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I. Introduction

As mentioned in [1], due to the way in which digital protection relays (DPR) of electric power system facilities perform their functions they constitute dangerous entry channels for intentional remote destructive impact (IRDI) into the power systems. IRDI can be qualified as:

a) Cyber attacks;

b) High Power Electromagnetic (HPEM) Threats, including High-Altitude Electromagnetic Pulse (HEMP) and Intentional Electromagnetic Interference (IEMI);

c) Function-technological (use of normal technological functions of protection relays, which were pre-set in such a way that in case of actuation without a cyber attack, for example, by activate the discrete input, the DPR will send corresponding commands to high-voltage circuit breakers, which will interfere with the normal functioning of the electric network or even the whole power system).

The IRDI can affect the DPR in the following ways:

- Create internal damage of microelectronic components accompanied by simultaneous malfunctioning of relay protection;
- Result in latent destruction of microelectronic components, which cannot be diagnosed under standard workability checks of a DPR, but which can emerge in the course of a DPR's operation as faulty performance of a specific aggregate of logical and computation operations;
- Result in the malfunctioning of DPR by interfering with its algorithm of operation (cyber attacks);
- Result in the malfunctioning of relay protection under full physical and software-based functionality of DPR (function-technological IRDI).

According to [1] there are passive and active methods of protection of DPRs from IRDI. The passive methods of protection include special broadband filters; special metal control cabinets; double and triple shielded and twisted cables; special protective paints, lacquers, films that reflect electromagnetic waves; curtains, carpets and hangings made of metallic fiber, special construction materials, which weaken electromagnetic radiation. The active methods of protection are based on a joint use of DPR and electro-mechanic protection relays (EMPR), which are more resistant to IRDI. At the same time there are two options of connecting DPR and EMPR: parallel connection and series connection [2]. The parallel connection of DPR and EMPR requires a full set of electro-mechanical protection relays designed to perform a total complex of protective functions. Moreover, this connection does not guarantee the absence of faulty and unnecessary actuations of DPR affected by IRDI. As mentioned in [1], faulty, unnecessary and abnormal actuations of DPR (the concepts offered in [3]) can result in larger damage than failures. The series connection of DPR and EMPR does not require using a full set of EMPR; however, a simple starting unit (SU) should be available. Besides, this type of connection prevents faulty and abnormal actuations of DPR affected by IRDI. This is why this type of connection is preferable. The specific example of this type of protection based on a specially designed unit with responsive electro-mechanic elements (reed switches) is described in [4, 5], Fig. 1.

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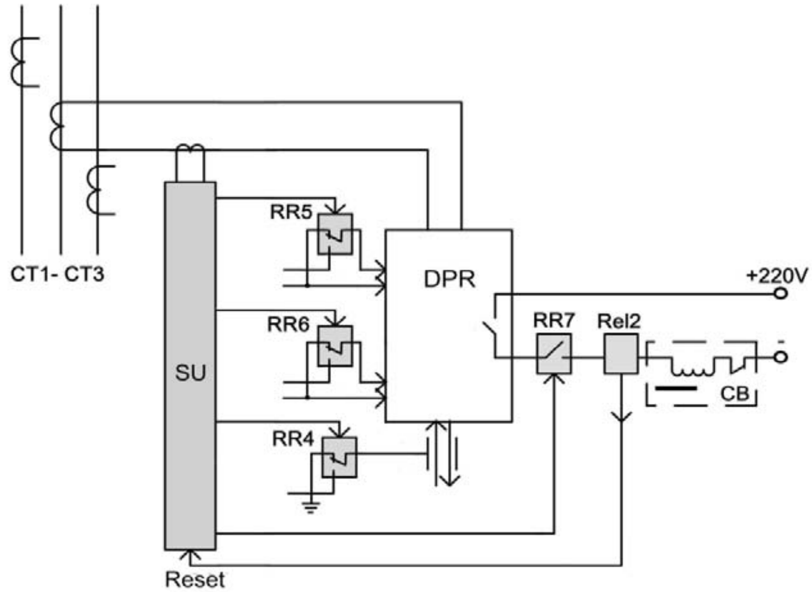

Fig. 1 : Electrical diagram of the active type unit presented in [4, 5] to protect the DPR from IRDI (SU - starting unit on the basis of a reed switch)

This device is designed to protect the DPR from function-technological IRDI – the most complicated IRDI, which cannot be controlled by any other means of protection. Obviously, the device described in [4, 5] is just an example of the concept, the purpose of which is to confirm the possibility of implementing the idea in practice, though it still needs further development, and improvement. Nevertheless, the example substantiates that the problem of DPR protection from function-technological IRDI can be successfully solved. It should be noted that the described device blocks the discrete inputs, communication and outputs of DPR in between the emergency modes, to which DPR should respond; efficiently protects it not only from function-technological IRDI, but also from internal damages, induced by powerful electro-magnetic impacts and cyber attacks affecting its sensitive inputs.

II. Protection Current and Voltage Circuits

In order to protect the DPR from internal damage related to effects of high-voltage impulses, which can get into its analogue inputs from current and voltage circuits and in order to protect the supply circuits the well known methods of improving the stability of electronic equipment to electro-magnetic impacts can be used. It should be noted that modern DPRs are already equipped with a built-in protection from these impacts, which corresponds to the requirements of the standards of electro-magnetic compatibility (EMC). However, IRDI are significantly different from electro-magnetic noises in terms of intensity and frequency range, stipulated by these standards. This is why the protection built into DPR should be significantly strengthened. This is one of the ways to improve DPR's resistance to IRDI. The other way is the use of additional external means of protection, such as passive means of protection (see above).

The elements that connect the analogue inputs of DPR with the external current and voltage circuits are the input current transformer (CT) and the voltage transformer (VT). And for this reason these elements will be affected by the powerful overloads of IRDI in the first turn. The input CT in DPR is simpler in terms of design. As a rule, this is a multi-loop secondary winding, wound on a ferromagnetic core and a primary winding, which consists of several coils of thick insulated wire, wound above insulated secondary winding, see Fig. 2.

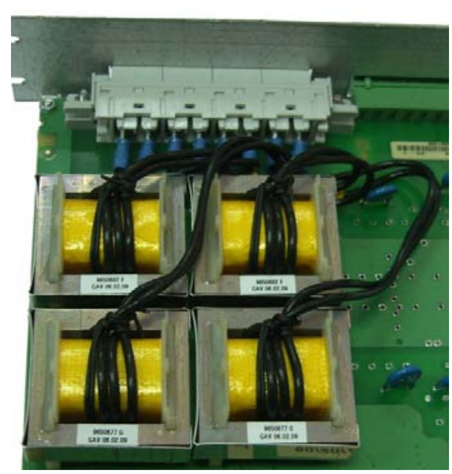

Fig. 2 : Example of a module of analogue inputs of DPR with installed CT. You can clearly see the primary winding, which consists of 4 coils of flexible insulated black wire

The methods of improvement of the structure's resistance to impacts of powerful impulse voltage are rather simple and include the following:

- Use of grounded shield (either foil or additional single-layer winding) located between the primary and the secondary windings;
- Encapsulation of the secondary winding by pouring it with epoxy resin, which will hardened in vacuum, see Fig. 3;
- Increasing insulation level between primary and secondary windings by use a wire with high-voltage insulation as the primary winding;
- Use of additional screens and semi-conducting covers, which equalize the electric field in the CT's design;
- Use of the insulated coating of CT magnetic core

There are many types of flexible wires in high-voltage insulation made of silicone, polyethylene, PTFE and rated for 10-25 kV voltage that are produced by several companies, such as: Teledyne Reynolds, Multi-contact; Allied Wire & Cable; Wiremax; Dielectric Sciences Inc., Axon' Cable, Daburn Electronics & Cable, Sumitomo Electric, Belden, Experimental design bureau of Cabel Industry, "Redkiy Cabel" LLC amongst others.

The recommendations for the improvement of resistance of VT are similar except for the fact that instead of a flexible wire with a high-voltage insulation as the primary winding, they use a winding wire with improved insulation of Class III according to IEC 60317-0-1 "Specification for particular types of winding wires – Part 0-1: General requirements – Enamelled round copper wire made of polyimide", where both coils are capsulated in vacuum.

Fig. 3 : Encapsulated current transformers with epoxy capsulated secondary winding hardened in vacuum. You can clearly see the primary winding, which consists of a single coil of flexible insulated wire

Since the increase of the cross section of the winding wire automatically results in an increase of insulation thickness and its electric strength, it is recommended to use a larger cross section wire regardless of natural increase of VT's size. Some manufacturers are producing winding wires with insulation made of polyamide, which withstands voltage 1.5 or even double voltage compared with that rated under IEC 60317-0-1. These manufacturers are, for example, P.A.R. Insulations & Wires Ltd of England, Bemka A. S. of Turkey amongst others. In order to ensure additional protection of VT, a special protective chain can be installed inside DPR on its primary winding, see Fig. 4.

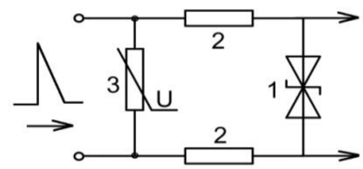

Fig. 4 : A diagram of efficient protective chain: 1 – semiconducting suppressor; 2 – current-limiting resistor; 3 – voltage depending resistor (VDR)

This chain, which contains a combination of elements with different specifications, ensures the most efficient protection from electromagnetic IRDI. In addition two low-voltage, opposite connected Zener diodes should be installed on the opposite sides of both internal VT and CT. They will restrict the voltage level of electromagnetic interference, which enters the input of an electronic circuit, if it manages to get to the secondary winding though all layers of insulation and the shield.

Usually, internal impulse power supplies of DPRs have built-in filters at the input, which include VDR, chocks and capacitors and are efficient in suppression of electromagnetic interferences, including IRDI. It is very important to equip all power supplies of DPR with these high quality filters.

III. Protection of Auxiliaru Power Supply

The measures mentioned above are related to the design of DPR and this is the responsibility of manufacturers. Besides these measures it is necessary to consider the measures of group protection of DPR, which include special relay cabinets [2] and other known measures of passive protection. Among these measures special filters need to be highlighted. They are connected at the entry ports of the voltage and current circuits into the relay room running from the external CT and VT located outside and into the AC supply circuits of the battery chargers. It should be taken into consideration that these are not just simple ordinary filters, which weaken natural electromagnetic interference, but filters that are specially designed to suppress electromagnetic impulse of a HEMP and powerful electromagnetic radiation of IRDI. Technical requirements to these filters are stipulated by military standards and reference books, such as MIL-STD-188-125 and MIL-HDBK-423.

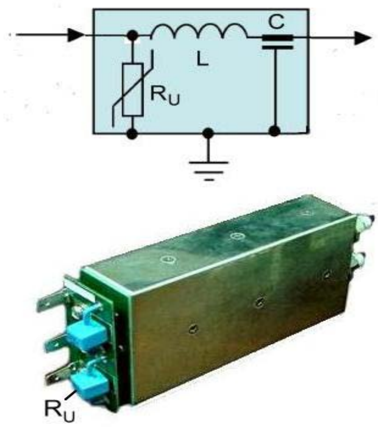

Fig. 5 : Layout of the filter and simplified circuit of one section of the filter designed to protect from IRDI. In practice the circuit contains several sections connected in series per each line. There is also a powerful varistor, $R_{U,}$ at the input of the device

These filters include kits of elements designed to suppress impulse overloads (as a rule, these are powerful VDR - varistors) and weaken high frequency signals (induced chocks connected in series and capacitors connected parallel), see Fig. 5.

The best respresentatives of such filters ensure damping of 80-100 dB of interference in a broad spectrum of frequencies: from tens of kilohertz to tens of gigahertz at full load with current ratings from tens to hundreds of Amps, see Fig. 6

Such filters are manufactured by various specialized companies, such as: ETS-Lindgren, Captor Corp., LCR Electronics, MPE, Transtector, Eurofarad, Holland Shielding System, European EMC Products Ltd., EMS Development Corp., Meteolabor, Fil-Coil, RFI Corp., Genisco Filter Corp. and others

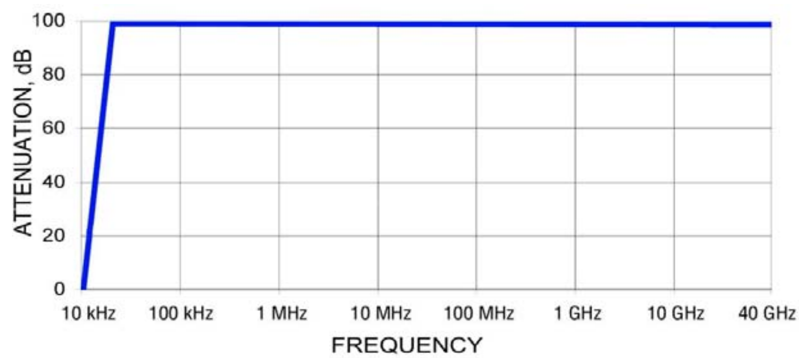

Fig. 6 : Typical frequency specification of filters designed to protect from IRDI

The filters designed for installation in the supply circuits of AC and DC current in single-phase and 3-phase consumers for current ratings from several tens of Amps to several thousands of Amps are available in the market, see Fig. 7.

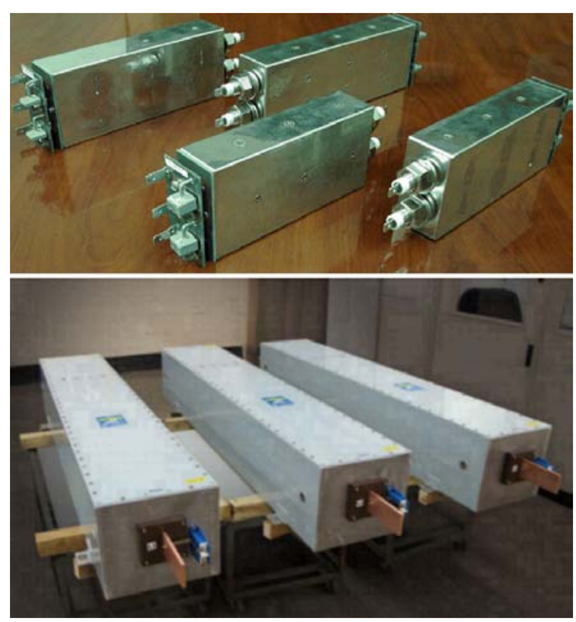

Fig. 7 : Powerful filters for supply circuits: Above - for current rating of several tens of Amps; below - for current rating above 1000 A

There are also less powerful filters for control circuits rated 1-3 A (which can be used to protect the secondary voltage circuits of external VT), see Fig. 8, as well as for communication and data transfer systems, see Fig. 9.

Fig. 8 : Filter for control circuit rated up to 1 A

Fig. 9 : Filter for communication and data transfer systems

Special devices can be used for additional protection of the system of the secondary DC power supply. They include powerful varistors and thermocouples, which disconnect the varistor and generate a signal in case the varistor damaged, see Fig. 10.

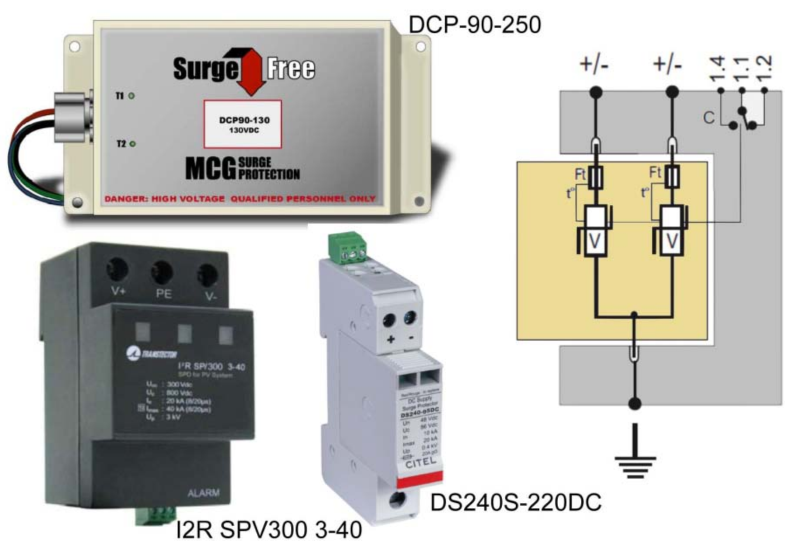

Fig. 10 : Protection devices for the system of secondary DC power supply

These devices are intended to protect the system of secondary DC power supply from impulse overloads.

IV. Conclusion

Thus, a conclusion can be made that today there are reliable methods of protection of DPR from all types of IRDI. The choice of one or another method of protection fully depends on a specific situation. The most comprehensive and efficient protection from all types of IRDI is provided by a complex protection, which includes both active and passive means of protection. It is clear that use of additional technical means will result in some degree of increase of relay protection system. However, taking into consideration that special protection from IRDI is not necessary for all the DPRs, the total cost increase of an electric power facility will not be significant. Besides, it should be taken into consideration that the use of protection from IRDI significantly increases DPR resistance to common electromagnetic interference, i.e., improves reliability of its operation not only under possible extreme conditions, but also under normal operation mode conditions.

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