

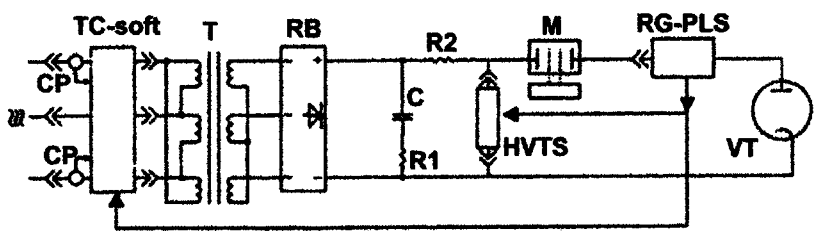

Figure 6.8e Version 5 of protection system.

Version 5.

A combined protection that responds only to internal breakdowns (di/dt), simultaneously shortening the HV circuits and disconnecting the power supply (1/2 cycle).

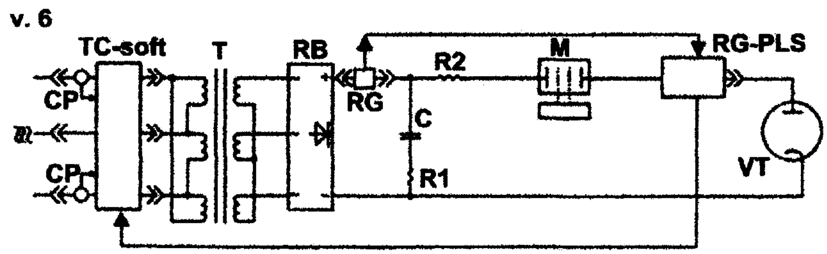

Figure 6.8f Version 6 of protection system.

Version 6.

A simplified low-cost protection system. It responds to internal breakdowns (di/dt) and overload (level current trip), but disconnects only the low voltage power supply line.

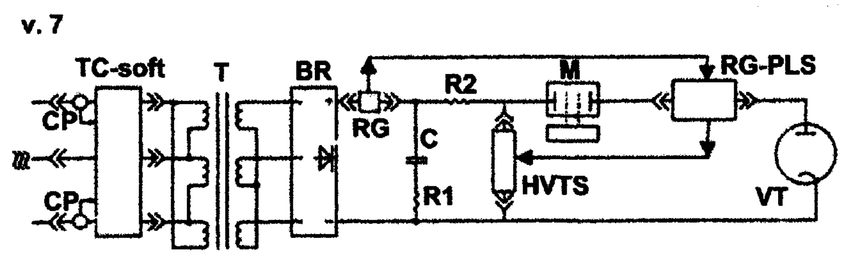

Figure 6.8g Version 7 of protection system.

Version 7.

A simplified protection system that shortens the HV circuits at internal breakdowns and current overload.

A protection system was tested at the Radar Division of Elta Electronics Industries (Ashdod, Israel). Components of the protection system were installed inside the CFA transmitter. The HVTS device was connected in parallel to the circuit, which contained a HV capacitor 1.5 μF, 23 kV and resistor 5 Ohm. The capacitor was charged to a different voltage, 2 up to 23 kV. The HVTS operates with interface RG-PLS-25 and provides a fast discharge of the HV capacitor over ballast resistor 5 Ohm. The total number of discharge cycles during test was 6. Full capacitor discharge was effective and very quick (6 to 28 μsec). The soft-start contactor was cut between the low voltage (440 V) power network and primary winding of HV transformer. Full connection of the HV transformer to the power network over the soft-start contactor occurred in 2 sec. Disconnection was instantaneous.

6.3 PROTECTION SYSTEM FOR POWERFUL INDUSTRIAL LASERS

The spark protection system, including HVTS, which operates in combination with interfaces RG and RG-PLS, was developed by us for Optomic Lasers Ltd (Ramat Gabriel Industrial Park, Israel).

The final product of Optomic Lasers was a high power CO_2 laser for industrial applications with a nominal output optical power of 1.6 kW. An RF-power generator operating at frequency 40.68 MHz and output power 25 kW supplies energy to the laser discharge. The energy consumption of the generator is 35 – 40 kVA. The basic element of the generator is a tube - the tetrode 4CW25,000A (anode voltage 10 kV, current up to 4 A), with the screen voltage 1400 VDC, greed voltage 350 VD and filament voltage 6.3 VAC), Fig. 6.9.

The laser discharge is a principally non-linear and load variable in time. The important processes for the discharge system are the following:

- discharge ignition;
- impedance matching between discharge and generator;
- stabilization of energy input in discharge.

The first stage of the discharge system is extremely difficult and dangerous because of very high mismatching between the discharge and the generator. Providing good matching during this stage is impossible in principle. VSWR during discharge ignition is indefinite and may reach very high values. This factor leads to a return of 60 – 70 % of generator output power. The RF-reflected power can lead to sparking inside the generator.

The main energy consumer is an anode of the tube (practically 90% of the total energy delivered to the tube). The high DC and RF voltages present on the tube's anode and in the output circuitry provide resonance for the working frequency and impedance matching with an outer network.

The essential problems of RF-design and exploitation of RF-generators based on HV powerful vacuum tubes is sparking inside resonant cavities. This problem exists less in power generators but obviously is greater for generators with output power more than 5 – 10 kW. Spark prevention is one of the tasks of the RF-generator design.

Another important problem is damage that sparks can cause. It is impossible to totally prevent sparking, therefore, it is important to a use a device that will not increase the harm caused by sparking inside of resonant cavities.

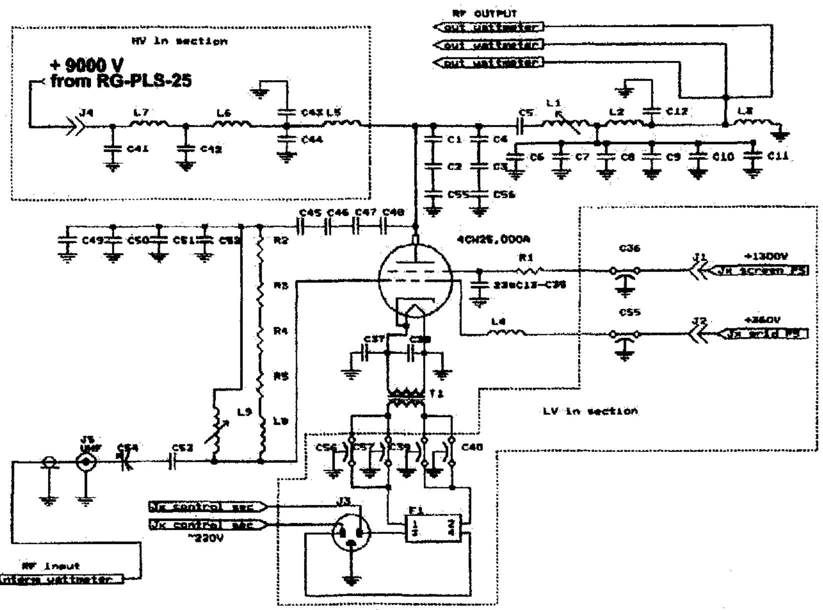

Figure 6. 9 Circuit diagram of final RF-stage of a powerful industrial laser.

The protection devices described above provide an ideal solution for damage prevention from sparks and other types of overcurrent processes inside the final amplifier for a 25 kW RF-generator of a powerful laser.

The key advantages of protection, based on described elements, are as follows:

- RG-interface relay is located close to the tube and can react with sparks faster than systems using secondary effects (for example, protection based on Hall effect sensors);
- HVTS provides full evacuation of a large amount of the energy stored in the reactive components of a YV power supply, Fig. 6.10.

In the Fig. 6.9 and 6.10, we show the real implementation of the sparks and overload protection system in Optomic's generator. Sparks and breakdowns of HV components (vacuum tube, RF capacitor and chokes) that may emerge in the final amplifier lead to the fast increase of anode current of the tube. The interface relay RG-PLS-25 is located in the anode power supply of the generator. Input 1 and Input 2 are connected in series with the ballast resistor R1 of the power supply. The high voltage passing through the RG-interface continues to the final amplifying stage of the generator. The shortening switch HVTS turns on in parallel with HV capacitor C1. Ballast resistors R12 and R1 serve for limitation of current in case of sparks at level 1.5 – 2 kA.

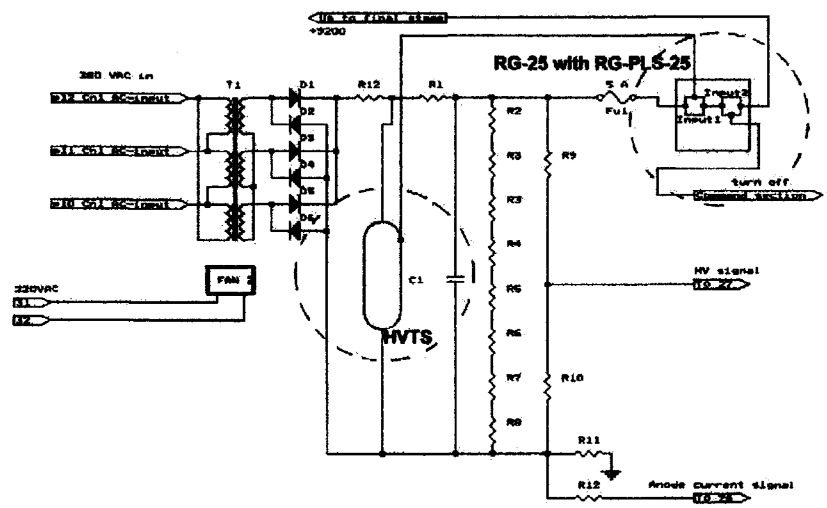

Figure 6.10 Anode power supply of powerful industrial laser.

Growth of anode current is detected by RG-PLS, which sends a turn off signal to the controller of the power generator. The controller turns off the operate state of the generator and indicates the high anode current fault. The RG-relay detects slow drifts of the anode current (reacts in the case of threshold overcoming) and fast growth of the anode current in the situation of sparks and other failures.

Nevertheless, a certain high amount of energy is stored by the HV transformer (Trl – 38 kVA) and by the HV filtering capacitor (C1 – 8 μF, 10 kV). In the case of sparks inside the final amplifier, this energy discharges through the spark channel and damages RF-parts of input and output matching circuitry and particularly the solid-state driver. It is extremely difficult to protect the driver from the spark damage because it is necessary to provide appropriate circuitry for the

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RFD-pulses on the one hand, and it is necessary to prevent a penetration of excessive energy with the same characteristic time parameters to the driver from the amplifier on the other hand. As a rule, the real driver damage is a burning of the pair of RF-transistors MRF-154 (the price of the transistor is 550 US$, for example).

The HVTS switch operating with interface relay RG-PLS-25 actually provides a solution for the fast evacuation of energy from reactive components and overcurrent protection of the final amplifier of Optomic's 25 kW generator.

The described protection system was installed for test inside of the industrial prototype of the Optomic 25 kW generator. The total test run time was 400 hours. During the test, the power generator was used for its normal purpose, i.e., for the laser excitation. The generator operates with the following parameter:

- output RF power 2 to 23 kW;
- input AC power 10 to 38 kVA;
- anode voltage 9200 V (non loaded) to 8800V (loaded);
- anode current 0.3 A (rest current) to 3.8 A (full loading);
- frequency of operation 2 Hz to 10 kHz;
- pulse time 10 μsec to 500 msec.

During the run of the tests, the examination of overload protection (Input 1) was fulfilled. The anode current was increased higher than 4.7 A (threshold determined by the tube specification is 5 A). The increase of the anode current was reached 30 times. 25 times the over current was reached by "tuning" inductor L1 (fig. 6.9) mismatching and 5 times occasionally with mismatched generator thermal drift. In all cases, the tested RG-25 interface acted normally and sent signals to the controller with a time delay 0.9 – 1.1 msec. The operating time of the controller (rate of switching off the power generator) is 15 – 20 msec.

For actual tests of the action of HVTS, the spark gap was organized inside the generator. The goal of the spark gap was to provide a real simulation of the sparks and the breakdown that could occur in the tube area. The implemented spark gap provides an arc discharge with the current up to 5 kA. The electrodes of the spark gap were implemented as two spheres with three centimeter diameter and 47 mm maximal distance between them.

The emergency situation (sparks in final stage) was repeated 40 times. In all cases, the RG-PLS-25 interface reacted adequately to the situation, namely it sent a turn off signal to the controller of the generator and switch on the HVTS that caused a shortening of the generator's final stage. During the tests, several sparks were organized without using the HVTS. The investigation of spots of the sparks on the spheres' surface showed that spots that use HVTS are essentially smaller than those without it. The measured time of switching of input 2 was 60 ± 10 μsec.

7

High-Voltage Devices for Industrial Applications

7.1 AUTOMATIC HIGH-VOLTAGE CIRCUIT BREAKERS

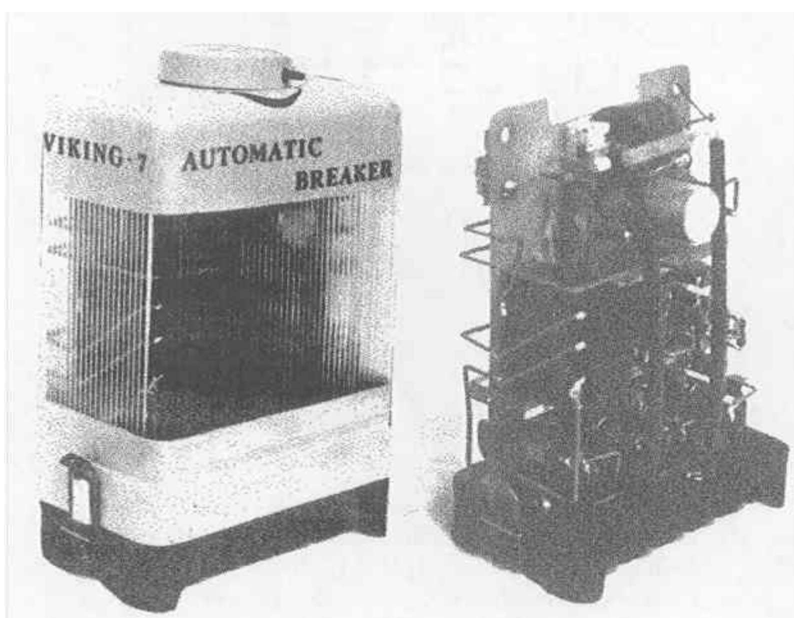

Figure 7.1 Automatic high-voltage one channel circuit breaker "VIKING-7".

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The "VIKING" series of HV automatic circuit breakers (ACB) is intended to be used as part of standard insulation testing equipment that applies high voltage to electric devices under test, and checks their insulation parameters through the current leakage levels.

The "Viking-7" series is designed based on a hybrid reed-thyristor technology, Fig. 7.2.

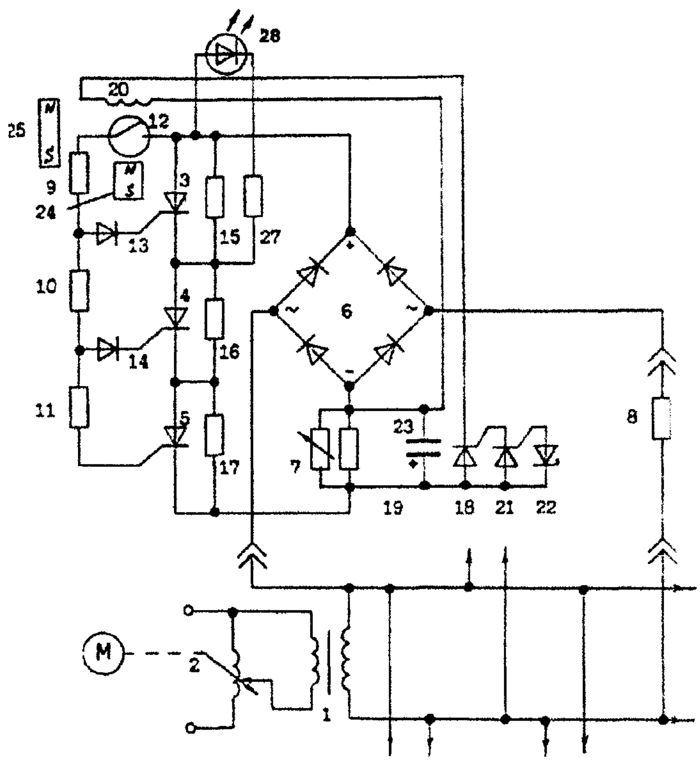

Figure 7.2 Circuit diagram for one channel automatic HV circuit breaker "Viking-7".

1 – HV transformer; 2 – variac with motor drive; 3...5 – HV thyristors; 6 – HV rectifier bridge; 7 – trip regulator; 8 – object under test; 9...11, 15...17 – resistors; 18...23 – elements of triggering circuit; 24, 25 – permanent magnets; 28 – trip indicator (LED).

"Viking-7" is provided with a manual-reset module, in which a permanent magnet 25 is used, Fig. 7.3.

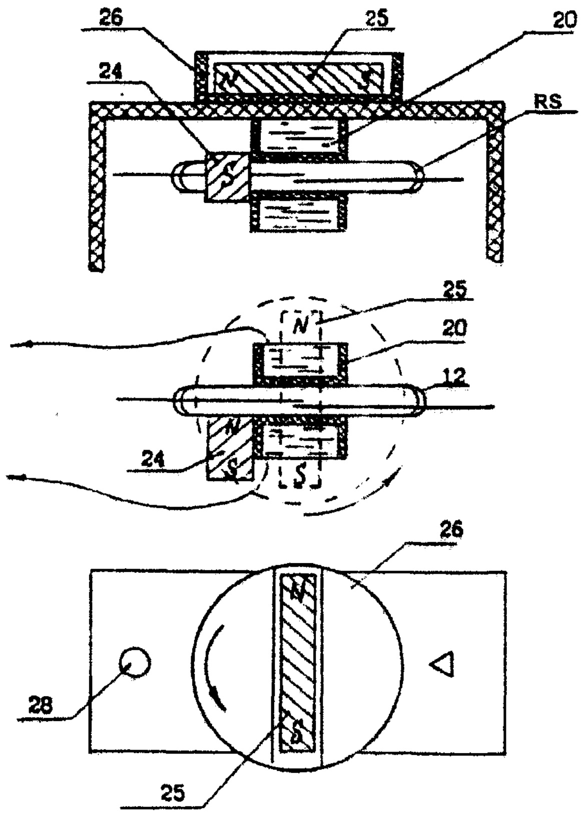

Figure 7.3 Construction of a manual-reset module in ACB "Viking-7".

12 (RS) – HV reed switch; 20 – trip coil; 24 – latching magnet; 25 – reset-magnet; 26 – revolving limb in upper part of ACB body; 28 – trip indicator (LED).

In its initial position, an axis of the permanent magnet is arranged perpendicularly to the axis of the reed switch, and therefore, has no affect on the reed switch.

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After tripping and disconnection a test object from the HV power supply (when the current running through it exceeds the admissible leakage current value), the reed switch is held by magnet 24 in the open position.

For manual-reset of a reed switch, a limb 26 with magnet 25 must be turning.

Main specifications of ACB "Viking-7":

Parameters	Value
Switching Voltage, V AC (rms)	100 to 3000
Maximum Interrupted Current, A (rms)	5.0
Dimensions, mm	140 x 100 x 60
Mass, kg	0.5
Number of Operations	10^6

Multi channel automatic HV circuit breaker "Viking-10", Fig. 7.4, enables

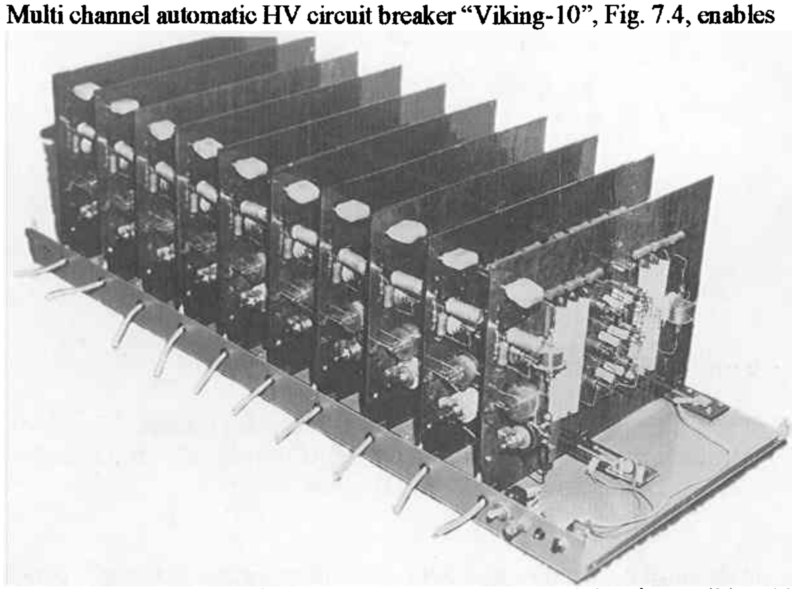

Figure 7.4 Multi channel automatic HV circuit breaker "Viking-10" (without lid).

the insulation testing equipment to test simultaneously many devices from a single HV power supply, Fig. 7.5.

Thus, the testing can be fully automated and much more efficient.

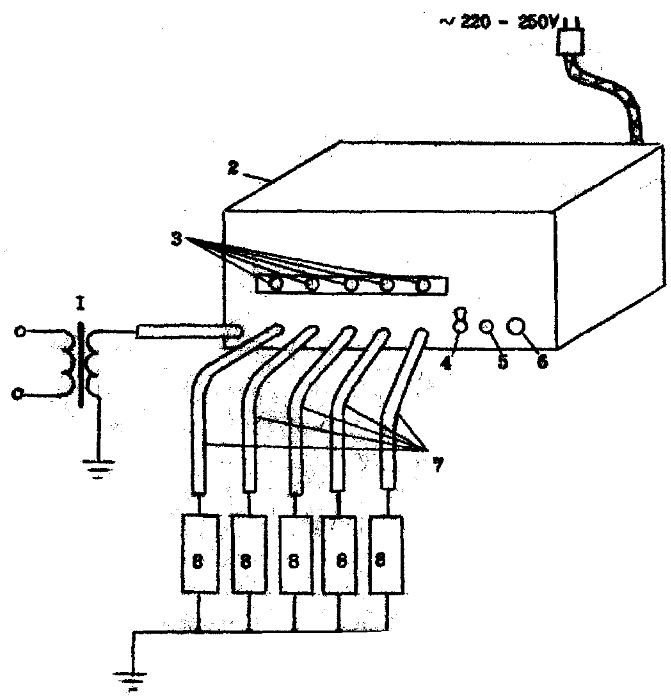

Figure 7.5 Block-diagram for outside connections of ACB "Viking-10".

1 – high voltage power supply; 2 – ACB "Viking-10"; 3 – trip indicators (LEDs); 4, 5, 6 – main switch and indicators; 7 – outputs (high voltage wires); 8 – objects under testing.

The HV circuit disconnection is accomplished without causing any electric arc during the first alternating current passing though the zero value and is not followed by overvoltage in the devices under test. When the current leakage through a channel exceeds a level trip, then the "Viking-10" disconnects that channel and turns ON the corresponding light indicator (LED).

The current level trip of each channel can be preset individually.

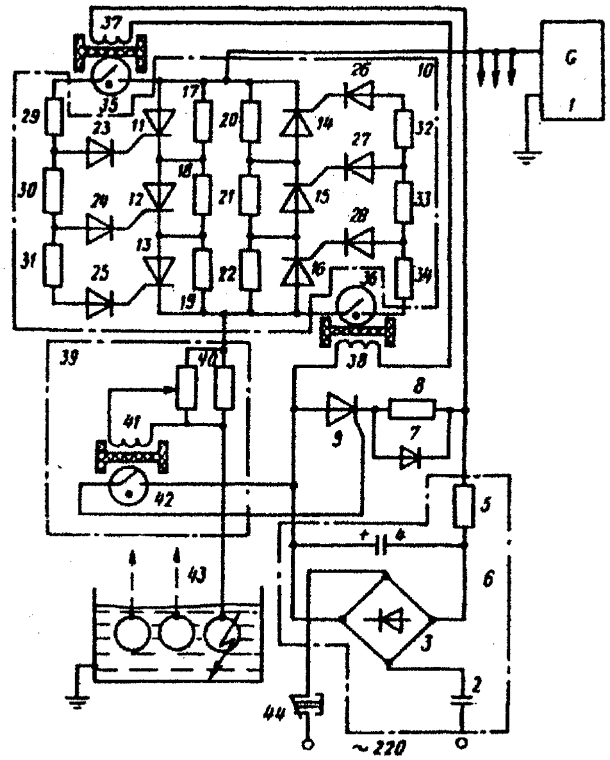

Figure 7.6 Circuit diagram for one channel of a multi channel automatic circuit breaker "Viking-10".

1 – HV power supply; 10 – hybrid reed-thyristor commutating unit; 37, 38 – HV reed switch relay; 39 – trip unit; 41, 42 – RG-relay; 43 – objects under test; 44 – reset switch.

Specifications of multi channel HV automatic circuit breaker "Viking-10":

Main Parameters	Value
Switching Voltage, AC, V (rms)	100...3000
Maximum Interrupted AC current, A (rms)	25.0
Range of current trip regulation, A	0.01...1.0
Dimensions, mm	
5 – channel breaker	430 x 325 x 260
10 – channel breaker	760 x 325 x 260

7.2 HIGH-VOLTAGE LABORATORY POWER SUPPLY

For small companies involved in the design and operation of electrical equipment, the issue of providing the work in progress with the needed test equipment is a difficult problem. The reason is that it is impossible to complete the job properly without test equipment on the one hand, and the very high cost of such equipment made by big companies (tens of thousands of dollars) makes it quite problematic on the other.

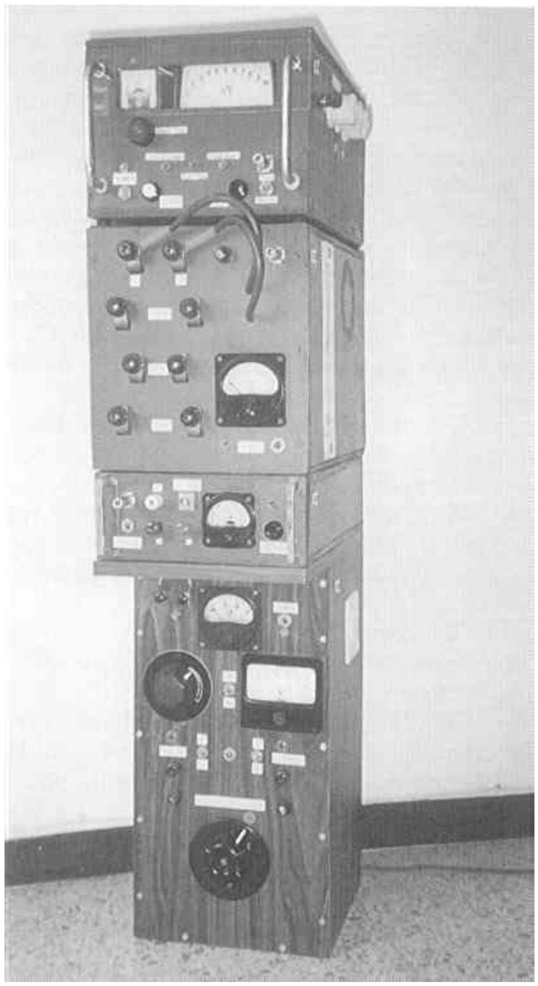

Figure 7.7 Universal desktop laboratory test installation.

In this respect, there is an urgent need for the design of a universal small-size and inexpensive test station intended for performing the following tests: functional testing of relays and automation devices; electric strength, arc and tracking resistance of electric insulators; testing of thermal and dynamic resistance of electrical device coils and contacts; testing of electric drives of different devices; generation of pulsating and stationary magnetic fields; point welding of micro-components; liquids and gases treatment with electric discharge, etc.

We designed and constructed a test station intended for these operations. This system can stand on the author's work table and occupies an area of 25 x 25 cm. In this book, we describe only an HV power supply (upper unit on Fig. 7.7).

The HV unit is provided with an automatic control and protection assemblies mounted in it. The HV part of the unit consists of step-up transformer T1, resistance voltage divider R2, rectifying bridge VD4 and condenser C, Fig. 7.8. Transistors VT1...VT3 with diode bridge VD5 and chain R4C2 are used for automatic smooth output voltage increase of the unit after S4 activation and relay K4 engagement. A timer (chain R8C3, transistor VT4, relay K5) provides a 1 minute time delay after the high voltage reaches the preset level and smooth automatic high voltage decrease to zero after this time period has elapsed. Reed switch current sensor K1 and K2 with thyristor VS2 and relay K3 protect the unit from overcurrent and the tested object from the thermal action of an electric arc in case of insulation breakdown. Tumble switch S2 can be used to set the unit to manual control mode in which the unit is automatically cut of and rectifier bridge VD5 shunted.

Any powerful n-p-n transistor can be used as VT1 with dissipation power no less than 160 W and collector current no less than 10 A. Condensers C1...C3 must have a low leakage current. Relay K5 must be a reed switch. HV divider R2 is formed with 8...10 (2W power) resistors, connected in series and arranged in a small enclosure and potted with epoxy compound. Elements R1 and VD2 protect the current meter (milliampermeter) from overcurrent at high discharges in the test object.

Current sensor K2 – is an RG-15 interface relay.

When the insulation control device is operated in automatic mode, pressing push button S4 activates the automation module. After the device is set to test mode (indicated by LED VD7), the required examined voltage is set once and is then automatically maintained unchanged during the test. Prior to connecting or disconnecting the tested object, the S3 push button must be pressed followed by extinguishing the HL3 indicator light.

If insulation breakdown in the tested object occurs and the protection is activated, the device operation is prevented (blocked), and its reactivation is made possible only after a momentary voltage cut off with tumble switch S5. In different arrangements of the control block elements, a number of special effects can be achieved.

For example, in order to obtain a steady arc on electrodes connected to the block output, it is set to automatic mode and current sensor K1 is cut off with tumbler S1. In this mode, the device features higher internal impedance and is not subjected to overloading. However, when condenser C1 is connected to the device output, a relaxation generator is formed, and high voltage pulsating discharges can be generated at the output electrodes with a frequency 0.5 - 1 Hz.

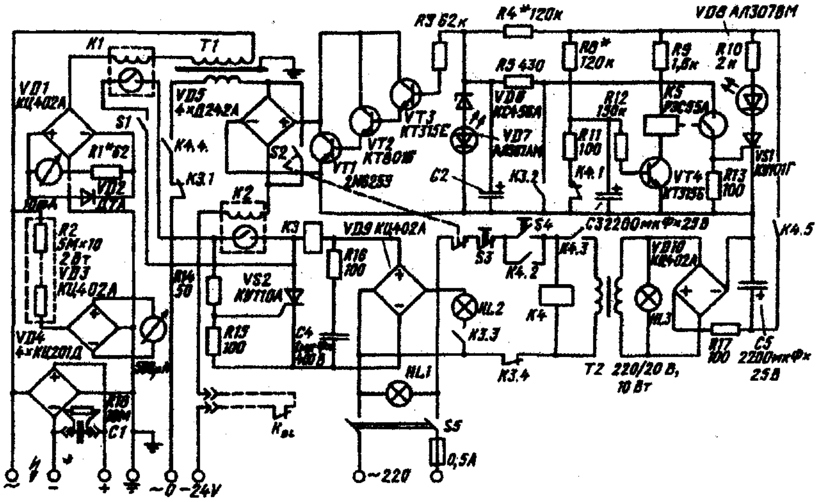

Figure 7.8 Circuit diagram of HV unit (10 kV output voltage, AC and DC).

Since the described high voltage device is a desktop device, its design provides for severe electricity safety precautions. HV transformer T1 output and all other HV outputs are made from HV wires. The body of transformer T1 and low voltage output of the unit are grounded. The test object is inserted in a closed plastic box with appropriate dimensions and bloc-contact (K_{BL} in fig.7.8) on its cover.

7.3 POWER RELAY WITH PROTECTIVE CONTACTS (REPROCON)

REPROCON is a commutation device of a new type. The new relay combines positive properties of powerful hermetic reed switches and an ordinary electro-mechanical apparatus. It has a powerful contact system located within a hermetic ceramic container that is filled with a moisture-free gas mixture: Nitrogen (N) – 90%, Hydrogen (H) – 10% with increased pressure.

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The coil is encapsulated with epoxy and located outside the hermetic container.

This ensures trouble-free commutation in severe environmental servicing conditions such as a dusty atmosphere in manufacturing enterprises, sea mist affecting ships or low air pressure in aircraft and military equipment, etc.

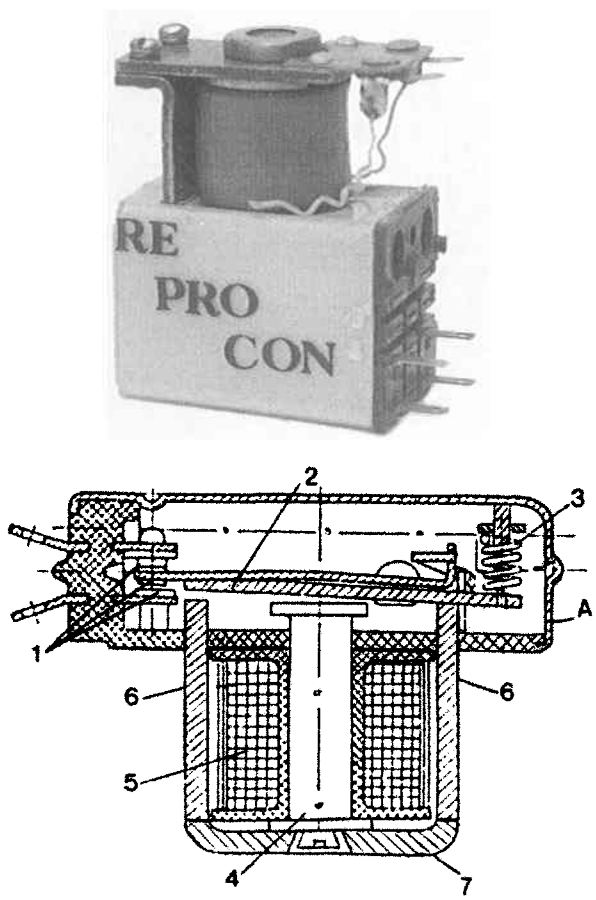

Figure 7.9 REPROCON device.

A – hermetic ceramic container; 1 – contacts; 2 – armature; 3 – spring; 4 – core; 5 – coil; 6 – yoke (stationary part) ; 7 – yoke (movable part).

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REPROCON also has good prospects for its application as a commutation device in electric motor control.

Table 7.1 REPROCON basic parameters

Nominal Switching Voltage, V: AC DC	 380 220
Nominal Switching Current, A: AC DC	 30 10
Test Insulation Voltage, V AC	2500
Control Power, VA	2.4
Operate Time, ms	15
Number of Operations, cycles	10^6
Contact Form	3NO and 3NC
Dimensions, mm	60 x 55 x 28
Weight, kg	0.25

In addition, REPROCON could be manufactured as large apparatus for a high current application in high capacity equipment.

7.4 THE USE OF HIGH-VOLTAGE RG-SERIES RELAYS IN ELECTRO-PHYSICAL INSTALLATIONS

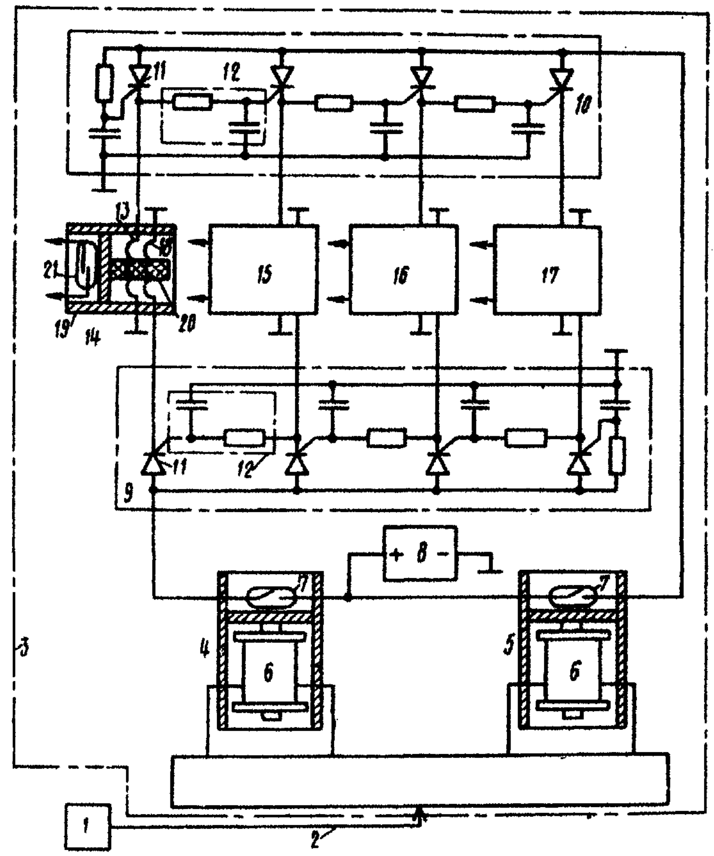

Figure 7.10 Control systems based on RG-relays for HV electro-physical equipment.

1, 2 – low voltage part of control system; 3 – HV part of control system; 4 and 5 – high voltage RG-relays; 6 – windings of RG- relays; 7 – reed switches; 8 – power supply, located on high potential zone; 9 and 10 – control circuits for latching relays; 11 – thyristor; 12 – RC time delay circuit; 14 – 17 latching relay (standard design or special HV design, based on RG-technology).

Low-voltage electric and electronic devices installed in high-voltage areas at a potential of tens to hundreds of kilovolts to earth are in general use in numerous electro-physical installations (EPI), such as preinjectors of synchrotrons, injectors of neutral atoms of additional plasma heating in "Tokamaks" and other massive EPI.

These devices are controlled from the earth potential by pulse commands and signals (A-type commands) transmitted at a very high speed, as well as by simpler "ON-OFF" type commands, which do not require high transmission speed (B-type commands). In all the above cases fiber-optical cables with electronic pulse shaper connected at the transmitting end and electronic amplifier connected at the receiving end were in use. Although fiber-optic cables are totally insensitive to electro-magnetic noise, the control system performance as a whole turned out to be inadequate because of highly sensitive IC electronic components.

In modern electro-physical equipment the power radiated from breakdown in high voltage circuits is so high, that it results not only in failure in the control system, but also in complete destruction of numerous electronic components. For this reason designers always prefer to use alternative jam-proof control systems. For example, in injectors of the "Tokamak-15" installation the electronic digital-to-analog converters for setting the glow voltage and arc current were replaced by a multirun variable potentiometer rotated by a motor via a long insulation shaft (the Efremov Research Institute for Electro-Physical Equipment, Petersburg, Russia).

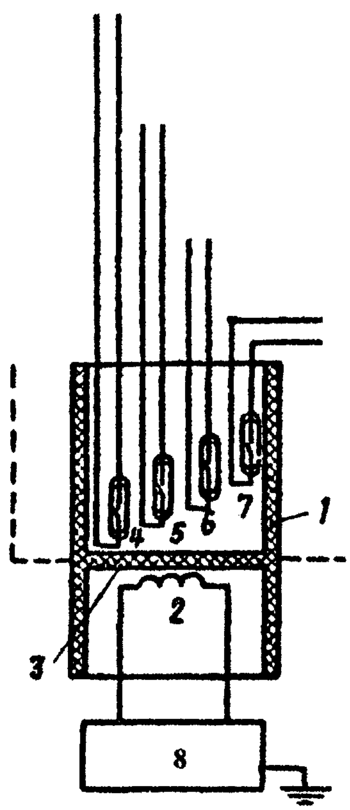

Figure 7.11 Multichannel high-voltage reed relay.

1 – HV insulation body (design based on RG technology); 2 – control winding; 3 – main insulator; 4...7 – reed switches, mounted in insulation body with different distance from control winding; 8 – power supply, located on low potential.

For better anti-jamming ability electro-mechanic relays are connected in electronic systems of arc control, heat and valves switching, and On and Off channels, yet this does not resolve all the problems.

High voltage RG relays enable one to apply a novel principle in designing of many control systems in electro-physical equipment. Moreover, single relays (RG series and other special series, see Appendix 2) are used along with more complex devices based on these relays, Fig.7.10.

In this device only two high voltage relays are used for switching of a great number of circuits at high potential. As high voltage relay 4 is energized, latching relays 14, and then 15, 16, 17 and so on are energizing by turns, causing their respective circuits switching by their contacts. De-energizing of high voltage relay 4 and energizing of high voltage relay 5 returns the latching relays to their initial state in the reverse order, namely: 17, followed by 16, 15 and so on.

In Fig. 7.11 is shown a multichannel high voltage reed relay used for circuits control in the high potential circuits. Reed switches possessed different sensitivities determined by their position relatively to the winding. The change of voltage value applied to the control winding will change the number of simultaneously energized reed switches.

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Appendix A: Selected Publications by the Author

1. Scientific papers available in international database:

*Exit Ei Compendex*Web*

Engineering Information Inc., Hoboken, New Jersey, USA
http://www.ei.org/engineeringvillage2/trial.html

1.1. ***Gurevich V. I.*** Enhancing reliability of electric power supply of unattended stations in transmission systems. – Telecommunications and Radio Engineering, 1989, v. 44, No. 8, pp. 40 - 43 (in English).
Order Number: *90120077229*

1.2. ***Gurevich V. I., Krivtsov V. V.*** High-voltage hercone-semiconducting devices for REA electric power supply systems. –Elektrosvyaz', 1991, No. 4, pp. 46 - 48 (in Russian).
Order Number: *92040461231*

1.3. ***Gurevich V. I.*** A high voltage switch with a magnetically controlled contact of a new type. – Elektrotekhnika, 1992, No. 12, pp. 42 - 44 (in Russian).
Order Number: *93050997196*

1.4. ***Gurevich V. I.*** A new generation of universal protection relays. – Elektrotechnika, 1994, No. 1, pp. 61 - 66 (in Russian).
Order Number: *94051298565*

1.5. ***Gurevich V. I.*** Autonomous radio equipment high voltage circuits protection against the current overload. – Elektrosvyaz', 1994, No. 6, pp. 28 - 30 (in Russian).
Order Number: *94091408066*

1.6. ***Gurevich V. I.*** Low-voltage hermetic commutators of a new generation. – Elektrotechnika, 1994, No. 4, pp. 45 - 47 (in Russian).
Order Number: *94122478997*

1.7. ***Gurevich V. I.*** Evaluation of the efficiency of high-voltage thyristor-controlled transmission-line voltage regulators. – Soviet Electrical Engineering, 1982, v. 53, No. 4, pp. 58 – 62 (in English).
Order Number: *83120174803*

1.8. ***Gurevich V. I., Savchenko P. I., Balakhonov A. M.*** Control of thyristors in power-transformer tap switch. - Soviet Electrical Engineering, 1980, v. 51, No. 7, pp. 61 – 67 (in English).

Order Number: *82060001872*

1.9. ***Gurevich V. I.*** The protection of high-voltage circuits of radio-electronic apparatus from current overloads. – Telecommunications and Radio Engineering, 1994, vol. 48, No. 9, pp. 40 – 45 (in English).

1.10. ***Krivtsov V. V., Gurevich V. I.*** New design principles of the over current protection based on magnetically excited contacts. – Power Engineering, 991, No. 6, pp. 38 – 43 (ISSN 0579-2983).

2. Recent publications (in Russian language):

2.1. ***Gurevich V. I.*** A new generation of devices and systems for over current protection of high voltage installations. - Elektrotechnika, 2000, No. 7, pp. 59 - 63 (ISSN 0013-5860).

2. 2. ***Gurevich V. I.*** Technical aspects of problem of earth fault protection for middle voltage distribution network. – Industrial Power, 2001, No. 1, pp. 34 – 37 (ISSN 0033-1155).

2. 3. ***Gurevich V. I.*** Hybrid power relays. – Industrial Power, 2002, No. 6, (ISSN 0033-1155.)

3. Some patents (Russia) and author's certificates (former USSR) on book's subject:

Patent Number, Inter. Class, Registration Date	***Name of Patent***	***Authors***
641536 H01H83/18, 1979	Power Direction Relay	V. Gurevich P. Savchenko
801129 H01H36/00, 1981	High Voltage Reed Switch Relay	V. Gurevich P. Savchenko
836704 H01H51/28, 1981	High Voltage Vacuum Relay	V. Gurevich
892604 H02M1/08, 1981	High Voltage Semiconductor Controlled Rectifier	V. Gurevich
892648 H02P13/16, 1981	A Device for Thyristor Control of High Voltage Switch	V. Gurevich

936349 H02P13/16, 1982	A Device for Thyristor Control with Antiparallel Connection of a HV Switch	V. Gurevich
947772 G01R19/00, 1982	A Device for Measuring the Gate-trigger Current	V. Gurevich P. Savchenko Y. Zhukovsky
1007143 H01H51/28, 1983	Reed Relay	V. Gurevich
1083249 H01H51/28, 1984	A Device for High Voltage Apparatus Control	V. Gurevich P. Savchenko S. Promyshlyaev

Pat. **125454** (Israel). High Voltage Reed Switch Relay. 1998 / V. Gurevich
Pat. **130032** (Israel). High Voltage Reed Switch Relay. 1999 / V. Gurevich
Pat. **130440** (Israel). High Voltage Reed Switch Relay. 1999 / V. Gurevich

4. Book: "High Voltage Devices with Reed Switches" (self-published by Russian), 2000.

The book contains some important relevant technical information, which was not included in "Protection Devices and Systems for High-Voltage Applications". The book was issued with very small circulation. In this connection we want to inform the readers on this book accommodation.

Address list for book location:

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"Gornorudnay Electrotehnika" 191123, S-Petersburg, Russia
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Federal State Unitar Enterprise "Central Research Institute of Nave Electrotechnic and Technology" Blagodatnaya St., 6, S-Petersburg 196128, Russia Mr. Viktor Efimof
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Kharkov Polytechnic Institute 61000, Kharkov, Ukraine
INVENTOR 61000, Kharkov, Ukraine, Bagratione St, 6
Research Scientific Center "Kharkovrelaycomplect" 3100124, Ukraine, Kharkov, PO Box 9619
Sevastopolenergo 99040, Ukraine, Sevastopol, Hrustaliov St, 44

USA
Library of Congress Washington, DC 20540, USA
Ford Motor Company Dearborn, MI , USA Mr. V. Krivtsov
Aleph International Corp. 1026 Griswold Ave, San Fernando, CA 91340, USA

Appendix B: Some Types of RG-relays with Special Characteristics

- for Ultra-High Voltage Applications
- with Powerful Magnetic Shielding
- Differential
- for External Installations
- Constant Magnet Operated
- with Many Levels Trip
- with Vacuum Main Insulator

B1 ULTRA HIGH VOLTAGE (150 – 200 KV) RG-RELAY "VIKING" SERIES WITH PROTECTION AGAINST AN EXTERNAL MAGNETIC FIELD

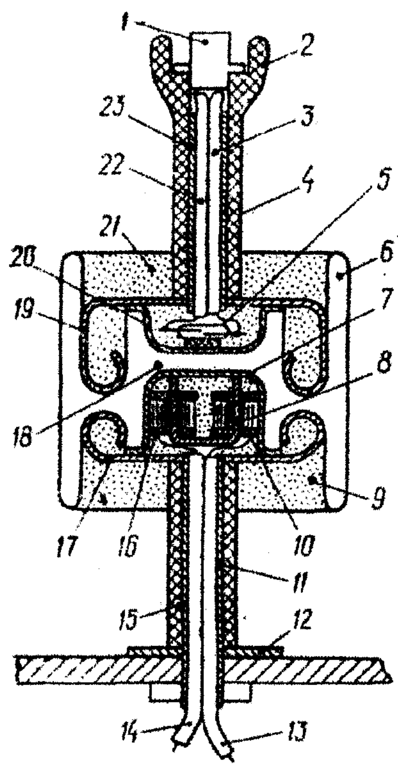

Figure B1.1 Ultra high voltage RG-relays: design.

1 – low voltage connector; 2 – insulator for low voltage connector; 3, 22 – HV cables (reed switch leads); 4 – HV bushing; 5 – reed switch; 6 – main insulator; 7, 20 – aluminum shields; 8 – magnetic core; 9, 21 – epoxy encapsulant; 10,16 – operate coils; 11, 15, 23 – lead shields; 12 – fastening element; 13, 14 – HV cables (operating coil leads); 17, 19 – ferromagnetic shields.

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Figure B1.2 Ultra high voltage RG-relays: outside.

B2 RG–RELAY WITH A HIGH LEVEL PROTECTION FROM AN EXTERNAL MAGNETIC FIELD

50 KV DC

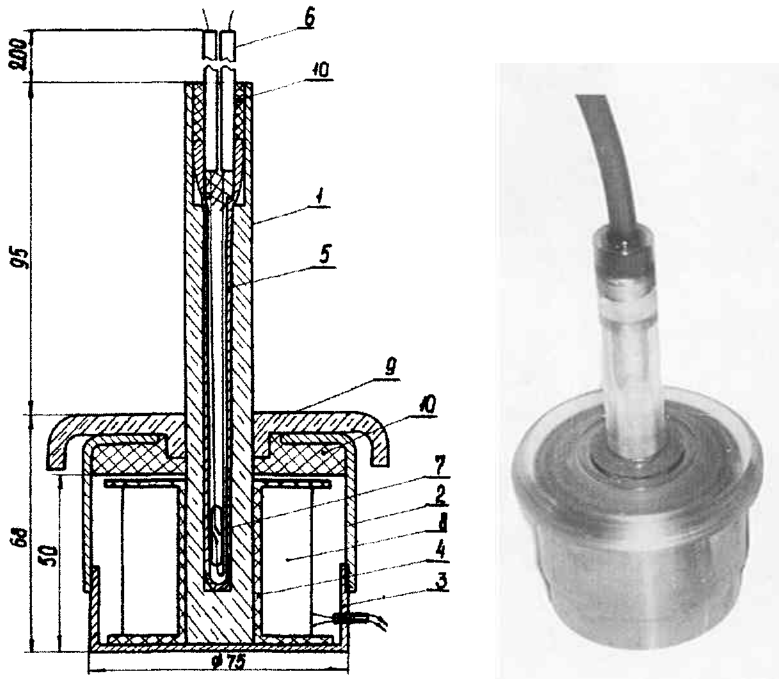
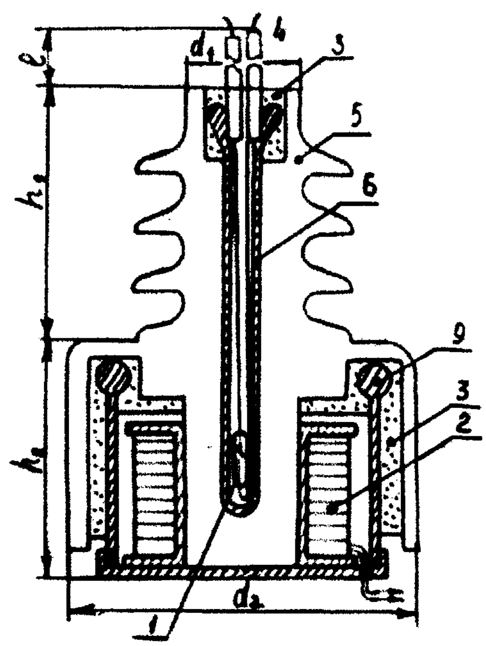


Figure B2 RG-relay with a high level protection from an external magnetic field.

1 – main insulator (made as one unit with 9 element); 2, 3 – thick wall ferromagnetic shield; 4 – coil; 5 – electrostatic shield; 6 – HV wires (reed switch's leads); 7 – reed switch; 8 – operate winding; 10 – epoxy encapsulant.

B3 RG–RELAY FOR OPEN EQUIPMENT AND EXTERNAL INSTALLATIONS



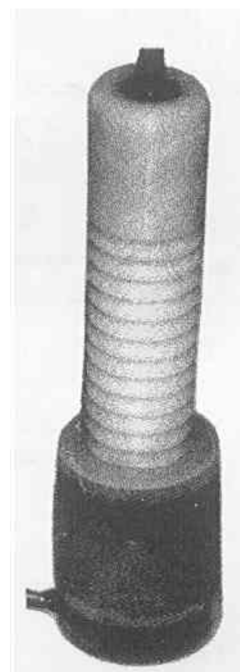


Figure B3 RG-relay for open equipment and external installation.

1 – reed switch; 2 – operate winding; 3 – epoxy encapsulant; 4 – high voltage cables (reed switch leads); 5 – main insulator; 6 – electrostatic shield; 9 – ferromagnetic shield.

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B4 RG-RELAY WITH VACUUM INSULATOR

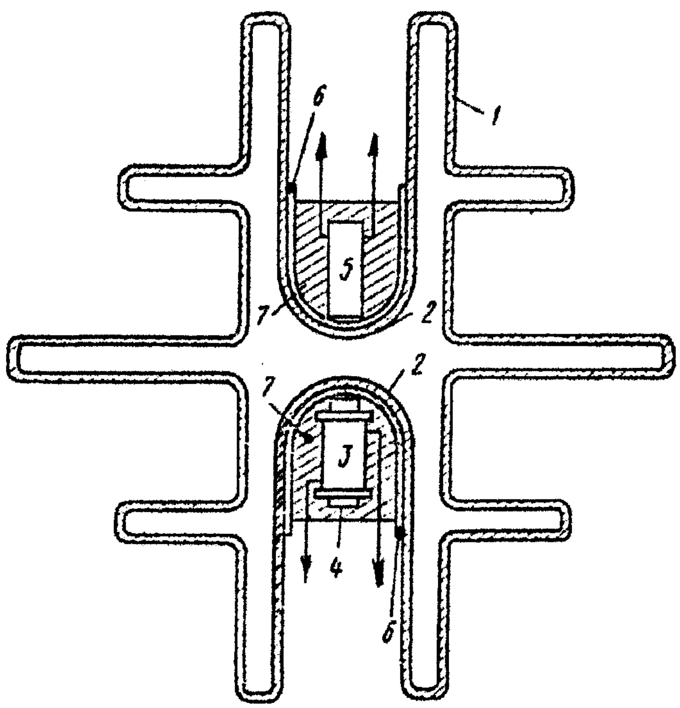

Figure B4 RG-relay with vacuum insulator.

1 – main insulator (vacuum chamber); 3 – operate coil; 4 – ferromagnetic core; 5 – reed switch; 6 – electrostatic shield or conductive cover; 7 – epoxy encapsulant

The key feature of this design is, that all elements are arranged outside of a vacuum zone. It eliminates many problems related to preservation (maintenance) of high vacuum in main insulator (vacuum chamber).

B5 RG-RELAY WITH MULTILEVELS TRIP

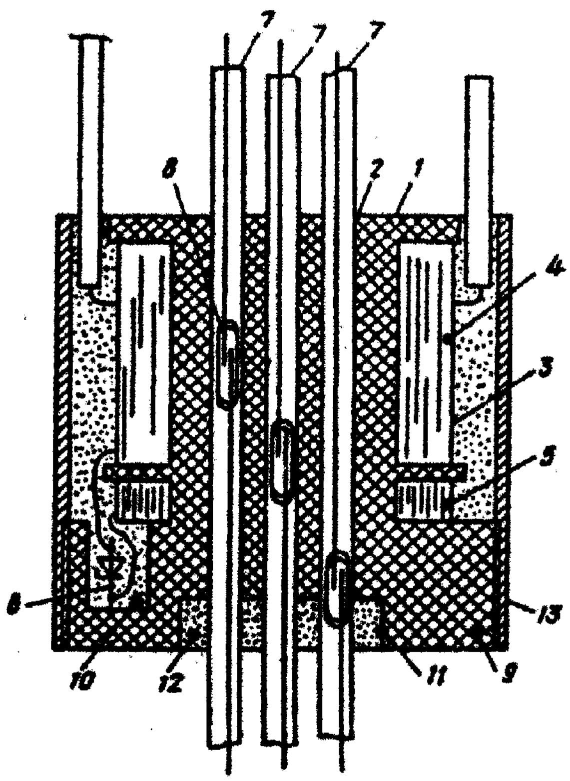

Figure B5 RG-relay with multilevel trip.

1 – main insulator; 2 – channels in main insulator; 3 – operate winding, containing two sections: 4 and 5 connected in series; 6 – diac for bypassing section 5; 7 – movable insulators; 8 – reed switches; 10, 11, 12 – epoxy encapsulant; 13 – ferromagnetic shield.

This version of the RG-relay assembly has a few trip levels and can be used for controlling for a current level in a high potential circuit. Each level of a trip can be adjusted separately: by movement of an appropriate movable insulator with a reed switch.

B6 DIFFERENTIAL RG-RELAY

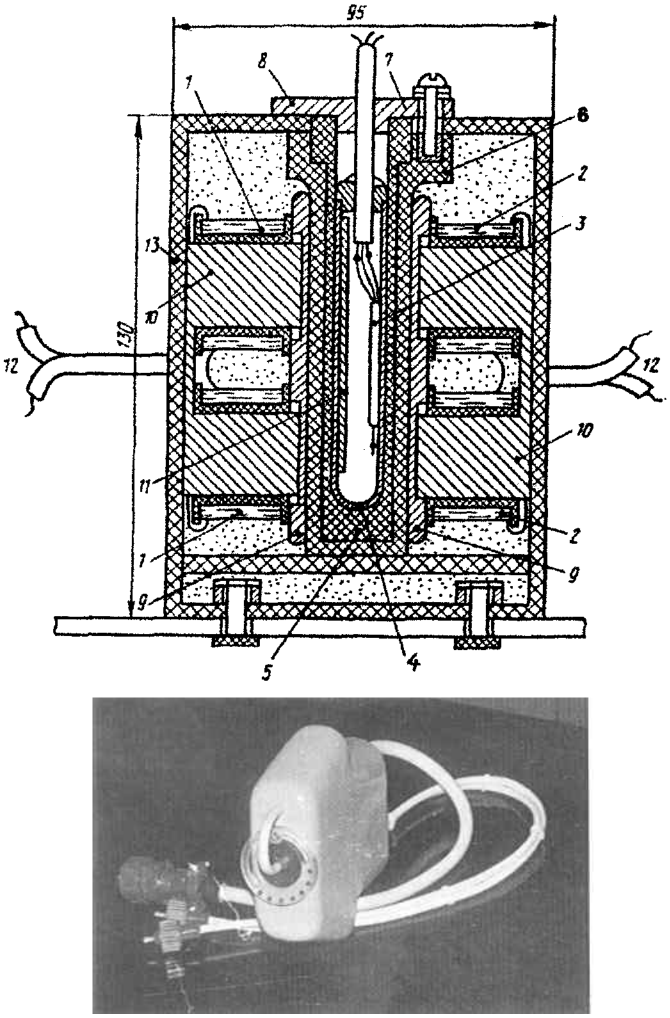

Figure B6 Differential RG-relay.

1, 2 – operate coils; 3 – reed switch mounted non symmetrical turn-in insulator; 4 – electrostatic shield of reed switch; 5 – turn-insulator; 6 – static main insulator; 7 – fixative element; 8 – limb; 9 – electrostatic shielding of cores; 10 – ferromagnetic cores; 11 – ferromagnetic shunt; 12 – HV cables (coils leads); 13 – insulating body.

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B7 CONSTANT MAGNET OPERATED RG-RELAY

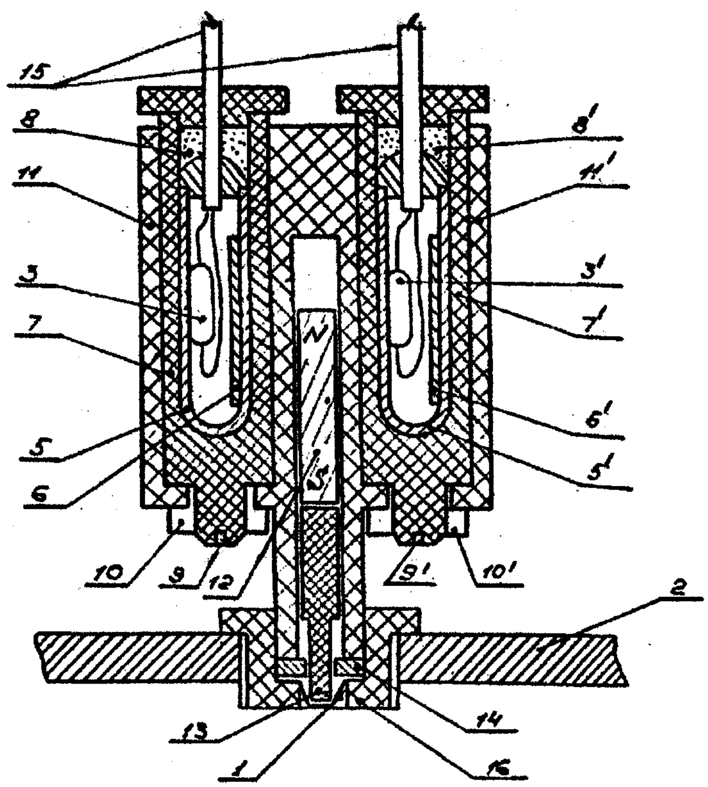

Figure B7 Constant magnet operated RG-relay.

1 – membrane; 2 – capacitor body; 3 – reed switches; 5 – electrostatic shields; 6 – ferromagnetic shunts; 7 – turn-in insulators; 8 – epoxy encapsulant; 9 – slits for tumbling of turn-insulators; 10 – fastening nuts; 11 – main insulator; 12 – movable magnet; 13 – rod; 14 – stopper puck; 15 – HV cables (reed switches leads); 16 – cork in capacitor body.

This RG-relay model intended for protection of HV capacitors, mounted on a high potential platform as a pressure gas relay.

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Appendix C: Environmental Tests of RG-relays for MIL-STD-202 Requirements

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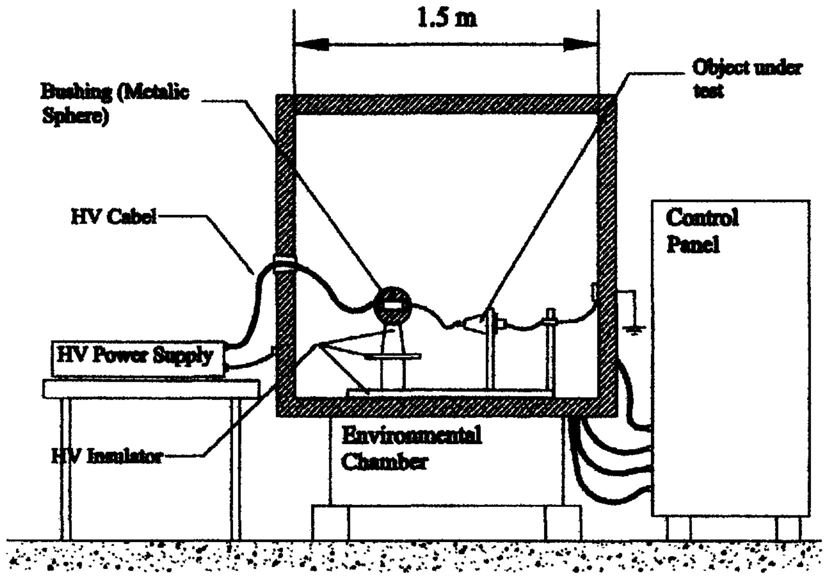
Environmental Tests for MIL-ST-202 Requirements

(Environmental Engineering Center of RAFAEL, Israel)

- Operation temperatures range –55 to +85°C
- Cyclical temperature change in range –55 to +85°C
- Air humidity 87% at a temperature of 40°C
- Low air pressure with high voltage applied – 87 mm Hg
- Vibrations resistance 10g at an oscillation amplitude frequency in range 10-500 Hz
- Repeated shock: 55 g, duration 2 ms, 10,000 impacts
- Single mechanical impacts: 30 g/s, ½ sinusoid with duration 11 msec.

Withstanding high voltage and operating current was checked after each environmental test.



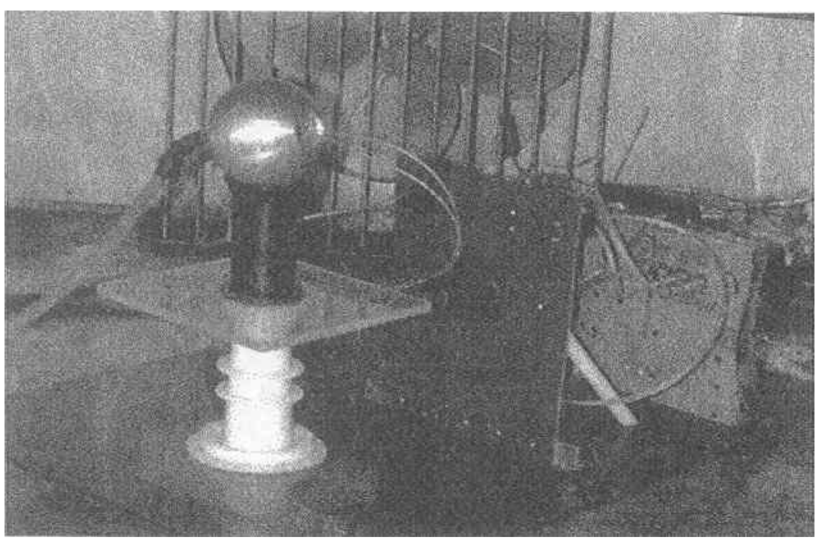


Figure C1 RG-relays in universal environmental chamber.

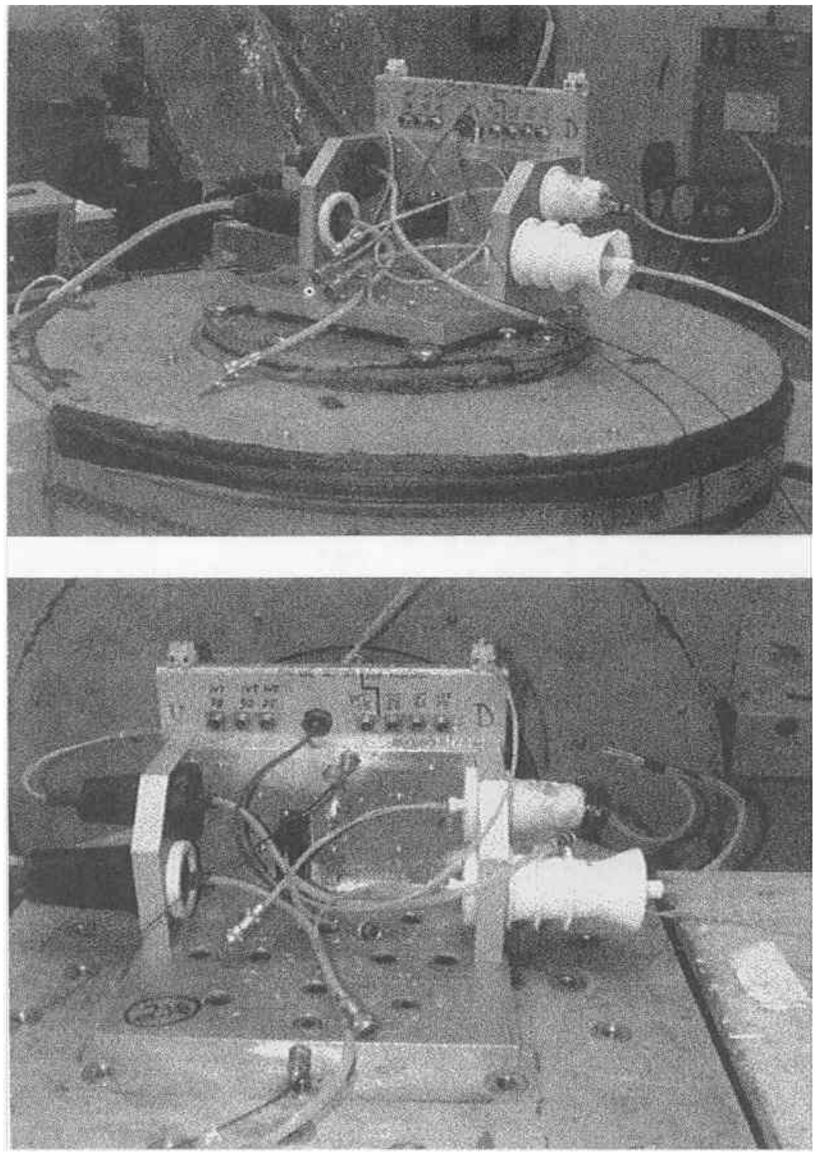


Figure C2 RG-relays on vibration test stand.

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Appendix D: Components Recommended for Use in HV Protection Devices

- Reed Switches
- Solid-State Modules
- High Voltage Thyristors
- High Voltage IGBT and Bipolar Transistors
- Electromagnetic Relays
- Miniature Connectors
- HV Cables
- Capacitors DC/AC

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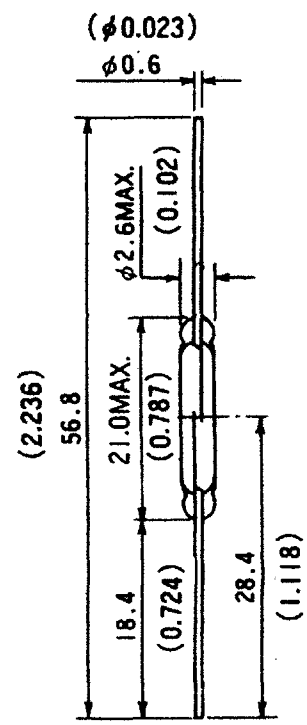
D.1 REED SWITCHES

D.1.1 Miniature Vacuum Reed Switches HYR2016 (ALEPH) and KSK1A79 (MEDER Electronic)

Contact Form	1A (1NO)	
Contact Material	Rhodium	
Max. Contact Rating, W	25	
Max. Switching Voltage, V DC	1000	
Max. Switching Current, A	1	
Max. Carry Current, A	2	
Max. Initial Contact Resistance, Ω	0.1	
Pull in Value (AT)	15 – 50	
Min. Breakdown Voltage, V DC	2500	
Max. Contact Capacitance, pF	0.4	
Min. Insulation Resistance, Ω	10^{11}	
Typ. Resonant Frequency, kHz	2.2	
Electrical Life (resistive lods: 1000 V, 10 mA)	2×10^6	
Operating Temperature, °C	-60 +85	

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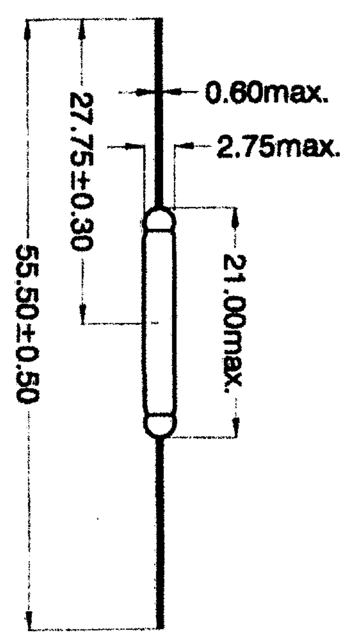
D.1.2 Miniature Gas Filled Reed Switch KSK-1A85 (MEDER Electronic AG)

Contact Form	1A
Max. Contact Rating, W	100
Max. Switching Voltage, V DC/VAC	1000
Min. Breakdown Voltage, V DC	4000
Max. Switching Current, A	1.0
Max. Carry Current, A	2.5
Max. Initial Contact Resistance, Ω	0.15
Pull in Value (AT)	20 - 60
Max. Contact Capacitance, pF	0.5
Min. Insulation Resistance, Ω	10^{10}
Typ. Resonant Frequency, kHz	-
Operating Temperature, °C	-40 +130
Operate Time, ms (max)	1.1
Release Time, ms (max)	0.25



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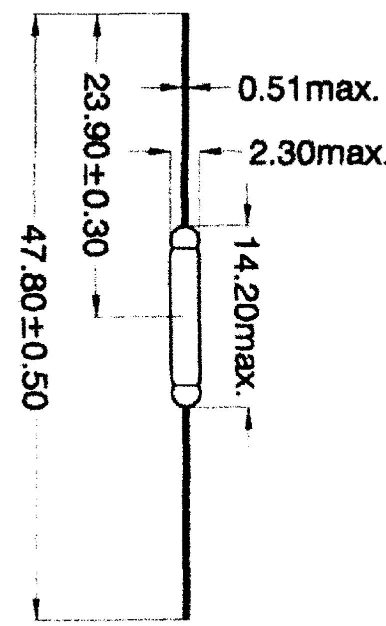
D.1.3 Miniature Reed Switch KSK-1A75 (MEDER Electronic AG)

Contact Form	1A
Max. Contact Rating, W	10
Max. Switching Voltage, V DC	500
Min. Breakdown Voltage, V DC	1500
Max. Switching Current, A	0.5
Max. Carry Current, A	1.0
Max. Initial Contact Resistance, Ω	0.20
Pull in Value (AT)	15 - 40
Max. Contact Capacitance, pF	0.4
Min. Insulation Resistance, Ω	10^{10}
Typ. Resonant Frequency, kHz	-
Operating Temperature, °C	-40 +130
Operate Time, ms (max)	0.5
Release Time, ms (max)	0.1



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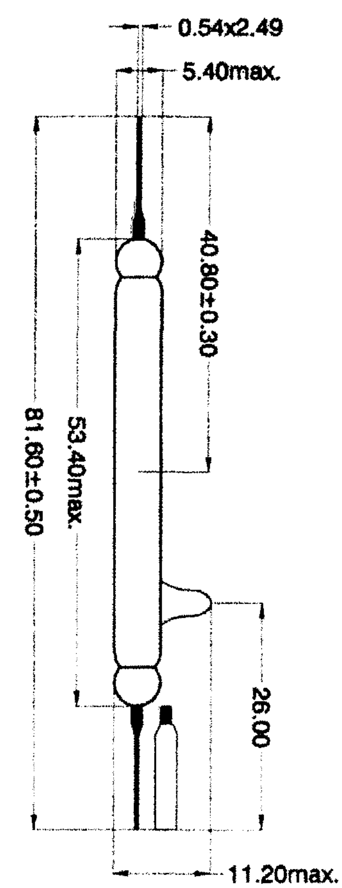
D.1.4 High Voltage Reed Switch KSK-1A83 (MEDER Electronic AG)

Contact Form	1A
Max. Contact Rating, W	50
Max. Switching Voltage, V DC	7,500
Min. Breakdown Voltage, V DC	10,000
Max. Switching Current, A	3.0
Max. Carry Current, A	5.0
Max. Initial Contact Resistance, Ω	0.15
Pull in Value (AT)	100 - 150
Max. Contact Capacitance, pF	0.8
Min. Insulation Resistance, Ω	10^{10}
Typ. Resonant Frequency, kHz	-
Operating Temperature, °C	-40 +130
Operate Time, ms (max)	3.0
Release Time, ms (max)	-



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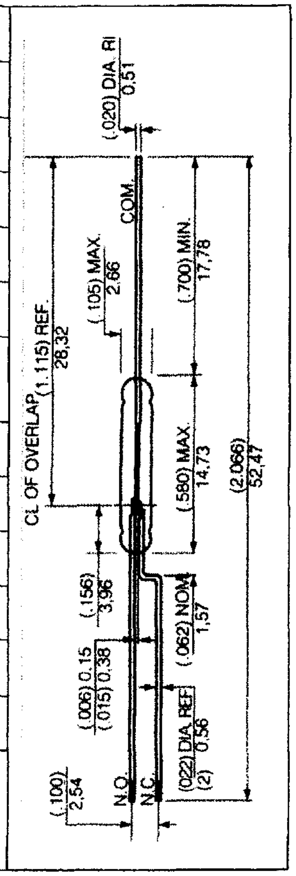
D.1.5 Miniature Reed Switch MDRR-DT (HAMLIM Inc.)

Contact Form	1C
Max. Contact Rating, W	5
Max. Switching Voltage, V DC	175
Min. Breakdown Voltage, V DC	200
Max. Switching Current, A	0.25
Max. Carry Current, A	1.5
Max. Initial Contact Resistance, Ω	0.1
Pull in Value (AT)	15 - 30
Max. Contact Capacitance, pF	0.1
Min. Insulation Resistance, Ω	10^9
Typ. Resonant Frequency, kHz	11
Operating Temperature, °C	-40 +125
Operate Time, ms (max)	0.7
Release Time, ms (max)	1.0



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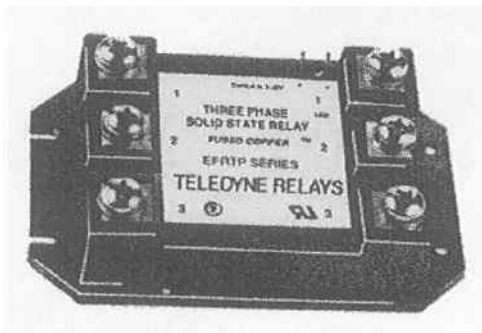
D.2 SOLID STATE MODULES

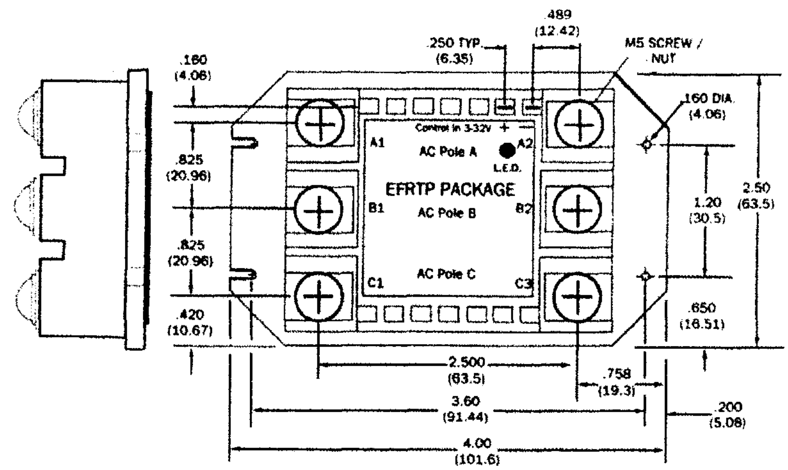
D.2.1 Three Phase SCR Module EFRTR1600660D150 (Teledyne Relays)



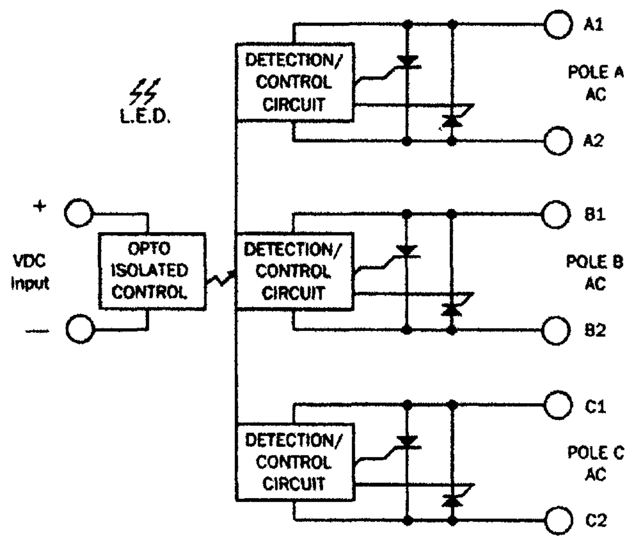
Main Parameters:

Load Voltage Rating, V AC	60 - 660
Frequency Range, Hz	47 - 400
Over Voltage Peak, V	1600
On-State Voltage Drop (for Max. Rated Current), V	1.7
Output Current Rating (per phase, for T < 85°C), A AC	150
Surge Current Rating (during 16.7 msec, non-repetitive), A	1950
Max. Turn-On time, msec (zero cross switching)	8.3
Max. Turn-Off time, msec	8.3
Leakage Current (off-state, T = 25°C), mA	0.5
dv/dt, typical, V/µs	500

Control Voltage, V DC	4.5 - 26
Control Current, mA	30
Isolation Level, V (rms)	4000
Operating Temperature, °C	-40 +125
Power Factor Range	0.5 - 1

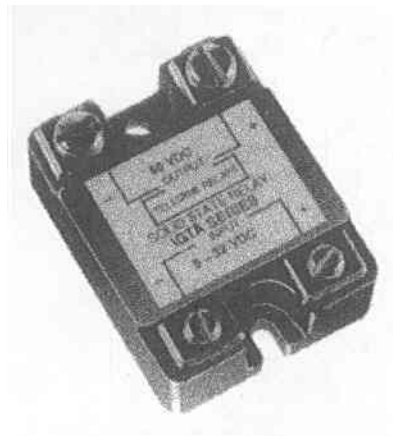


Mechanical Specification of Three Phase SCR Module EFRTR1600660D150



Block Diagram of Three Phase SCR Module EFRTR1600660D150

D.2.2 Single IGBT AC/DC Module IGTA1200480R100-L (Teledyne Relays)



Main Parameters:

Load Voltage Rating, V AC or DC	48 - 480
Frequency Range, Hz	75
Over Voltage Peak, V	1200
On-State Voltage Drop (for Max. Rated Current), V	2.5
Output Current Rating (per phase, for T < 85°C), A	100
Pulsed Current Rating, A	480
Max. Turn-On time, msec	4.8
Max. Turn-Off time, msec	0.16
Leakage Current (off-state, T = 25°C), mA	5
dv/dt, typical, V/µs	500
Control Voltage, V DC	3.5 - 15

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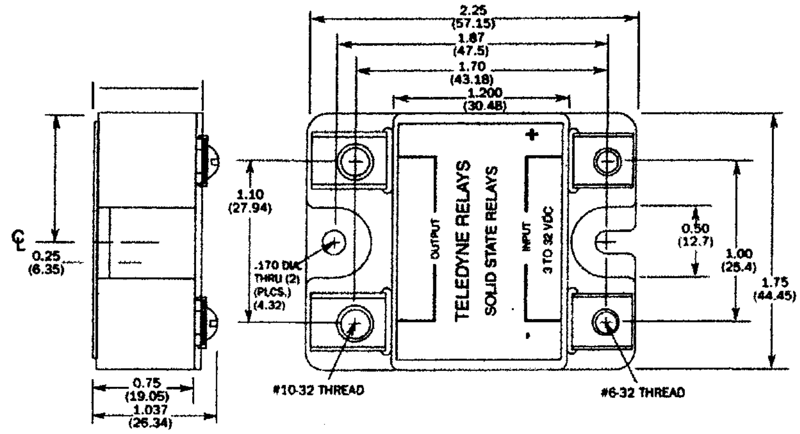
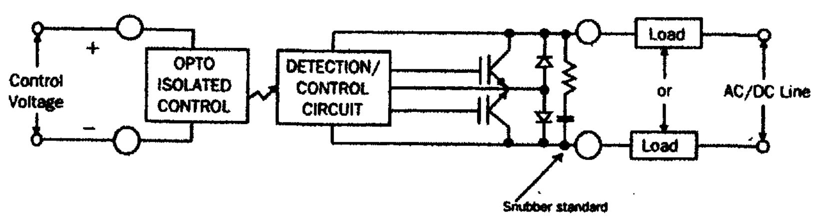
Control Current, mA	30
Isolation Level, V (rms)	2500
Operating Temperature, °C	-40 +125
Power Dissipation, W	500



Mechanical specification of single AGBT AC/DC module IGTA1200480R100-L



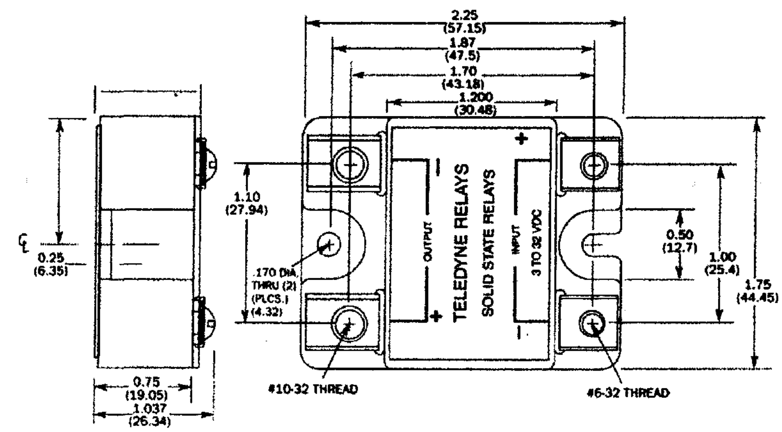
Block diagram of module IGTA1200480R100-L

D.2.3 Single IGBT DC Module IGTD1200480R100-L (Teledyne Relays)

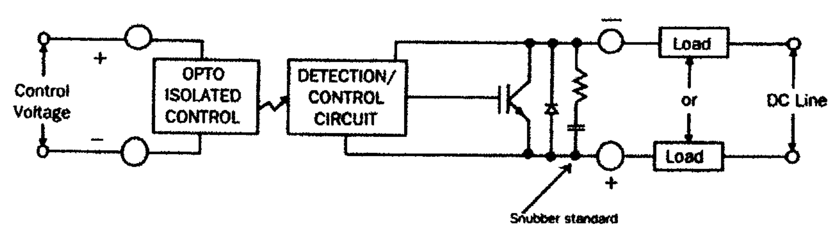
Main Parameters:

Load Voltage Rating, V DC	48 - 800
Frequency Range, Hz	75
Over Voltage Peak, V	1200
On-State Voltage Drop (for Max. Rated Current), V	2.5
Output Current Rating (per phase, for T < 85°C), A	100
Pulsed Current Rating, A	480
Max. Turn-On time, msec	4.8
Max. Turn-Off time, msec	0.16
Leakage Current (off-state, T = 25°C), mA	1
dv/dt, typical, V/µs	500
Control Voltage, V DC	3.5 - 15
Control Current, mA	30

Isolation Level, V (rms)	2500
Operating Temperature, °C	-40 +125
Power Dissipation, W	500



Mechanical specification of single IGBT DC module IGTD1200480R100-L



Block diagram of single IGBT DC module IGTD1200480R100-L

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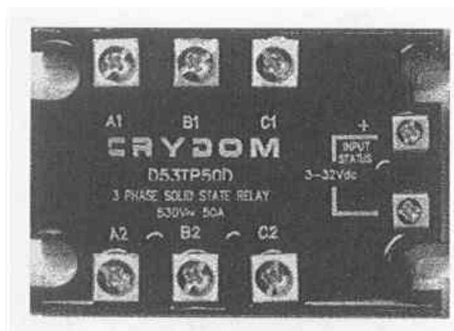
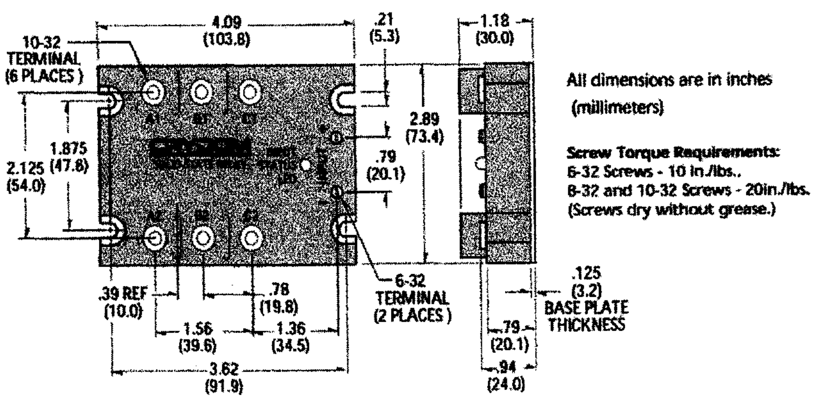
D.2.4 Three Phase SCR AC Module D53TP50D (Crydom)



Main Parameters:

Load Voltage Rating, V AC	48 - 530
Frequency Range, Hz	47 - 63
Over Voltage Peak, V	1200
On-State Voltage Drop (for Max. Rated Current), V	1.6
Output Current Rating (per phase, for T < 85°C), A AC	0.05 - 50
Surge Current Rating (during 16.7 msec, non-repetitive), A	625
Max. Turn-On time, msec (zero cross switching)	½ cycle
Max. Turn-Off time, msec	½ cycle
Leakage Current (off-state, T = 25°C), mA	10
dv/dt, typical, V/μs	500
Control Voltage, V DC	3 - 32

Control Current, mA	10
Isolation Level, V (rms)	4,000
Operating Temperature, °C	-40 +125
Power Factor Range	0.5 - 1



Mechanical specification of three phase SCR AC module D53TP50D

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D.2.5 One Phase SCR AC Module HD4890 (Crydom)

Main Parameters:

Load Voltage Rating, V AC	48 - 530
Frequency Range, Hz	47 - 63
Over Voltage Peak, V	1,200
On-State Voltage Drop (for Max. Rated Current), V	1.7
Output Current Rating (per phase, for T < 85°C), A AC	0.04 - 90
Surge Current Rating (during 16.7 msec, non-repetitive), A	1,200
Max. Turn-On time, msec (zero cross switching)	½ cycle
Max. Turn-Off time, msec	½ cycle
Leakage Current (off-state, T = 25°C), mA	10
dv/dt, typical, V/μs	500
Control Voltage, V DC	3 - 32

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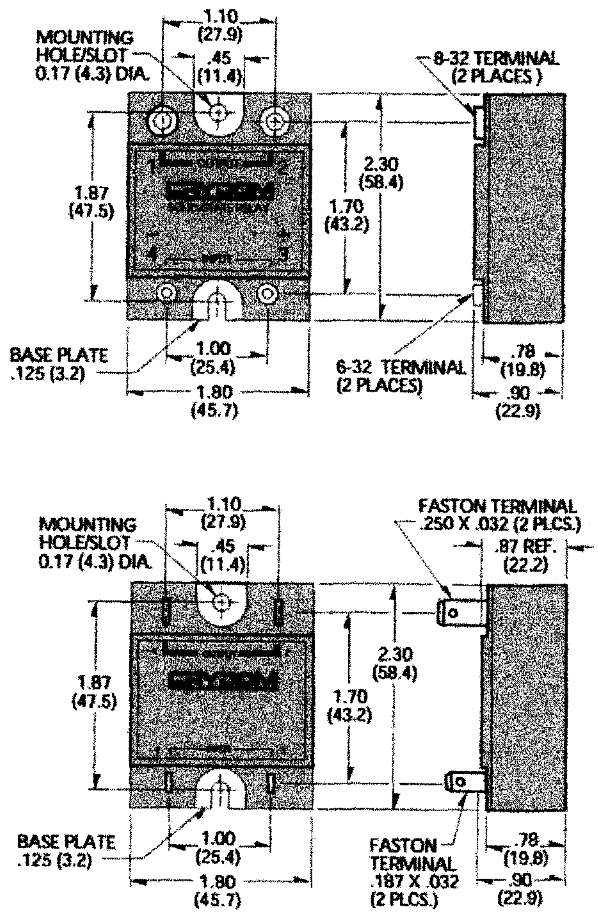
Control Current, mA	2
Isolation Level, V (rms)	4,000
Operating Temperature, °C	-40 +125
Power Factor Range	0.5 - 1



Mechanical specification of one phase SCR AC module HD4890 for two terminal types

D.3 HIGH-VOLTAGE THYRISTORS

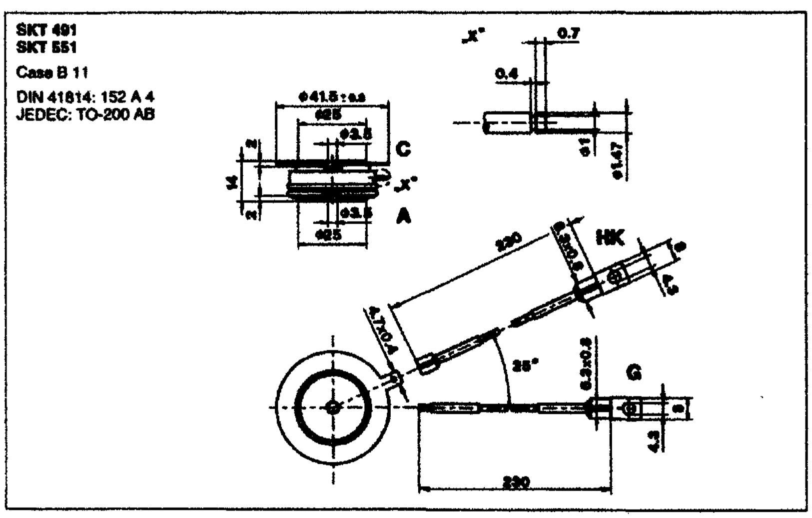
D.3.1 High Power and High Voltage Thyristors SKT 491/22E, SKT 551/18E (SEMIKRON)

Main Parameters

Symbol	Conditions	SKT 491	SKT 551	Units
I_{TAV}	sin. 180; (T_{case} = . . .); DSC	490 (80)	550 (85)	A °C
I_{TSM}	T_{vj} = 25 °C T_{vj} = 125 °C	8 000 7 000	9 000 8 000	A A
i^2t	T_{vj} = 25 °C T_{vj} = 125 °C	320 000 245 000	405 000 320 000	A^2s A^2s
t_{gd}	T_{vj} = 25 °C I_G = 1 A di_G/dt = 1 A/µs	typ. 1		µs
t_{gr}	V_D = 0,67 · V_{DRM}	typ. 1		µs
$(di/dt)_{cr}$	f = 50 ... 60 Hz	125		A/µs
I_H	T_{vj} = 25 °C; typ./max.	150 / 500		mA
I_L	T_{vj} = 25 °C; R_G = 33 Ω; typ./max.	0,5 / 2		A
t_q	T_{vj} = 125 °C; typ.	50 ... 150		µs
V_T	T_{vj} = 25 °C; I_T = 1500 A; max.	2,1	1,65	V
$V_{T(TO)}$	T_{vj} = 125 °C	1,1	0,925	V
r_T	T_{vj} = 125 °C	0,7	0,45	mΩ
I_{DD}; I_{RD}	T_{vj} = 125 °C; V_{RD} = V_{RRM} V_{DD} = V_{DRM}	50		mA
V_{GT}	T_{vj} = 25 °C	3		V
I_{GT}	T_{vj} = 25 °C	250		mA
V_{GD}	T_{vj} = 125 °C	0,25		V
I_{GD}	T_{vj} = 125 °C	10		mA
R_{thjc}	cont.; sin. 180; DSC/SSC rec. 120; DSC/SSC	0,045 0,047 / 0,100 0,054 / 0,113		°C/W °C/W °C/W
R_{thch}	DSC/SSC	0,012 / 0,024		°C/W
T_{vj}		− 40 ... + 125		°C
T_{stg}		− 40 ... + 130		°C
F	SI units US units	5,2 ... 8 1200 ... 1800		kN lbs.
w		105		g

Thyristor SKT 551/18E

Thyristor	V_{RSM}, V	V_{RRM} V_{DRM} V	dv/dt V/μs
SKT 491/22E	2300	2200	1000
SKT 551/18E	1900	1800	1000



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D.3.2 High Power and High Voltage Thyristors SKT 1000/28 E L2, SKT 1200/18E (SEMIKRON)

Main Parameters

Symbol	Conditions	SKT 1000	SKT 1200	Units
I_{TAV}	sin. 180; T_{case} = 85 °C; DSC	1000	1200	A
I_{TSM}	T_{vj} = 25 °C; 10 ms	19 000	30 000	A
	T_{vj} = 125 °C; 10 ms	16 500	25 500	A
i^2t	T_{vj} = 25 °C; 8,3 ... 10 ms	1 800	4 500	kA^2s
	T_{vj} = 125 °C; 8,3 ... 10 ms	1 360	3 250	kA^2s
t_{gd}	T_{vj} = 25 °C I_G = 1 A di_G/dt = 1 A/μs	typ. 1		μs
t_{gr}	V_D = 0,67 V_{DRM}	typ. 2		μs
$(di/dt)_{cr}$	f = 50 ... 60 Hz	125		A/μs
I_H	T_{vj} = 25 °C; typ./max.	250 / 500		mA
I_L	T_{vj} = 25 °C; R_G = 33 Ω; typ./max.	0,5 / 2		A
t_q	T_{vj} = 125 °C; typ.	100 ... 250		μs
V_T	T_{vj} = 25 °C; I_T = 3600 A; max.	2,0	1,65	V
$V_{T(TO)}$	T_{vj} = 125 °C	1,14	0,95	V
r_T	T_{vj} = 125 °C	0,243	0,18	mΩ
I_{DD}; I_{RD}	T_{vj} = 125 °C; V_{RD} = V_{RRM} V_{DD} = V_{DRM}	100		mA
V_{GT}	T_{vj} = 25 °C	5		V
I_{GT}	T_{vj} = 25 °C	250		mA
V_{GD}	T_{vj} = 125 °C	0,25		V
I_{GD}	T_{vj} = 125 °C	10		mA
R_{thjc}	cont.;	0,021		°C/W
	sin. 180; DSC/SSC	0,0225 / 0,054		°C/W
	rec. 120; DSC/SSC	0,027 / 0,060		°C/W
R_{thch}	DSC/SSC	0,005 / 0,010		°C/W
T_{vj}		− 40 ... + 125		°C
T_{stg}		− 40 ... + 130		°C
F	SI units	22 ... 25		kN
	US units	5000 ... 5600		lbs.
w		550		g

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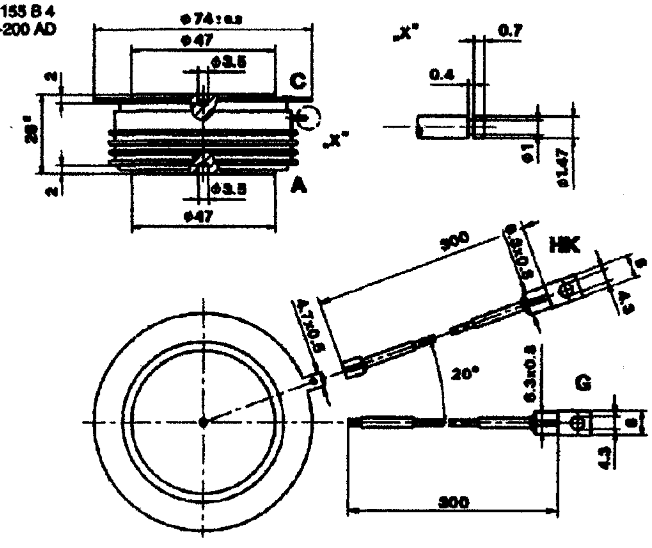
Thyristor	$V_{RSM,}$ V	V_{RRM} V_{DRM} V	dv/dt V/µs
SKT 1000/28 E L2	2900	2800	1000
SKT 1200/18 E	1900	1800	1000

SKT 1000
SKT 1200
Case B 14
DIN 41814: 155 B 4
JEDEC: TO-200 AD



[1] SKT 1000/. . . L 2: 27,5 mm

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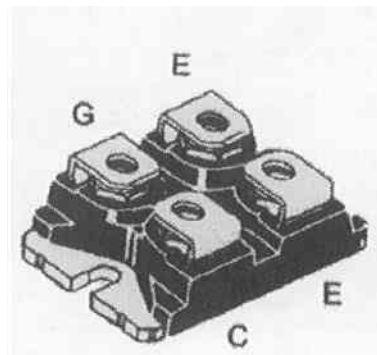
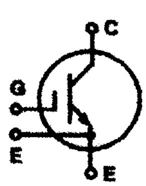
D.4 HIGH-VOLTAGE HIGH POWER TRANSISTORS

D.4.1 High Power and High Voltage IGBT Transistors IXDN 75N120A, IXDN 55N120AU1 (IXYS)



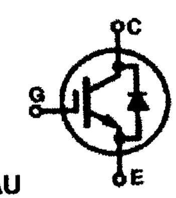
miniBLOC, SOT-227 B

Transistor Type / Parameter	V_{CES}, V	I_C (25°), A	I_C (90°), A	I_{CM}, 25°C, 1 ms, A	V_{CE}, V	P_C, W	V_{ISOL}, AC, 1 min, V
IXDN75N120A	1200	120	70	240	2.5	630	2500
IXDN55N120AU1	1200	85	52	170	2.5	450	2500



IXDN 75N120A

IXDN 55N120AU



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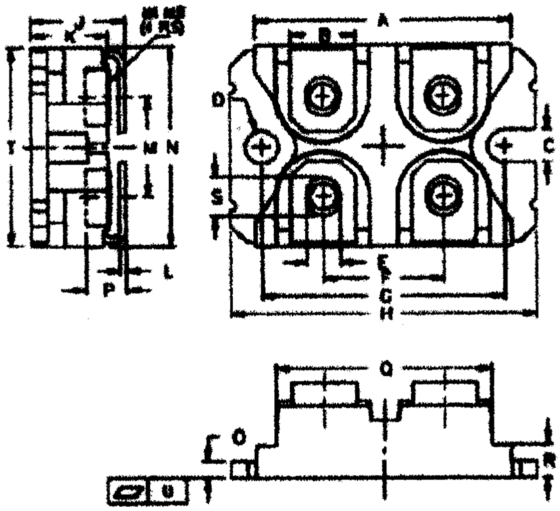
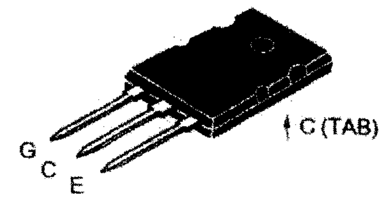
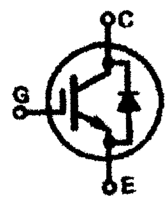


Dim.	Millimeter Min.	Millimeter Max.	Inches Min.	Inches Max.
A	31.5	31.7	1.241	1.249
B	7.8	8.2	0.307	0.323
C	4.0	-	0.158	-
D	4.1	4.3	0.162	0.169
E	4.1	4.3	0.162	0.169
F	14.9	15.1	0.587	0.595
G	30.1	30.3	1.186	1.193
H	38.0	38.2	1.497	1.505
J	11.8	12.2	0.465	0.481
K	8.9	9.7	0.351	0.382
L	0.75	0.85	0.030	0.033
M	12.6	12.8	0.496	0.504
N	25.2	25.4	·0.993	1.001
O	1.95	2.05	0.077	0.081
P	-	5.0	-	0.197

D.4.2 High Power and High Voltage IGBT Transistors

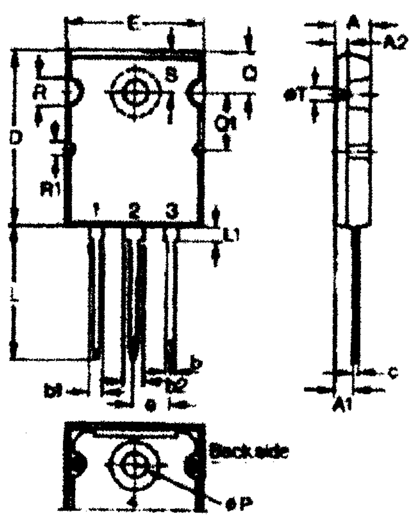
IXSK35N120AU1 (IXYS)





TO-264 AA

Transistor Type / Parameter	V_{CES}, V	I_C (25°) A	I_C (90°) A	I_{CM}, 25°C, 1 ms A	V_{CE}, V	P_C, W	V_{ISOL}, AC, 1 min V
IXSK35N120AU1	1200	70	35	140	4	300	-



Dim.	Millimeter Min.	Millimeter Max.	Inches Min.	Inches Max.
A	4.82	5.13	.190	.202
A1	2.54	2.89	.100	.114
A2	2.00	2.10	.079	.083
b	1.12	1.42	.044	.056
b1	2.39	2.69	.094	.106
b2	2.90	3.09	.114	.122
c	0.53	0.83	.021	.033
D	25.91	26.16	1.020	1.030
E	19.81	19.96	.780	.786
e	5.46 BSC		.215 BSC	
J	0.00	0.25	.000	.010
K	0.00	0.25	.000	.010
L	20.32	20.83	.800	.820
L1	2.29	2.59	.090	.102
P	3.17	3.66	.125	.144
Q	6.07	6.27	.239	.247
Q1	8.38	8.69	.330	.342
R	3.81	4.32	.150	.170
R1	1.78	2.29	.070	.090
S	6.04	6.30	.238	.248
T	1.57	1.83	.062	.072

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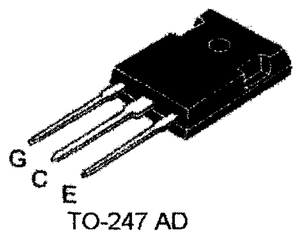
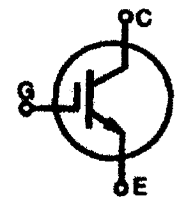
D.4.3 High Power and High Voltage IGBT Transistors

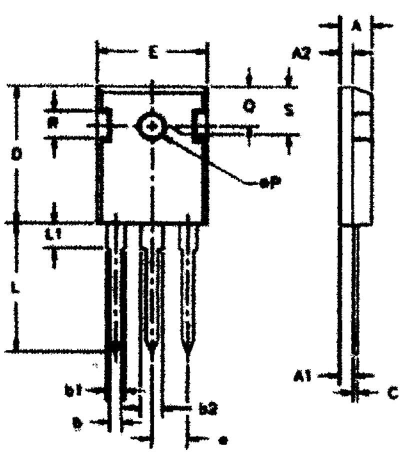
IXSH45N120

(IXYS)





Transistor Type / Parameter	V_{CES}, V	I_C (25°), A	I_C (90°), A	I_{CM}, 25°C, 1 ms, A	V_{CE}, V	P_C, W	V_{ISOL}, AC, 1 min, V
IXSH45N120	1200	75	45	180	3	300	-



Dim.	Millimeter Min.	Millimeter Max.	Inches Min.	Inches Max.
A	4.7	5.3	.185	.209
A_1	2.2	2.54	.087	.102
A_2	2.2	2.6	.059	.098
b	1.0	1.4	.040	.055
b_1	1.65	2.13	.065	.084
b_2	2.87	3.12	.113	.123
C	.4	.8	.016	.031
D	20.80	21.46	.819	.845
E	15.75	16.26	.610	.640
e	5.20	5.72	0.205	0.225
L	19.81	20.32	.780	.800
L1		4.50		.177
ØP	3.55	3.65	.140	.144
Q	5.89	6.40	0.232	0.262
R	4.32	.5.49	.170	.216
S	6.15 BSC		242 BSC	

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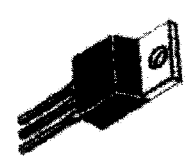
D.4.4 High Power High Voltage N-P-N Bipolar Transistors (Motorola)

Type	Package	U_{CEO}, V	U_{CES}, V	h_{FE}	$I_{C\,max}$, A	P_D, W	f_T, MHz
BUX85	TO220AB	450	1000	30	2	50	4
MJE18002	TO220AB	450	1000	14 - 34	2	40	12
MJE18204	TO220AB	550	1200	18 - 35	5	75	12
MJL16218	TO264	650	1500	4 - 11	15	170	2.5
MJF18002	TO220	400	1000	14 – 34	2	25	13
MJF18004	TO220	450	1000	14 - 34	5	40	13
MJF18006	TO220	450	1000	14 - 34	6	40	14
MJF18008	TO220	450	1000	16 - 34	8	45	13
BUX98	TO204AA	400	1000	8 min	30	250	-

Package Styles

TO204AA



TO220AB

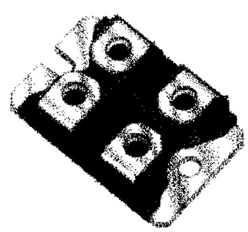
TO220 (Isolated)

TO264

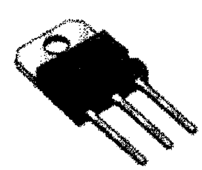
D.4.5 High Power High Voltage N-P-N Bipolar Transistors (STMicroelectronics)

Type	Package	U_{CEO}, V	U_{CES}, V	h_{FE}	I_C max, A	P_D, W	f_T, MHz
ESM6045AV	ISOTOP®	450	1000	150 (Darlington)	72	250	-
BUF460AV	ISOTOP®	450	1000	15	80	270	-
BUV48B	TO218	600	1200	-	15	125	-
BUX98C	TO3	700	1200	-	30	250	-
BU505	TO220	700	1500		2.5	75	-
THD277H1	ISOWATT® 218	700	1500	6 - 13	8	50	-
BU508A	TO218	700	1500	-	8	125	-
BU208A, D	TO3	700	1500	-	8	150	-
THD200F1 THD215H1	ISOWATT® 218	700	1500	6	10	57	-

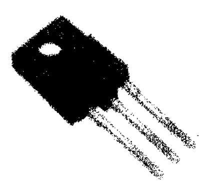
Package Styles



ISOTOP®



TO-218



ISOWATT-218

TO-220

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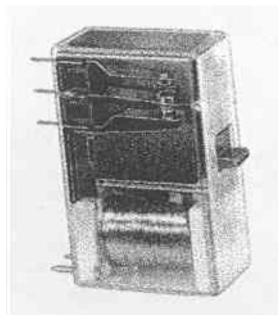
D.5 LOW-VOLTAGE ELECTROMAGNETIC RELAYS

D.5.1 Latching Relay Type 707 (Gruner AG)



Contact Arrangement	1 CO
Max. Switching Voltage, V AC	440
Max. Switching Current, A	20
Max. Switching Power, kVA	5
Test Voltage, kV (eff.): Open Contacts/ Contacts to Coil	1/4
Contact Material	AgCdO-AgNi
Mechanical Life, operations	10^6
Operating Voltage, V DC	6 – 48
Operating Power to Set, W	0.9
Pulse to Set, ms	20
Set by Manual Operation	available
Ambient Temperature, °C	-25 +70
Dimensions, mm	37.4 x 13.1 x 25.0
Weight, g	21

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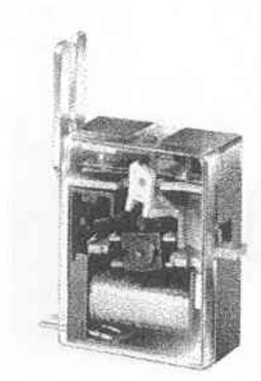
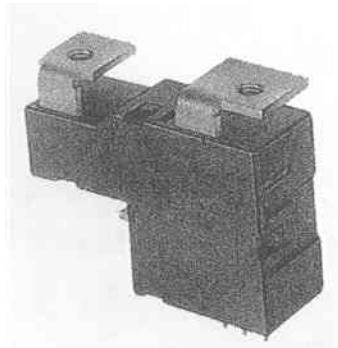
D.5.2 Latching Relay Type 704 (Gruner AG)



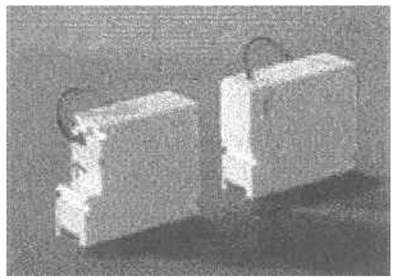
Contact Arrangement	1 NO
Max. Switching Voltage, V AC	440
Max. Switching Current, A	40
Max. Switching Power, kVA	10
Test Voltage, kV (eff.): Open Contacts / Contacts to Coil	1.5 / 4
Contact Material	$AgSnO_2$
Mechanical Life, operations	10^6
Operating Voltage, V DC	6 – 48
Operating Power to Set, W	2.0
Pulse to Set, ms	20
Set by Manual Operation	available
Ambient Temperature, °C	-25 +70
Dimensions, mm	39.0 x 15 x 29.3
Weight, g	36

D.5.3 Latching Relay Type 720 (Gruner AG)



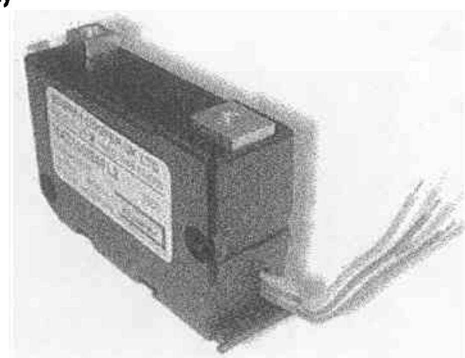
Contact Arrangement	1 NO
Max. Switching Voltage, V AC	440
Max. Switching Current, A	100
Max. Switching Power, kVA	25
Test Voltage, kV (eff.): Open Contacts / Contacts to Coil	2 / 4
Contact Material	$AgSnO_2$
Mechanical Life, operations	10^6
Operating Voltage, V DC	6 – 48
Operating Power to Set, W	3.0
Pulse to Set, ms	20
Set by Manual Operation	available
Ambient Temperature, °C	-25 +70
Dimensions, mm	60 x 22 x 40
Weight, g	75

D.5.4 Latched Micro Contactor MXW (Enbray Cooper Ltd)



Contact Arrangement	1 NO
Max. Switching Voltage, V AC	-
Max. Switching Current, A	100
Max. Switching Power, kVA	-
Test Voltage, kV (eff.): Across Open Contacts Contacts to Coil	 - -
Contact Material	-
Mechanical Life, operations	-
Operating Voltage, V DC	10 – 50; 70 - 250
Operating Power to Set, W	-
Pulse to Set, ms	10 - 250
Set by Manuel Operation	-
Ambient Temperature, °C	-
Dimensions, mm	47 x 39 x 16
Weight, g	-

D.5.5 Latched Micro Contactor MXT (Enbray Cooper Ltd)



Contact Arrangement	1 NO
Contact Rating, V AC	250
Max. Switching Current, A	100
Max. Switching Power, kVA	-
Test Voltage, kV (eff.): Across Open Contacts Contacts to Coil	 1 4
Contact Material	-
Mechanical Life, operations	10^6
Operating Voltage, V DC	5 - 24
Operating Power to Set, W	-
Pulse to Set, ms	60
Set by Manual Operation	available
Ambient Temperature, °C	-10 +90
Dimensions, mm	64 x 49 x 24
Weight, g	-

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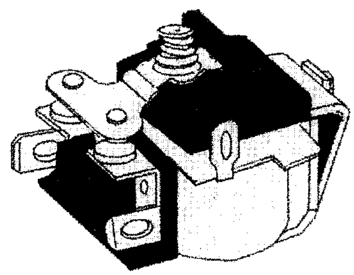
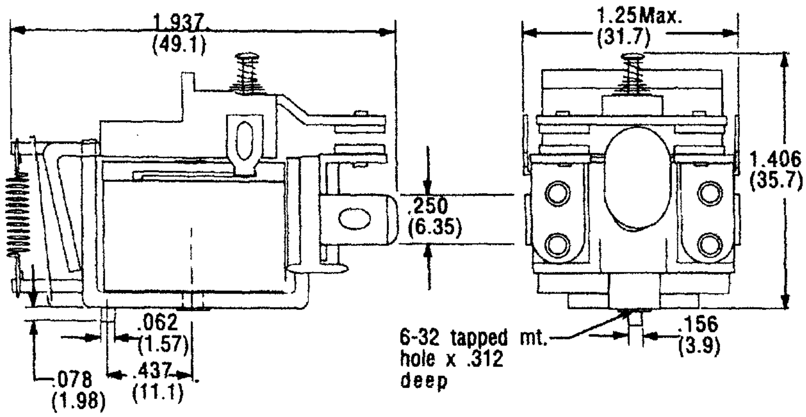
D.5.6 One Pole Power Miniature Electromagnetic Relay W88UKDX-2 (Magnecraft & Struthers Dunn)



Max. Switching Current, A AC (resistive load)	30
Max. Switching Voltage, V (rms)	600
Max. Switching Power, VA	-
Dielectric Strength, V (rms): - contact to coil - across open contacts - contact to frame	 3,000 1,000 3,000
Contact Material	¼'' Silver alloy, Gold flashed
Contact Resistance, mΩ	50
Operate Time, msec	25
Release Time, msec	20
Life Expectancy, operations - mechanical - electrical	 5×10^6 10^5
Operating Voltage, V DC	12
Temperature, °C	-10 +60
Vibration Resistance (functional)	5 g's 10 to 55 Hz
Shock Resistance (functional)	5 g's 11 ms



Mechanical specification of W88UKDX-2 relay

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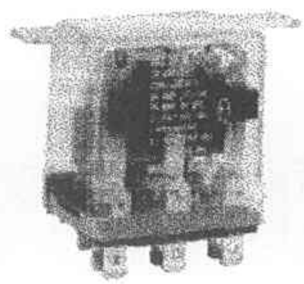
D.5.7 Three Pole Power Miniature Electromagnetic Relay
375TM 21014-81
(Deltrol Corp.)



Main parameters:

Max. Switching Current, A AC (resistive load)	30 (for 300 V AC) 15 (for 600 V AC
Max. Switching Voltage, V (rms)	600
Max. Switching Power, VA	7,200
Dielectric Strength, V (rms): - contact to coil - across open contacts - contact to frame	 3,750 2,200 3,750
Contact Material	¼'' Silver Cadmium Oxide
Contact Resistance, mΩ	-
Operate Time, msec	15
Release Time, msec	10
Life Expectancy, operations - mechanical - electrical	 10×10^6 10^5
Operating Voltage, V DC	12
Temperature, °C	-10 +50

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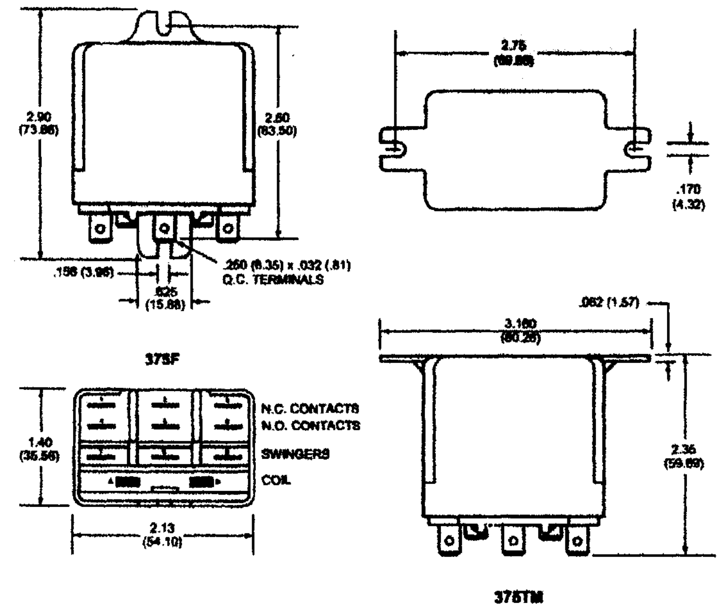

Mechanical specification of electromagnetic relay 375TM 21014-81

D.5.8 One Pole Power Miniature Electromagnetic Relay 275T 21004-81 (Deltrol Corp.)

Main parameters:

Max. Switching Current, A AC (resistive load)	35 (for 300 V AC) 15 (for 600 V AC)
Max. Switching Voltage, V (rms)	600
Max. Switching Power, VA	-
Dielectric Strength, V (rms): - contact to coil - across open contacts - contact to frame	 2,200 1,200 2,200
Contact Material	¼" Silver Cadmium Oxide
Contact Resistance, mΩ	-
Operate Time, msec	15
Release Time, msec	15
Life Expectancy, operations - mechanical - electrical	 10×10^6 10^5
Operating Voltage, V DC	12
Temperature, °C	-45 +80

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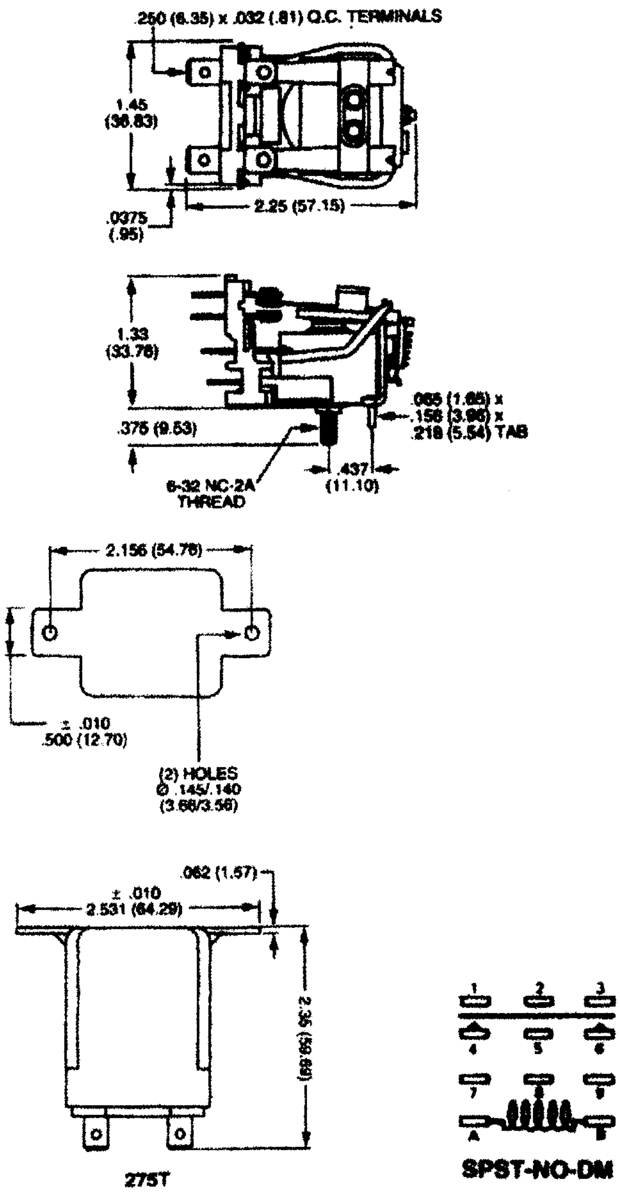

Mechanical specification and contact configuration of 275T 21004-82 relay

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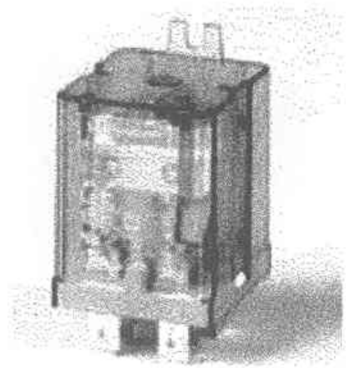
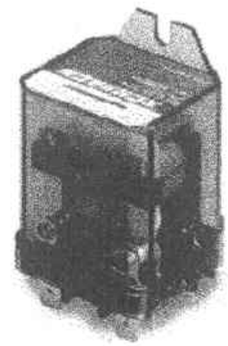
D.5.9 One Pole Power Miniature Electromagnetic Relay 65.31- 0300 (Finder)



Main parameters:

Max. Switching Current, peak, A AC (resistive load)	50
Max. Switching Voltage, V (rms)	400
Max. Switching Power, VA	7,500
Dielectric Strength, V (rms):	2,500
Contact Material	AgCdO
Contact Resistance, mΩ	-
Operate Time, msec	25
Life Expectancy, operations - mechanical - electrical	 10×10^6 50×10^3
Operating Voltage, V	6…110 DC, 6…240 AC
Temperature, °C	-40 +50

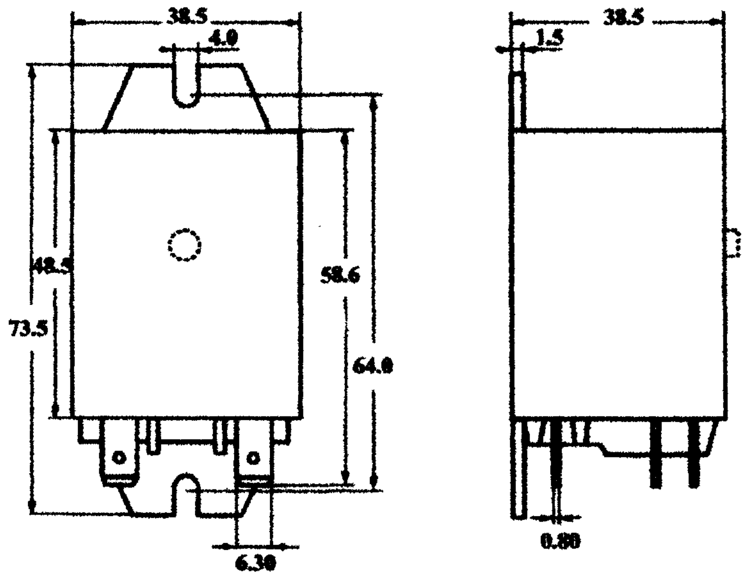
D.5.10 One Pole Power Relays RMC and RMD (Schrack)



Main parameters:

Contact Configuration	1NO + 1NC for **RMC** 1NO (bridging) for **RMD**
Rated Current, A Make Current, A	30 60
Max. Switching Voltage, V (rms)	440
Max. Switching Power, VA	7,500
Dielectric Strength, V (rms):	2,500 (coil to contacts) 1,500 (open contacts)
Contact Material	AgCdO
Operate/Release Time, msec	17/18
Life Expectancy, operations - mechanical - electrical	 10×10^6 50×10^3
Operating Voltage, V	6…220 DC, 6…400 AC
Temperature, °C	-40 +60

Cover with mounting brackets, FASTON 250



Mechanical specification of RMC and RMD relays

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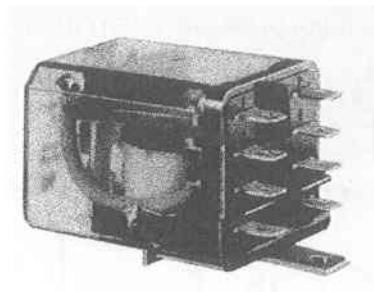
D.5.11 Single Pole Power Relay 188 Type (Midtex Relays, Inc)



Main parameters

Contact Configuration	1NO + 1NC
Rated Current, A	15
Max. Switching Voltage, V (rms)	480
Max. Switching Power, VA	-
Dielectric Strength, V (rms):	2,500 (coil to contacts) 750 (open contacts)
Contact Material	AgCdO
Operate/Release Time, msec	-
Life Expectancy, operations - mechanical - electrical	 10×10^6 10^5
Operating Voltage, V	5...110 DC, 6...240 AC
Temperature, °C	-45 +60

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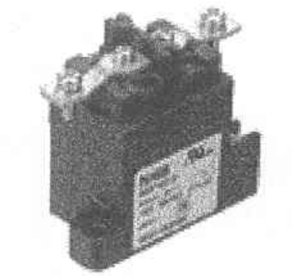
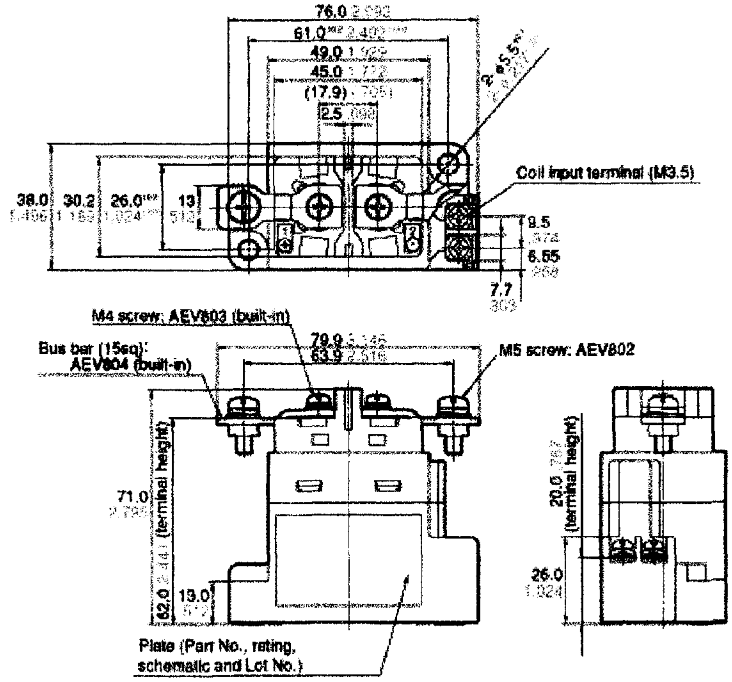
D.5.12 One Pole Power Electromagnetic Relay EP 60A (Matsushita Electric Works, Ltd)



Main parameters

Nominal Switching Current, A AC/DC Short term current, A for 15 min Max. cut-off current, A (300V DC, 5 cycles)	60 120 600
Max. Switching Voltage, V AC (rms) DC	 277 400
Max. Switching Power, VA	-
Dielectric Strength, V (rms): - contact to coil - across open contacts	 2,500 2,500
Contact Material	Gold-clad
Contact Resistance, mΩ	100
Operate Time, msec	50
Release Time, msec	30
Life Expectancy, operations - mechanical - electrical (60A, 400 V DC, L/R=1ms)	 2×10^5 3×10^3
Operating Voltage, V DC	12

Temperature, °C	-40 +80
Vibration Resistance (functional)	4.4 g's 10 to 200 Hz
Shock Resistance (functional)	Min. 196 m/s^2 20 g



Mechanical specification of EP 60A relay

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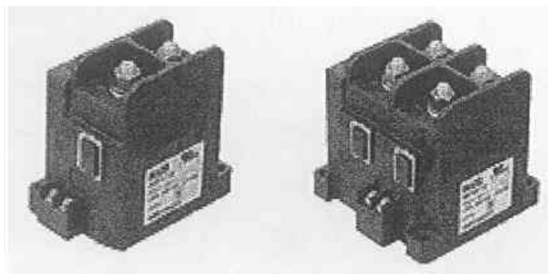
D.5.13 One & Two Poles Power Electromagnetic Relays EP 150 A and EP 150 A2 (Matsushita Electric Works, Ltd)



Main parameters:

Nominal Switching Current, A AC/DC Short term current, A for 10 min Max. cut-off current, A (300V DC, 3 cycles)	150 300 2,500
Max. Switching Voltage, V AC (rms) DC	 277 400
Max. Switching Power, VA	-
Dielectric Strength, V (rms): - contact to coil - across open contacts	 2,500 2,500
Contact Material	Gold-clad
Contact Resistance, mΩ	100
Operate Time, msec	50
Release Time, msec	30
Life Expectancy, operations - mechanical - electrical (150A, 400 V DC, L/R=1ms)	 10^5 3×10^3

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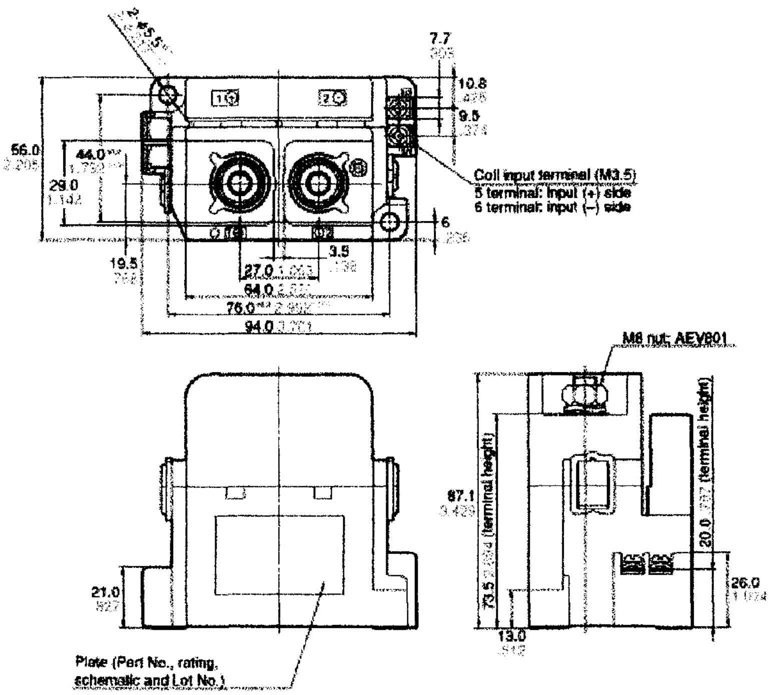
Operating Voltage, V DC	12
Temperature, °C	-40 +80
Vibration Resistance (functional)	4.4 g's 10 to 200 Hz
Shock Resistance (functional)	196 m/s^2 20 g



Mechanical specification EP 150 A type relay

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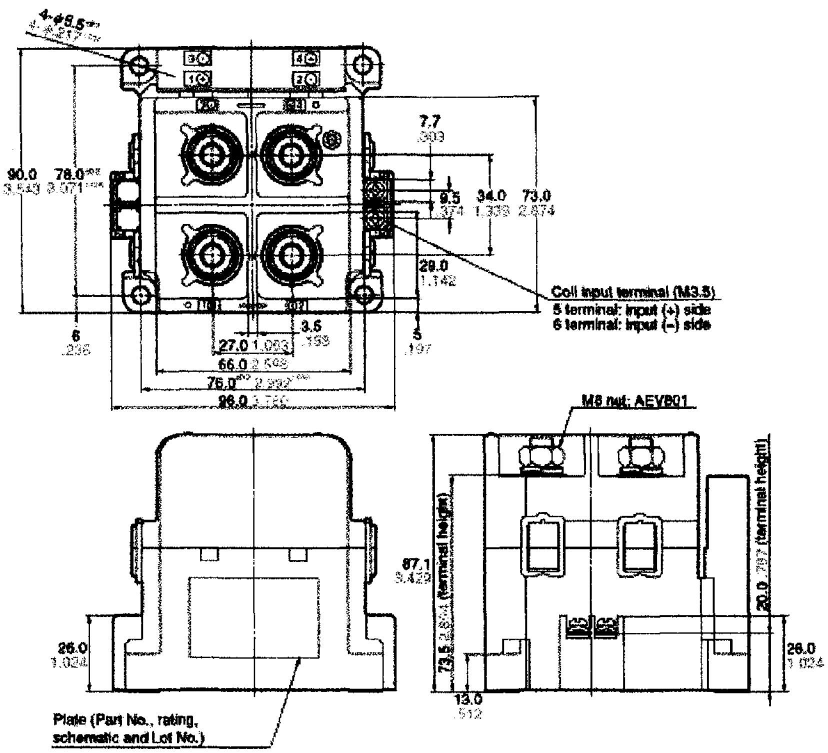

Mechanical specification EP 150 A2 type relay

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D.5.14 High Voltage Relays RL21 and RL42 series (SPS Electronic GmbH)

Max. Switching Current, A AC (resistive load) Max. Carry Current, A AC	10 30
Max. Switching Voltage, V (rms)	5,000
Max. Switching Power, VA	5,000
Dielectric Strength, V (rms):	8,000
Contact Material	AgCdO
Contact Arrangement RL21 RL42	 1 Changeover 2 Changeover
Contact Resistance, mΩ	-
Operate/Release Time, msec	30
Life Expectancy, operations - mechanical - electrical	 5×10^6 10^5
Operating Voltage/Current	24 V DC/ 0.2 A
Temperature, °C	-25 +40

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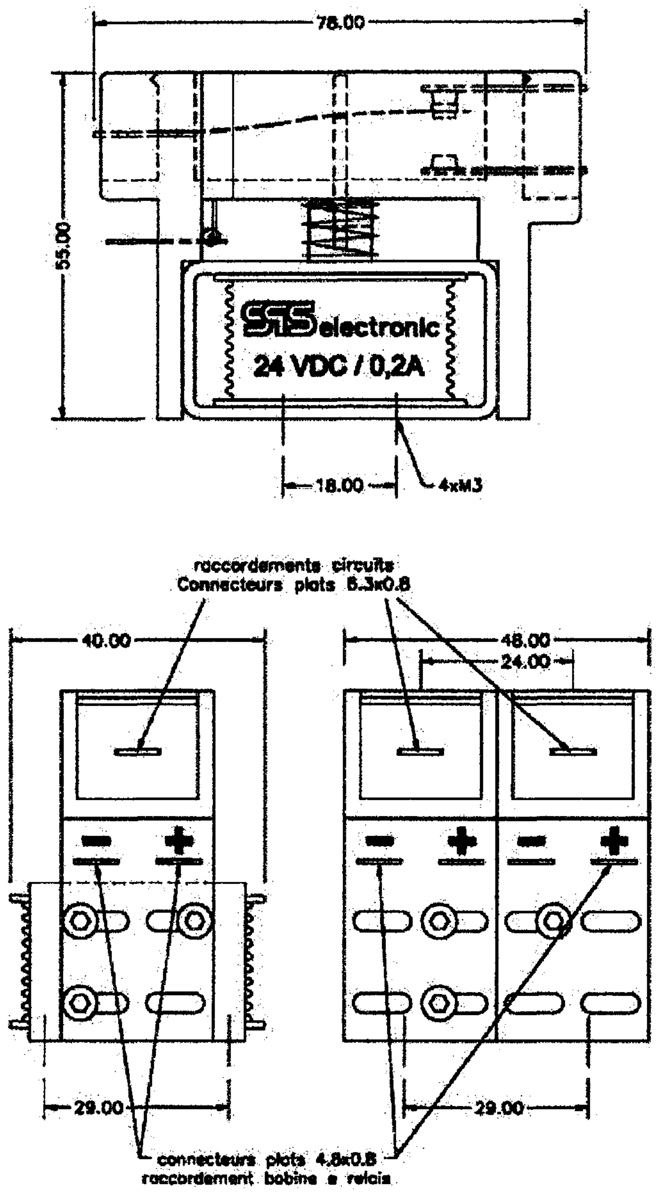

Mechanical specification RL21 and RL42 type relays

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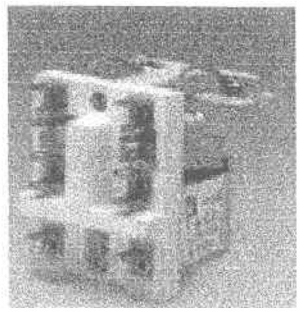
D.5.15 High Voltage Relay AT series (ITALIANA RELE)



Max. Switching Current, A AC (resistive load)	10
Max. Switching Voltage, V (rms)	5,000
Max. Switching Power, VA	5,000
Dielectric Strength, V (rms):	8,000
Contact Arrangement	1 or 2 Changeover
Contact Resistance, mΩ	-
Operate/Release Time, msec	40/20
Life Expectancy, operations - mechanical - electrical	 5 x 106 105
Vibration resistance Shock resistance	5 g (10-55 Hz) 5 g (11 ms)
Temperature, oC	-20 +50
Overall dimensions, mm	60 x 48 x 70
Weight (approx.), g	200

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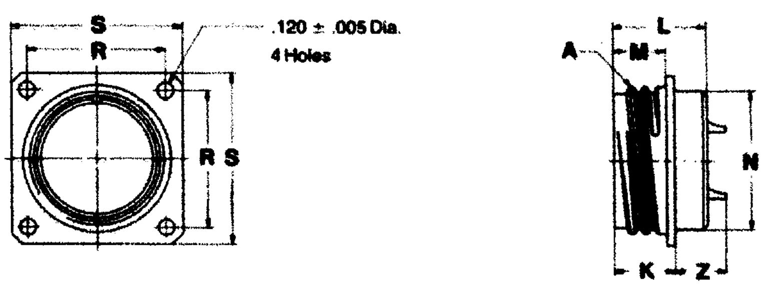
D.6 CONNECTORS

D.6.1 Miniature Cylindrical Connectors

PC02A-8-4-P-001 (Box mounting receptacle)
PC06W-8-4-S-001 (Straight Plug)
(Amphenol Corp.)

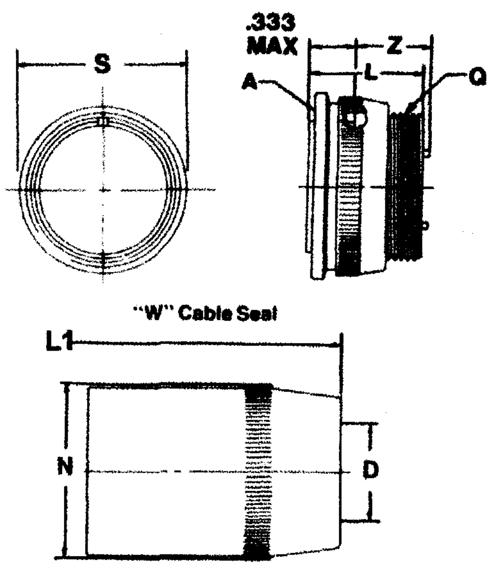
Main Parameters:

Contact Number	Current, A	Operating Voltage, V AC	Test Voltage, V AC	Maximal Voltage Drop, mV
4	7.5	600	1,500	55



Box mounting receptacle dimensions (inch)

S	R	L	M	K	Z
0.812	0.594	0.801	0.406	0.469	0.466



Straight plug dimensions (inch)

S	L	Z	L1	N	D
0.729	0.875	0.627	1.680	0.547	0.230

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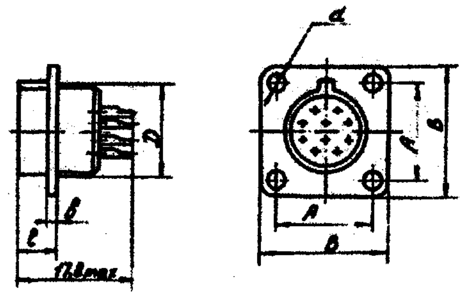
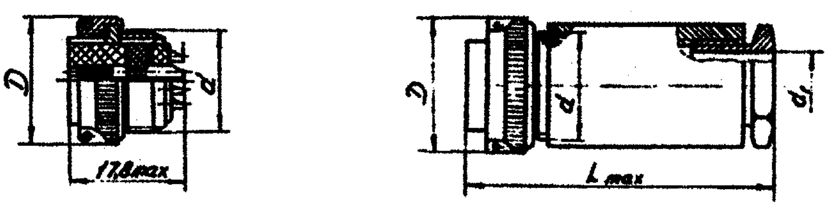
D.6.2 Miniature Cylindrical Connectors
PC4 TB (Mounting receptacle)
PC 4TB (Cable plug)
(Elecon, Russia)



Box mounting receptacle dimensions (mm)

l	b	D	d	A	B
5.9	1.4	M10	2.2	11.8	16.5



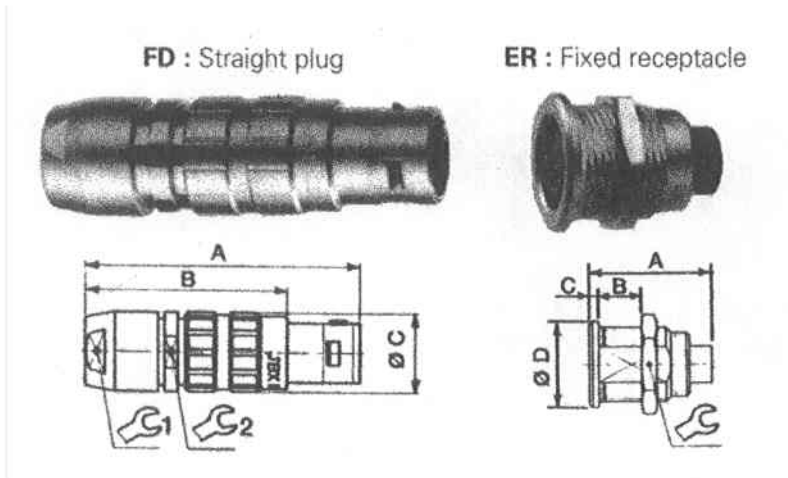
Straight plug dimensions (mm)

D	d	d1	L_{max}
14	M10	6	36

Main Parameters:

Contact Number	Current, A	Operating Voltage, V	Operating Temperature, °C	Contact Resistance, mΩ
4	3.7	200	-60 +85	5

D.6.3 Miniature Push-Pull Connectors JBXFD0G04FSSDDS (Straight Plug) JBXER0G04MSSDS (Fixed Receptacle) (Framatome Connectors Jupiter)



A = 39		A = 19
B = 29	All dimensions in mm	B = 8
C = 10		C = 1.2
		D = 10

Main Parameters:

Contact Number	Current, A	Operating Voltage, V	Operating Temperature, °C	Contact Resistance, mΩ
4	7	600 DC 460 AC (rms)	-40 +125	4

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D.7 HV CABLES AND CABLE ASSEMBLIES (REYNOLDS INDUSTRIES INC.)

Reynolds HV cables finds typical applications in radar, CRT displays, laser systems and a wide range of other HV applications.
All operating voltage ratings are applicable from sea-level to 70,000 feet and temperature −55 to 125°C.
Etched surface of cables intended for increase of adhesion to epoxy encapsulant

HV FEP Etched Cables

HV FEP Etched Cables with a "Nomex" Woven Jacket

Main parameters:

P/N	Conductor AWG No.	Cross Section, mm^2	Outer Diameter, mm	Max. Operat. Voltage, kV DC	Test Voltage, kV DC
178-8195 & 178-8361 (with Nomex jacket)	20	0.62	2.54	30	50

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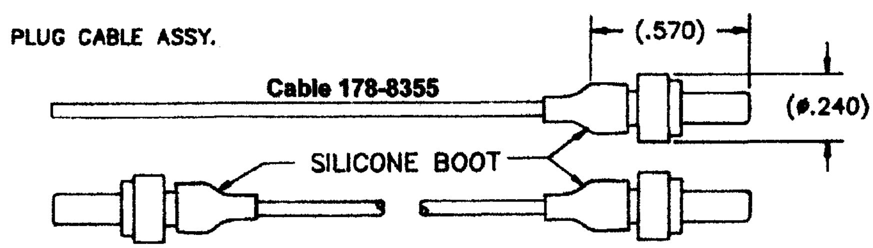
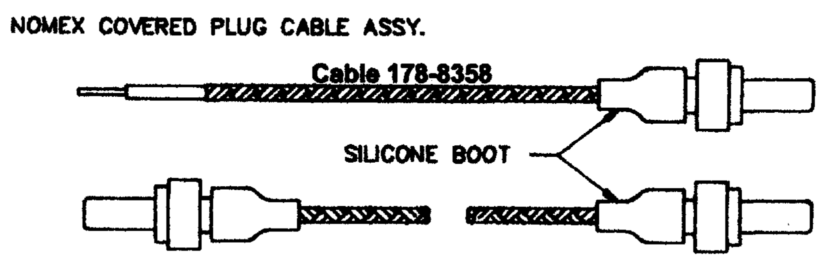
178-8355 & 178-8358 (with Nomex jacket)	24	0.24	1.27	18	36

Cable Assemblies

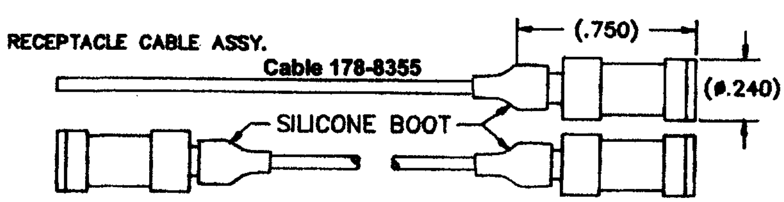




Cable Assemblies	P/N
Without Jacket	
Single Ended Cable Assy. with Cable 178-8355	178-8166
Double Ended Cable Assy. with Cable 178-8355	178-8169
Nomex Covered	
Single Ended Cable Assy. with Cable 178-8358	178-8174
Double Ended Cable Assy. with Cable 178-8358	178-8177

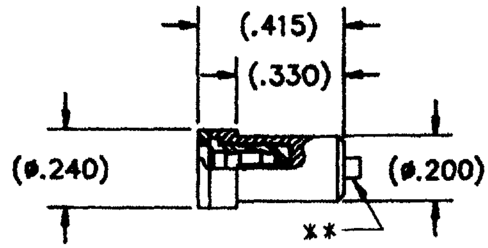
Receptacle Cable Assemblies

178-8110 (Single Ended)
178-8180 (Double Ended)



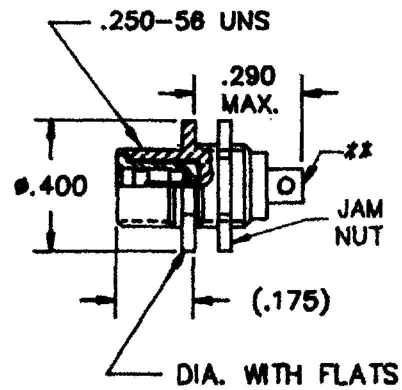
PANEL CONNECTOR (DAP)

P/N 178-7937

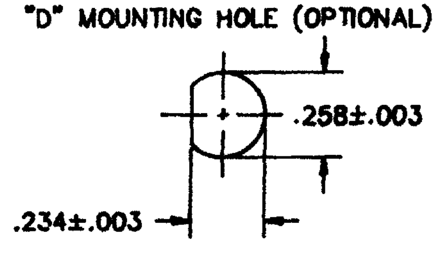


Recommend bonding into epoxy G-10 plate .080 or .120 inch thick.
Hole dia. .243 in.

THREAD COUPLING RECEPT.
PANEL MOUNT (ULTEM)
P/N 178-8370



"D" MOUNTING HOLE (OPTIONAL)



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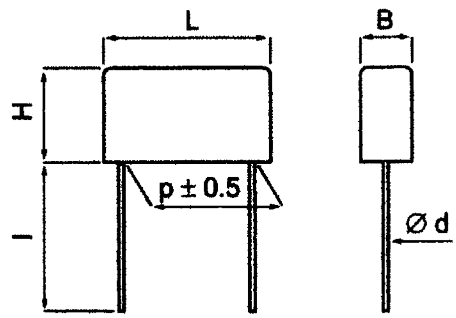
D.8 CAPACITORS DC/AC

D.8.1 Encapsulated Pulse Capacitors with Double Metallized Polyester Film as Electrodes and Polypropylene Dielectric PHE 428 type (EVOX RIFA)



Rated Voltage, VDC AC (Peak)	630 400	1,600 630	2,500 1000
Temperature Range, °C	-55 +105		
Rated Temperature, °C	85		
Dissipation Factor (tanδ), for 23 °C 1 kHz 10 kHz 100 kHz	 0.03% 0.04 – 0.06 % 0.15%		
Capacitance Range, μF	0.01 – 1.2	0.0027 – 0.33	0.001 – 0.15
Standard Capacitance Tolerance, %	5		
Standard	IEC 60384-17 Grade 1.1		

Dimensions

Voltage, V Capacitance, μF	Article Code	Dimensions, mm					
		B	H	L	I	p	d
630 VDC 400 VAC							
0.01	PHE428MB5100J	5.5	10.5	18.0		15.0	0.8
0.1	PHE428MD6100J	10.5	19.0	26.0	30.0	22.5	0.8
0.47	PHE428MR6470J	15.0	26.0	41.0		37.5	1.0
1.0	PHE428MR7100J	19.0	36.0	41.0		37.5	1.0
1,600 VDC 630 VAC							
0.01	PHE428RB5100J	8.5	16.0	18.0		15.0	0.8
0.047	PHE428RF5470J	10.5	20.5	31.5	30.0	27.5	0.8
0.1	PHE428RR6100J	13.0	24.0	41.0		37.5	1.0
0.33	PHE428RR6330J	21.0	38.0	41.0		37.5	1.0
2,500 VDC 1,000 VAC							
0.01	PHE428TD5100J	9.0	18.5	26.0		22.5	0.8
0.047	PHE428TR5470J	13.0	24.0	41.0	30.0	37.5	1.0
0.1	PHE428TR6100J	19.0	36.0	41.0		37.5	1.0
0.15	PHE428TR6150J	21.0	38.0	41.0		37.5	1.0

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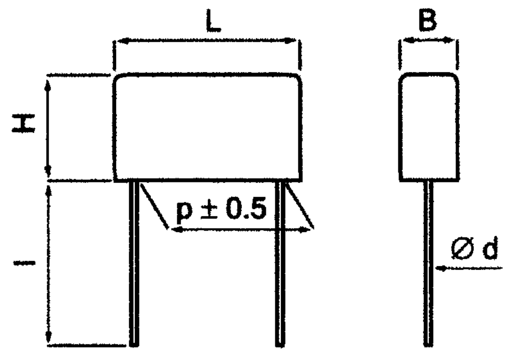
D.8.2 Metallized Polypropylene Winding Encapsulated Capacitors PHE 844 Type (EVOX RIFA)

For worldwide use as electromagnetic interference suppressor in X1 class and across-the-line applications.



Rated Voltage, VAC (Peak) 50 - 60 Hz	440
Temperature Range, °C	-40 +105
Rated Temperature, °C	85
Dissipation Factor (tanδ), for 23 °C 1 kHz 10 kHz 100 kHz	 0.1 % 0.1 – 0.5 % 0.6 – 0.9 %
Capacitance Range, μF	0.1 – 2.2
Standard Capacitance Tolerance, %	20
Maximal dU/dt, V/μs	100

Dimensions

Capacitance, μF	Article Code	Dimensions, mm					
		B	H	L	I	p	d
0.1	PHE844RD6100M	8.0	16.0	26.0	30	22.5	0.8
0.22	PHE844RD6220M	11.0	21.5	26.0		22.5	0.8
0.47	PHE844RD6470M	15.5	24.5	26.0		22.5	0.8
1.0	PHE844RF7100M	21.0	30.0	31.5		27.5	0.8
1.5	PHE844RR7150M	19.0	36.0	41.0		37.5	1.0
2.2	PHE844RR7220M	21.0	38.0	41.0		37.5	1.0

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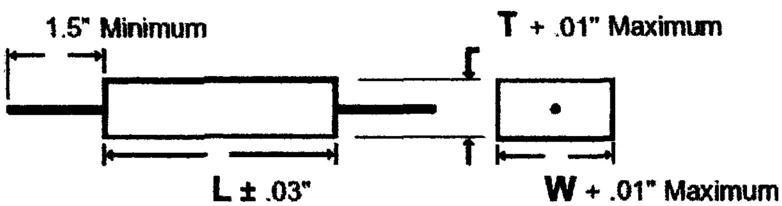
D.8.3 Paper/Mylar and Foil Epoxy Case, Rectangular Axial Lead High Voltage Capacitors AE3 type (American Capacitor Corp.)



Rated Voltage, V DC AC (Peak)	3,000 1,500	5,000 2,500	10,000 5,000	20,000 10,000	30,000 15,000
Temperature Range, °C	-55 to +125				
Rated Temperature, °C	-55 to +85				
Capacitance Range, μF	0.001-0.2	0.001-0.2	0.001-0.1	0.001-0.02	0.001-0.01
Standard Capacitance Tolerance, %	(last digit in Part Number) J ± 5%, K ± 10%, M ± 20%				
Standard	MIL-STD-202				

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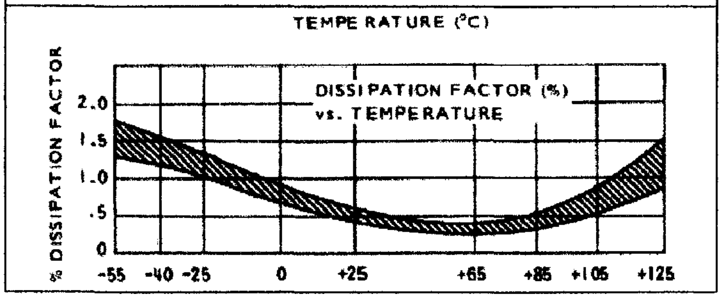
Dissipation Factor - tanδ (Test Frequency: 1000 Hz, Temperature: +25°C)



Dimensions:

Voltage, Capacitance, μF	Dimensions, inch			Part #
	T	W	L	
3,000 VDC 1,500 VAC				
0.01	0.45	0.68	1.40	AE3FX103K
0.05	0.76	0.96	2.40	AE3FX503K
0.1	0.86	1.06	3.40	AE3FX104K
0.2	0.95	1.15	4.40	AE3FX204K
5,000 VDC 2,500 VAC				
0.01	0.76	0.96	1.60	AE3HX103K
0.05	1.06	1.33	2.40	AE3HX503K
0.1	1.06	1.33	3.40	AE3HX104K
0.2	1.06	1.53	4.40	AE3HX204K
10,000 VDC 5,000 VC				
0.01	1.06	1.33	2.60	AE3MX103K
0.02	1.06	1.33	3.60	AE3MX203K
0.05	1.33	1.53	4.60	AE3MX503K
0.1	1.94	2.12	4.60	AE3MX104K
20,000 VDC 10,000 VAC				
0.005	1.33	1.53	4.75	AE3EY502K
0.01	1.65	1.87	4.75	AE3EY103K
0.02	2.12	2.31	4.75	AE3EY203K

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Appendix E: Insulation Materials for Production of RG-relays

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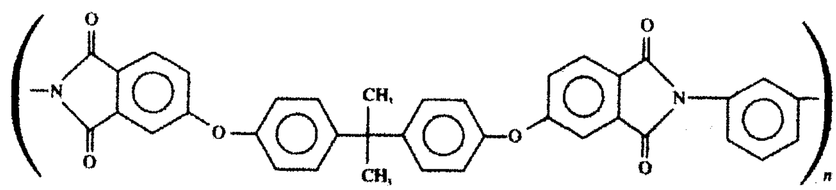
E.1 HIGH TEMPERATURE ENGINEERING THERMOPLASTIC MATERIAL ULTEM-1000

(GE PLASTICS, BOEDEKER PLASTICS INC, ERTA EPS, POLYPENCO)

In 1982 General Electric introduced ULTEM, a polyetherimide (PEI) with the following structure:



They exhibit the following key characteristics:

- Very high tensile strength without using reinforcement
- A glass transition temperature of 215°C, a deflection temperature of 200°C and a Vicat softening point of 219°C
- A high UL Temperature Index of 170°C (for mechanical with impact)
- Flame resistance (LOI of 47 and UL94 V-0 rating at 0.41 mm thickness)
- Very low smoke emission
- Excellent hydrolytic stability
- Excellent electrical properties
- UV and gamma radiation resistant

The polyetherimides are competitive not only with other high-performance polymers such as the polysulphones and polyketones but also with polyphenylene sulphides, polyarylates, polyamide-imides and polycarbonates.

Typical application for ULTEM resins include:

- electrical/electronic applications;
- aircraft/aerospace interiors;

- high temperature lighting;
- medical instruments trays;
- high voltage applications

Typical Properties of ULTEM-1000:

MECHANICAL PROPERTIES	
Tensile Strength	15,200 - 16,500 psi (105 Mpa)
Tensile Elongation at Break, %	60 - 80
Flexural Strength	20,000 – 22,000 psi (152 Mpa)
Flexural Modulus	480,000 – 500,000 psi (3,310 Mpa)
Compression Strength	21,900 - 22,000 psi (152 Mpa)
Compression Modulus	480,000 psi (3,310 Mpa)
Hardness, Rockwell	M112/R125
IZOD Notched Impact	0.5 ft-lb/in
THERMAL PROPERTIES	
Coefficient of Linear Thermal Expansion	3.1 x 10-5 in/in/°F 5.6 x 10-5 m/m/°C
Thermal Conductivity	0.22 W/m-°C
Maximal Operating Temperature	171°C
PHYSICAL PROPERTIES	
Density	1.28 g/cm3
Water Absorption (24 hours, 23 oC)	0.25 %

ELECTRICAL PROPERTIES	
Dielectric Strength, short time, 1.6 mm thick in air in oil	 33 kV/mm 28 kV/mm
Dielectric Constant (100 Hz – 1 MHz)	3.15
Dissipation Factor 1 kHz – 1 MHz 2450 MHz	 0.0012 0.0025
Volume Resistivity at 50 % RH	6.7×10^{17} Ω-cm

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E. 2 EPOXY ENCAPSULANT STYCAST 2651-40

(Emerson & Cumming)

STYCAST 2651-40 is a two component, low viscosity epoxy encapsulant with excellent adhesion to metals, plastics and ceramics. It can be cured at room or elevated temperature.

Its viscosity at room temperature is approximately 30 Pa.s prior to the addition of a catalyst. Viscosity will greatly decrease by the addition catalyst and elevation of the temperature to 40°C.

Only CATALYST-11 must be used for a combination of ULTEM elements and an elevation of temperature!

When cured at an elevated temperature with CATALYST-11, STYCAST 2651-40 meets MIL-1-16923 Standard for types B, C, D.

It is stable over a temperature range of –75 to +175 °C.

Standard color is black.

Main Properties (after curing by CATALYST-11):

Hardness (Shore D), minimum	85
Compressive Strength, minimum, MPa	100
Elastic Modulus, Compressive, MPa	5,400
Impact Strength, J/cm	1.6
Thermal Conductivity, W/m-K	0.5
Coefficient of Linear Thermal Expansion, $10^{-6}K^{-1}$	45
Linear Shrinkage During Cure, %	0.2 – 0.4
Volume Resistivity, Ohm.cm, minimum	10^{13}
Dielectric Constant	
60 Hz	4.7
1 kHz	4.5
1MHz	3.8
Dissipation Factor (60 Hz – 1 MHz)	0.02
Dielectric Strength, kV/mm	17.7
Moisture Absorption, maximum, for 24 hours, %	0.1

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Appendix F: Engineering Equations for Calculations of Magnetic Conductivity in Magnetic Circuits and Electrical Fields for Some Forms of Electrodes

(can be used for development RG-relays)

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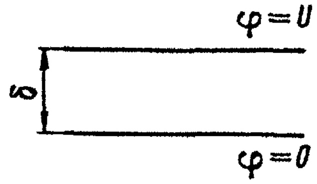
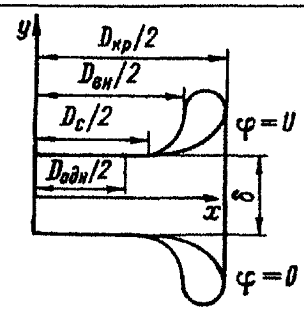
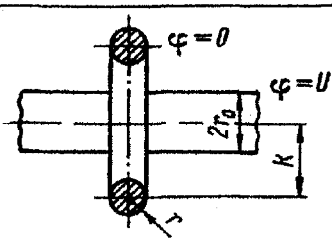
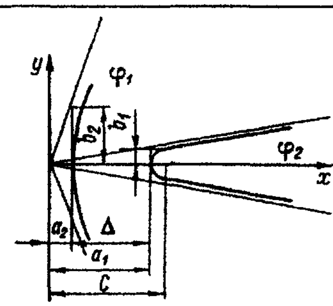
F1 ELECTRICAL FIELDS FOR SOME FORMS OF ELECTRODES

	U/δ
	$\dfrac{E_{cp}}{\sqrt{1+e^{2\varphi}+2e^{\varphi}\cos\Psi}}$ $e^{\varphi}=-\cos\Psi$, φ & Ψ — Polar Coordinates
	$R \gg r_0, R \gg r$ $\dfrac{2U}{r_0 \ln \dfrac{R^3}{2rr_0}}$
	$\dfrac{Uc}{a_1 b_1 \left(\mathrm{Arch}\,\dfrac{c}{a_2} - \mathrm{Arch}\,\dfrac{c}{a_1}\right)}$

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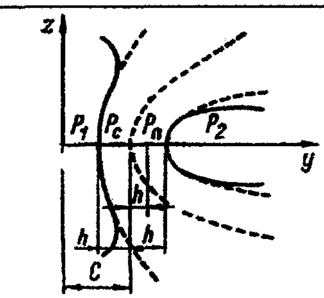
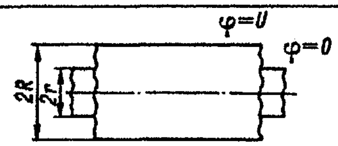
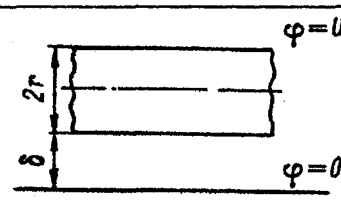
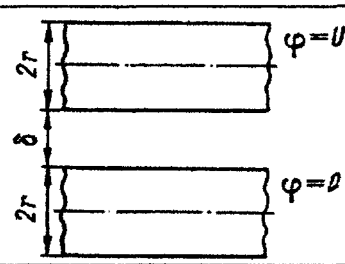
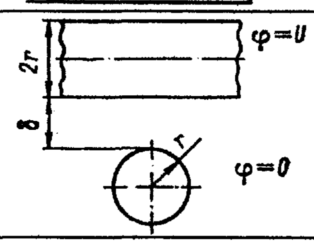
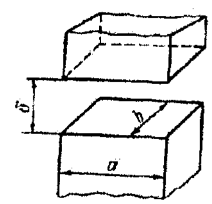
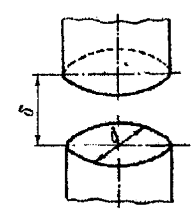
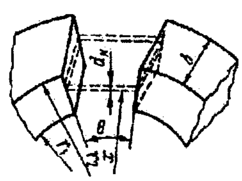
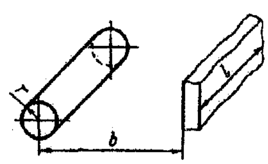
	$\frac{U\,(R+r)}{2rR\ln\left(\frac{R}{r}\right)}$; $R=c+h;\quad r=c-h$
	$\frac{U}{r\ln\frac{R}{r}}$
	$\frac{0{,}9U}{r\ln\frac{r+\delta}{r}}$
	$\frac{0{,}45U}{r\ln\frac{r+0{,}5\delta}{r}}$
	$\frac{0{,}45U}{r\ln\frac{0{,}5r\delta}{r}}$

F.2 MAGNETIC CONDUCTIVITY OF MAGNETIC CIRCUITS

Geometrical Form	Magnetic Conductivity
	$\Lambda = \mu_0 \dfrac{ab}{\delta}$
	$\Lambda = \mu_0 \dfrac{\pi d^2}{4\delta}$
	$\Lambda = \mu_0 \dfrac{b}{\theta} \ln \dfrac{r_2}{r_1}$, θ — in radian
	$\Lambda = \mu_0 \dfrac{2\pi l}{\ln l + \sqrt{b^2 - r^2}}$; $\Lambda = \mu_0 \dfrac{\pi l}{\ln \dfrac{2b}{r}}$, $b > 4r$

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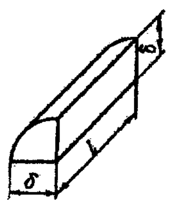
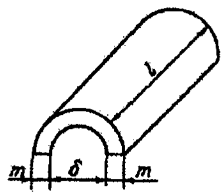
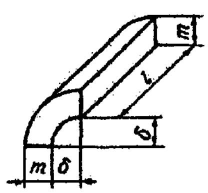
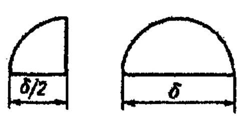
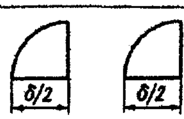
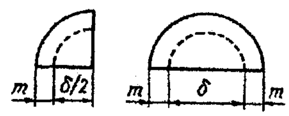
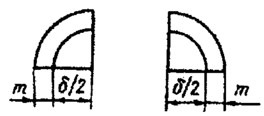
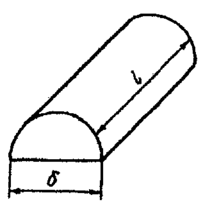
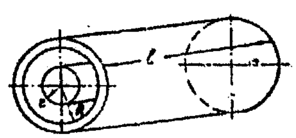
	$\Lambda = \mu_0 0{,}52l$
	$\Lambda = \mu_0 \dfrac{2l}{\pi(\delta/m + 1)}$, $\delta < 3m$; $\Lambda = \mu_0 \dfrac{l}{\pi} \ln\left(1 + \dfrac{2m}{\delta}\right)$
	$\Lambda = \mu_0 \dfrac{2l}{\pi(\delta/m + 0{,}5)}$, $\delta < 3m$; $\Lambda = \mu_0 \dfrac{2l}{\pi} \ln\left(1 + \dfrac{m}{\delta}\right)$
	$\Lambda = \mu_0 0{,}077\delta$
	$\Lambda = \mu_0 0{,}308\delta$

	$\Lambda = \mu_0 \dfrac{m}{4}$
	$\Lambda = \mu_0 \dfrac{m}{2}$
	$\Lambda = \mu_0 0{,}26l$
	$\Lambda = \mu_0 \dfrac{2\pi l}{\ln R/r}$ If $r > \delta$, $\delta = R - r$, $\Lambda = \mu_0 \dfrac{2\pi (r + \delta/2)\, l}{\delta}$

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