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CURRENT-OVERLOAD PROTECTION IN HIGH-VOLTAGE EQUIPMENT

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In the past decade, extensive use has been made of equipment operating at high voltages (10-100 kV) – in particular, military and civilian radar stations, powerful signal transmitters for communications, radio, and TV systems, industrial lasers, X-ray equipment, powerful electron–ion technological units, equipment for inductive heating and melting of metals, industrial electron accelerators for irradiating materials, and electrophysical equipment.

Despite considerable progress in developing such equipment, there is still a pressing need for systems protecting such equipment from current overloads due to breakdown of the insulation on high-voltage leads or breakdown within high-voltage instruments. The former is due to challenging operating conditions and the penetration of moisture and dust into the equipment; the latter is due to unpredictable internal failure of the high-voltage vacuum electronic devices (klystrons, tetrodes, etc.) used in such equipment, failure of the semiconductor components of the high-voltage rectifiers, etc.

Traditionally, current-overload protection in such equipment is based on the use of current sensors and electronic relays in low-voltage or grounded circuits. However, such protection is by no means always effective. Some of the problems associated with this approach are as follows.

1. Complex equipment contains not one but several high-voltage circuits, often with different potentials relative to ground, different internal resistance, and different working currents. In these conditions, it is difficult to adjust the sensor in the common ground circuit so that it is equally effective for all these circuits.

2. The need to include a current sensor in the common ground circuit imposes certain constraints on the circuit design, resulting in more complicated and more expensive equipment.

3. With deterioration in the grounding circuits (especially for mobile equipment), the sensor in this circuit is not only subjected to high voltage but serves to expose the low-voltage circuits to high voltage, with all the familiar negative consequences for the equipment itself and for the staff.

4. Internal power sources of high-voltage equipment always include a power filter with reactive components at the output, so as to smooth the pulsations of the high-voltage rectifier. On switching off such a power source on the low-voltage side (220, 380 V) of the power grid, the reactive components in the filter will continue to supply the arc at the breakdown point until they are completely discharged. If protective short-circuiting (crowbar protection) of the high-voltage power source on the high-voltage side is attempted, instead of shutdown on the low-voltage side, the components of the high-voltage rectifier and supply transformer will be seriously overloaded, with a sharply increased risk of failure.

5. The use of mass-produced pulsed high-voltage devices such as thyratrons or triggered spark gaps for such protective short-circuiting leads to other problems on account of the very small time (a few microseconds) during which the discharge current is able to flow. Such devices allow very low currents to flow for longer times. For example, the HY-3202 unit produced by EG & G Electro-Optics (United States), with high parameters (U_a = 32 kV, I_a = 20 kA), permits a mean anode current of only 0.5 A. It is difficult to organize a discharge time of a few microseconds for the powerful reactive components of the filter. Furthermore, this is by no means always feasible, since ordinary large filter capacitors do not permit large discharge currents, and therefore they may only discharge through limiting resistors, i.e., for a time greater than a few microseconds. Also, thyratrons require continuous power supply to the incandescence circuit, as for ordinary electric lamps (6.3 V, 18 A).

6. When a power source containing a powerful stepup transformer, a rectifier, and a high-capacitance smoothing filter at the output is connected to the power grid, there is a considerable power surge, overloading all these components and requiring selective detuning of the current sensor, which significantly reduces the effectiveness of the safety system.

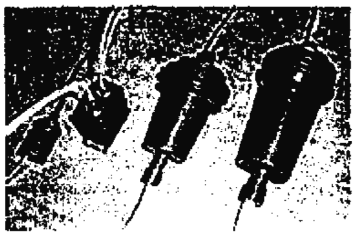

Fig. 1. IVT high-voltage insulating interfaces: from left to right, IVT-15, IVT-25, IVT-50, and IVT-70, respectively.

The development and improvement of safety systems for high-voltage equipment has been reported in [1-6] and elsewhere. Some of the devices developed are used at many Russian enterprises (such as the All-Russian Scientific-Research Institute of Radioengineering, the Antei Scientific Production Combine, the Scientific-Research Institute of Electrophysical Equipment, and the Pravdinsk radio-relay equipment plant). A new generation of such systems has been developed to address the problems noted here. These systems are in experimental operation at the Israeli concerns Optomic Lasers (in the generator supplying power to a metal-cutting laser) and ELTA (in a radar station transmitter).

The new devices include the INTERVOLTEC® series of high-voltage insulating interfaces, a series of thyristor switches controllable from these interfaces, and a series of high-voltage thyristor short-circuiting modules.

Three series of high-voltage insulating interfaces have been developed: IVT, IVT-PLS, and IVT-BUS.

The first series consists of five instruments: IVT-15, IVT-25, IVT-50, and IVT-70, for operation at dc voltages of 15, 25, 50, and 70 kV, respectively (Fig. 1). The operating principle of these devices is based on separation of the electrical and magnetic components of the electromagnetic field. Each device includes a magnetic-field source (coil), connected in the high-voltage current circuit, as well as a sealed-contact reed relay and a layer of high-voltage insulation, which is transparent to the magnetic component of the field and completely insulates the relay from the electrical component of the field.

Each instrument in the series performs four distinct functions:

1) measuring the current in the high-voltage circuit;
2) regulating the triggering threshold;
3) electrical uncoupling between the high- and low-voltage circuits;
4) acting as a high-speed output relay in a low-voltage circuit.

The leads of these instruments are made from Reynolds high-voltage wire with fluoroplastic insulation specially activated to ensure good adhesion with epoxy compound. This wire has a maximum working voltage of 30 kV with an external diameter of 3 mm. In some cases, a tube of silicon resin is also applied to the high-voltage leads. The basic insulator and all the internal structural elements are made of cast ULTEM-1000 polyetherimide plastic, with the following parameters:

Electrical strength	30
Tangent of dielectric-loss angle (1 MHz)	0.013
Dielectric constant (1 MHz)	3.15
Working temperature range, °C	(−60)-(+170)
Hardness (Rockwell)	125
Elastic modulus (psi)	475,000
Water absorption (%, 24 hr)	0.25

This material is characterized by excellent parameter stability, high chemical stability, mechanical strength, and resistance to UV and gamma radiation.

After assembly, all the internal cavities of the device are filled under vacuum with STYCAST epoxy compound, whose temperature coefficient of linear expansion is very close to that of ULTEM; its working temperature range is from −75 to +175°C; it has very good mixture fluidity and excellent electrophysical characteristics.

The components that are moved in regulating the triggering threshold are lubricated with a special electrically conducting material based on silver dissolved in oil, which prevents corona formation in the thin air gap.

Table 1 summarizes the basic parameters of IVT equipment.

Table 1

Parameter	INTERVOLTEC®			
	ICT-15	IVT-25	IVT-50	IVT-70
Rated dc voltage, kV	15	25	50	70
Test dc voltage (1 min), kV	20	35	70	90
Triggering-current range, for various models, A	*A*–0.01-0.02 *B*–0.02-0.03 *C*–0.03-0.05 *D*–0.05-0.10 *E*–0.10-0.20 *F*–0.20-0.50 *G*–0.50-1.00	*A*–0.025-0.05 *B*–0.05-0.10 *C*–0.10-0.25 *D*–0.25-0.50 *E*–0.50-1.00 *F*–1.00-2.50 *G*–2.50-5.0	*A*–0.25-0.5 *B*–0.5-1.0 *C*–1.0-3.0 *D*–2.0-5.0	*A*–0.05-0.3 *B*–0.15-0.5 *C*–0.25-2.5 *D*–1.0-5.0
Limiting current in control circuit (length 1 sec)	Ten times the maximum triggering current for each model			
Control signal power, W	0.2-0.4	0.2-0.5	0.5	0.9
Maximum switchable output-circuit voltage, V: dc ac	 600 400			
Maximum switchable output-circuit current, A	0.5			
Maximum switchable output-circuit power, W	25			
Maximum triggering frequency	100			
Maximum triggering time, msec (depending on control-circuit inductance)	0.5-1.0			
Control-circuit parameters: resistance, Ω inductance, mH	 15-1300 23-400	 1-600 0.12-900	 0.8-50 0.26-70	 0.8-50 0.26-70
Maximum dimensions, mm	Ø26×47	56×27×70	Ø75×150	Ø75×190
Mass, g	45	130	370	620

In terms of resistance to environmental factors, the equipment satisfies the US MIL-ST-202 standard and its Russian analogs All-Union State Standards GOST V20.57.406-81 and GOST V20.39.404-81 for imported equipment and aviation equipment operating at altitudes up to 15 km. For example:

Working temperature range, °C	(−55)-(+85)
Cyclic temperature variation within the range, °C	(−55)-(+85)
Moisture content of air at 40°C, %	87
Reduced air pressure at high voltage, mm Hg	87
Vibrostability for oscillations of amplitude 1.5 mm at 10-500 Hz, g	10
Multiple 2-msec mechanical impacts (10,000 impacts), g	60
Individual 11-msec semisinusoidal mechanical impacts, g/sec	30

In current-overload protection systems, IVT interfaces are usually included at a break in the high-voltage current circuit of the power supply, in series with a load at an effective current of up to 10 A (pulsed currents of amplitude up to 30 A) or connected to a shunt at currents above 2 A (Fig. 2). The low-voltage output of the interfaces is usually connected to the low-voltage thyristor contactor of a direct starter (TCDS) or soft starter (TC-soft). The interface is triggered when the current in the high-voltage circuit exceeds a specified value (Fig. 3). The triggering time of the interface depends largely on the ratio of the overload current to the rated current (I/I_{rat}); see Fig. 4.

The IVT-PLS interfaces (Fig. 5) are combined pulsed–analog units and, in contrast to IVT instruments, do not react to constant current. The IVT-PLS is triggered under the action of a current surge with large di/dt. The IVT-PLS interface has a built-in filter preventing triggering as a result of short modulation-current pulses in the circuit being monitored. Interfaces of this type may be produced for different ranges of triggering currents (from fractions of an ampere to tens of amperes); within each range, there is a triggering-threshold regulator. The IVT-PLS interface may be connected with any other IVT interface, organizing a common output circuit such that a powerful current

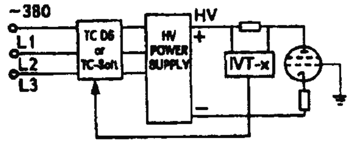

Fig. 2

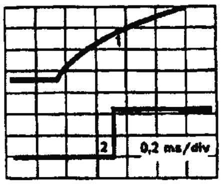

Fig. 3

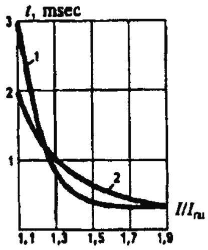

Fig. 4

Fig. 5

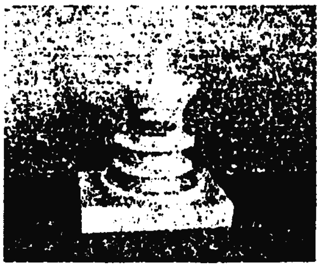

Fig. 6

Fig. 2. Typical circuit configuration of IVT interfaces.

Fig. 3. Triggering characteristic of IVT units: 1) current variation in IVT input circuit; 2) signal in IVT output circuit.

Fig. 4. Dependence of the triggering time of IVT interfaces on the ratio of the overload current I to the rated triggering current I_{ru}.

Fig. 5. External view of IVT-PLS interface.

Fig. 6. IVT-BUS interface with connectors to high-voltage bus.

pulse is formed when either interface is triggered, or two independent outputs. In the latter case, the output sealed-contact reed relay of the IVT interface controls a thyristor switch in the low-voltage circuit, while the pulsed IVT-PLS output controls both a low-voltage thyristor switch and a high-voltage thyristor short-circuiting unit. With relatively slow increase in current in the circuit, the IVT is triggered, and the low-voltage thyristor switch operates with fast

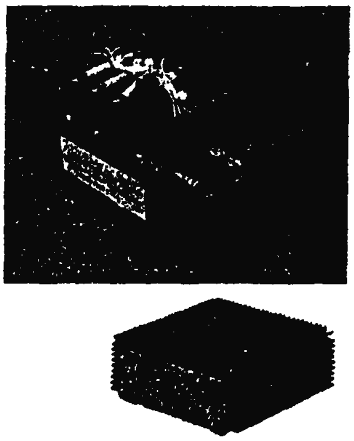

Fig. 7

Fig. 8

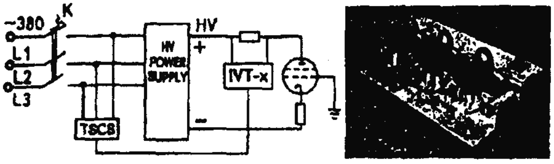

Fig. 9

Fig. 7. TCDS thyristor contactor of direct switch in open form and external view of closed radiator housing for this contactor.

Fig. 8. TC-soft soft-starting thyristor contactor before installation in radiator housing: on the left, three-phase CRYDOM thyristor contactor with current sensors; on the right, control-system printed circuits.

Fig. 9. External view and circuit configuration for TSCS thyristor short-circuiting unit.

current surges, in which the leading front is steep (as in internal breakdown), the IVT-PLS is triggered and sends control signals simultaneously to the low-voltage switch and to the high-voltage short-circuiting unit. Thus, protection of the equipment against all types of damage is ensured. The dimensions of the IVT-PLS interface are 96 × 61 × 55 mm.

The IVT-BUS interfaces (Fig. 6) are intended for use in the power industry. All these interfaces are mounted in identical dielectric housings (diameter 80 × 130 mm) and connected by special adapters (requiring no drilling of holes) to current leads with an ac voltage of 6-24 kV. These housings are intended for internal installation in substations and switching stations and are tested to determine not only the voltages (1-min and pulsed voltages) they can withstand but also the level of partial discharges.

The IVT-BUS-CD unit is a digital current sensor with a triggering threshold in the range 100-10,000 A, intended for use in automatic grid equipment [6-8].

The IVT-BUS-CA unit is a high-voltage analog current converter with a rectilinear output characteristic (Fig. 7), intended for use with electronic current meters.

The IVT-BUS-VD unit is intended for monitoring the presence of voltages in the given phase and may be used to monitor the phase losses in three-phase electrical networks, to signal grounding of the phase in grids with an insulated neutral line [9], etc.

Fig. 10

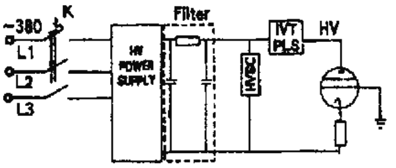

Fig. 11

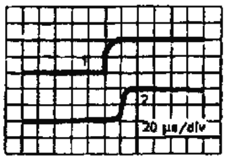

Fig. 12

Fig. 10. HVSC high-voltage thyristor short-circuiting units of rated voltage 15, 5, and 22 kV.

Fig. 11. Circuit configuration of HVSC unit.

Fig. 12. Triggering characteristic of HVSC unit controlled by IVT-PLS interface: 1) variation in current in IVT-PLS input circuit; 2) switching current of HVSC unit.

As already noted, safety systems for high-voltage equipment include not only interfaces but also semiconductor switchgear.

The simplest device is the TCDS thyristor contactor of a direct switch (Fig. 7), based on a CRYDOM three-phase thyristor module and a simple semiconductor control system for combined operation with IVT equipment. The contactor is intended to control a three-phase load with a rated voltage up to 440 V, a rated current up to 80 A, and a frequency of 50-400 Hz. The contactor is fitted with built-in current-overload protection and may be placed in a special radiator housing (Fig. 7). The load is turned on by command from any external control unit, and emergency shutdown is by command from any IVT device.

The TC-soft thyristor contactor (Fig. 8) allows the power source to be smoothly switched on, eliminating magnetization-current surges of the power transformer in the low-voltage circuit and charging-current surges of the filter in the high-voltage circuit. This unit differs from the TCDS contactor only in the presence of a special control circuit ensuring smooth variation in the switching angle of the power thyristors when the contactor is turned on.

IGBT-based power contactors are under development. Their advantage is fast shutdown (tenths of a microsecond); their disadvantage is increased size.

Another semiconductor power switch component is a low-voltage thyristor short-circuiting unit (Fig. 9), which creates an artificial short-circuit on the low-voltage side of the power source at the command of the IVT interface and thereby sharply reduces the input voltage to the power source. The duration of the short-circuit at the maximum permissible current (3-4 kA) corresponds to the triggering time of the automatic cutout K (Fig. 9). The advantages of this device over that considered previously are its markedly higher speed (of the order of 10-15 μsec) and the elimination of the radiator, since the thyristors in this device are switched off and only draw current in an emergency, for a very limited time (20-30 msec).

For rapid withdrawal of energy from the reactive components of the filter on the high-voltage side of the power source, HVSC high-voltage thyristor short-circuiting units may be used (Figs. 10 and 11); these units are developed for rated voltages of 5-25 kV and discharge currents of up to 4 kA, sustained for up to 10 msec. The energy withdrawn by such devices is several orders of magnitude greater than the energy of known gas-discharge and vacuum switch units. The total triggering time of the HVSC units controlled by an IVT-PLS interface is 20 μsec (Fig.

12).

The universal set of components described in the present work permits the creation of current-overload protection systems for high-voltage equipment that are highly effective but differ in complexity, functional capabilities, and cost. Currently, these components are being prepared for mass production in Russia, under the author's guidance.

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