7.8.8.1 **Control of Thyristors on Direct Current**

As has been mentioned above, the thyristor in the initial position is blocked in both current directions and for correct (nonemergent) unblocking, it is necessary to create certain conditions for current and voltage:

- Forward voltage not exceeding forward breakover voltage should be applied to the thyristor (Figure 7.81)
- In the “Gate–Cathode” circuit there should be current of positive direction enough for thyristor unblocking both by value (0.05 to 0.2 A for power thyristors) and by duration (tens and hundreds of microseconds)

Under such conditions, the thyristor will be switched ON and current will flow through its main “anode–cathode” junction. The control junction (gate-cathode) will be shunted by forward current, and further operation of the thyristor will not depend on current in the gate circuit. The thyristor state after it has been enabled will be fully determined by the forward current value in the “anode–cathode” circuit which is by load resistance. If this current exceeds the hold current ($I_{HOLD}$ in Figure 7.81), the thyristor will be conductive. If it is less than the hold current, the thyristor will be immediately switched OFF.

In the scheme shown in Figure 7.90a, the thyristor VS1 is switched ON at the moment when the resistance $R_1$ decreases to a value sufficient for the gate current in the circuit, corresponding to the unblocking control current of the given thyristor. When the thyristor is enabled, the resistance $R_1$ is shunted by low resistance of the main opened junction (anode–cathode) and does not affect the state of the thyristor.

In the circuit shown in Figure 7.90b, current in the gate circuit arises only at the moment of closing of the control contact ($S_1$). The resistor $R_2$ is almost always used in such circuits to prevent the pulse noise from getting to the gate circuit, and spontaneous thyristor opening. In the circuit shown in Figure 7.90c, the control junction of the thyristor (gate-cathode) is constantly shunted by the contact ($S_1$). When the contact opens, current of the resistor $R_1$ changes its direction, passing to the circuit of the gate and opening the thyristor.

And how can an opened thyristor be switched OFF? It is not that easy to do on direct current (Figure 7.91). Methods applied in practice usually come to break circuits of anode current (a); shunting of the thyristor with an additional contact (b) or a transistor (c); reduction of anode current to a value less than the hold current (d); use of the charged capacitor $C$, which is connected parallel to the thyristor, at the moment when the thyristor
must be switched OFF and runs down on it, creating current of the opposite polarity blocking the thyristor (e). All of these methods of forced closing of thyristors are called "forced commutation" (in contrast to "natural" commutation on AC). The method of closing of thyristors with the help of capacitors, like similar methods used for switching OFF of thytratrones (Figure 7.22) was the most popular. In the circuit in Figure 7.91e the resistance of the resistor $R_1$ is much less than the load resistance $R_L$, which is why at the first moment after thyristor switching ON its node, the current passes not through the load but through the resistor $R_1$ charging the capacitor C. After that, the current ceases passing through the capacitor, which is why the anode current of the thyristor passes to the parallel branch with the load $R_L$. When the contact $S_1$ is closed (an additional thyristor $VS_2$ can be used instead of it, see Figure 7.92), the voltage of the charged capacitor is applied to the thyristor with the opposite polarity ("plus" to the cathode, "minus" to the anode), causing blocking of the thyristor.

Pulse circuits of thyristor control, with a transformer in the gate circuit, were very popular due to the fact that such small transformers allowed application of control pulses to the gate circuit of the power thyristor, which is under the full potential of the power source (which can be hundreds and even thousands of volts), directly from low voltage

![Figure 7.91](image)

**FIGURE 7.91**
Principles of switching OFF of thyristors on direct current.

![Figure 7.92](image)

**FIGURE 7.92**
Pulse control circuit providing "forced commutation" of the main thyristor ($VS_1$) on direct current.
microelectronic control devices, and also to control a group of thyristors connected in series and designed for work under high voltages (Figure 7.93).

Sometimes it is necessary to connect thyristors in parallel in order to increase switched current. Like in the case of the series connection, one has to balance the work conditions of all the thyristors connected to the group because of the natural parameters of dispersion of the thyristors, but instead of balancing of voltage it is essential to balance currents passing through thyristors connected parallel, which is much more difficult. In such cases, more ponderous and expensive inductive reactors must be applied (Figure 7.94).

### 7.8.8.2 Control of Thyristors on Alternating Current

In AC circuits, the thyristor can be used without a forced cut-off, because every half-period the sinusoidal current passes through the zero value and at that moment conditions for thyristor cut-off are created, however, for switching of both half-waves of current, two inverse-parallel connected thyristors (Figure 7.95a), or a thyristor connected to the diagonal of the rectifier bridge (Figure 7.95b), are required.

![Figure 7.93](image1)

**FIGURE 7.93**
Series connection of thyristors with pulse control. $R_{sh}$ — shunting resistors equalizing voltage distribution between thyristors connected in series; $R_1C_1$ and $R_2C_2$ — circuits protecting thyristors from spikes during switching processes.

![Figure 7.94](image2)

**FIGURE 7.94**
Parallel connection of thyristors with balancing reactors.

![Figure 7.95](image3)

**FIGURE 7.95**
Thyristor AC switches.
In circuits of AC switches controlled by an additional contact, (Figure 7.95a — and this can be a reed switch) in the closed position of the contact in the gate circuit of thyristors, quite short control pulses are automatically formed from the anode voltage (Figure 7.96). In order to switch three-phase loads, a three-phase switch constructed on the same principle is used (Figure 7.97). Why is forced commutation of thyristors (Figure 7.98) needed if they are cut off while crossing the zero value of the current sine?

**FIGURE 7.96**
Oscillogram of pulses of the gate current automatically formed in the gate circuit of a thyristor AC switch (Figure 9.95a).

**FIGURE 7.97**
Three-phase thyristor switch based on inverse-parallel connected thyristors.

**FIGURE 7.98**
Three-phase contactor with forced commutation. 1—3 — Main groups of thyristors switching the load; 4—7 — additional groups of thyristors controlling capacitors C1 and C2.
Forced commutation is used on alternating current when one needs to speed up the cut-off of thyristors without waiting for current to cross the zero value. Such necessity arises in high-speed switching devices. The principle of accelerated switching by a thyristor on alternating current is similar to that on direct current; the use of previously charged capacitors connected to the thyristor by the opposite polarity; some solutions concerning circuits may differ, though (Figure 7.98).

### 7.8.8.3 Diac, Triac, Quadrac

As in the case with transistors, there are several types of thyristors differing by their properties and characteristics. First of all, this is the so-called symmetrical thyristor — “triac” (the last two letters stand for “alternating current”). The symmetrical thyristor as it follows from its name has a symmetrical VAC (Figure 7.99), that is, when there is a control signal, it applies current in both directions and can replace two standard thyristors connected inverse-parallel (Figure 7.100). It is obvious that a triac has a more complex structure than a standard thyristor. It is no longer a four-layer device, like a thyristor. It is five-layer device, with a thyristor only as a part of a more complex structure.

In theory, the triac can be enabled at any combination of voltage polarities on main electrodes and on the gate. That is why it is quite senseless to indicate the main electrodes as an “anode” and a “cathode” and they are marked simply as M1 and M2. But it is correct for so-called “four-quadrant” (or 4Q) triac only.

![Figure 7.99](image1)

**Figure 7.99**

VAC of a symmetrical thyristor “triac” (thyristor for alternating current). FB — forward branch; RB — reverse branch; Ic — gate current.

![Figure 7.100](image2)

**Figure 7.100**

Triac structure, symbolic notation and thyristor equivalent.
Such triac can be triggered in all four quadrants, Fig. 7.101. Three-quadrant triacs (3Q triac) allow triggering in quadrants I, II and III only. 3Q triacs are more efficient in applications that have non-resistive loads, such as motor control applications, transformer loads, ignition circuits, etc.

For these types of applications 4Q triacs must include additional protection components to minimize the effects of false triggering (uncontrolled triac conduction). These include RC snubbers across the main terminals of the triac and an inductor in series with the triac. 3Q triacs have eliminated or reduced the need for protection components, making system design for non-resistive loads more reliable, cheaper, and smaller. At more prevalent and more reliable 3Q triac VAC does not look as nice as in Fig. 7.99, and the symmetrical thyristor is not in fact all that symmetrical: the turn-on gate current with certain (reverse) voltage polarity on the main electrodes, appears to be 3–5 times as much as with other (forward) polarity. Of course one can construct a control system capable of generating more powerful control pulses compensating for this difference in sensitivity.

As it can be seen, rejection of the names of the main electrodes “anode” and “cathode” is not quite defensible, since despite triac “symmetry” it is essential to designate from which electrode the control signal will be applied to the gate.

Like a standard thyristor, a triac can be controlled in different ways in real constructions of switching devices (Figure 7.102). It should be taken into account that physically the triac does not comprise two thyristors connected in parallel, as it is shown in Figure 7.100. It only functions as two inverse-parallel connected thyristors on alternating

**FIGURE 7.101**
Preferred combinations of polarities of the signal of control and voltage on the main outlets for triac.
current. (Note: Alternating current; a triac is not designed for work on DC and unlike a pair of inverse-parallel connected thyristors, does not operate very stably on DC.)

Besides a triac there are some other variants of thyristors, like a dinistor, for instance (Figure 7.103a), which in fact is a standard thyristor without a gate outlet, being enabled when the voltage applied to it (between the anode and the cathode) is increased to the level of forward breakover voltage (Figure 7.81). Such devices are produced in Russia, but are not well known in the West. More popular are devices controlled by voltage without a gate based on triacs, not thyristors. They are called a “diac” (Figure 7.103b). Some firms produce semiconductor devices with a triac and a diac combined in its structure (Figure 7.103c). Such devices are called a “quadrac.”

The so-called “gate turn-off thyristors” (“GTO-thyristors,”) are of special interest. As one can conclude from its name these are thyristors which can be not only turned ON but also turned OFF by a signal received on the gate (Figure 7.104). You probably remember how the control circuit should be complicated in order to disable the thyristor at the required moment. The GTO-thyristor allows simplification of the solution to the problem (Figure 7.105).

The GTO-thyristor is enabled like a standard thyristor, only it requires a longer gate current pulse for reliable enabling, and has a quite high hold-on current ($I_{HOLD}$), that is it requires a higher value of direct anode current in order to remain in the open state after completion of the gate current pulse. The thyristor is disabled by the pulse of current in the gate of the opposite polarity, with greater amplitude than the pulse of enabling current has (which can reach one fifth up to one third of anode current!). That’s why circuits of the GTO-thyristor usually contain storage reactive elements (capacitors,}

![Figure 7.102](image1)

**FIGURE 7.102**
Some methods of triac control and its connection to a three-phase circuit.

![Figure 7.103](image2)

**FIGURE 7.103**
Different types of thyristors: dinistor (a), diac (b), quadrac (c).
chocks), creating strong current pulses needed for thyristor closing. For example, in the circuit on the left (Figure 7.105), the thyristor is enabled by the pulse of a charge of the capacitor ($C$) through the resistor ($R_1$) when control voltage ($U_{\text{contr}}$) is applied, and is disabled by the current of a discharge of this capacitor through the resistor $R_2$ when the control contact is closed.

In very high power applications, which require operating at high voltage, high current, and high temperatures, the use of silicon (Si) devices is restricted. Silicon carbide (SiC) has superior physical properties like a wider band gap, higher thermal conductivity, higher breakdown voltage, and higher temperature handling capability, which make it potential material to overcome the limitations of Si. For the last few years various SiC devices have been developed to be used in power applications, including SiC GTO thyristors for voltages above 6 kV and an operating temperature of 250°C.

In the last few years, many new super-powerful semiconductor switching devices have appeared in the market, so many new names and abbreviations, that even for the expert it is difficult to understand all of them. Here for example, are only some of the new thyristor types:

- MCT (MOS-Controlled Thyristor), Figure 7.106a
- FCTh (Field-Controlled Thyristor)
- SITh (Static Induction Thyristor)
Within the framework of our book we cannot consider in detail all of the newest types of power electronic switches, but two recent ones should be mentioned nevertheless.

ABB semiconductors recently developed a new type of power switch with an architecture combining the best features of an IGBT and a GTO thyristor. Called the Integrated Gate Commutated Thyristor (IGCT), the new solid-state switch is for high-voltage applications of up to 6.9 kV, with maximum ratings of 4000 A (Figure 7.107). As it is possible to see from Figure 7.107, an ignition or control circuit of thyristors (driver) is made on a printed-circuit-board and integrated into the common module together with the power structure. It relieves users of “headaches” caused by complex and difficult systems based on such thyristors, and simplifies their use greatly.

The method to achieve unity gain used in the ETO thyristor is to insert an additional switch in series with the cathode of the GTO. The cathode of the GTO is the emitter of the internal n–p–n transistor, so the series switch is referred to as the emitter switch (Figure 7.108). The ETO thyristor was developed at Virginia Tech under a program directed by Sandia National Labs. The ETO thyristor was initially developed as an extremely high-power switching device to be used in power conversion systems within electric utility grids. However, the ETO thyristor has properties which also make it an attractive option for other high-power applications, such as large multi-megawatt electric motor drive controllers. ETO thyristors are capable of switching current up to 4 kA and voltage up to 6 kV. Although the ETO has the highest power handling capabilities of all solid-state switches, its greatest benefits may well be its low cost and reliability. Other competing power switching technologies for high-power GTO and IGCT — are complex and bulky with either less than half the switching speed (GTO) or costly (IGCT). The commercialized ETO switch is projected to cost less than $1000, compared with $1900 for a typical high frequency IGCT switch.

**FIGURE 7.106**
Equivalent circuit diagram for MCT (a) and MTO-thyrists (b).
7.9 Optoelectronic Relays

The blocked n–p junction in semiconductor devices (diodes, transistors, thyristors) may begin to allow electric current to pass under the effect of energy of photons (light). When the n–p-junction is illuminated, additional vapors of charge carriers — electrons and holes causing electric current in the junction — are generated within it. The higher the intensity of the luminous flux on the n–p junction is the stronger the current is. Optoelectronic relays (Figure 7.109) comprise a light-emitting element which is usually made on the basis of a special diode (light emission diode [LED]), an n–p junction emitted by photons when current passes through it, and a receiver of the luminous flux (a photodiode, a phototransistor, a photothyristor). Usage of the two series connected photo-MOS transistors (“A” connection in Figure 7.110) as output elements allows the optoelectronic relay to switch either AC or DC loads with nominal output current rating. Connection “B” with the polarity and pin configuration as indicated in the schematic, allows the relay to switch DC load only, but with current capability increases by a factor 2.

The photo-emitting and the photo-detecting elements are almost entirely isolated from one another, can be placed in the same case, or may be separated by flexible glass fiber of 5 to 10 m or more in length (Figure 7.111). There is a great diversity of
circuits and constructions of optoelectronic relays, including those containing built-in invertors or amplifiers (Figure 7.112). A similar principle serves as a basis not only for miniature devices in chip cases, but also for practically all power semiconductor relays and contactors.
It should be noted that the external designs of not only miniature optoelectronic relays in chip cases, but also of more powerful semiconductor relays of various firms, are very much alike (Figure 7.113). Such relays are usually constructed according to a similar scheme (Figure 7.114), with only some slight variations. As a rule they comprise an RC-circuit (the so-called “snubber”), and a varistor protection outlet, protecting the thyristors from overvoltages. They often contain a special unit (a zero voltage detector) controlling the moment when the voltage sinusoid passes through the zero value and allowing it to
enable (and sometimes to disable) the thyristor at the zero value of voltage (so-called “synchronous switching” — Figure 7.115). Synchronous switching (especially at its high frequency) allows a considerable reduction of both the number and the amplitude of spikes, and high-frequency harmonics arising at transient switching processes in the load circuit.

More powerful single-phase and three-phase contactors for currents of 10 to 150 A, produced by different companies, also have a similar construction (Figure 7.116). Like the monophase variant, three-phase contactors can comprise built-in RC-circuits and varistors, and a zero voltage detector. It is only natural that when current of tens of amperes must be switched, a compact contactor requires the use of quite a large and
As with standard electromagnetic relays, Phoenix also produces optoelectronic relays in cases of peculiar shapes, designed for installation on a standard DIN rail (Figure 7.117). As with standard electromagnetic relays, Phoenix also produces optoelectronic relays in cases of peculiar shapes, designed for installation on a standard DIN rail (Figure 7.118).

**FIGURE 7.116**
(a) Single-phase semiconductor AC contactors for currents of 10 to 75 A, produced by the companies: Teledyne, Crydom, Crouzet, Gunther. (b) Three-phase semiconductor contactors for currents of 50 to 150 A and voltage of 630 V, produced by different companies. (c) Standard scheme of a three-phase optoelectronic AC contactor.
FIGURE 7.117
Thyristor contactors with heat sinks.

FIGURE 7.118
Optoelectronic relays produced by Phoenix. (Phoenix Contact GMbH & Co. catalog.)
7.10 Super-Power Electronic Relays

Absolutely unique high-speed solid switches (relays) for voltages of tens of kilovolts and currents of tens and hundreds of amperes (though in the form of very short pulses), are produced by the German company Behlke (Figure 7.119). The solid structure of such relays consists of a great number (up to a few hundreds) of series connected layers of MOSFET or IGBT elements (transistors) placed on the same ceramic plate. Such relays are capable of switching voltages up to 65 kV and pulse currents with amplitudes of up to 10 kA (with a pulse width up to 100 µsec).

More powerful switching devices for working voltages of up to hundreds of kilovolts, capable of allowing currents of up to thousands amperes pass for long periods of time, are constructed on the basis of opto-thyristors (Figure 7.120) connected in series. Such
thyristors contain built-in optical fiber several meters in length, directing the luminous flux to the area of the semiconductor structure, which is responsible for enabling of the thyristor (Figure 7.121). The dielectric properties of optical fiber allow entire insulation of the thyristor connected to the high-potential circuit from the earthed control system. This allows the manufacture of unique constructions of such thyristors connected in series. First of all, the thyristors are mounted in modules (Figure 7.122) containing transient elements of the control system, and elements of the thyristor are protected from over-voltages.

These modules are then used to construct huge thyristor units (Figure 7.123). Such units serve as a basic component of so-called High-Voltage Direct Current Links, for high-voltage power transmission lines, which have been quite popular all over the world lately. High-voltage direct current links for AC power lines allow linkage of power-supply systems of different countries, having different voltage levels and different requirements for characteristics of electric energy. Such links also allow a considerable increase in the robustness of the power-supply system. Of course such thyristor units are

![Construction of a light-triggered thyristor.](image1)

**FIGURE 7.121**
Construction of a light-triggered thyristor. (Toshiba Corp. catalog. High Power Semiconductors.)

![Light-triggered thyristors module](image2)

**FIGURE 7.122**
Light-triggered thyristors module (Toshiba). (Toshiba catalog. Directly Light-triggered Thyristor Valve.)
only part of the most complicated complexes, comprising computer systems for control and protection in emergency modes, and a special system for cooling of the thyristors, with the help of deionized (that is dielectric) water, supplied directly to the high potential, and to many other sophisticated systems.

7.11 Hybrid Relays

After we have considered some specific devices along with many of the problems frequently occurring in them — arcing on contacts, and alternatives of noncontact devices which are capable not only of switching circuits but also of synchronous switching with circuit voltage, the following question can arise: If noncontact relays are so good, why are contact ones still in use along with them?

As the reader has probably guessed, there is no perfect device (like there is no perfect friend, wife, car, etc.), which can meet all the requirements. One of the most essential disadvantages of semiconductor relays is increased (in comparison with the closed contact) resistance in the open state, which accounts for great heating of semiconductor elements when nominal current passes through them, and the necessity for big and heavy heat sinks with forced air or water cooling. Apart from additional costs for electric energy, there are also problems in compact portable and airborne equipment concerning utilization of unnecessary heat released by powerful semiconductor relays. In many types of such equipment one has to fight practically for every watt of heat. In addition,
seamiconductor-switching devices are more sensitive to overloads in emergency modes, and to overvoltages, than contacts of electromechanical relays.

As soon as designers had realized these problems of semiconductor switching devices, they began to attempt to solve them. They were not very original in their solutions: suggesting combining useful properties of each device, having taken into account advantages and disadvantages of each device. This was the usual solution in engineering, biology, and chemistry.

The first attempts of this kind were aimed at increasing the effectiveness of arc extinction, with the help of a powerful diode (Figure 7.124). Shunting of the bridge contact of the power contactor, of the KTU-4A type (Russia) by a diode, as shown in Figure 7.124, enhanced conditions of arc extinguishing a little bit, and this made possible the use of a contactor with a nominal voltage of 630 V, for a voltage of 1140 V. In standard (not bridge type) contact systems with an arc chute, the diode is connected to an additional electrode fixed between the arc-suppressing horns on the contacts (in this case both circuits are equivalent during arc extinguishing). During one of the voltage half-periods of power supply the diode is opened, and shunts a part of the arc (A2, or an arc on one of the contacts of the bridge) through the additional electrode placed in the arcing zone. This part of the arc is extinguished, and the gap between the contacts where the arcing occurred, is deionized. By the next voltage half-period of the power supply, when the diode is blocked, the arc will not be restored. Total time of arcing in such devices is reduced by 2 to 4 times.

In the device shown in Figure 7.125, the main contacts MC are shunted by two parallel circuits, each of which contains a diode, auxiliary contacts and a current coil. Auxiliary contacts 1 and 2 are linked with a drive of the main contact, and are closed simultaneously with it. Opening of the main contacts occurs without arcing, as load current turns to one of parallel branches (depending on the voltage polarity). The drive of the main contact unblocks (relieves) auxiliary contacts 1 and 2. One of them opens immediately and the second remains closed under the retaining effect of the electromagnet (3 or 4) with the

FIGURE 7.124
Simplest hybrid-switching devices, with a diode facilitating extinguishing of an electric arc.

FIGURE 7.125
A hybrid switching device with diodes providing switching of the load at the zero value of the current.

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corresponding polarity. When the current sinusoid approaches the zero value, the force of this electromagnet becomes so weak that the corresponding auxiliary contact opens (without arcing and without current) breaking the load circuit once and for all.

Thus there is no arcing on the main contact as it opens because it is shunted with an auxiliary contact, and arcing does not occur on the auxiliary contact because it opens at the zero value of the current. A contactor of the KVKh type for a nominal current of 250 A (maximum making current 6900 A, breaking current — 3250 A) and voltage of 1140 V, sized 400 × 354 × 190 mm, was designed on the basis of a similar principle in the former U.S.S.R. in the 1970s. Testing of this device proved that after 440 commutation cycles with a current of 1000 A, wear of the contacts deviated only 10% from the wear that was deemed permissible.

When high-power thyristors appeared, engineers focused on the use of them instead of diodes in hybrid devices, which allowed considerable simplification (and sometimes even leaving out) of the most unreliable parts of these devices — the mechanical blockings (Figure 7.126). In such a circuit, when the main contact MC is closed, the thyristors are

![Diagram](image)

**FIGURE 7.126**
Scheme and construction of a one pole of a thyristor unit of three-phase hybrid contactors KT64 and KT65 (Russia). 1 — case; 2, 6, 8 — outlet wire with the main current; 3 — thyristors VT1, VT2; 4 and 5 — insulated flexible outlets; 7 — magnetic core of the current transformer; 9—11 — elements of thyristor protection.
enabled and allow the current to pass if the anode–cathode voltage reaches 6 to 10 V. Such conditions are created at the beginning of the process of opening of the main contact, when there is a short arcing with voltage of over 10 V. This voltage applied to the thyristors is enough to enable them. The current flows to the thyristor circuit with the corresponding voltage polarity at the given moment, and the arc on the main contacts decays. The control signal in the gate circuits of the thyristors disappears, but the thyristor, enabled before that, remains conductive until the current sinusoid passes through the zero value, when it is fully blocked, disabling the load.

In 1970s and 80s in the former U.S.S.R., a whole family of contactors were produced on the basis of such circuits, for nominal currents from 160 up to 630 A and voltages of 380 to 660 V (Figure 7.127). Similar devices were produced by the some Western companies. Some disadvantages of such devices can be explained by the powerful current transformer, which is not always adequate in different modes. That is why there were some attempts to get rid of it due to low-power miniature auxiliary contacts of such construction that would not complicate the mechanical parts of the contactor. It was suggested that a reed switch placed near the control coil of the main contact (Figure 7.128), could be used as such an auxiliary contact. Such a contact operates simultaneously with the main contact, but it is not connected to it mechanically.

In high-voltage hybrid-switching devices current transformers are usually used (Figure 7.129). The drawbacks of the devices mentioned above are that they only weakened the impact of arcing, but were not capable of eliminating it. There are a great
number of patents describing hybrid relays with a complex control system, based on complex integral circuits (IC) which analyze load voltages and current curves, and give commands for enabling and disabling of high-power electronic elements in such a way.

**FIGURE 7.129**
High-voltage hybrid switching device on thyristors.

**FIGURE 7.130**
Functional diagram (a) and external design (b) of a hybrid relay XV series (Teledyne Relays). Nominal current 30 A, voltage 420 V AC, dimensions: 61.3 × 44.5 × 45 mm. (Teledyne Relays online catalog 2004.)
that the possibility of arcing on the main contact is entirely ruled out. Such circuits require current sensors (though miniature ones), voltage, and cope well with the problem of synchronization of operation of semiconductor and electromagnetic elements in normal modes of exploitation, though they may be inadequate in different emergency and transient modes or when there are higher harmonics or overvoltages in the current. Besides, they are too complex and expensive. Another type of electronic control circuit is based on the commands of enabling and disabling of electronic elements, and on an

![Diagram of a hybrid relay based on the principle of event-tracing.](image)

**FIGURE 7.131**
(a) Scheme of a hybrid relay based on the principle of event-tracing. (b) External design of preproduction models of hybrid relays in one and three-phase construction for current of 50 A and voltage of 440 V, designed by the author.
internal electromagnetic relay with certain time delays. Such devices do not require control of current and voltage phases, and they are much simpler than the former ones, but for reliable operation there should be reserves of time intervals because small time delays may lead to nonsynchronous operation of high-power elements (internal electromagnetic relays have quite large dispersals of make delays). Such devices are less “intelligent,” even less so than earlier models with current transformers, because the operation is based on a fixed internal algorithm, independent from the real modes of operation of the switching device. Nevertheless, this very principle (as the simplest one) was the basis for some production-run models (Figure 7.130). The author of this book tried to contribute to the invention of hybrid relays and designed a construction without sensors of current phase and sensitive electronic amplifiers. It did not have a fixed internal algorithm based on fixed time delays as well. The principle of such a solution was based on tracing of events which is actuation of a certain element of the circuit on the signal from another element, providing such actuation in a certain operation mode (Figure 7.131). This provided a minimal number of simple elements, reliability of functioning, and independence of the circuit operation from changes of parameters of certain elements in time (or in temperature), minimal make delay and dropout time of the device.
8

Time Relays

Let us remember that relays are usually defined as devices that can only be in extreme stable states and can switch from one state to another, stepwise, even when the input actuating quantity varies smoothly. In that definition, there is not a single word about the character of the actuating action. Most often, such actuating action is current, which is why relays that are energized by electrical current (voltage) are the most widespread. The bulk of this book is devoted to this type of relays, but this is not the only type of relay that exists. There are relays responsive to light, temperature, location in space, air or liquid pressure, air or liquid speed, etc. Obviously, it is impossible to consider all known types of relays in detail within just one book, but in order to get a complete picture one should be familiar with at least some of them.

One of the most widespread types of relays (after electrical relays) is "time relays." Usually these are relays operating with a certain delay with regard to the signal applied to the relay input, which is why frequently the term "time-delay relay" is used. As the change of state of a relay is accompanied by a certain delay with regard to the signal applied to its input, one can say for sure that, apart from its other functions, every relay also functions as a time relay. Sometimes standard electromechanical relays are used to enhance stability of complex automatic control systems. Their only function is to provide a certain signal delay, the value of which equals its own make delay. In terms of engineering, "time relays" or "time-delay relays" are usually defined as relays in which the time-delay function dominates, and in which the characteristics of that function are enhanced, by one means or another.

8.1 Electromagnetic Time Relays

Let us remember that the pick-up (and drop-out) time of a standard electromagnetic relay includes two major composites: time of increasing (or decreasing) of current while winding up to the operating (releasing) current value, and armature traveling time. The simplest way to increase the pick-up (drop-out) time of a standard electromechanical relay is to increase the first composite. For this purpose an additional short-circuited winding is placed on the relay core (Figure 8.1), with resistance \( R_2 \), number of turns \( W_2 \) and inductance \( L_2 \).

When working voltage is applied to the main relay winding, the current in it builds up from zero to its steady-state value. According to the law of electromagnetic induction, current variation in the main winding (and therefore also the magnetic flux \( \Phi \) in the core with the additional winding) causes current of the opposite direction in the
FIGURE 8.1
Electromagnetic time delay relay with an additional short-circuited winding ($R_2, W_2, L_2$) on the core.

FIGURE 8.2
Building up of the magnetic flux when the relay with the short-circuited winding is switched ON (a) and fading of the magnetic flux as the relay is switched OFF (b). $\Phi_1$ — Magnetic flux of the main winding; $\Phi_2$ — magnetic flux of the short-circuited winding; $\Phi_3$ — compound flux; $t'$ — pick-up (drop-out) time of the relay without short-circuited winding; $t$ — pick-up (drop-out) time of the relay with short-circuited winding.
flux $F_2$ whose direction is opposite to the main magnetic flux and therefore weakens it. When the power supply is switched OFF, the main magnetic flux falls to the zero value and the magnetic flux of the short-circuited winding prevents this fall by delaying the drop-out time of the relay (Figure 8.2b).

The less the resistance of the short-circuited winding $R_2$, the more it affects the pick-up and drop-out times of the relay. That is why in practice thick copper slats (2) or disks, which are put directly onto the core under the main winding 1 (Figure 8.3), are used instead of short-circuited winding.

Additional short-circuited winding. This additional current creates an additional magnetic flux [$\Phi_2$] whose direction is opposite to the main magnetic flux and therefore weakens it thus delaying the relay pick-up (Figure 8.2a), and vice versa, when the voltage of the power supply is switched OFF, the main magnetic flux falls to the zero value and the magnetic flux of the short-circuited winding prevents this fall by delaying the drop-out time of the relay (Figure 8.2b).

The less the resistance of the short-circuited winding $R_2$, the more it affects the pick-up and drop-out times of the relay. That is why in practice thick copper slats (2) or disks, which are put directly onto the core under the main winding 1 (Figure 8.3), are used instead of short-circuited winding.
It appears that if this copper slat is shorter than the core and is placed not in the center but along the edges of the core (Figure 8.4), then in one case, we will have a relay with a prevalence of the delay for pick-up, and in the other case, we will have a relay with a prevalence of the delay for drop-out. When the size of the copper slat and of the winding...
of the relay is the same, the delay for the dropout is almost two times as long as that of the pick-up, which is that in order to equalize these values the copper slats and coils must have different sizes for relays with a delay for pick-up, and for relays with a delay for drop-out (Figure 8.4).

Though the time delay in this case is not very long and usually does not exceed 0.5 to 3 sec, relays with electromagnetic delays have been used for years due to their simplicity and reliability, and not only in miniature relays but also in high-power relays (Figure 8.5). In some old constructions (Figure 8.6), there was even continuous adjustment of the time delay within 0.75 to 3 sec by moving a slotted steel block (12) in the “increase” or “decrease” direction by means of a pin (13).

8.2 Capacitor Time Relays

It is possible to hold back building up of the current in the winding of a DC relay by quite a large value with the help of a capacitor shunting the winding of the relay (Figure 8.7). In the first case the capacitor (C) practically does not affect the pick-up time of the relay, because its charging current is limited by the resistor (R). In the steady-state mode, the capacitor is charged up to the value of the power supply voltage. When the supply circuit of the winding of the relay is broken, the charged capacitor starts to discharge, through the resistor (R). The value of the discharge current of the capacitor is limited by the same resistor and also by the resistance of the winding of the relay, as in order to hold the relay in a closed position much weaker holding current (the current of the capacitor discharge) is required than pick-up current (the current absorbed in the charging capacitor in order to delay the pick-up of the relay). Such circuit in most cases is able to cope with its task quite successfully, but when the natural resistance of the winding is quite high (tens of kΩ, for example), the resistance of the limiting resistor R must also be high, otherwise the capacitor C will affect the pick-up time of the relay. But in this case total resistance of
the winding and of the resistor \( R \) appears to be so high that discharge current of the capacitor with switched OFF power supply of the relay is not enough to hold the relay and obtain the required time delay. In such cases one may use an additional diode \( D \), which allows the capacitor to discharge through it directly to the relay winding, leaving out the limiting resistor \( R \) (Figure 8.8). But the charged capacitor \( C \) (Figure 8.7b) has internal resistance close to zero, and at the first moment when the relay is switched ON will short-circuit the winding of the relay.

When the capacitance is quite high, the voltage on the winding is completely determined by the charge level. In its turn the charging speed of the capacitor with a permanent voltage of the supply source is determined by the so-called “time constant” \( \tau \) of the circuit: \( \tau = RC \).

By changing the resistance of the resistor \( R \) and the value of the capacitor \( C \) in this circuit, it is possible to change the delay time of such a relay. Usually simple time relays with a time delay of up to 10 sec are based on this principle.

8.3 Relays with Clockwork

The integration of the electromagnetic relay with clockwork provides practically unlimited time delay. The clockwork may have a spring drive or an electric drive. Earlier time relays with clockwork look very much like ordinary clocks (Figure 8.9). Their construction does not differ much from that of a standard clock: similar clock spring, similar mechanism. The only difference is that electric contacts are attached to the clockwork. Later on, electric drives appeared: solenoid, inductive, motorized ones. In some constructions a spring clockwork was applied and an electric motor used for automatic winding-up of the spring. In the 1960s time relays with clockwork launching with the help of a solenoid were widely used (Figure 8.10). The construction of this device consists of a separate clockwork in a disk-shaped steel case, with a scale, contacts, and a solenoid. The solenoid is linked with the clockwork with the help of a pin (4) from the clockwork case. The
FIGURE 8.9
Time relay produced in 1935 (General Electric Co.); (a) with a spring and manual winding up; (b) with an electric motor. (General Electric G.E.C. catalog of electrical installation material 1935.)

FIGURE 8.10
A time relay with a spring clockwork and a starting solenoid. 1 — solenoid winding; 2 — upper part of the solenoid armature; 3 — return spring; 4 — pin; 5–7 — elements of mechanical gear; 8 — drive spring of the clockwork; 9 — ratchet latch; 10 — contact traverse; 11 — friction device; 12 — axis; 13–18 — elements of the clockwork; 19 — snap-action contacts; 20 — movable contact; 21 — stationary contact; 22 — slipped contact.

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Clockwork is fixed on the solenoid in such a way that the pin in the initial position is lifted up and the spring (8) is stretched. When the solenoid is energized, its armature (2) is retracted and releases the pin (4). Affected by the spring (8) the clockwork begins to turn the traverse (10) with a movable contact (20). The time delay is determined by the distance between the movable contact (20) and the stationary one (21) and is adjusted by repositioning of the stationary contact (21). When the power supply of the solenoid is switched OFF, the strong restoring spring (3) returns the drive spring of the clockwork next to the pin (4) to its initial position. Relays of such type were quite massive (Figure 8.11) and heavy (more than 1.5 kg).

In the time relay with a motor drive, the clockwork was set in motion by a small synchronous electric motor with a reduction gear and a solenoid was used to return it to its initial position (Figure 8.12). In such a relay the required time delay is displayed on the scale. When the relay is switched ON (when the power supply is applied to it) the DC motor with a reduction gear and the solenoid are both powered at the same time. The motor rotates the mechanism until the time set on the scale. At that point the output

**FIGURE 8.11**
Internal section of a time relay with a spring clockwork and a powerful two-coil starting solenoid of the RZf type. (AEG)

**FIGURE 8.12**
A time relay of the MC-13 type (General Electric), with a motor drive and a solenoid, produced in the 1950s. 1 — oil bearings; 2 — contact D; 3 — contact arm H; 4 — contact arm G; 5 — contacts C; 6 — contact arm A; 7 — contact B; 8 — latch; 9 — solenoid’s armature; 10 — solenoid’s coils; 11 — pointer. (General Electric catalog. Definite time-control relay type MC-13.)
contact closes, the additional contact breaks the supply circuit of the motor, and the solenoid opens. Switching-off of the solenoid causes the mechanism affected by the restoring spring to return to its initial position.

**FIGURE 8.13**
High-precision time-delay relay series MZ-54 with synchronous motor and solenoid clutch (Schleicher).
1 — Function selector; 2 — internal frequency selector; 3 — timing range indicator; 4 — timing range selector; 5 — setting mark; 6 — elapsed-time indicator; 7 — contact position indicator.

**FIGURE 8.14**
Construction of the time relay with a solenoid drive.
1 — solenoid; 2 — worm-gearing; 3 — clockwork; 4 — movable contact; 5 — stationary contact; 6 — scale of the time delay.
As the voltage frequency in the AC circuit is quite stable, many companies at the same time, produced relays based on an AC synchronous electric motor, the motor speed of which depended on the frequency of the supply main. The company Schleicher produced a whole series of time relays based on this principle (Figure 8.13). Upon energization, the solenoid couples the swing-out gear train axle to the timing mechanism, actuates the instantaneous contacts, and cocks a switch lever by spring tension. Simultaneously, the synchronous motor starts to rotate and the timing period commences. Upon the expiry of the preset time, the timing mechanism releases the cocked switch lever, which snaps the delay contacts into the operating position and de-couples the gear train axle. The timing mechanism reverts immediately to the “before-start” condition. Upon de-energization, the solenoid and all contacts revert to the “before-start” position.

There are constructions in which a solenoid rather than a motor is used in order to make it cheaper (Figure 8.14). The armature (1) of such a solenoid is connected to the worm gear (2) transforming the linear displacement of the armature into the rotating

**FIGURE 8.15**

Construction of the time relay of the RBM-12 type with a synchronous motor and a retractable (like a solenoid) rotor. 1 — motor starter; 2 — rotor; 3, 4, 5 — gear wheels; 6 — reduction unit; 7 — thumb frame with contacts; 8 — contacts; 9 — drag-bar for adjustment of stationary contacts (time delay); 10 — pointer; 11 —return spring; 12 — stop; 13 — lock; 14 — spring.
FIGURE 8.16
(a) Construction of a motor time relay of the RXKP-2 (ASEA-ABB) type with delays from 30 sec to 60 h. 1 — synchronous motor; 2 — spring; 3 — projection on intermediate disc 11; 4 — setting screw for scale range; 5 — scale range index; 6 — setting knob for operating time; 7 — operating time scale; 8 — running time scale; 9 — running time recorder; 10, 13 — crown wheels; 11 — intermediate disc; 12 — planet wheel; 14 — return springs; 15 — gear train; 16 — clutch; 17 — pinion; 18 — worm; 19 — stop; 20 — instantaneous contact; 21 — armature. (b) External design of a motor-time relay of the RXKP-2 type without cover (ASEA-ABB). 1 — Synchronous motor; 2 — contact system; 3 — mechanical transmission. (c) Fragment of mechanical transmission of a motor-time relay of the RXKP-2. (ABB)
motion of the elements winding up the spring. The moment of rotation of the spring through the clockwork makes the movable contact (4) move evenly until it closes with the stationary contact (5).

In the time relay shown in Figure 8.15, the rotor (2) is retracted to the starter (1) (it goes up), when the current in the winding reaches a certain value and its gear wheel (3)
engages the gear wheels of the reduction unit. At that point, the wheel (5) with the frame (7), with contacts fixed onto it, begins to rotate. As the frame (7) rotates, the contacts fixed onto it touch the corresponding stationary contacts, according to the time defined for the position of the contacts. Such relays were produced in the 1960s by the Cheboksar Electrical Equipment Plant (the former U.S.S.R.).

Similar relays were produced by many companies until the 1970–80’s, and some of them are still used today (Figure 8.16). Of course modern relays, based on the same principle (a small synchronous electric motor with a reduction unit that sets the clockwork in motion) look more modern (Figure 8.17), but do not differ much from constructions designed years ago, in the 1970–80’s.

One version of a motor-driven time relay is a Cam Program Timer (Multi-cam Timer, Re-cycle Timer, Repeat Cycle Timer, etc.), (Figure 8.18). When energized, a program timer continues and synchronously repeats a preestablished sequence of ON–OFF switching events. The program timer may be set for frequency and duration of timed events. The frequency (interval) is the time between the “On” and “Off” cycles. The frequency may be set from intervals of several minutes to several hours. The duration (cycle) is one revolution of the output camshaft (camshaft speed). Duration may be set from 1 sec to 30h. An automatic reset feature (in some models of such devices) allows function synchronizing with other system controls. This feature provides an interesting variety of timing combinations.

8.4 Pneumatic and Hydraulic Time-Delay Relays

Time relays with a clockwork allow one to obtain very long delays, measured in tens of hours, but such delays are not always necessary and it is not always financially favorable to use expensive relays in order to obtain delays from just a few seconds up to one minute (the most frequent range of delays), which is why along with complex mechanisms based on clockwork or an exact electric motor, there are also simpler devices, consisting of a solenoid and an air or liquid damper delaying retraction and return of the relay armature (core) to its initial position.

The Allen West & Co. produced relays with time delays, provided by deceleration of the solenoid core with the help of a viscous fluid (Figure 8.19). In this construction an additional rod with a plate and holes was fixed on the end of the core. It was placed in a vessel with silicone oil. When current was applied to the winding of the solenoid, the core was slowly retracted into it, as the oil flowing through the small holes in the plate prevented its movement. Of course, such a relay could not provide delays as long as motor relays, but it was quite suitable for delays of a few seconds.

The essential disadvantage of such relays was a strong dependence of the time delay on the ambient temperature (Figure 8.19b), caused by changes of oil viscosity due to changes in its temperature. In addition to that, the time delay also was very dependent on the voltage applied to solenoid.

Pneumatic time relays in which air was used instead of viscous fluid lacked this disadvantage (Figure 8.20). In the relay in Figure 8.19, the block (2) links three elements of the relay: the solenoid core (1), the micro switch (4), and the rubber diaphragm (5) of the pneumatic decelerator. When the solenoid (1) is switched ON, its core is immediately retracted into the coil (in contrast to relays with a liquid damper), the pusher (8) goes down and releases the block (2). Affected by the spring (3), the block (2) begins descending,
following the pusher (8), although slowed by the diaphragm (5), which straightens gradually up when the upper part of the decelerator is filled with air. The air is drawn into this part through a small hole, the section (and therefore the time delay) of which is adjusted by the needle (6). The micro switch (4) picks up when the upper part of the decelerator has already been filled with air (Figure 8.21).

Such relays provided accuracy of the time delay within 10 to 12% in a wide range of temperatures. The coil of the solenoid could be switched both to AC and DC circuit and the time delay did not depend on the voltage in the circuit. The simplicity of obtaining time delays from a few seconds up to tens of seconds, and even as much as a few minutes, as well as the relative stability of the time delays, made this type of relay very popular on the market. Such relays were produced by many firms and had various external designs, but the principle of operation and basic elements remained the same (Figure 8.20).

Pneumatic time relays are still used nowadays. These are usually small light add-on devices to relays and contactors, adjoined to electromechanical relays like an additional unit of contacts (Figure 8.22).
FIGURE 8.20
Pneumatic relay with delay 0.4 to 180 sec long, produced in the U.S.S.R. in the 1950-70’s. 1 — Electric magnet; 2 — block; 3 — spring; 4 — micro switch operating with delay; 5 — rubber diaphragm; 6 — needle; 7 — snap-action micro switch; 8 — pusher.

FIGURE 8.21
Pneumatic time relay of the VR1wa542 type with a time delay within 0.2 to 30 sec. 1 — Coil of the electromagnetic drive; 2 — standard micro switch; 3 — air-chamber; 4 — rubber siphon; 5 — armature of the electromagnetic drive.
8.5 Electronic Time-Delay Relays

One may say that electronic relays are perhaps the best relays in this class of devices. They provide more stable time delays throughout a very wide range and may be adjusted with very high accuracy; however, it is not correct to say that electronic time relays have superseded motor driven or pneumatic relays, since electronic time relays were produced when both transistors and thyristors were unknown, and developed along with motor, hydraulic, and pneumatic relays.

The similar RC-circuit was the basis for an electronic relay. It was used to obtain time delays in capacitor time relays (see above). The general idea behind electronic time relays was that an electronic amplifier was inserted between the timing capacitor and the output relay (Figure 8.23). This allowed a considerable reduction in the current used by the relay from the capacitor. On the one hand it helped to increase time delays to tens and hundreds of seconds, and on the other hand it allowed reduction of the volume of the timing capacitor and enhanced its stability.

In 1950–70’s electronic time relays based on gas-discharge thyratrons were especially popular (see above). Many variants of such relays were produced by the AEG Company (Figure 8.24), and some others. Depending on the value of the installed capacitor, time delays of such relays ranged as 0.1 to 5 sec; 1 to 10 sec; 5 to 50 sec, etc. With the help of an additional external capacitor, it was possible to increase the time delay up to 3 min. Accurate adjusting of time within the range was carried out with the help of a potentiometer ($P$) (Figure 8.24). In this device, the pick-up of the thyratron (Tr) takes place at a certain voltage value ($U_{\text{pick-up}}$) on the grid (gate) of the thyratron. At the first moment after applying voltage of power supply to device, when the capacitor ($C$) is discharged, the voltage on the grid equals zero. As the capacitor ($C$) is charged through the divider ($R_3$) and potentiometer ($P$), the voltage on it (and therefore on the gate of the thyratron) increases.
gradually increases up to the pick-up voltage of the thyratron, which energize of the output relay \( (D) \). The position of the curve characterizing the speed of charging depends on the charging resistance \( (R_3 + P) \).

The more this resistance is, the more mildly the curve goes up (Figure 8.25): \( P_3 > P_2 > P_1 \).

The time constant is \( \tau \) is defined as the multiplication of \( RC \), and graphically can be illustrated as the intersection of the tangent passing through the initial point of the curve of the charge, with a horizontal right line \( E \) corresponding to 0.63 of the voltage on the capacitor established at the end charge. This section is chosen to be a working one because the linearity of the characteristic remains there. The disadvantages of such devices are a small working current of the gas-discharge thyratron in the open state, which requires
application of a high-sensitivity output relay, and also quite a strong dependence on the opening of the thyatron from ambient temperature.

When such solid-state devices as transistors and thyristors appeared, the production of relays gradually started to redirect to them. Time relays on solid-state devices have turned out to be very simple and reliable (Figure 8.26). In the device based on a dinistor (Figure 8.26a), the latter remains closed and the output electromagnetic relay without current until the capacitor charges to the voltage of breakdown of the dinistor. After that the capacitor is discharged through the open dinistor to the relay winding, causing its energization. The energized relay then starts to self-feed through its own contact $K$.

FIGURE 8.26
Electronic time relays on solid-state elements. (a) — With a dinistor VS; (b) — with unijunction transistor VT and on a thyristor VS.

FIGURE 8.27
Circuit diagram for time-delay relay SAM-11 type. (General Electric. Timing Relays. Instruction GEC-7393D.)
In the second device after the capacitor $C$ is charged to the voltage on the Zener diode $Z$, the unijunction transistor VT is enabled and the capacitor $C$ is discharged through the control gate of the thyristor VS. The latter is switched ON and energized the output relay $K$. This scheme is very reliable and has been popular for decades. Suffice it to say that the General Electric Co., has produced time relays until recently for important systems of printed-circuit board with electronic components.

As one can see, the electronic components of the relay, which look huge and heavy for such a simple circuit, occupy a very small part of the construction, and this is not the only peculiarity of the construction. Note how slantwise and awry the elements are placed on the printed-circuit board (Figure 8.28). This is because a work piece with previously applied conducting cooper lines is used as a printed-circuit board, since it does not require etching.

Such work pieces are usually used by young radio-amateurs who do not have enough money to buy required materials. Another peculiarity of this construction is an “original” scale of time delays made in the form of dents (in some constructions in the form of hairlines) extruded by a pointed instrument on an aluminum plate. You may ask how is such a scale used? Here is the answer: you should open the instruction manual and find the matching explanation for each point on the scale!. Why is it all so difficult? Because the great dispersion of parameters of electronic components prevents us from using a previously graduated scale in this circuit. Of course one may have provided for additional foot-note elements to compensate the range of values, but GE found another solution: they just fix hairlines or points on each relay unit according to the results of testing.

Despite these peculiarities this construction is still reliable and well fits the standard range of protective relays produced by the GE. On the basis of this scheme GE also produced twin time relays (Figure 8.29), with two independent time delays for use in relays of remote control of high-voltage lines. These relays provided accuracy of maintenance of time intervals of $\pm 4\%$ within temperatures of $-20$ to $+60^\circ C$.

Relays of the 7PS10 type produced by Siemens (Figure 8.30) are based on the same principle of operation. However, unlike relays of the SAM-11 type, this relay is compact
FIGURE 8.29
Twin time relays designed for two stages of time delay in zones of remote protections of high-voltage lines. (General Electric. Timing Relays. Instruction GEC-7393D.)

FIGURE 8.30
7PS10-type time relay (without a protective case) based on an RC-circuit with a unijunction transistor and thyristor. (Siemens. Protective Devices Catalog NS 1-89.)
and light because an especially designed plastic case is used for its production. In addition, the relay has a normal scale of time delays, which are observed with quite high accuracy. For example, the inaccuracy of a relay with a maximum time delay up to 10 sec is only $\pm 0.5\%$. Naturally, an increase of the time delay causes a lowering of accuracy. For relays with a working range of 10 to 100 sec, inaccuracy is already $\pm 8\%$. These are quite good figures for such simple relays. They are obtained due to the individual adjusting of each relay during the process of production.

When integrated circuits appeared, characteristics of electronic relays were enhanced considerably. The use of a high-quality operational amplifier, made in the form of chips, allowed production of high-accuracy time relays with very long time delays (tens and hundreds of seconds) on the basis of the RC-circuit (Figure 8.31).

In this device the first operational amplifier ($C$) works in the comparator mode (that is the mode of the comparison circuit) and the second one ($A$) — in the mode of amplification. Increasing voltage from the charging capacitor ($C_1$) is applied to the direct input of
the comparator, and stable reference voltage from the divider (R2…R5) is applied to the second (inverse) one. When voltage on the charging capacitor (C1) reaches the reference one, the comparator (C) pick-up and its output signal will be amplified by the operational amplifier and applied to the winding of the output electromagnetic relay (K). The time delay is adjusted by changing the reference voltage with the help of the resistor (R4). A great number of time relays for industry and power engineering were produced on the basis of this principle by various companies in the 1970–80’s (Figure 8.32). Moreover, several series of special-purpose IC chips containing most of the necessary elements for production of time relays based on this principle were produced. The most popular one was the chip of the so-called 555 series.

With this chip all that has to be done to obtain a high-quality time relay is to connect several resistors, a timing capacitor and an output relay to the chip (Figure 8.33). Several timers can be connected to drive each other for sequential timing (Figure 8.34). The sequence is started by triggering the first timer, which runs for 10 msec with R1C1. The output then switches low momentarily, and starts the second timer, which runs for 50 msec with R2C2, and so forth. It is clear that an increase of values of R and C will cause considerable increase in the time delay.

**FIGURE 8.33**
Structure (a) and circuit (b) of external adjunctions of the integral chip of the 555 series. \( R_T \) and \( C \) — Timing elements; \( \text{Rel} \) — output relay.
In order to increase time delay it was suggested to use a pulsing charge of the timing capacitor (C), with short rectangular-shaped pulses. When the pulse applied to the capacitor from the special generator is short, it does not have enough time to be charged fully and the voltage on it slightly increases. At that point there is a pause, during which the capacitor is not charged, and then again a period of charging (Figure 8.35).

The most perfect type of electronic time relay is the digital relay, which operates time relay are a highly stable pulsed oscillator (G) and a pulse counter (CR). The counter starts counting pulses until the number reaches a given value (with the help of the set-circuit) corresponding to the required time delay. At that point that a signal appears at the input, which is amplified and proceeds to the output relay. Simultaneously, the pulse counting stops and as the input voltage is switched OFF, the device returns to its initial state.

![Figure 8.34](image1.png)

**FIGURE 8.34**
Circuit diagram for sequential timing with IC 555 series.

![Figure 8.35](image2.png)

**FIGURE 8.35**
Structure (a) and diagram (b) of operation of a semiconductor time relay with pulsing charge of the capacitor.
FIGURE 8.36
Simplified block diagram of a digital time relay. PS — stabilized power source; Set — installation circuit of the initial state; G — pulse generator; CR — pulse counter; A — amplifier; K — output electromagnetic relay.

FIGURE 8.37
(a) Structure of a programmable timer of the MC14541B type (Motorola). (b) Oscillator frequency as a function of $R_{TC}$ and $C_{TC}$. 

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FIGURE 8.38
(a) Electronic time relays of the SZT 420 type with a time delay adjusted within 1.5 to 30 sec by a potentiometer (Schleicher). (b) Electronic time-delay relay of the RXKF-1 type (ASEA), 80 msec to 300 sec. 1 — output relay coil; 2 — contacts; 3 — printed circuit board; 4 — programmable timer MC14541B type (see Figure 8.37). (c) Electronic time relay of the ETR-U type with a time delay of 1 to 250 sec, fixed with the help of a set of micro switches. The case is designed for installation on standard DIN rails (Phoenix Contact). (d) Electronic time-delay relays of the 715 type (Midtex). The enclosure of these relays (d) and plugs are industry standard 8 and 11 pin octal, with a side terminal strip for flush mounting, and an 11 pin square base. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . (Continues)
In order to simplify development and production of digital time relays, producers of chips put on the market special-purpose chips containing inside a case, an oscillator, a pulse counter and timing RC elements providing a specific frequency of the oscillator, depending on the required time delay.

A wide range of time relays containing a special integrated circuit, an electromagnetic output relay, and special auxiliary elements, are produced in different cases (Figure 8.38) by different companies.

One of versions of the time-delay relays is the so-called “True-OFF Delay Relay,” Figure 8.38e. When voltage is applied to the input terminals, the relay energizes. Timing
Time Relays

starts when power is removed from input terminals (OFF delay begins without auxiliary voltage). At the completion of the delay cycle, the relay is de-energized and the output contact transfer is made. If voltage is reapplied during the delay period, the relay remains picked up and the timer resets to zero. Voltage must be applied for a minimum of 0.5 sec to assure proper operation. Energy in delay cycle for such relays is provided by internal capacitor and time delay generally does not exceed 300 sec.

Instrumentation and Control Systems, Inc. is known for unique line of timer modules designed for printed circuit mounting. These timers are thick film hybrid analog circuits or digital countdown circuits with thick conformal coating. Conformal coating is the process of spraying a dielectric material onto a device component (on printed circuit board, for example) to protect it from moisture, fungus, dust, corrosion, and thermal shock. M.G. Chemicals is the largest manufacturer of such cold sprays and protective coatings (urethane, silicone, and acrylic). With such coatings, the timers (small, light, inexpensive) have proved reliable year after year. Such timers are very convenient for using as elements at designing complex electronic devices. Numerous time ranges (0.1 sec to 10 h), functions, and voltages (12 to 240 V AC, DC) are available.

The LEACH Company produces a whole series of electronic time relays with a powerful integral output relay, with a time delay ranging from 0.1 to 600 sec (by changing the value of the external resistor) (Figure 8.39). LEACH time-delay relays are designed with thick film hybrid microelectronic timing circuits, are packaged in a hermetically sealed military style enclosure and designed to withstand severe environmental conditions encountered in military and aerospace applications. These relays are suitable for use in power control, communication circuits, and many other applications where power switching and high reliability are required over a wide temperature range (−55 to 125°C).

![Figure 8.39](image)

Electronic time relays for military and aerospace application (LEACH, 2004).

8.6 Attachments to Standard Electromagnetic Relays

Lately, universal attachments to standard electromagnetic relays containing electronic elements of time delay, made in the form of separate modules connected to standard electromagnetic relays, have become especially popular (Figure 8.40). Type 618 is an electronic time-delay module that provides a 0.5 or 2 A SCR output to drive relays. By wiring in series with multiple power relays, a versatile timing function is attained. The module is available with 3/16 in. quick-connect, solid axial, or flying leads. Fixed and externally
adjusted resistor units are available. The units are fully encapsulated and are versatile and economic, especially when used in conjunction with power relays in the 30-A rating category.
designed for a series connection with a load of any type with nominal voltage of 24 to 240 V of alternating or direct current, up to 1 A. When an external variable resistor with 10 kΩ resistance is connected, the time delay may be adjusted within 1 to 1000 s.

Internal elements of the construction are covered with epoxy resin. The case is equipped with a universal fastening. Such modules containing a thyristor or a triac as an output switching element may be used not only for delayed switching-ON of an electromagnetic relay, but also as an independent relay for switching-ON of solenoids, signal lamps and other low-power loads. Especially produced for relays with plugs for industry standard 8 and 11 pin octal, many companies manufacture small “time cubes” inserted between a standard plug-in relay and its socket (Figure 8.42). Inside such a “time cube,” there is a small printed-circuit board with electronic components providing time delay of the external relay.

8.7 Microprocessor-Based Time-Delay Relays

Recently universal microprocessor timers with new functions and interesting features have appeared in the market (Figure 8.43). Some of these timers have unique characteristics, for example, time relays produced by ABB-SSAC (Figure 8.44). The TRDU Series is a versatile universal time-delay relay with 21 selectable single and dual functions. With the progress in microprocessor technique and distribution on the market universal multifunction timers, necessity to classify these functions has appeared. Now the technical
specifications on the timers specify numbers of standard functions, frequently without additional explanations. Some standard functions of multifunction timers are shown in Table 8.1. The dual functions replace up to three timers required to accomplish the same function. Both the function and the timing range are selectable with switches located on the face of the unit.

The TRDU is the first in market series of time delay relays and includes 21 timing functions. One TRDU replaces hundreds of conventional time delay relays. Any one of the 10 single-functions or 11 dual-functions is easily selected by transferring one or more of the 6 programming switches. Timing functions include: delay-on-make, delay-on-break,
interval, single shot, recycling, motion detector, accumulating functions, inverted functions, and combinations of these.

The TRDU’s time delay is adjusted by closing a combination of 10 binary DIP switches. Available time delays range from 0.1 sec to over 1705 h in eight ranges. Timing accuracy is ± 0.1% and setting accuracy is ± 0.1% over the full adjustment range. Industry standard 8 and 11 pin base wiring makes substitution simple and fast, with no rewiring required.

<table>
<thead>
<tr>
<th>Standard Function Number</th>
<th>Flow Diagram</th>
<th>Function Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td></td>
<td>ON-delayed</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>OFF-delayed</td>
</tr>
<tr>
<td>16</td>
<td></td>
<td>ON- and OFF-delayed</td>
</tr>
<tr>
<td>21</td>
<td></td>
<td>Fleeting output on making</td>
</tr>
<tr>
<td>22</td>
<td></td>
<td>Fleeting output on breaking</td>
</tr>
<tr>
<td>42</td>
<td></td>
<td>Flashing (blinked)</td>
</tr>
<tr>
<td>81</td>
<td></td>
<td>Pulse generating</td>
</tr>
<tr>
<td>82</td>
<td></td>
<td>Pulse forming</td>
</tr>
</tbody>
</table>
8.8 Accelerated (Forced) Relays

In modern automatic control systems there is a need not only for relays with increased make delay time but also for relays with reduced (in comparison with standard ones) make delay time. The simplest way to accelerate pick-up of the relays is a series connection of an additional resistor to the winding, designed for reduced pick-up voltage (Figure 8.45). At first sight such a technical solution seems quite strange: a lot of energy which may be used for the creation of a more powerful magnetic flux caused by the coil of the relay is dispersed on such additional resistors.

But all this is not so simple, and relays were designed by quite inventive man. The make delay time of the electromagnetic relay that is the time from the beginning of the voltage supply to the winding until the moment when the armature stops:

\[ t = t_s + t_m \]

\( t_s \) is the starting time, that is the time from the moment of voltage supply to the winding until the beginning of armature motion and

\( t_m \) is the time of motion (traveling) of the relay armature from the initial position to the final one.

As the winding of the relay has quite considerable inductance, the current in it does not reach the steady-state value immediately, but increases gradually. Starting time is a period of time necessary for current increase in the winding to the value when the electromagnetic force is enough for overpassing of frictional forces, and the elastic force of the spring, and the armature begins to move. It is obvious that this time will mostly depend on the inductance of the winding. Theoretical conclusions prove that the starting time may be calculated by the formula:

\[ t_s = \frac{L}{R} \ln \left( \frac{1}{1 - \frac{I}{I_s}} \right) \]

where \( L \) is the inductance of the winding, \( R \) the resistance of the winding, \( I_s \) the current when the armature starts to move and \( I \) the steady-state current value in the winding.
The value $L/R = \tau$ is called as the "time constant of the winding."

To reduce the time constant of the relay (in order to enhance its speed of operation), one employs a winding for pick-up voltage two to three times lower than the used supply voltage (apparently such a winding contains two to three times fewer turns) and the voltage excess is reduced by additional resistors connected in series with the winding of the relay. Such a connection causes reduction of the general inductance ($L$) of the circuit and an increase of the resistance ($R$). According to the given formula, this leads to a sharp reduction of the time constant of the relay. Thus the total pick-up time of the relay may be reduced by 40 to 50%.

The very same method of enhancement of the speed operation of electromagnetic relays is used in the case considered above. Frequently another method of enhancement of the speed operation of the relay is used. It consists of shunting of this additional resistance for the period of relay pick-up (Figure 8.46). Increased voltage is applied to the winding of the relay (that is, increased current flows through it) during the pick-up. Such method of enhancement of the operation speed of the relay is called "forcing."

The principle of forcing is that voltage from the power supply, exceeding the value permissible by conditions of heating of the winding, is applied to the winding of the relay with the help of a control element. This voltage is applied to the winding for the short period of time, only for the pick-up.

At that point the voltage on the winding is reduced with the help of the control element to the level permissible by the conditions of heating. Thus during the starting period, a large starting current flows through the winding of the relay, which develops a great attractive effort. After the pick-up, the current of the winding and its magneto-moving force (m.m.f.) decrease, but the armature remains in the attracted position because when gaps are small the attractive effort of the electromagnet is great, even with low currents.

An additional contact of the same relay shunting the additional resistance ($R$) during the pickup (Figure 8.46a), or the capacitor ($C$) (Figure 8.46b), may serve as a control element. In case a capacitor is used, the relay is energized by the large charging current of the

**FIGURE 8.46**
Principle of forcing of the relay.

**FIGURE 8.47**
Circuits of forcing of the relay with two windings. M — main coil; S — start coil.
capacitor. After charging, the current does not flow through the capacitor, whose function is similar to the function of a break contact.

Ratios of fixed values of voltage, current, and m.m.f during starting, corresponding to values during the maintenance period, are called forcing coefficients of voltage, of current, or of m.m.f. accordingly.

Another widespread method of forcing of power relays is the use of two windings: a main one (a holding one) and an auxiliary one (a starting one) (Figure 8.47). During the pick-up of the relay the main winding may be shorted by the additional contact (Figure 8.47a), or may be connected parallel to the start winding. Quick pick-up of the relay is carried out by the powerful start winding, having low resistance and small inductance for short-term passing of large currents. After the relay is energized and the additional contact opens, the start winding is connected parallel to the main one, or is simply disabled.
Temperature or thermal relays belong to the second (or even probably to the first) most popular type of special-purpose electric relays. There are two basic types of such devices: relays with input energizing quantity in the form of heat, and relays with an input quantity in the form of electric current. Relays of the first type are applied for direct temperature control of different units. Relays of the second type are used as protective relays from current overload, for various electrical customers. In the latter case, electric current is transformed to the heat inside the relay first, and when the temperature of the internal thermal element reaches a certain value (and the relay is energized) — to an output electric signal. As the temperature of the internal heating element of the relay depends both on the value of the current passing through it and on the time of exposure of this current, such a relay turns out to be “intelligent”: its speed of operation appears to be dependant on the overload current of the unit being protected. If the overload is small, such a relay allows the protected unit to operate for quite a long time without being disabled, because such overload may be temporary and may be caused by end-around of operation of the unit. If the overload current is quite high, the relay quickly disables the protected unit and does not allow it to break down. The higher the overload current is, the quicker the heating element is heated and the quicker the relay disables the protected unit (Figure 9.1).

In thermal relays of both types, there must necessarily be an additional functional element transforming the heat to an electric signal. In thermal relays, two basic types of transformation are used:

1. With an intermediate transformation of the heat to the mechanically moving internal components and with further exposure to the contact connected to the external electric current.
2. Direct transformation of the heat to an electric signal: variable resistance or voltage, for example. This voltage is amplified by an electronic amplifier with an electromechanical or semiconductor (solid-state) relay on output.

9.1 Relays Based on a Bimetal Thermal Element

In relays with intermediate mechanical moving of elements affected by heat, several basic types of the following elements are used: bimetallic, dilatometer, hydraulic, mercury.

The bimetal element is most frequently used in relays. Such an element is a straight or coiled plate (or more rarely a coiled thin belt) made of two layers of metals with different linear expansion coefficients. If one heats such a plate, it will bend in the direction of the
metal with the smaller linear expansion coefficient (Figure 9.2). The bimetal strip is heated by the source, the temperature of which is under control. In some cases, it may be heated with the help of a heating spiral, as shown on the Figure 9.2, or by direct current passing through the plate, and in other cases both by the spiral and direct current. When strong currents (50 A and more) are applied, a current shunt is used to unload the bimetal strip from over-current.

The mechanical force developed by such a plate while bent is used to operate the relay contacts. As bending of the bimetal strip (like the moving of mechanical parts of all other types of thermal relays) takes time, there is usually no direct connection of such a plate with the contacts, as shown on the Figure 9.2, otherwise they would be strongly scorched by electrical arc when they slowly separate.

To accelerate disconnection of contacts, a special spring is installed between them and a bimetal strip (Figure 9.3b,c,e). It makes the movable contact ‘’jump,’’ and is made in the form of an ‘’instant-make’’ spring or snap disk (Figure 9.3d), or the contacts are equipped with some other element providing an instantaneous contact switch (snap-action contact) as the actuating force smoothly increases (Figure 9.3a).

**FIGURE 9.1**
Typical relationship between the operating time and the overload factor (the ratio of the actual pick-up current to the adjustable preset current) for a thermal relay controlling the current in the circuit of the protected unit. 1 — Zone of protective characteristics when the relay is energized from the cold state; 2 — when the relay is energized from the hot state (after it has been previously heated by the overload current).

**FIGURE 9.2**
Principle of operation of a bimetal heating element. 1 — Metal with a small linear expansion coefficient; 2 — metal with a large linear expansion coefficient; 3 — heater.
As the temperature level must be controlled in various different devices (ranging from cases of semiconductor devices and windings of electric motors, to electric kettles and boilers for water heating), constructions of relays may be very different. For example, thermal relays in round copper cases having 10 to 25 mm in diameter (Figure 9.4), based on the construction diagram in Figure 9.3d, are widely used as integral elements molded to the controlled unit or installed on its surface.

Thermal relays of such type are quite reliable and are applied even in military equipment (Figure 9.5). These relays are capable of functioning in a very wide range of temperatures: \(-60 + 265°C\) (fixed pick-up temperatures ranging from \(+30\) to \(+250°C\)) and their contacts can switch current up to 25 A at a voltage of 27 V.
FIGURE 9.4
(a) Thermal relay based on bimetal element in the form of a preliminary bent disk — snap disk (a) Relay in plastic cylindrical case widely used for protection of household and industrial appliances. (b) Series 5100 immersion-type, hermetically sealed relay (Airpax Corp.) used on water-cooled engines, hydraulic systems, degreasers, industrial air compressors, and tanks. (c) Thermal relays installed on a heat sink of powerful semiconductor devices. 1 — thermal relay; 2 — powerful transistors evolving heat; 3 — aluminum heat sink for cooling of transistors.
An auto-cutout of an electric kettle, so well known to us, also contains this bimetal strip (Figure 9.6). The bimetal element BM in this switch is made in the form of a disk with two notches and a reed placed in the center. When the element is heated with steam vapors, its reed bends slowly at first and then roughly (like an “instant-make” spring) and affects the contact system with an indexing mechanism through the pusher.

In 1967, in the former U.S.S.R. the differential temperature relay of the DTP-3M type was designed to protect power electric motors from overloads (Figure 9.7). This relay had great selectivity to the overload type of the motor and was more adequate to the real state of the protected unit. This was accomplished by the use of two bimetal strips placed at different distances from the heat-conducting cover of the relay. At long overloads of the motor with a repetition factor of 1.5 to 2 of the nominal value, the speed of winding temperature increase does not exceed 0.5°C/s. At such low speed of temperature change, both bimetal strips (4 and 5) are heated practically to the same temperature and bend equally.

When the limiting temperature is reached and the bending ends of bimetal strips 4 and 5 touch the stop (10) they cease moving together. It is only the upper plate (4) that continues bending. The pin (2) passes through the hole in the lower (already stationary) plate (5) and unbends the spring (6), with the contact (8) breaking the circuit (Figure 9.7b). In emergency modes, the rate of temperature change of the windings of the motor increases sharply. The upper bimetal strip (4) is quickly heated and begins to bend while the lower plate remains in the initial position. Because of this, the contacts

---

**FIGURE 9.5**
Thermal relay of the AD-155M type for application in military equipment (Russia). 1 — Board; 2 — column; 3 — sphere-shaped bimetal strip; 4 — terminals for external connections; 5 — stationary contact (silver); 6 — movable contact (silver).

**FIGURE 9.6**
Construction of an auto-cutout of an electric kettle.
open at considerably lower temperatures on the cover of the relay and at a slight bend of the bimetal strip 4 (Figure 9.7c). Pick-up of this relay is biased at increase of temperature rate.

### 9.2 Protective Thermal Relays

In the protective thermal relay for high currents (up to 200 to 300 A — Figure 9.8), a shunt for current unloading of the bimetal element and a complex method of heating of the bimetal element (by the direct current passing through it and an additional heater) are applied. For large currents, an ordinary current transformer is sometimes used, also, the secondary winding of which (as is usual with a current of 5 A) supplies a small heating element.

The contact system is constructed according to Figure 9.3c and is equipped with an instant-return spring, providing stepwise opening of the contacts. Relays of such type are used for protection from overload of electric motors with power up to 100 to 200 kW, DC.
Thermal Relays

and AC, with difficult starting conditions (that is with great starting duration, and a
greater starting current ratio). The external shunt is used with load currents over 50 A.

Contacts of thermal relays designed for protection of powerful consumers cannot
switch the full current of the load (100 to 200 A, for instance) and are usually used only
for control of a powerful contactor (Figure 9.9). As it can be seen from the circuit shown in
Figure 9.9, the shunt, the heating element, and the bimetal element of the thermal relay
are connected directly to the circuit of the main current, and its main contacts — to the
supply circuit of the coil of the external powerful contactor.

In most cases, the contactor is usually combined with the thermal relay (Figure 9.10),
into one construction so that the circuit of the main contacts of the contactor is connected
in series with the circuit of heating element, and the output contact of the thermal relay
(normally closed) is switched in the supply circuit of the contactor coil.

Due to such connection, as the thermal relay picks up, the load circuit is broken not
by its low-power contacts, but by the main contacts of the contactor. The heating
elements (Figure 9.10b) are often made as removable ones (like in the example considered
above) so that they can be easily and quickly replaced. For each type of heating element,
the current and proper pick-up time of the thermal relay are indicated by the manu-
facturer. Usually heating elements are heated to high temperatures during operation
and glow a bright red, which is why cases of thermal relays are made of heat-resistant
plastic.

Protective thermal relays for smaller currents (a few amperes protractedly and tens of
amperes in case of emergency switching) were produced in the 1940–70’s of the last

![FIGURE 9.8](image)
Protective thermal relay of the TPA and TPB series (Russia) for high currents. 1 — External shunt; 2 — heater;
3 — bimetal strip; 4 — instant-return spring; 5 — intermediate chock; 6 — movable contact; 7 — stationary
contact; 8 — stop.

![FIGURE 9.9](image)
Circuit diagram for connection of a thermal relay (TR) to an external contactor (C). 1 — Shunt (or current transformer);
2 — heating element; BM — bimetal element.
The thermal unit consists of a current coil (as primary transformer coil) placed over a bimetal helix that acts as a short-circuited secondary transformer coil. The current heats the helix causing it to rotate in a direction that closes the hand reset contacts. Tripping current is adjustable from 90 to 110% of coil rating.

The instantaneous unit is the small electromagnetic relay with hinge-type armature mounted on the right front side of the relay. It operates over a 4 to 1 range and has its calibration stamped on a scale mounted next to the adjustable pole piece. Why is the

FIGURE 9.10
(a) Modern protective thermal relays designed for mounting directly on the power relay (contactor). (b) Power contactor integrated with the thermal relay assembly. 1 — Main outlets of a contactor; 2 and 3 — units of auxiliary contacts; 4 — main contact unit of the thermal relay assembly; 5 — fastening and electrical bond of the heating elements. (c) Removable heating elements.
instantaneous unit needed? The answer is that the thermal process of heating and mechanical moving of the end of the bimetal strip is inertial. Even at a five-to tenfold overload current, a certain time is needed to heat the strip. As a rule, such sharp current rushes in the controlled circuit occur because of a short circuit, when there is no need for the time delay produced by the bimetal strip. On the contrary, the short circuit must be disabled as soon as possible. It is the instantaneous unit that helps to accelerate the pick-up of the relay at high currents.

The protective thermal relay of the TMC11A type, produced by General Electric Co. (Figure 9.12), is notable for its original construction.
FIGURE 9.12
(a) Type TMC11A thermal protection relay (GE). (b) Thermal unit of TMC11A relay with operating coil removed.
9.3 Automatic Circuit Breakers with Thermal Elements

Relays of the type described above are used for protection of powerful electric motors having high ratios of starting currents. For similar purposes, so-called “automatic circuit breakers” are used (Figure 9.13). These contain a bimetal heating element with an integral electromagnet with a coil for high currents — like the relays considered above. An armature of the clapper-type (or solenoid type) of this electromagnet is mechanically connected to the same contact mechanism as the bimetal strip.

Such complex relays are usually called “protective circuit breakers,” “automatic circuit breakers,” or just “circuit breakers,” although there is no logic in this name. By the principle of operation this device is a protective relay of direct action and is designed for protection from overloading. This is the main function of the device. Due to a special lever connected to a release, the device may also be used for manual switching of the load in normal modes; that is, it may serve as a standard circuit breaker (this probably reflects the origin of the name of the device), however, if one takes into account that some types of thermal and electromagnetic relays (see the section on “Latching Relays” in Chapter 16 of this book) also have a lever for manual closing and opening of contacts, the use of the word “circuit breaker” to denote a protective relay does not seem very logical.

In this book, which is devoted to relays (not to circuit breakers), we will continue to call such complex devices “relays,” using the term which correctly reflects the functional characteristics of these devices. Such relays have complex constructions, with a great number of interacting elements. Devices produced by various companies differ considerably from each other by construction; however, they are all based on the same principle, contain similar basic elements (Figure 9.14), and have similar design characteristics (Figure 9.15).

The “e” zone of the characteristic belongs to short-circuit currents exceeding nominal currents of relay adjustment by 50 to 100 times. An additional increase of speed of
operation in this zone is provided due to the electrodynamic repulsive force of the contacts. You remember that we considered methods of compensation for this repulsive force (see Chapter 3). In constructions of protective relays with high commutation current, this effect is not compensated, rather, it is additionally accelerated by the same technical methods, only applied vice versa (Figure 9.16).

Thermal and electromagnetic releases in such powerful devices are equipped as a rule with adjusting elements placed on the front panel (Figure 9.17). In power protective relays (Figure 9.19), a microprocessor release is sometimes used. This simulates the time–current characteristic by a purely electronic method, and provides the working order of the device, similar to complex action relays.

Use of a microprocessor not only allows reiteration of the time–current characteristic of the complex relay but also construction of each period of this characteristic with the required parameters (Figure 9.18). According to the type of time–current characteristics and functions, protective relays of the types considered above are divided into the following classes:

In particular devices, especially ones of the microprocessor type, combinations of several classes are possible. For example: LI, LSI or LSIG. According to the standard IEC 60898-1: “Circuit-breakers for over-current protection for household and similar installations,” the relays illustrated in Figure 9.13 are classified by the pick-up current as follows:

![FIGURE 9.13](image)

**FIGURE 9.13**
Modern protective complex action relays: single-, double- and triple-circuit ones and their circuit diagrams (in the three-phase form).
FIGURE 9.14
Typical construction of a protective complex action relay. 1 — Movable contact; 2 — stationary contact; 3 and 5 — clips for attachment of external circuits; 4 — knob for manual control; 6 — bimetal plate; 7 — armature of the electromagnet; 8 — coil of the electromagnet; 9 — arc-suppressing lattice.

FIGURE 9.15
Time—current characteristic of the LN500 and LN630 type protective complex action relay (ABB SACE), with nominal currents of 500 and 630 A. a — Thermal releases (bimetal element) in cold conditions; b — thermal releases (bimetal element) in service conditions; c1 — adjustable electromagnetic releases (minimum setting value); c2 — adjustable electromagnetic releases (maximum setting value); d — total break time of electromagnetic releases; e — break times by electrodynamic effect (ABB).
Type | Ranges of instantaneous tripping current
---|---
B | Above 3$I_N$, up to and including 5$I_N$
C | Above 5$I_N$, up to and including 10$I_N$
D | Above 10$I_N$, up to and including 50$I_N$

The inscription “C16” on the relay means, for example, that the nominal current (that is, the nominal load current continuously admissible without break-up) of this relay equals 16 A. When this current is exceeded, the overload protection, based on a bimetal strip with a time delay inversely proportional to the passing current, begins to work. When currents of short-circuits are above $5 \times 16 = 90$ A, an electromagnetic release (without time delays) immediately responds. Switching capacity of this relay allows switching of short-circuit current up to $10 \times 16 = 160$ A, for many cycles.

As it can be seen from all of the above, there exist a number of classification systems of such relays (automatic circuit breakers). One of the most widespread in European systems

![Contact repulsion principles](image)

**FIGURE 9.16**
Contact repulsion principles, used in complex action protective relays. (a) Double contact with double repulsion force; (b) use “extractor” (magnetic core pushes or pulls) for moving contact; (c) simple repulsion loop.

![Figure 9.17](image)

**FIGURE 9.17**
A fragment of the front panel of a power protective relay, with elements of adjustment of the operation threshold of the electromagnetic (to the left) and thermal (to the right) releases. In tables: nominal pick-up currents $I_m$ and $I_n$, and corresponding minimum and maximum values.

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was a German standard DIN VDE 0641 and 0660. According to these standards, automatic circuit breakers were divided into the four following groups (Table 9.1). Moreover, it turns out that many companies (for example, ABB) simply “invented” their own classifications, having nothing in common with other standards, and applied only for items produced by their company (Table 9.2).

The new type of protection devices, named: “Hydraulic–magnetic circuit breakers”, now available in market (see Chapter 16).

### Table 9.1
Circuit Breaker Classification According to German DIN VDE Standard

<table>
<thead>
<tr>
<th>Type</th>
<th>Nominal Current, $I_N$ (A)</th>
<th>Trip Level for Thermal Unit</th>
<th>Trip Level for Electromagnetic Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>6 to 10</td>
<td>$1.5 I_N-1.9 I_N$</td>
<td>$3.6 I_N-5.25 I_N$</td>
</tr>
<tr>
<td></td>
<td>16 to 25</td>
<td>$1.4 I_N-1.75 I_N$</td>
<td>$3.36 I_N-4.9 I_N$</td>
</tr>
<tr>
<td></td>
<td>32 to 50</td>
<td>$1.3 I_N-1.6 I_N$</td>
<td>$3.12 I_N-4.55 I_N$</td>
</tr>
<tr>
<td>B</td>
<td>6 to 63</td>
<td>$1.13 I_N-1.45 I_N$</td>
<td>$3 I_N-5 I_N$</td>
</tr>
<tr>
<td>C</td>
<td>6 to 63</td>
<td>$1.13 I_N-1.45 I_N$</td>
<td>$5 I_N-10 I_N$</td>
</tr>
<tr>
<td>K</td>
<td>0.2 to 63</td>
<td>$1.05 I_N-6 I_N$</td>
<td>$8 I_N-14 I_N$</td>
</tr>
</tbody>
</table>

### Table 9.2
ABB Classification for Circuit Breakers

<table>
<thead>
<tr>
<th>Type</th>
<th>Nominal Current, $I_N$ (A)</th>
<th>Trip Level for Thermal Unit</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>6 to 63 (in 10 steps)</td>
<td>$3 I_N-5 I_N$</td>
<td>Designed primarily for use in cable protection applications</td>
</tr>
<tr>
<td>C</td>
<td>63, 80, 100, 125</td>
<td>$5 I_N-10 I_N$</td>
<td>For medium magnetic start-up currents</td>
</tr>
<tr>
<td>K</td>
<td>6 to 63</td>
<td>$8 I_N-12 I_N$</td>
<td>For high in-rush magnetic start-up currents from motors, transformers and other equipment</td>
</tr>
<tr>
<td>D</td>
<td>6 to 63</td>
<td>$15 I_N$</td>
<td>A very low short circuit trip setting, in order to protect semiconductor or other sensitive devices</td>
</tr>
<tr>
<td>Z</td>
<td>6 to 63</td>
<td>$2 I_N-3 I_N$</td>
<td></td>
</tr>
</tbody>
</table>
9.4 Dilatometer Relays

Dilatometer relays have quite a simple construction (Figure 9.20). As it can be seen from the above principal diagram, the dilatometer thermal relay contains three basic components: elements with a high and low linear expansion coefficient, and electric contacts. Elements with different linear expansion coefficients are rigidly mounted with each other at one point in such a way that as these elements are heated, the free end of one of them (the rod) shifts from the free end of the other one (the tube) and operates the electric contacts. Very often, dilatometer relays are made in the form of a brass (or nickel, for high temperatures) tube 5 to 8 mm in external diameter and 100 to 300 mm in length. Inside this tube there is a rod made from special material (Invar for temperatures up to 200°C, quartz and porcelain for temperatures up to 1000°C). The rod and the tube are rigidly mounted at the end.

On the open end of the tube, there is a plastic case with a contact system and a snap-action contact (Figure 9.21b). The relay of such a type can be found in various kinds of household and industrial appliances. Most likely, your water-heating boiler contains this very type of a thermal relay.

Thermal relays have so many widespread applications that some companies completely specialize in the manufacture of such relays (Control Products, Portage Electric Products, Claus Schafer GmbH). Some of these relays have unusual designs, for example:

- A dual set-point snap-action thermal switch allows control of two circuits at different temperatures
A nonresettable thermal switch; a snap-action single operation switch whose reset temperature is less than $-35^\circ C$ prevents the thermo-switch from resetting under normal operating conditions.

9.5 Manometric Thermal Relays

In large industrial refrigerators and other types of industrial plants, thermal relays of the manometric type were widely adopted (Figure 9.22). Such relays are called “manometric” because they are constructed with a combination of a manometer and a contact.
But unlike the open system of manometer, connected to a unit with controlled gas or liquid pressure, the thermal relay already contains a hermetically closed vessel filled with liquid or gas. The pressure inside it depends on the temperature. Usually this vessel is made in the form of a small metal ampoule connected to the relay case by a long flexible tube. In the case, there is a standard for the manometer metal tube (coiled around) and a contact system, which usually consists of ready-made micro switches (Figure 9.23). A hermetic metal ampoule with a controlled temperature is placed inside the unit. As the temperature increases, the pressure of the liquid in this ampoule increases as well. It is then transferred to the coiled monometric tube. Affected by the increased pressure, the turns of this coil start to move apart (like in a manometer) and operate the contacts through the pusher. Sometimes they connect a pointer to the coil, thus obtaining a temperature scale, giving us a so-called “indicating” relay that is a relay combined with a measuring tool. Such devices are installed on all power high-voltage transformers for control of the temperatures of the oil filling such transformers.

9.6 Mercury Thermal Relays

Mercury electro-contact thermometers, differing from standard mercury thermometers by a sealed wire leading from the capillary with the mercury, may be also considered to be variants of “indicating relays” (Figure 9.24). Mercury going up the capillary closes these wire leads as it reaches a fixed temperature. The current switched by such relays is not very strong (not more than tens of milliamperes) and requires amplification for
control of the power final control elements. Some variants of such devices have a mechanism for adjusting of the operation setting within the whole temperature range permissible for each given thermometer. Such relays are notable for two scales: an upper one for the capillary without mercury (which serves only for the adjustment of the fixed operation temperature and indication of the cursor position) and a lower one — for the capillary with mercury. The fixed temperature is adjusted with the help of a very thin straight piece of wire, buried in the capillary with mercury to the fixed depth. The wire is moved with the help of the permanent magnet (5), molded with plastic and equipped with a knob for rotation. Inside the thermometer shell there is a second magnet rotating freely under the effect of the magnetic field of the external magnet (5). This internal magnet transmits its rotation to the thin screw where there is a slider with a wire-electrode linked to it. With the help of this simple mechanism, the rotating movement of the magnets is converted (translated) to displacement of the wire-electrode in the capillary the mercury.

9.7 Thermal Relays with Reed Switches

Due to their precisely defined operational threshold (pick-up) to the smooth increase of their actuating value (a very important property of thermal relays), reed switches were applied in thermal relays. But as for reed switches, the actuating quantity is a magnetic flux so in such devices, transformation of heat to a variable magnetic flux is required. Such transformation is carried out in thermal relays with the help of permanent magnets moved by elements sensitive to temperature (Figure 9.25). Usually this is a bimetal strip, made of metals with a memory effect or siphon filled with gas and expanding as the temperature increases.
The property of permanent magnets to reduce sharply the magnetic flux as increased temperatures approach the Curie point is applied in the simplest relays of fire alarms responding to increased temperature. The Curie point of standard magnets made from metal alloys is in the high temperature area and inapplicable in fire alarm systems. However, magnets produced from ferrite powder by pressing, lose all of their magnetic properties at temperatures of about 70°C. Such a magnet, in the form of a small ring, put on the reed switch, is used in fire alarm relays (Figure 9.26).

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9.8 Semiconductor Thermal Elements and Thermal Relays

Various electronic temperature relays are widely used and produced. There are a great number of modifications of such relays, but they are all based on the same principle. Such a relay contains a semiconductor thermo-sensitive element, changing its electric resistance with temperature change, an electric amplifier — usually in the form of a chip, and an output switching element at the output (a standard electromagnetic relay or a power solid-state switch). Thermo-sensitive elements may have different forms and sizes: drop-shaped, in the
form of rings, resembling standard resistors, and even sealed ones (Figure 9.27). Depending on the type of the temperature characteristic, there are two classes of thermo-sensitive elements: “thermistors” and “posistors.” The resistance of the former decreases as the temperature rises (negative resistance temperature coefficient). The resistance of the latter increases in the working zone (positive resistance temperature coefficient) (Figure 9.28).

These elements are also called “NTC termistor” and “PTC termistor,” or “NTC resistor” and “PTC resistor” (negative temperature coefficient [NTC]; positive temperature coefficient [PTC]). Materials for production of thermo-sensitive elements are various different oxides belonging to the class of semiconductors: ZnO, MgO, Mn₃O₄, Fe₂O₃, and some sulfides as Ag₂S and others.

The electronic amplifiers with the output switching elements may also be very different. The external design and constructive diagrams of some of these amplifiers are shown in Figure 9.29 as examples.

One of the applications of this device is protection of power motors from overheating. Thermo-sensitive elements are placed in different parts of the winding of the motor stator and are connected to the electronic block (Figure 9.29b). Cera-Mite Corp. (U.S.A.) produces RTC resistors especially for direct protection of circuits from overcurrents (Figure 9.30).
The PTC resistor’s unique property of dramatically increasing its resistance above the Curie temperature makes it an excellent candidate for overcurrent protection applications. Overcurrent situations in electronic devices occur due to voltage fluctuations, changes in load impedance, or problems with the system wiring. PTC thermistors monitor current in series connected loads, trip in the event of excess current, and reset after the overload situation is removed, creating a new dimension of flexibility for designers. Hold currents from 5 mA to 1.5 A are available in PTCR diameters from 4 to 22 mm ("hold current" — \( I_{H} \) — is the maximum continuous current at which a PTCR can be maintained in a low resistance ON state, while operating at rated ambient temperature (typically 25°C). To prevent nuisance tripping, choose the rated hold current to be greater than the normal current expected).

During normal operation, the PTCR remains in a low base resistance state. However, if current in excess of the hold current \( I_{H} \) is conducted, \( I^2R \) losses produce internal self-heating. If the magnitude and time of the overcurrent event develops an energy input in excess of the device’s ability to dissipate heat, the PTCR temperature will increase, thus reducing the current and protecting the circuit.

The current required to trip \( (I_T) \) is typically specified as two times the hold current (2 \( \times I_{H} \)). Trip current is defined as the minimum rms conduction current required to guarantee thermistor switching into a high resistance state (Figure 9.31), at a 25°C ambient temperature. PTCRs reset after an overcurrent situation. Protection levels may be set lower than possible with fuses, without having to worry about nuisance trips.

The temperature at which the PTCR changes from the base resistance to the high resistance region is determined by the PTCR ceramic material. The switching temperature \( (T_{SW}) \) described by the boundary between regions 1 and 2 (Figure 9.31) is the temperature point at which the PTCR has increased to two times its base resistance at a 25°C ambient \( (R_{SW} = 2 \times R_{25}) \). Design flexibility is enhanced by Cera-Mite’s wide selection of ceramic PTCR materials with different switching temperatures (Figure 9.32). Cera-Mite offers a wide selection of ceramic PTC materials providing flexibility for different ambient temperatures. Close protection levels are possible by designing resistance and physical size to meet specific hold current and trip current requirements.

PTC current limiters are intended for service on telecom systems, automobiles, control transformers (as inrush current limiter), or in similar applications where energy available is limited by source impedance. They are not intended for application on AC line voltages where source energy may be high and source impedance low.

Lately temperature sensors have appeared based on operational amplifiers, releasing current or voltage proportional to the temperature of the case, and having a linear
FIGURE 9.29
(a) Electronic amplifier with relay characteristic designed for work with a thermo-sensitive element as a thermal relay (ZIEHL). To the left on the printed circuit board, one can see an output electromagnetic relay in a white plastic case; to the right on the printed circuit board — the transformer of the internal power supply. (b) Electric circuit of an electronic thermal relay (ZIEHL) with thermo-sensitive elements for control of temperature of windings of the electric motor (M). (c) External design and circuit diagram of an EMT-5-type termistor overload relay. (Klokner-Moeller, Germany, 2004. Online Internet catalog.)
FIGURE 9.30
Resettable PTC resistors for overcurrent protection (Cera-Mite Corp., U.S.A.).

FIGURE 9.31
$R$ vs. $T$ operating characteristics of a PTCR.

FIGURE 9.32
Characteristics of ceramic PTC materials for different ambient temperatures.
characteristic at the output, for example, the LM135/235/335 series (Figure 9.33). IC 135/235/335 series is a precision temperature sensor. Operating as a two terminal Zener diode, it has a breakdown voltage directly proportional to absolute temperature at $+10 \text{ mV/}^\circ\text{C}$. Applications for the device include almost any type of temperature sensing over a $-55$ to $+150$ $^\circ\text{C}$ temperature range, with a $200^\circ\text{C}$ over range also available.

Other examples: LM35CZ-type and 590kH-type integral circuits (Figure 9.34). The LM35 is a three-terminal integrated circuit TO-92 plastic packaged temperature sensor, giving a linear voltage output of $10 \text{ mV/}^\circ\text{C}$. Available in two versions, one operating from $0$ to $+100^\circ\text{C}$ (DZ version), the other from $-40$ to $+110^\circ\text{C}$ (CZ version). Ideally suited for ambient temperature measurements, such as providing cold junction compensation for thermocouples. Accuracy: $\pm 0.4^\circ\text{C}$.

The 590kH is functionally a two-terminal circuit temperature transducer, which produces an output current proportional to absolute temperature. The device acts as a high impedance, constant current regulator, passing $1 \mu\text{A/}^\circ\text{C}$. Laser trimming of the chip is used to calibrate the device to $298.2 \pm 2.5 \mu\text{A}$ at $298.2$ K ($+25^\circ\text{C}$). Since the 590kH is a current sourcing device, it is ideally suited for remote sensing applications where the output can easily be transmitted over a two-wire twisted pair line, without degradation of...
FIGURE 9.34
Temperature sensors based on operational amplifiers. (a) LM35CZ type (National Semiconductors); (b) 590 kH type (Phillips).

FIGURE 9.35
Programmable temperature controller TMP01FP type in 8-pin Mini-DIP package (Analog Devices).
performance due to line resistance, connector resistance or noise. Operating temperature range: \(-55\) to \(+150\)°C.

Besides such simple temperature sensors in the form of chips, whole programmable temperature controllers are also produced (Figure 9.35). The TPM01PT is a temperature sensor which generates a voltage output proportional to temperature (from \(-55\) to \(+150\)°C) and a control signal from one of two outputs when the device is either above or below a specific temperature range. High and low temperature trip points are determined by user-selected external resistors. Typical applications include: over or under temperature sensor or alarm, board level temperature sensing, temperature controllers, electronic thermostats, remote sensors, and process control.

Some semiconductor temperature sensors change resistance stepwise, that is they have relay characteristics and can be realistically called “thermal relays” (it is obvious, that it is not difficult for realizing with the help of electronic schemes, see Chapter 7), for example, a solid semiconductor thermal relay, encapsulated in small T018 type packages, with electrically isolated mounting tabs (Figure 9.36). When heated, the sensor exhibits a high resistance until the transition temperature region is reached, centered around \(+57\) or \(+75\)°C, depending on type. The resistance then changes rapidly from approximately 100 kΩ down to approximately 100 Ω for approximately a 10°C change. The reverse characteristic, with little hysteresis, is followed when cooling.

The Amperite Company produced a TSW series power thermal cut-out solid-state relays for fixed cut-out temperature from 0 to 150°C, provide a simple means to monitor temperature, using a solid-state sensing device (Figure 9.37). When the temperature exceeds the customer specified value, the output relay change state. Upon sensor cool-down, the contacts return to the de-energized position. Maximum switching voltage is 125 V AC (up to 50 VA) or 60 VDC (up to 30 W).
10

Protective Current and Voltage Relays

10.1 What are “Protective Relays”

What are “current relays” and “voltage relays” and what is the difference between them? These relays are specially designed for current or voltage level control in electric circuits of high and low voltage, and for generation of certain output signals, when the current or voltage level deviates from a preassigned value. Such relays are also called “measuring relays,” since in the process of operation they constantly measure the level of the actuating value. Very often the output signal of such relays affects the power shutdown device, de-energizing the load and thus protecting it (or the main supply) from damages in emergency modes, which is why such relays are also called “protective relays.”

Some relays of this type have powerful contacts directly switched to the protected circuit, or a powerful electromagnet mechanically linked with the power shutdown device. Such relays are called “direct-action” relays (Figure 10.1a). Low-power relays, which only give control signals to an independent power-switching device (a circuit breaker, for example), are called “indirect-action” relays (Figure 10.1b). In the above examples the relays are connected directly to the controlled current circuit. Such relays are called “primary” ones. As a rule, coils of primary current and voltage relays are designed for currents not exceeding 50 to 200 A, and for voltages of not more than 400 V.

10.2 Current and Voltage Transformers

And what should be done when one needs to control currents of hundreds and thousands of amperes, or very high voltages? In this case the relays are connected not directly to the strong current or high-voltage circuit but through special matching transformers called “current transformers” (CT) and “voltage transformers” (VTs). Relays connected to the controlled circuit through such intermediate transformers are called “secondary” ones (Figure 10.2).

What are CTs and VTs? Like any transformer, a low-voltage CT consists of a primary winding designed for the current in the controlled circuit, a secondary winding to which relays and measuring devices are connected, and also a laminated steel core (Figure 10.3a). Sometimes there is no primary winding in a CT, and the transformer itself looks like a toroid (Figure 10.3b). In this case copper wire or the bus bar is used as a primary winding (it is considered to contain one turn). The primary currents of CT can reach tens of thousands amperes. Standard values for secondary currents are 5 or 1 A. It is for these
FIGURE 10.1
A schematic plot illustrating the principle of application of primary relays, “direct-acting” (a) and “indirect-acting” (b). R — relay; TC — trip coil; CB — circuit breaker.

FIGURE 10.2
A schematic plot illustrating the principle of application of secondary relays, “direct-acting” (a) and “indirect-acting” (b). CT — current transformer.

FIGURE 10.3
Principle of construction of CTs. P — primary winding; S — secondary winding; C — laminated steel core; R — relay.

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current values that most relays in the world are constructed today. The ratio of the primary current (voltage) to the secondary current (voltage) is called the transformer ratio. As a rule, in the CT there is a layer of insulating material between the windings and the core. Transformers designed for operation under high voltages are insulated with particular care. Earlier transformers for middle-class voltages (6 to 36 kV) used to be insulated with the help of special cloth tapes impregnated with a so-called asphalt-base insulating compound, after having been wound around (Figure 10.4).

As it can be seen from Figure 10.4, it was only the piece of bus bar used as a primary winding that was insulated. The magnetic core in such construction was not insulated. After assembly, the whole transformer together with the magnetic core was covered with black varnish (based on a similar asphalt-based insulating compound). Such transformers did not look aesthetically beautiful.

Modern CTs of such class are molded with a special high-quality epoxy resin after assemblage, at the factory. The molding process is carried out with vacuum and increased pressure cycling, thus providing full impregnation of all CT elements and preventing the formation of air bubbles inside both the transformer and the magnetic core. The process results in quite aesthetic solid constructions (Figure 10.5a).

Recently are more and more widely applied CTs with the split core (Figure 10.5b). Such transformers are convenient for mounting and dismounting. After installation of two half of core and connection among themselves, they strongly snuggle up to each other. Magnetic properties of such core do not differ almost from solid core. One kind of such CT is the CT with flexible core (Figure 10.5c).

The constructions of transformers designed for current control in high-voltage transmission lines (160, 400 kV and more) differ considerably from the ones considered above due to special internal and external elements providing the required insulation level between the windings, and also between the windings and the case (Figure 10.6). The main insulation in such transformers consists of winding around of the primary turn by many layers of specific paper tape alternating with aluminum foil, and further filling of all free space with liquid transformer oil (Figure 10.7).

CTs and VTs are essential parts of relay protection systems in the power industry, where relays simply cannot be used without such transformers. Moreover, there are a number of peculiarities in the operation of such transformers, which require the relays to have specific characteristics. In this connection we have to consider in greater detail CT and VT.
FIGURE 10.5
Modern CTs. (a) bushing and toroidal type; (b) split core; (c) with flexible core

FIGURE 10.6
(a) Bushing CTs assemblies (three separate CTs). (b) Location of a single CT, or CT assemblies, on a power transformer’s HV bushing. 1 — Lower connecting piece; 2 — undoing connection bolt; 3 — lower fastening; 4 — replacing porcelain; 5 — head armature; 6 — loosening nut.
First of all, the construction diagram in Figure 10.7 is not the only one that exists. Secondary windings with cores can be placed not only on the lower part of the transformer but also in the center, and even on the upper part (Figure 10.8). The traditional scheme, with a lower position of secondary windings, allows us to place the center of gravity of the construction very low, providing high resistance of the upper transformer to turnover. Upper position of the secondary windings, on the contrary, sharply reduces transformer resistance but allows us to simplify and reduce the price of construction of the high-voltage insulation. Availability of windings entirely separated from each other, supplied with separate magnetic cores (these are windings with different parameters and characteristics as a rule) means that in the case of a CT there are several (usually three to four) separate CTs, the primary windings of which are cut into the common controlled current circuit.

The “head” of the transformer, that is an upper metal reservoir, has a complex construction with many barriers, tubes, and valves. There is more than one purpose for this part of the transformer. First, it serves as a shield equalizing the electric field in the area of current outlets connected to the high-voltage line, which is why one of the outlets of the primary winding is connected with the internal (in some construction, external) bridge to the reservoir. Second, this reservoir serves as damper absorbing excess of oil from the main part of the transformer when the temperature increases. Third, this reservoir, with the help of the so-called water seal, prevents transformer oil contact with outdoor air containing moisture.
The purpose of the aluminum foil layers (or a thin grid of aluminum foil, to be more exact) in the main insulation of the primary turn is even more interesting; at first sight it may seem that inclusion of metal layers to the insulator is unnatural.

You may be even more surprised to learn that the outer layer of this foil is linked with a special outlet placed on the outer surface of the transformer tank, and that this outlet is not a simple one. It passes through a small ceramic insulator (9) and is grounded with the help of an additional insulator, and then connected by the bridge to the same tank? What a strange conglomeration of structural components absolutely absurd at first sight? In fact everything has its important purpose. Metal foil, for example, serves as an electrode of the capacitor, forcedly equalizing high-voltage distribution by the thickness of the insulating layer, and also as an electrostatic shield equalizing local electric field strengths in the transformer construction. This allows enhanced reliability and enhanced service life of the high-voltage insulation. The additional insulator on the tank, through which the conductor linking the foil with the grounded tank comes out, is used only for diagnostics of the high-voltage insulation state. As the foil inside the tank is fully insulated both from high potential and from ground potential, if one measures such insulation characteristics as resistance, capacity, polarization index, and the dielectric dissipation factor between the external outlet (9) of the foil, and the outlets connected to the high-voltage circuit, one can make conclusions about the state of some parts of the high-voltage insulation of the transformer (unfortunately, a more thorough consideration of these problems is beyond the limits of this book). The second part of the insulation is
checked between the outlet (9) and the grounded tank of the transformer. As these measurements take place at relatively high voltages, the outlet (9) must be well insulated from the tank. With measurements completed, the outlet (9) is again connected to the tank with the help of the bridge.

In sealed switchgears with gas insulation, filled with sulfur-hexafluoride (SF₆), CTs of appropriate construction, also filled with this gas, are used (Figure 10.10). Once the necessity arises to use external CTs and VTs for voltages of 400 kV and more, cascade constructions consisting of two to three units connected in series, are used. Each of these
units is a self-contained transformer (Figure 10.11). An interesting peculiarity of the CT construction, shown in Figure 10.11, is a switch (1) also linking sections of the primary winding (four single-turn U-shaped sections) in different combinations, in series or parallel, providing values of nominal primary currents: 500, 1000, and 2000 A.

In a CT the primary winding consists of the first half-turn, with very low resistance, while in a VT the primary winding has many turns and possesses very high impedance.
because the total working voltage is applied to this winding. When the primary winding is switched to the so-called “phase” voltage, which is between the phase of high-voltage and the “ground” (the most often used connecting mode of a VT), only one outlet of the winding is supplied with a high-voltage outer insulator. Its second outlet is usually linked with the VT case (as a rule, with the help of an additional small insulator on the tank), which has similar construction and for some constructions (usually at voltages of no more than 36 kV) both transformer outlets may have high-voltage insulation (Figure 10.12b).

For very high voltages this so-called cascade construction is used. It consists of several transformers, connected in series and placed in the same case (Figure 10.13), and also of transformers of the capacitor type (Figure 10.14). The principle of operation of the latter differs greatly from all others. In fact one can hardly call them transformers. According to their principle of operation, these devices might belong to voltage dividers rather than to transformers (Figure 10.14b).

As can be seen in Figure 10.14a, a transformer for a voltage of 800 kV has quite an exotic design, due to two toroids, in the central part and at the upper point. These toroids are made of separate elements — as a rule aluminum ones, with a semicircular polished surface, and serve the purpose of equalizing the electric field and reducing its strength. Recently, capacitor-type transformers have also been produced for lower voltages (Figure 10.15).

Like in any voltage divider, in the capacitor-type VT (Figure 10.14b) there is a high-voltage arm \( (C_1) \)-on which the bulk of the high-voltage drop, and a low-voltage arm \( (C_2) \), from which the low level voltage appears. In fact, the high-voltage arm is formed not by one, but by several capacitors (a VT of 765 kV class contains 6 such capacitors), connected in series, which are easy to see in constructions of such transformers. In some VTs the
low-voltage arm is supplied with a throttle (L) and a low-VT (T) providing the VT with characteristics similar to a standard coil VT. The capacitor-type transformers are much cheaper than the standard ones at high voltage levels, and are not prone to such VT “diseases” as “ferro-resonance,” which usually leads to the “lethal outcome” of the VT and severe accidents in the circuit.

CTs and VTs of the opto-electronic type have been developed for a few decades in many countries (Figure 10.16). They are based on the application of Kerr and Pockelce electro-optic effects (for voltage measurements) and the Faraday magneto-optic effect (for current measurement). The Faraday effect can be found in the rotation of the polarization plane of linearly polarized light in optically active material, caused by an external magnetic field.
FIGURE 10.14
(a) High-voltage VTs of capacitor type of the 345, 362, and 800 kV class. (b) Principle of construction of VTs of the capacitor type.
If the transducer is placed in the magnetic field of the measured current, one can determine the current strength by measuring the angle of rotation of the plane of light polarization. As a working substance in magneto-optical converters, glasses containing lead oxide (so-called flints, crowns) are usually used, and also fused quartz. Iron–garnet films are especially sensitive to magnetic fields. In this device (Figure 10.16) the polarized ray from the grounded source comes through an optical fiber (or through any other type of light-guiding fiber) to the Faraday cell (2), placed on the high potential. In this optical cell the light flux changes its polarization vector, depending on the value of the magnetic flux affecting it. At that point the light ray, modulated in such a way, returns to the ground potential, where it is converted to electric current and is amplified.

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In VTs Kerr or Pockelce’s cells are used instead of Faraday cells (Figure 10.17). The light flux in them is modulated not by the magnetic field but by the electric field in the active material placed between the electrodes, to which the measured voltage is applied. The
Kerr effect occurs in many isotropic substances (benzene, epoxy resin, etc.), very often nitrobenzene, which produces the biggest effect, is used. The Pockels linear electro-optic effect can be observed in piezoelectric crystals placed into the electric field. This effect is seen most apparently in crystals of ammonium dihydro-phosphate (NH₄H₂PO₄) and potassium hydro phosphate (KH₂PO₄), in the longitudinal electric field created by ring electrodes (7), (Figure 10.17b). Pockels cells typically work with five to ten times lower voltages than the equivalent Kerr cell.

Such devices have been designed for the last 30 to 40 years already, but only recently have optical transformers appeared on the scene. The NxtPhase Optical Current Sensor replaces conventional CTs and brings a new level of accuracy to current sensing over a range of 1 A (rms) to 63 kA (rms), from 115 to 500 kV (Figure 10.18). The sensor is based on the Honeywell Fiber Optic Gyro system, which has a trusted reputation for accuracy and reliability in aeronautic and space industries for both commercial and military applications. The sensor can be column mounted on an advanced polymeric insulating column, or bus mounted with a suspension insulator to bring the optical fiber to ground.

The NxtPhase Optical Current Sensor consists of a specialized opto-electronic convert signal (1) from a light emitting diode into two linearly polarized signals, both sent through a polarization maintaining optical fiber to the sensing head. At the top of the column there is a circular polarizer (2) that converts the two linear-polarized light signals into right and left circular polarizations. The light signals (3) travel around the conductor many times. The magnetic field created by the current flowing in the conductor slows one signal and accelerates the other (the Faraday effect). As the circularly polarized signals complete their path around the conductor, they are reflected by a mirror (4) and travel back through the fiber, the direction of their polarizations having been reversed. Along this reverse path, the effect is doubled. Both signals make their way back to the circular polarizer, which converts them back into linearly polarized light beams. Light 6 travels back down the column to the opto-electronics (1). The difference in the speed of propagation has been translated into a phase shift between the linear signals. Since both signals

![Figure 10.17](image-url)
FIGURE 10.18
Optical CT developed by the NxtPhase Corp. (NxtPhase Co. catalog 2005).

FIGURE 10.19
(a) Hybrid current-voltage sensors produced by Lindsey (U.S.A.). Insulating class: 15 to 35 kV (1) and 69 kV (2). Current ratio 600:5 A. (b) AKS series device — combine a current sensor and a relay in a single split-core package (LEM online catalog 2005).
have traveled an identical path, vibration and temperature changes have affected them equally — the highly accurate current measurement remains unaffected.

Hybrids of CTs and VTs are also produced in lots. In fact, CTs or VTs are never used alone in electric power stations or substations. They are always used together. Very often both the CTs and VTs are switched to the same high-voltage line. Each of them is equipped with expensive high-voltage insulation. It occurred to the engineers of the Lindsey Company (U.S.A.) to combine a current and a voltage sensor in one construction, so a hybrid of them appeared (Figure 10.19), which is much cheaper than two separate transformers and which uses less place than is necessary for two separate transformers. For the time being such hybrids do not have very high characteristics for current and voltage, but they are sufficient for many practical applications.

Other interesting hybrids are the combination of current sensor and protective relay in a single package (Figure 10.19b). LEM Components has introduced families of current monitoring relays that uniquely combine a current sensor and a relay in a single split-core package. By requiring fewer connections, the new devices offer increased reliability and up to a 50% reduction in installation time. This makes them particularly suitable for cabinet applications in process automation. The new product families are available for AC current (AKS series) and DC current (DKS series) from 1 to 200 A. They can be powered internally or externally. The output can be normally open or normally closed with a solid state or a dry contact relay compatible with AC or DC secondary circuits. The design’s clamp-on function allows mounting on site without splitting conductors, reducing the number of actions (no disconnection of the cable) and cutting installation time still further thereby increasing safety.

The most important characteristic of VTs and CTs is their accuracy, which greatly depends on their load level, and for CTs also on the current ration in the primary circuit. As we know, other conditions being equal, current $I$ in the circuit depends inversely on the load resistance $R$: $I = \frac{U}{R}$. But this means that current in the input circuit of the current relay will depend on resistance of the input circuit itself, which is on the parameters of the relay. And what shall one do if several relays of different types are connected to the same CT? What accuracy can we speak about in this case? Actually, current in the secondary circuit of the CT (unlike in all other transformers types) does not depend on the resistance of the load. And does the Ohm’s law work? It does. Only not the law for a sub-circuit:

$$I = \frac{U}{R}$$

but rather this one, for a whole circuit

$$I = \frac{U}{R + r}$$

where $R$ is the resistance of the load, and $r$ is the internal resistance of the source, that is impedance of the secondary winding of the CT. Under the stipulation that $r \gg R$, the current in the circuit does not depend on the resistance of the load (relay coil).

In standard power transformers which are so-called “voltage sources,” the resistance of the load is much higher than the internal resistance of the windings ($R \gg r$), which is why the load current is inversely proportional to its resistance. The CT operates in the mode of “current source” and differs from all other transformers by the fact that the resistance of its secondary circuit is higher than the resistance of the load, and that determines the current in the circuit. The secondary current depends only on the primary
current and on the transformation ratio. In order for the CT to operate well in this mode, the load resistance cut in to the circuit of the secondary winding must be very small. The CT operates well even with fully shorted secondary winding, and vice versa; it “feels bad” if the load resistance gets high or the secondary circuit appears to be broken. In the latter case, the CT works as a step-up transformer with a large transformation ratio and the voltage level on terminals of the secondary winding may reach several thousands of volts (Figure 10.20). Such voltage is dangerous, and besides it may lead to damages of insulation of the low-voltage secondary winding. There have been cases of explosion of CTs caused by gases accumulated in the transformer because of long-term exposure to partial discharges at an open-circuit winding, which is why such mode of operation of the CT must be ruled out. In cases where, in multi-winding CTs, some windings are not used, they must be shorted by jumper straps. To protect the CT from spontaneous opening of secondary circuits the author suggested the use of simple electronic devices which short-circuit the secondary winding of the CT in cases of inadmissibly high voltage on it (see V. Gurevich, Protection Devices and Systems for High-Voltage Applications, 2003, Marcell Decker, NewYork).

(a) The voltage shape and (b) level on the terminals of the secondary open-circuit winding of the CT and the voltage amplitude, depend on construction peculiarities and the current in the primary winding of the CT.
As in any other technical device, losses also take place in CTs. Because of these losses not all primary current is transformed to the secondary circuit. Such losses may cause current error in the CT. In addition, current in the secondary circuit is slightly displaced in phase with regard to primary current, which causes angle error of the CT. Losses in CTs saturated, there remains a directly proportional dependence between primary and secondary currents. When the primary current rises, the degree of saturation of the magnetic core iron increases as well, and the corresponding characteristic begins to turn down (Figure 10.21), and when the CT load increases, the degree of deviation of the characteristic increases as well (as the demagnetizing effect of the secondary current decreases).

To estimate the condition of the iron of the CT, its volt–ampere characteristic is read while gradually increasing alternating current is applied to the secondary winding, and the voltage on the terminals of this winding is measured. At that point it is compared with its manufacturing characteristic One should bear in mind that these characteristics are obtained for simulated conditions of CT testing and do not reflect real correlations between currents and voltages in normal CT operation, but they do allow us to trace some faults in CT, which is why they are always read from the CT when new equipment is put into operation or at periodic tests.

CTs designed for measuring purposes work within the nominal currents on the straight-line portion of the characteristic, which is why they possess fine precision. Measuring CTs are produced for the following accuracy classes: 0.2, 0.5, 1, 3, 5 (with the class number corresponding to the error in percentage).

CTs used with protective relays work in emergency modes with currents considerably exceeding nominal ones, that is the curvilinear portion of the magnetization curve (Figure 10.23). That is why the indication of CT classes for relay protection also contains primary current ratio limits with respect to its nominal value when the indicated error is still to be taken into account. For example, the indication 5P30 means that the error for that given CT does not exceed 5% at primary currents exceeding the nominal value by 30 times.

Other conditions being equal, in order to provide the given error, the load power connected to the secondary circuit of the CT must not exceed the nominal power of the CT. With the nominal current, the load power will be determined by its resistance:

\[ P = Z_2 \times I_2^2 \]

where \( Z_2 \), load resistance; \( I_2 \), secondary current.
That is why one can say that the lower the resistance of the external circuit connected to the CT, the less the loading degree of the CT and the less the error is. The character of the load affects the CT error considerably: an increase of the inductive load component leads to an increase of current error and a decrease of angle error.

There is a great variety of winding connections between the CT and the relay in three-phase networks. Some of them are shown in Figure 10.24. The scheme of the so-called “full star” (Figure 10.24a) responds to all types of short-circuits (between phases and one phase to ground) and is used in circuits with grounded neutral, in which short-circuit currents are possible even only in one phase. Simplified and cheaper circuits of the so-called “unfull star” (Figure 10.24b and c), are often used in electric circuits with an insulated neutral in which considerable short-circuit currents are possible only at a phase-to-phase fault, when considerable currents always flow in two phases. At any combination, fault of phases short-circuit current will flow through at least one CT. One can simplify the scheme even more by connecting the CT to the current difference between the two phases. In this case, it is enough to have just one current relay to protect a three-phase line.

On the scheme in Figure 10.24e, current in the circuit equals the vector sum of the secondary currents of the three phases. In the normal mode, this sum is about zero.

FIGURE 10.22
Actual volt-ampere characteristics of CTs with different transformation ratios are indicated in technical specifications.

FIGURE 10.23
Forms of secondary currents in CT in emergency modes (overcurrents). The error of the CT is indicated in percentage points.
Current in the relay appears only when one or two phases are completed to the ground. Such a connection scheme is also called a “zero-sequence current filter.”

In some rare cases, two CTs (with the same transformation coefficient) are used rather than one CT, on the same circuit (in one phase). Their secondary windings are connected with each other in series or parallel (Figure 10.25). In series connections, the current in the load does not change in comparison with the current from one CT (that is, the transformation coefficient does not change either), and in parallel connections it equals the sum of both CTs (the transformation coefficient of the circuit is half as much as the transformation coefficient of one CT). In series connections of the CT, the load is proportionally divided between all CTs, which is why such a connection allows the use of low-power transformers to supply the load, consuming much power. Parallel connections are used for loads requiring increased current, or to obtain nonstandard transformation coefficients.

The error of VTs is determined by two components: by no-load current and by load current. Both cases involve additional energy losses. In the former case, these are losses caused by the magnetization of iron of the magnetic core. In the latter case, losses in the winding copper are caused by load current passing. The error from no-load current is usually much less than the error from load current; nevertheless obligatory checks of VTs imply no-load current measurements because it characterizes the state of the iron and the winding of the transformer. Like in the CT, there are two error components in the VC: by

FIGURE 10.24
Some variants of connection of CTs and relays in three-phase circuits. CT — current transformers, R — current relays.
voltage and by angle (the phase displacement between primary and secondary voltage). The angle error much depends on the character of the load. If the load is active \( (\cos \varphi = 1) \), the angle error is negative. When the load is inductive \( (\cos \varphi = 0.5) \), the angle error turns to positive and increases linearly as the load increases. To lower, the VT voltage error for a nominal load, secondary voltage is artificially increased and one introduces a certain initial positive error maximum permissible during no-load operation. As the load increases, this initial positive correction is gradually compensated due to the negative error, and when it reaches the nominal load, the total resultant error turns out to be minimal. To unify and standardize the VT, it is usually designed for a secondary voltage of 100 or 100/\( \sqrt{3} \) V. As has already been mentioned, VTs are prone to so-called “ferroresonance,” which can disable the transformer.

Ferro-resonance is a nonlinear resonance phenomenon that can affect power networks. The abnormal rates of harmonics and transient or steady-state overvoltage and overcurrents that it causes are often dangerous for electrical equipment. VT operation failures in distributing power circuits and in generator voltage circuits are quite common. On evidence derived from various sources, about 10% of installed VTs (for 6 to 36 kV) fail to operate annually in circuits with short circuit current to ground equal to 10 A. The parent cause of this phenomenon is the thermal destruction of the high-voltage winding of the VT by large currents, resulting in transformer core saturation and a drastic drop of its reactance (the main component of the impedance).

Usually the core saturation occurs during oscillation in the circuit, formed by circuit capacitance and transformer nonlinear inductivity. Such an oscillation process is initiated by unstable single-phase short-circuit to ground (Figure 10.26); partial phase operation of the VT itself results from the blow-out of fuses in high-voltage circuits; VT operation on “idle” buses; partial phase operation of the power transformer accompanied by overvoltages on the VT, etc.

The oscillations frequency may vary for different oscillation origins, parameters of the specific VT and specific circuits. In large VTs designed for 160 to 400 kV and more, the case in point is sub-harmonic frequencies 10, 12.5, 16.6, 25 Hz. In 6 to 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 ferro-resonance protecting devices for large VTs rated for 160 to 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 to 0.7 V, which disrupts the oscillation process (Figure 10.27). Unfortunately, this device may have designer’s defects and may work very unreliably.

For medium-size VTs rated for 6 to 24 kV, simpler means are used. For example, for efficient protection against ferro-resonance of transformers with an “open triangle” type winding, it is a good practice to connect a 5 to 150 Ω resistance in parallel to this winding. Another common way of protection against ferro-resonance is to include a 3 to 5 kΩ resistor to the VT neutral terminal.

The author has not encountered reports that analyze the influence of such protection against ferro-resonance means on VT operation errors, but experience shows that designers ratings of VT loads (relay protection circuits, measurements, and registration of energy consumption) take into account only the nominal power range of the VT for

![Figure 10.26](image1.png)

**FIGURE 10.26**
Oscillograms of current and voltage in a VT during a single line to ground short circuit.

![Figure 10.27](image2.png)

**FIGURE 10.27**
Device for VT protection against ferro-resonance (Haefelly). 1 — Chock of low frequency filter (16 Hz); 2 — electronic control board; 3 — solid-state contactor; 4 — low resistance noninductance resistor (0.5Ω).
which its nominal accuracy level is preserved. However, some Western manufacturers supply VTs with antiferro-resonance resistors, which load the VTs to 60 to 80% of their nominal power. The result is overloaded voltage circuits; consequently VT operation error goes beyond the accuracy grade, and power consumption registration circuits powered by the 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 ferro-resonance.

Some simple automatic devices for VT protection from ferro-resonance are suggested by the author in his books: *High-Voltage Automatic Devices with Reed Switch* (2001, Haifa) and *Protection Devices and Systems for High-Voltage Applications* (2003, Marcell Decker, New York).

VTs for voltage up to 36 kV can be connected to interphase voltage, or between the phase and the ground. As a rule they are protected by fuses (Figure 10.28). High-voltage fuses (Fu1 and Fu2) cannot protect the VT when the circuit of low-voltage load is overloaded because of high internal resistance of the transformer. That is why additional fuses are installed in the low-voltage area. VTs of a higher class are connected phase-to-ground and do not contain fuses.

10.3 Instantaneous Current and Voltage Relays

The simplest and most widely used type of relay protection is the so-called “overcurrent cut-off” or “instantaneous current relay.” As one can conclude from the name, a relay designed for such protection must pick-up immediately without a time delay (TD) when current overpasses the predetermined (by adjusting the relay) value.

10.3.1 Protective Relays of the Electromagnetic Type

Electromagnetic relays of such type energized when the predetermined current threshold is overpassed (so-called “current relays,” which differ from standard electromagnetic
relays only by the winding containing a small number of turns wound around with thick wire, and by the unit of the adjusting pickup threshold).

Like in standard electromagnetic relays, in such current relays different types of magnetic systems described above are used. One of the simplest is a magnetic system of the solenoid type with a retractable armature (Figure 10.29). When current reaches a certain value, the armature is retracted to the coil and closes the contacts. When the current decreases, force of gravity makes the armature return to its initial position. The position of the armature in the coil changes, and so does the threshold of the relay pick-up. The scale (6) is used for rough estimation of pick-up current. Relays of this type have been produced by the General Electric Company for tens of years, since the middle of the last century, and work successfully in thousands of electric power stations and substations around the world. The same principle is used to produce modifications of relays, with two and three independent relays mounted in the same case (Figure 10.29c), current relays with integrated auxiliary multi-contact relays.

Relays with three units, each of which is adjusted to a certain pick-up current, are used for selective three-stage protection of electric power lines. Every current protection device has a certain service area (work zone) on the protected line. This is caused by the fact that the wire of the power line has a certain impedance which considerably limits short-circuit current, if the point of fault is tens of kilometers of distance from the place of the current relay installation. In cases of such remote short circuits, the protective relay may not detect the fault (Figure 10.30). In the given example, when the short circuit occurs at the beginning of the line (point 1), current of about 1600 A flows through the relay (we mean both the relay and the CT). When the short circuit occurs at point 2, the current passing through the relay decreases to 900 A, and at the remote short circuit at the point 3, this current (less than 600 A) approximates the pick-up threshold of the relay (500 A). This relay will not respond at all to short circuits at points 4 and 5 because these faults are out of relay working zone. But how do we provide protection for a power line outside the working zone? The solution is, together with a relay providing instantaneous (INS)
current cut-off, an additional current relay with a TD is installed at the same place (Figure 10.31).

When short circuit occurs both protections installed in the substation (1) start to work in the cut-off, both the instantaneous cut-off and the TD. Obviously, the instantaneous cut-off will pick up first and disable the whole line with the help of switch CB1.

The TD relay will not pick up because of its TD, but if short-circuit current is not enough for the instantaneous cut-off pick-up (that is if the short circuit is out of its working zone), it is only the TD relay that will pick up because it is adjusted to a smaller current trip than the instantaneous relay current cut-off (that is, it has a larger zone of operation). First, it is necessary for protection of that part of line (L1), which remains out of the zone of operation of the cut-off relay INS (the TD Zone), and secondly it is needed for backup protection of the remote part of the line when the relay or the high-voltage circuit breaker malfunctions on other portions of the line. For example, if switch CB2 is not switched off for some reason, when a short circuit occurs on the part of the line L2, the

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**FIGURE 10.30**
Diagram explaining the principle of operation of the overcurrent instantaneous (cut-off) relay on a portion of a long power line. \( I_{sc} \) — Short-circuit current at the point of the installation of the relay \( R \); \( I_{pick-up} \) — pick-up current of the relay; \( L \) — maximum area of the protected zone \( Z \); CB — circuit breaker; \( I_2 \) — current passing through the relay when short circuit occurs at point 2; \( I_3 \) — current passing through the relay when short circuit occurs at point 3; 1 — curve of short-circuit variation along the line; 2 — zone of insensitivity of the relay.

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**FIGURE 10.31**
A composite single-line diagram of overcurrent protection for high-voltage transmission line. G — power source (power station); CB — circuit breakers; INS — instantaneous (cut-off) current relays; TD — time delay current relays; T — power transformers; L — parts of transmission line.
second stage of the TD of the TD relay, installed in the first substation, will pick up and
will disable the whole line with help of switch CB1. However, to prevent switching off of
CB1 before CB2, and CB2 before CB3 in the normal mode, selectivity of operation
protection must be provided.

The general principle here is as follows: the farther the protection from the power
supply is, the smaller pick-up current it must be designed for, and the more TD it must
have \( t_1 < t_2 < t_3 \), Figure 10.31). The condition of selectivity of operation protection that
must be provided is that the portion of the line closest to the fault from the power supply,
is the portion that must be disabled. If the short-circuit current still does not disappear,
the second portion, which is more distanced from the place of fault and closer to the
supply, etc. Such an approach allows us to provide maximum survivability of the line,
and maximum resistance of the line to faults.

Despite the term “instantaneous current” relay, it does have its own nonzero pick-up
time, like any other relay. Moreover, the pick-up time of this relay depends on the current
value in the winding. This should not surprise you if you recall the fact that the pick-up
time of any electromagnetic relay decreases when the ratio of the voltage applied to the
winding (or of the flowing current) with regard to its pick-up voltage (current) increases.
Taking into account that a current relay works with high ratios of current in the winding,
one can easily guess what kind of time–current characteristic it will have (Figure 10.32). It
is worth mentioning that the construction of a relay with an armature of the plunger type
can be used not only as a current relay, but also as a voltage relay — with winding, of
course, which is wound around with a great number of turns of thin section. GE produced
the so-called Ground Detector PJCL type for the detection of grounds on ungrounded AC
generator field circuits.

This relay consists of two plunger-type units (such as shown in Figure 10.29), a
transformer, and a diode bridge, all in one case. The relay is operated from a grounded
voltage source connected through one plunger-unit coil to the machine field circuit

FIGURE 10.32
Time–current characteristic of the instantaneous current relay PJC. (General Electric Instruction GEH–1790A.)
(Figure 10.33). When a ground on the normally ungrounded field completes the circuit, the unit picks up.

The AC supply voltage is transformed, rectified, and filtered, producing a DC operating voltage for the relay with a ripple of one-half volt or less. This is applied between the ungrounded field and the ground. An indicating light on the front of the relay shows that the DC operating voltage is available.

One of the plunger-type units picks up if a ground develops on the field circuit. The other removes the operating unit from the grounded field and closes a contact for tripping or alarm. Reset is either by hand or electrically, through the test–reset switch. An AC machine field circuit is usually operated ungrounded, and a single ground does not damage the machine; however, a second ground can cause considerable damage, so protective equipment is therefore recommended to detect the first ground. The PJC type relay (Figure 10.33) serves this function. It can be used either to sound an alarm or to remove the load from the machine. The PJC type relay may be used with machine fields rated 375 V or less. It should not be applied where the exciter reverse voltage can rise above 500 V.

Voltage relays with a so-called “floating core” (a light core vertically “floating” in the magnetic field of quite a large coil) were investigated by Igor Gurevich (Kharkov, former U.S.S.R.) in the 1970s (Figure 10.34). He designed and constructed a lot of voltage relays...
based on the similar principle, with different types of the contact systems: from a standard microswitch to a mercury contact, a reed switch, and an optical photosensor. Such relays were used in different automatic control systems; automatic control with voltage level control, in which one such device was used both as a relay of overvoltage and a relay of undervoltage.

The RXOTB-23-type relay (ABB) has a very original principle and a simple design. This is a three-phase under-voltage relay that operates for symmetrical or asymmetrical voltage drops, or for phase failures (interruption in the AC supply). The RXOTB-23 is used, among other uses, as protection for control equipments and thyristor converters.

Three-phase input voltage is rectified in a six-pulse bridge having avalanche diodes, and is then supplied to a measuring dry-reed relay via a voltage divider having a variable resistor. The operating value is set with the aid of the resistor to between 50 and 100% of the rated voltage, and when any of the incoming voltages drop below the set value, the dry-reed relay disengages and interrupts the supply to the output auxiliary relay (Figure 10.35). After activation of the reed relay by the “start” push-button (and release “start” push-button, of course) its coil appears under the lowered voltage because of a voltage drop on the potentiometer. In this condition the slightest voltage reduction will be enough for the release of the reed relay. The level of release voltage is adjusted by the potentiometer.

Relays with a turning armature (Figure 10.36) were also widely used as instantaneous current and voltage relays. A Z-shaped turning armature was used in the ET-520-type relay, a predecessor of the RT-40 relay.
This old relay had lower pick-up power than the PT-40-type relay (and therefore created a smaller load for the CT). The turning armature of both relays is constructed in a particular way, which provides increased reset ratio.

Use of a magnetic system of this type in measuring current and voltage relays is not a Russian invention. A current relay with a magnetic system similar to the famous one produced by Siemens was already described by Manfred Schleieher in his book: *Die moderne Selektivschutztechnik und die Methoden zur Fehlerortung in Hochspannungsanlagen*, Berlin, Verlag von Julius Springer, 1936. That magnetic system was most likely invented long before 1936 if one takes into account the fact that the first protective relays were developed by the industry already at the beginning of the 20th century.
When we considered magnetic systems of standard (not measuring) electromagnetic relays, we mentioned that to increase the pick-up reliability (accurateness) of such a relay, an input value (of current or voltage) exceeding by 1.2 to 1.8 times the pick-up value of the relay must be applied to its winding. This excess is called the pick-up safety factor. Measuring relays adjusted for a certain level of input value must provide accurate and reliable pick-up at a gradual increase of the input value, and when it reaches the established level without any safety factor. Theoretically any relay by definition can take up only extremely steady positions, $A$ and $B$ (Figure 10.37). Here is how it happens: current in the relay winding creates a magnetic field in the core and in the working gap between the armature and the core. The magnetic field in the gap creates electromagnetic torque, affecting the movable armature in the direction in which the moving armature will reduce the air gap.

When the current in the winding reaches a value equalling pick-up current, the electromagnetic torque $M_E$ of the relay will reach the nominal value $M_{Enom}$ (Figure 10.38), and the armature will begin to move. As can be seen in Figure 10.38, in the process of moving of the armature the electromagnetic torque $M_{ETrip}$ spontaneously

**FIGURE 10.37**
Typical characteristic of relay devices. $A$ and $B$ — extreme steady positions of the relay; $\alpha_{init}$ and $\alpha_{fin}$ — initial and final armature angle; $I_p$ and $I_R$ — pick-up and release parameter (current).

**FIGURE 10.38**
Pick-up process of an electromagnetic relay of the clapper type.
increases, while the current value in the coil remains the same. This happens because changing of the armature position (an increase of angle $\alpha$) leads to a reduction of the air gap $d$ in the magnetic system (that is, reduction of the magnetic resistance of the circuit and an increase of the magnetic flux), so we have a circuit with positive feedback. As is well known such systems, when out of balance because of slight changes of the input value, cannot stop until they reach the new steady state (electronic circuits of this kind are called triggers).

Changing of the electromagnetic torque of the relay in the process of changing of the armature angle (or of the air gap in the magnetic system) is called the tractive effort characteristic of the relay. Changing of the counter torque of the spring in the process of changing of the armature angle (or of the air gap in the magnetic system) is called the mechanical (or load, or force, or displacement) characteristic of the relay.

It is clear that the relay will be in an ON state until its tractive curve will be higher than the load one. The intersection of these characteristics at a common point, means balance is achieved at that point, that is hovering of the relay in the intermediate position.

As can be seen in Figure 10.38, such balance is possible only at the initial point, when current has not yet started flowing in the winding and there is still no armature movement. As soon as $M_{E_{\text{ OPER}}}$ is greater than $M_{\text{spring initial}}$, the armature pickups and begins to move and these characteristics do not intersect anywhere. When current in the relay winding is reduced to the initial pick-up current value, that is when $M_{E_{\text{ OPER}}}$ is reduced to $M_{E_{\text{ REL}}}$, the tractive effort curve of the relay (now $M_{E_{\text{ REL}}}$) is lower than the load curve $M_{\text{spring}}$, and the armature returns to its initial position.

The air gap in the magnetic system increases, the magnetic flux is automatically reduced (at constant value of current in the winding) and the relay quickly returns to its initial state.

It is obvious that the quality of the pick-up process of the relay and the release ratio (the width of the loop in Figure 10.39) is determined by the coordination of these characteristics. Throughout the long history of the development of relays there have been many attempts to create constructions with numerous springs and additional ferromagnetic elements, in an attempt to combine relay characteristics in the best possible way.

However, all of these previous attempts turned out to be too complicated and unreliable. Only traditional clapper-type relays, and relays of the solenoid type remain in practical use, although these too are still by no means the best solution, if one takes into account coordination of characteristics. In this sense more complex relays with a Z-shaped turning armature, possessing specific relay characteristics, appeared to be of a

![Figure 10.39](image_url)

**FIGURE 10.39**
Characteristics of a relay with a magnetic system with a Z-shaped turning armature.
in the final position of the armature is minimal and the electromagnetic torque is maximal when the relay has picked up. This means that for return (switching OFF) of the relay, a considerable reduction of current in the coil is required. In contrast, in relays with a Z-shaped turning armature, there is no such sharp intensification of the electromagnetic moment when the air gap is reduced, because when the armature turns, the electromagnetic torque arm is reduced simultaneously. In the extreme armature position \( \alpha_{\text{Fin}} = 90^\circ \), Figure 10.36b) when the electromagnetic force developed by the coil is maximal, the electromagnetic torque decreases to zero (since the entire electromagnetic force is applied along the armature and the arm of force equals zero) and there is no value that can make it turn. Of course, the working area of the relay does not include this extreme armature position \( \alpha_{\text{Fin}} = 90^\circ \), Figure 10.36b). It is limited by the position \( \alpha_{\text{FinW}} < 90^\circ \) because when \( \alpha_{\text{Fin}} = 90^\circ \) the armature cannot create contact pressure. Nevertheless, the electromagnetic moment in the switched-ON position of this relay appears to be less than in relays of other types. This means that for reset of this magnetic system a slight reduction of current in the coil is required; in other words this magnetic system has a very high release ratio (a narrow loop on the characteristic, Figure 10.37).

The PT-40-type relay with a half-Z-shaped armature has similar positive properties, which is why it has been applied in industry and in the electric power industry for such a long time. In the PT-40-type relay, there is also an additional component on the common axle with a turning armature: a brake drum (7) (Figure 10.36c) with radial partitions filled with dry quartz sand. This component is a damper, reducing sharp acceleration of the movable system, vibration of contacts when they collide, and vibration of the armature caused by the alternating magnetic field. Vibration is extinguished by friction between the grains of sand.

Two relay windings can be connected to each other in series or parallel, thus allowing a change of the pick-up threshold of the relay by two times. The PT-40-type relay is produced for nominal currents from 0.2 to 200 A. The pick-up time of the relay does not exceed 0.1 sec at \( 1.2I_N \) current and 0.03 sec at \( 3I_N \) current. For application at currents protractedly exceeding pick-up current (up to \( 30I_N \)), the relay must be supplied with an integrated saturating transformer, a diode bridge rectifier. This modification of the relay is called PT-40/1D.

As in the cases considered above PT-40 current relays also serve as the base for voltage relays (PH-51, PH-53), differing from PT-40 relays only by the winding. Separate coils in this relay allow creating on the basis of this construction a relay picking up from the difference of magnetic fluxes created by the currents in the relay coils. In the PH-55-type

**FIGURE 10.40**
Circuit diagram of PH-55-type relay.
relay of synchronism control (Figure 10.40), each coil has two insulated half-windings with equal total section of wire copper.

The lower winding of one of the coils is linked with the upper half-winding of the other coil. Such linking allows us to obtain two insulated windings with strictly equal parameters, and a coupling coefficient between the windings, approximating 1. Each of the windings is connected to one of the synchronized voltages through the additional resistor. Resistances, the number of turns of the windings and the polarity of their connection are chosen in such a way that when nominal voltages coinciding by phase are applied to both windings, the total magnetic flux created by the windings will be fully compensate and there will be no electromagnetic torque in the movable system of the relay. When vectors of synchronized voltages diverge, or one of them decreases, the total magnetic field will be unbalance and the relay picks up.

For the cases when a voltage relay with an increased release ratio (0.85 to 0.9) is needed, the winding of this relay is connected to Zener diodes (Figure 10.41). The pick-up
threshold of the relay is adjusted with the help of a potentiometer (R1) supplied with a scale.

Simple instantaneous current and voltage relays were also produced on the basis of electromagnetic relays with a clapper armature (Figure 10.42). The pick-up threshold was adjusted in such relays by changing the spring stretch. Current relays were produced for nominal currents from 0.05 to 50 A, and voltage relays-for nominal values from 5 to 200 V. The size of the relay is $67 \times 41 \times 135$ mm. General Electric is still producing relays of such type (Figure 10.43). The HFC relay is a group of three independent relays equipped with a latch and a pointer flag.

It should be noted that relays of clapper type used as current relays have simpler constructions than relays with a turning armature (like PT-40), but they do not work as well when ratios of overload current are not enough. When current gradually increases in the relay winding and its value approximates the pick-up current value, the armature of such relays begins vibrating too much.

Large power relays with pick-up currents up to 630 A have the same constructive scheme (Figure 10.44). The REV-800 relay is designed for work in DC circuits. Nominal pick-up currents of different types of relays vary from 1.6 to 630 A. The pick-up threshold is adjusted by changing the tightness of the restorable spring. The size of the relay is $155 \times 190 \times 180$ mm, and the weight is 3.5 kg.

Relays with similar constructions are also produced for work in AC circuits with nominal pick-up currents of up to 1500 A. Such relays belong to the so-called “primary” (see above)
class of relays, which are switched to the circuit of high current directly, without auxiliary CTs. It should be noted that the percentage of primary relays with regard to the total number of produced relays is quite small, but nevertheless some companies continue producing such relays, mostly for DC circuits where it is impossible to use CTs (Figure 10.45). Different variants of these relays have pick-up currents from 1 to 6000 A. Pick-up time does not exceed 10 msec and the error is ± 5% from setting. The magnetic system consists of a U-shaped iron with a hinged-armature. The latter actuates the contacts. The relays can be equipped with a mechanical latch and indicator flag, which can be reset by a button.

Relays of similar construction, designed for protection of DC and AC circuits, are produced by Siemens (Figure 10.46). The 3UG1 instantaneous electromagnetic overcurrent relay (Figure 10.46) consists of a high-armature magnetic system mounted on a moulded plastic base, together with a single-pole auxiliary switch.

With currents below the operating value, the armature is held in the rest position by a spring. Given an overcurrent equal to the preset value, the armature is instantaneously attracted and the auxiliary switch actuated. The armature returns to its rest position once the overcurrent has dropped to less than 50% of the lowest setting.

Automatic switches with an electromagnetic trip (without a thermal bimetal element) also belong to protective instantaneous current relays (Figure 10.47). Such relays cannot be used for protection from overloading because they do not contain bimetal elements with a
TD dependent on current. The main function of these relays is instantaneous switching off of short-circuit currents with high ratios (5 to 20) with respect to the nominal current.

Like in the case of thermal relays, there are a lot of constructions of such instantaneous current relays, but their basic elements are the same: a current coil (or a portion of a bus bar for strong currents) connected in series with the protected load; a retractable (solenoid) or clapper armature, a spring, a trip mechanism and a contact system with an arc-suppressing unit.
10.3.2 Electronic Current and Voltage Relays

In the 1970s many key international companies developed electronic protective relays (Figure 10.48a and b) while continuing active production of electromagnetic relays.

The printed circuit board, with cheap electronic components installed on the board and soldered by fully automatic systems functioning without man’s control, was considered to be more progressive and cheaper for production than precision electromechanical units of manual assemblage and adjustment. Other difficulties for the user, for example the need to locate malfunctions in electronic relays, the ways of repairing them, resistance of relays to overloads, overvoltages and interferences — all of these inevitable concomitants of electric networks, were not taken into account.

FIGURE 10.48
As a rule, such relays contained an electronic measuring body in which the input values (current or voltage) were converted to low-level voltage, proportional to the input value and compared by level with the voltage on the electronic reference element. If the measured voltage is higher (or lower) than the reference voltage, a signal appears at the output of the compared element. It is amplified by an electronic amplifier and is applied to the winding of the electromagnetic output relay.

Simple types of such relays contained one channel with described elements, and more complex ones — two similar channels (like the RUy22-type relay produced by AEG — Figure 10.49). In earlier relay constructions, these channels had very simple circuits with two to three transistors, with a reference element on a Zener diode D1 (Figure 10.50). The ASEA Company produced RXIK-1-type relays based on similar principles of operation and made as a separate construction (Figure 10.51); however, they contained neither an individual output point electromagnetic relay nor the power source required for relay operation. This was a separate module which could work only with other modules containing the missing components, which well fit the concept of modular construction of relay protection systems, “COMBIFLEX,” actively developed by the ASEA at that time.

**FIGURE 10.49**
Diagram of function of a two-channel electronic current (voltage) relay. (a) Relay controlling the over-and undervalue. (b) relay controlling the two-stage overvalue.
FIGURE 10.50
Circuit diagram of one channel of an RUy22-type relay (AEG).

FIGURE 10.51
RXIK-1-type modular relay containing only an electric transducer in its case (1974, ASEA). (ABB Buyer’s Guide, 1990.)
According to this concept, the company did not aim at producing a protective relay with complex functions as a whole, but rather built such complex protective systems out of separate simple relay-"blocks." Perhaps that idea was right in 1970s, but it proved to be a failure when units of miniature specialized processors, capable of functioning as a cupboard full of such COMBIFLEX "units," began to appear.

The main drawbacks of the so-called "static" electronic relays based on this principle, were limited sensitivity to changing of the input signal, and a not very high release ratio (0.7 to 0.8), caused by hysteresis of the Zener diode.

The so-called dynamic relays are free from this drawback. They have appeared recently and have practically replaced semiconductor static relays in protective systems. The general principle of functioning of such relays is that during operation, a special threshold circuit (a comparator, a univibrator, or a trigger) is switched ON every half-period, when the amplitude of the input current (voltage) reaches the value equaling the reference voltage, and returns to its initial position (switched OFF) when the sinusoid of the input current (voltage) passes through the zero value, or when the input signal changes its polarity (Figure 10.52). Thus during the whole period when the affecting input value exceeds the prescribed level, the sensitive element of the relay is automatically switched from one mode to another, synchronously with the sinusoid of the controlled current. To rule out the possibility of influence of signal oscillations on the stability of the state of the output unit, a pulse stretcher (or an integrator) is used. It is based on a capacitor charging

**FIGURE 10.52**
Simplified diagram of the function of an electronic relay of the dynamic type. **Inp** — input value (current, voltage); **Meas** — measured voltage obtained by rectification and proportional transformation of the input value; **Pick-Up** — comparator pick-up threshold; **Comp** — voltage at the output of the comparator; **Out** — output voltage of the electronic circuit.
during the ON-state of the threshold circuit and maintaining the output element in the ON-state during the pause between pulses. To increase noise-immunity of the relay, an RC-circuit is cutting between the comparator and the output amplifier. It delayed picking up of the output unit up to a few tens of milliseconds. If the high level input signal is of short duration, which is typical of noise, the output unit will not have time to pick up during the noise.

The release ratio of this circuit equals 1, since the relay returns to its initial position every time the amplitude of the sinusoid of the controlled current is not sufficient for repeated (during each half-period) starting of the threshold element. This has nothing to do with the hysteresis of elements of the circuit.

One can adjust the pick-up threshold of the relay by changing the reference voltage value with the help of a potentiometer. Practically all electronic current and voltage relays produced in 1980–90’s on, are based on a similar principle (Figure 10.53).

10.3.3 Reed Switch Current Relays

For construction of instantaneous overcurrent and overvoltage relays reed switches were also used, although not so widely as relays of the types mentioned above.

According to the information we have, the simplest reed switch current relays (Figure 10.54) were produced only in the former U.S.S.R., and are still produced in Russia. These are simple constructions containing a large reed switch installed with a possibility
of turning on the bus bar section or on the coil. As the reed switch turned relatively of magnetic field supply (bus bar or coil), its sensitivity to the magnetic field of current passing through the bus bar or the coil changed (see Figure 5.76). Such relays are designed for work in DC circuits only.

Nominal values of currents for different modifications of these relays lie within 400 to 1000 A (with bus bar) and from 1.6 to 250 A with coil. A series of protective hybrid (reed-electronic) current relays was designed by the author of this book in the 1980–90’s, and was put into production under his direction. These relays are still produced in the Ukraine under the brand ‘Quasitron’ by a private company, ‘Inventor’ (Kharkov).

The ‘Quasitron’ is a multipurpose protection relay based on a hybrid (reed-electronic) technology, with very high noise immunity (Figure 10.55a). A current sensor may be mounted into the relay unit (as shown in Figure 10.55a) or mounted outside the relay unit on an additional plate (Figure 10.55d). One relay unit may be used simultaneously with several different types of current sensors, each of which has a different current pick-up value.

All sensor outputs are connected to the relay unit via low-voltage wires. The relay unit has three time–current characteristics (T1–T3) (Figure 10.56), one of which can be selected by a customer by means of jumpers on resistors R1, R2 (see Figure 10.55b). For this purpose one (or two) jumper(s) may be cutting.

As the circuit configuration (Figure 10.55b) becomes simpler, it does not contain ICs; its active solid-state components (transistors) do not constitute a threshold element and are merely used as a simple amplifier. An interface between the electronic circuit and the outside network bus is implemented via an insulated interface, based on a reed switch (K1), which also plays the role of threshold elements and starts vibrating with double network frequency when the relay picks-up. The contact erosion-free capacity of the reed switch (about $10^6$ to $10^8$ operations) along with the short period of the maximum current relay’s ON-state ensures the required commutation resource of the relay.

The amplifying module of the base circuit is nothing more than a compatibility link between the integrating couple (L1–L2C1), and the output auxiliary relay (K2) provides

FIGURE 10.54
Reed switch current relays with a bus bar section, and with a coil. Sizes of bus bar are shown in the table (to the left).
Protective Current and Voltage Relays

(a) (b) (c) (d) (e) (f) (Continues)
for the stability of the ON-state of the relay under the K1 (reed switch) vibration conditions.

The "Quasitron" is a relay of the dynamic type (see above), with a high release ratio (0.85 to 0.95). This is caused by the algorithm of its operation: return of the relay to the initial position is not connected with hysteresis of the reed switch, as it follows the current sinusoid and switched OFF forcefully every half-period. This is perhaps the only one type of electro-mechanic relay (the reed switch is an electro-mechanical element) capable of working in the dynamic mode peculiar to electronic relays. 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 power circuit pulse interference. The effect of the magnetic component of the dissipation fields can be

FIGURE 10.55 (Continued)
(a) Hybrid over-current protection relay of the “Quasitron” series (without protection lid). (b) Circuit diagram of “Quasitron” relay. K1 — Reed switch; L1, L2 — input current coils; K2 — output auxiliary relay. (c) A "Quasitron" imbedded current sensor, with adjustable current trip level. 1 — Limb; 2 — movable dielectric capsule; 3 - level indicator of current pickup; 4 — ferromagnetic screen; 5 — coil; 6 — reed switch. (d) External low voltage current sensors for “Quasitron” relays. 1 — Cutting-circuit sensor type 1 for current pick-up 0.01 to 100 A; 2 — sensor type 2 for bus bar and cable installation (30 to 5000 A). (e) Outside dimensions of external low voltage current sensor, Type 1. 1 — External wires of current circuit; 2 — plate; 3 — fixative element; 4 — limb; “output” is connected to relay unit. (f) Outside dimensions of sensor type 2 for bus bar and cable installation. (g) Circuit diagrams of type 2 sensors. 1 — for current level 100 A and more; 2 — for low current levels.

FIGURE 10.56
Time–current characteristics of “Quasitron” relay.
This 1.5 mm screen shields the reed switch in the fields with an intensity much higher than that of the dissipation fields under actual operating conditions.

For different applications of the "Quasitron" device several types of output modules are available (Figure 10.57). For "Quasitron" relays not only were low-voltage current sensors designed, but also high-voltage current sensors that can be installed directly onto the high-voltage line without CTs (Figure 10.58). Without a doubt, one advantage of this sensor is its compactness and the possibility of direct installation on the high-voltage wire. This is important from the point of view of cost reduction of high-voltage equipment, and from the point of view of minimization of compact distributing devices of the cabinet type. On the other hand, that compactness and the lack of necessity for high-

![Diagram](image1)

**FIGURE 10.57**
Output modules for "Quasitron" relay. (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. K2 — contact of output auxiliary relay, mounted on PCB in relay unit; R — load of resistive or resistive-inductive type.

neutralized by introducing a ferromagnetic screen into the relay design (see Figure 10.55c). This 1.5 mm screen shields the reed switch in the fields with an intensity much higher than that of the dissipation fields under actual operating conditions.

![Diagram](image2)

**FIGURE 10.58**
(a) Construction of the high-voltage current sensor of the "Quasitron" relay. 1 — Main insulator; 2 — fixative plate; 3 — inside nut; 4 — semiconductive cover; 5 — bushing; 6 — fixative nut; 7 — fastener; 8 — reed switch; 9 — bus bar. (b) External design of the high-voltage current sensor of the "Quasitron" relay.
voltage CT applications do not allow modernization of existing compact distributing devices, since there no place for an additional CT was envisaged.

Entire independence on the one hand and full compatibility on the other hand allow the relay to provide complex protection simultaneously of all circuits (both low-and high-voltage ones, with different current settings) of the complex electrical installation with the help of only one “Quasitron” relay unit.

In the case of a single AC relay when picking up excess of a given setting in the high-voltage circuit and switching of the auxiliary relay of the low-voltage circuit (Figure 10.59) is required, it is possible to use a high-voltage sensor with an integrated electronic filter, transforming the reed switch vibration at its pick-up to a standard signal of the “ON–OFF” type (Figure 10.60).

**FIGURE 10.59**
Principle of application of a single AC relay with high-voltage insulation. 1 — Conductor line; 2 — relay; 3 — high-voltage wire; 4 — low-voltage auxiliary relay; 5 — diode.

**FIGURE 10.60**
Electronic filter integrated to the high-voltage current sensor. After the sensor has been assembled, all inner space is filled with epoxy resin.
10.4 Current Relays with Independent “Time-Delays”

10.4.1 Relays with Integrated Clockwork

When protective relays began to be used in the power industry it became clear that just instantaneous relays are not enough for effective protection. As mentioned above, only a set of relays with different and at the same time matched pick-up currents, and different TDs, can provide selectivity of protection on long power lines.

Already at the beginning of the last century direct-action relays (that is relays directly affecting the driving gear of the switching apparatus), with the simplest integrated clockwork providing the required TD, were produced (Figure 10.61). The pick-up time of such a relay is determined by the balance of three constituents: power of attraction of the armature to the core, opposing force of the spring, and the position of the lower end of the spring depending on the anchor clockwork.

The Anchor mechanism (anchor) (Figure 10.62) consists of an anchor wheel, a fork, and a balance (double pendulum) — the part of the clockwork transforming energy from the main part of the driving wheel (in clocks — a spring) to pulses transmitted to the balance to maintain a strictly determined oscillation period necessary for uniform rotation of the pinion mechanism.

The principle ideas of such mechanisms were laid already in the 17th century, but its modern design derives from efforts in the 18th and 19th centuries of many watchmakers, the especially distinguished ones being Abraham-Lui Breget and Jorge Leshaut. Even the famous playwright Pierre Ogusten Bomarschet turned his attention to improvement of this mechanism — the main clock unit, determining its accuracy.

When the running torque affects this mechanism from the direction of the driving wheel, the anchor fork (3) moves the teeth of the anchor wheel (4) one by one at a certain speed that
Spring was selected in such a way that the electromagnetic torque developed by the coil was enough for full overcoming of its resistance at high current ratios only (more than 2 to 3). In this case, the armature overcame the resistance of the spring and was immediately attracted to the pole of the magnetic core before the clockwork started operating. At currents in the coil equaling 1.1 to 1.5 of the nominal value the armature began moving but the relay was not activated because of increasing resistance of the spring. The lower end of the spring activates the anchor mechanism which slowly releases the lower end of the spring by reducing its tension and allowing the armature to go on moving. The speed of the lower end of the spring is constant and does not depend much on the tautness of the spring. Obviously, when initial current is strong in the relay winding, the degree of the initial

![Anchor clockwork](image)

**FIGURE 10.62**

Anchor clockwork. 1 — Driving wheel; 2 — balance-wheel; 3 — anchor fork; 5 — ratchet spring; 6 — ratchet-wheel; 7 — pinion.

...does not depend (much) on the running torque. In this relay, shown in Figure 10.61, the spring was selected in such a way that the electromagnetic torque developed by the coil was enough for full overcoming of its resistance at high current ratios only (more than 2 to 3). In this case, the armature overcame the resistance of the spring and was immediately attracted to the pole of the magnetic core before the clockwork started operating. At currents in the coil equaling 1.1 to 1.5 of the nominal value the armature began moving but the relay was not activated because of increasing resistance of the spring. The lower end of the spring activates the anchor mechanism which slowly releases the lower end of the spring by reducing its tension and allowing the armature to go on moving. The speed of the lower end of the spring is constant and does not depend much on the tautness of the spring. Obviously, when initial current is strong in the relay winding, the degree of the initial

![KAM-type direct-action current relay](image)

**FIGURE 10.63**

KAM-type direct-action current relay with an integrated clockwork (1937, “Elektroapparat” plant, Russia). 1 — Magnetic core; 2 — stopper; 3 — current coil; 4 — striker-pin; 5 — retractable armature (hollow cylinder); 6 — spring; 9 — rack; 8 — space for the clockwork; 10 — cover; 11 — breaking shaft; 12 — rod of the breaking shaft; 13 — ratchet-wheel; 14 — anchor mechanism; 15 — pendulum.
tension of the spring will be greater and the armature will move closer to the pole of the magnetic core. This means that at high current the armature has less travel to its final position which is why the time of operation of the anchor mechanism, releasing the end of the spring at a constant speed, will be less, meaning that the TD of the relay (until its complete pick-up) will be less.

Relays with similar principles of operation (only not of clapper type, but with a retractable armature) were produced in the 1930s in the former U.S.S.R. by the Leningrad plant “Electroapparat” (Figure 10.63). In this relay when current equaling or exceeding setting current passes through the coil (3), the armature (5) starts going up into the coil and also carries the striker-pin (4) through the spring (6). As this pin is linked with the rack of the clockwork, it slows down movements of the armature in the upper direction, as in the example considered above. When the armature (5) reaches its extreme upper position, it turns the rod (12) of the shaft (11) with the help of the striker (4) and the shaft turns and releases the latch of the trip, thus putting into action the breaking mechanism of the switch. At high current ratios, the armature immediately reaches its top position and activates the breaking mechanism of the switch with the help of the striker-pin (4). Thus the relay has two areas on its time characteristic (Figure 10.64): a TD dependent on the current and a constant delay caused by mechanical displacement of construction elements.

The relay coil has several taps and by switching of them, one can choose one of the characteristics. In addition, by displacing the whole clockwork up or down of the rod (7) one can change the TD value of the clockwork. Release ratio of the relay in the dependent part of the characteristic equals 0.6 to 0.8, and for work in the independent part of the characteristic — 0.8 to 0.9. Minimal pick-up time in such construction of the relay is 0.7 sec in the independent part of the characteristic and almost 1 sec in the dependent one. These are quite high values (several times higher than modern protective systems provide) for effective protection. The KAM relay was produced until 1940, when it was slightly modified and was produced commercially in the U.S.S.R. by several plants under the names RTB, RTM, and RMB. The problem of low performance remained in all of these relays.

Strange as it might seem, nowadays that computers and microprocessors are widely used in relay equipment, the RTB relay with its almost 70-year history (basically a KAM relay with an enhanced clockwork) is still produced toady, by the Repair Enterprise Lenenergo (St Petersburg, Russia).

Some current relays produced contain such a set of elements in their construction that it may be difficult to define to what class of relays they belong to. For example, the primary direct-action relay of the MUT-1 type (Figure 10.65) contains an integrated CT, an
instantaneous element, a TD element based on a synchronous motor, and a thermal (bimetal based) element. The nominal current of the MUT-1 relay lies within 1.5 to 300 A, the adjuster of current ratio of instantaneous cutoff — within 2 to 20, pick-up current of the thermal element — within 0.9 to 2.5 of the nominal current, and pick-up time of the thermal element — 15 to 120 min.

In the 1960–70’s many leading companies produced indirect-action current relays with an integrated clockwork. A typical example of such a relay is the widespread RSZ 3gk heavy device (its size is 342 × 165 × 152 mm and its weight 6.8 kg), containing three current units with independent adjusting consisting of clockwork, three units with adjustable instantaneous pick-up thresholds and the clockwork itself (Figure 10.66).

Current relays (or units of relays) with a TD are usually indicated by the symbol $I_>$ and instantaneous relays (or units of relays) by the symbol $I\gg$. These symbols are quite logical and easily memorized. The former characterized the relay picks up at a current exceeding a certain value (as a rule this is a relay with a TD) and the latter characterized the relay picks up at a current much exceeding a preset value (this is a characteristic of instantaneous relays). Relays of maximum and minimum voltage are marked similarly ($U_>$, $U<$).