A Case Study of An Analogical Distance Relay for the 110kV Electric Power Lines

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Abstract: - This article presents the basic principles of the analogical protections used for protecting the highvoltage electric lines (110 kV). A study for implementation of an analogical distance protection RD 110, for a high-voltage line is performed (a practical example). For the analogical relay the protection adjustment for an electric grid of 110 kV is presented. The distance relay is operating in association with the currentdisconnecting delayed directional homopolar protection, with the automatic rapid reclosing protection and with the synchronism relay. An analysis is achieved upon these types of analogue protections for protecting the high-voltage grids, because they are still used in practice.

Key-Words: - Electric lines, High-voltage, Analogical protections, Distance protections

1 Introduction

One of the main conditions imposed on electric installations is the safety in operation, e.g. the consumers' continuous power supply.

Ensuring the electric installation's operation without interruption has a special importance, both because the consequences of the disturbances in operation could be very severe, and that the electric installations are more exposed to faults than other kind of installations [1, 2].

The gravity of the consequences comes first from the fact that a defect which appears in an electroenergetic system can affect the entire system's operation and, second, can lead to extremely high destructive effects [3].

In high-voltage electric grids various protections are used, among which the distance protections have an important role [1, 4].

The main role of the relay protection and the automations used in electro-energetic fields consists in limiting the effects of the faults that appear and ensuring the consumers' continuous power supply.

Protection by relays of an electric installation is formed by the totality apparatus and devices destined to ensure automatically the disconnection of the installation in case of an occurring or an abnormal operation regime, dangerous for the installation; in case of defects and abnormal regimes that do not represent an immediate danger, the relay protection does not trigger the installation's disconnection, but signals the abnormal regime's occurrence.

The world's trend in the field of high-voltage relay protection is to replace the analogue protections with digital ones [5, 6, 7, 8].

Still, there are many practical applications using the analogue protections for the protection of the high-voltage electric grids. For this reason, a careful analysis of the utilization and adjustment possibilities must be made [9, 10].

Disconnection is achieved by commanding the activation of the switches that connect the protected equipment to the other elements of the energetic system.

The automatic separation of the fault installation from the rest of the electric system has three objectives:

- to prevent the expansion of the defect, respectively the extension of its effects on other installations from the electric system;

- to prevent the damage on the installation where the defect appeared, by rapid interruption of all possibilities of propagating the fault;

- to establish a normal operation regime for the rest of the electric system, thus ensuring better conditions for the continuity of the consumers' supply.

From the above, it results an important particularity of the electric and electronic protections: from the total possible states in which these can operate, monitoring the operation of the electric elements, the protections should distinguish accurately two situations, the normal operation regime and the fault regime. The protections should act only in the last case and isolate the electric equipment from the rest of the system.

From here it results that in the protections' operation intervene long "stand-by" periods in which these should be able to drive correctly.

The protections contribute to ensuring the following operation requirements of electric equipment: continuity and safety in operation, high quality of the supplied electric power as well as the integrity of the component equipment. In order to fulfil these requirements, the protections should have a high safety degree in operation, rapidity and to satisfy also other conditions: selectivity and sensitivity.

The base conditions mentioned above can only be fulfilled using relatively simple elements: with discontinuous action e.g. relays with dynamic commutation (electromechanical relays) or static commutation (electronic relays or with magnetic elements). In the last two decades, there have appeared and developed digital protection systems and with computers.

2. Performances imposed to the electric systems' protections

Due to the complexity of the problems that should be solved by the protections used for protecting the electric equipments, those are imposed a series of conditions, among which the most important are: selectivity, sensitivity, rapidity and safety in operation.

Selectivity

By selectivity of a protection is understood its capacity to disconnect the electric equipment from the rest of the electric grid, when the fault has appeared, by means of the closest switches. In case when, from certain reasons, this cannot be achieved, the protections should isolate the fault by disconnecting other switches, in such way to be disconnected as fewer consumers possible.

An energetic system can be divided in protected areas for:

- synchronous generators;

- transformers;

- collecting bars;

- electric transport and distribution lines;

- electric motors.

Achievement of the selectivity condition imposes the protections the following:

- to act at faults in the protected equipment;

- to not act at faults from the neighbour electric

elements, leaving the possibility to liquidate the fault by their protections, but not being prepared to act if the fault was not liquidated.

For the protections against abnormal regimes, that act at signalling, by selectivity is understood their capacity to indicate precisely to the working personnel the equipment that must be monitored.

The selectivity condition is achieved by different means. At some protections, this condition is fulfilled by the operation principle itself, like in case of differential protections, which are also called protections absolutely selective. The major protections act also on the neighbour elements, and the selectivity condition is obtained by introducing of some additional means as delay elements and/or directional elements.

Sensitivity

By sensitivity of a protection is understood the capacity of that protection to act to all faults for which it was provided, regardless the values of the monitored electric measures (currents, voltages, impedances) by means of which is determined the moment when the fault appeared. The problem of the sensitivity of a protection is put for that domain of the above mentioned electric measures, situated in the neighbourhood of the normal operation regime of the electric equipment.

Sensitivity of a protection is evaluated by means of the sensitivity coefficient. For the maximal current protections, the sensitivity coefficient represents the ratio between the minimum value of the calculated short-circuit current I_{scminc} (for which the protection should act) and the value of the protection's star-up current I_{pp} (for which the protection acts):

$$k_s = \frac{I_{sc\,min\,c}}{I_{pp}} \tag{1}$$

The current I_{scminc} is calculated from the concrete operating conditions of the protected equipment, at a time equal with the one for driving the protection, in case of a metallic short-circuit, in the limit zone where the protection should act, and the current I_{pp} is determined depending on the protection type and its concrete operation conditions.

Due to neglecting of the active components of the impedances of the short-circuit loops, the real short-circuit current's value I_{scminr} from the protected equipment is smaller than the one determined by calculation:

$$I_{scminr} < I_{scminc} \tag{2}$$

The current protection should act also at the minimum value of the real short-circuit current, e.g.: $I_{pp} = I_{scminr}$ (3) By the (2),(3), expression (1) of the sensitivity coefficient becomes:

$$k_s = \frac{I_{sc\,min\,c}}{I_{sc\,min\,r}} > 1 \tag{4}$$

As result, the value of k_s for the maximal current protections should be always more than 1. For different concrete situations, the values of k_s are imposed by norms for each protection type.

Rapidity

Rapidity is one of the most important conditions that the protections should fulfil, first the ones mounted on the protected equipments that operate at high and very high voltages.

This condition is determined by the multiple implications and consequences of the delayed disconnection of the equipment where the fault was produced, both on this one and on the electric system's operation.

The danger of losing the stability of operation in parallel of the synchronous generators during shortcircuits is the most dangerous emergency in electric systems. In case of short-circuits, it takes place the discharge of active power of the synchronous generators, depending on the fault's type (the most at the three-phased short-circuit and the less at the single-phased one) as well as the distance from the generator to the defect (the maximum discharge takes place at the terminals' short-circuit). If the short-circuit is liquidated in a sufficiently small time, the danger of getting out from synchronicity of the synchronous generators is reduced, the more the disconnecting time is more reduced. The supply voltage of the consumers from the area is reduced during short-circuit.

The energetic equipments travelled by the shortcircuit currents, as well as the element in which the fault appeared, are affected by the thermal and electro-dynamic effects of the currents, as well as by the electric arc from the fault's place, in a measure the more reduced as the short-circuit is liquidated in a shorter time.

In presence of a rapid protection is increased also the efficiency of other automation installations from the system. It's the case of the rapid automatic reset installations. In conditions of a rapid protection, that limits the fault's extension and favours the extinction of the electric arc, for the environment's de-ionization remains a greater time, which improves the probability of the reset's success. *Safety*

By the safety of a protection is understood its capacity to act always correctly, than and only when are fulfilled the actuating conditions and never without these conditions. In this way can be defined the actuation's safety and the non-actuation's safety. The safety condition can be improved by using of some specific measures.

In the protections' designing phase should be aimed diagrams as simpler possible, achieved with equipment with high reliability degree in operation. Moreover, beside the base protection will be provided, when the case, also local spare protections and/or distance spare protections.

In the protections' execution-mounting phase, the electric and mechanical mounting operations should be of best quality, in order to exclude the conductors' interruptions, short-circuits between them as well as also the wrong actuation of the relays due to vibrations.

In the operation phase, the checking, repair and adjusting operations should be of best quality and executed at the planned terms or anytime necessary.

3. Principles of Analogical Distance Relay

3.1. Operation principles

Fig.1 presents an example of high-voltage electric grid that contains equipments that can be protected.



Fig.1. Example of protected electric equipments

The protected areas of these equipments' protections are delimited by dotted line. In fig.1: M- motor; B – high voltage bar; Tr – transformer (high voltage/medium voltage); L - high voltage line; G – generator [1].

In fig.2 the automatic protection system for an electrical equipment is presented. In fig.2: CT - current transformers, VT - voltage transformers, IB - input block, PDB - processing and decision block,





Fig. 2. Automatic protection system for an electrical equipment



Fig.3. Three-phase high-voltage circuit breaker of 110 kV from an electric power station – old constructive version



Fig.4 Three-phase high-voltage circuit breaker of 110 kV from an electric power station – modern constructive version

A distance protection is an universal protection, that can be used in grids of any configuration. Distance protection is a protection that measures the distance between the protection's mounting place of and the place of defect, controlling the switch's activation, thus the interruption of the deffective suply with a delay as big as the distance to the place of the fault. Thus, the distance protection's acting time depends on the distance between the protection's mouniting place and the place of the defect.



This variation of time depending on distance can be linear or in steps, the last being used exclusively in distance protections, because it allows better lagging of the protections characteristics of different lines from a grid and leads in general to smaller disconnecting times [7].

From fig.5 is found that for a distance smaller than l_1 , the activation is produced rapidly, at time t_1 . This is called the protection's step I of time, and the distance l₁ the zone I or its distance step I. A defect produced at a distance bigger than l_1 but smaller than l_2 , is disconnected at time t_2 . The distance l_2 is the zone II or step II of the protection's distance, and time t_2 – the $\hat{\Pi}^{nd}$ step of time. In a similar way the next distance and time steps are defined. Both the distance and the time steps are adjustable. The distance relays, regardless of their constructive principle, show erors both in determining the distance up to the defect location, and in delaying the drive. The error in appreciating the distance does not exceed in general 20%, which must be taken into account when chosing the protection's characteristic. If these errors would not be taken into account, zone I of the distance protection would be chosen as equal to the line's length, this leading to the rapid disconnection of the defects on the entire line's length. Due to the error in appreciating the there is the possibility of rapid distance. disconnection also of defects that apppear on other lines, in the immediate vecinity of the bars from the station at the other end of the protected line.

For this reason, step I of the distance protection is adjusted usually at only 80% from the protected line's length.



Fig.6. Protection characteristic of the distance protection – example

Fig.6 represents an example of achieving a protection by distance relays with characteristics in steps, into a grid supplied by both ends.

In case of a defect in point K_1 , the line's disconnection is produced rapidly by both line's ends. In case of a defect in K_2 , switch 5 will activate rapidly, and the protection of switch 2 will activate in the IInd step.

If the switch or the protection refuses to operate in case of a defect on the line, it activates the switch of the neighbour line, at the command of the distance protection with the time of the IInd or IIIrd step, after the shortcircuit's location.

The distance protection of a line consists meanwhile also in spare protection for the adjacent elements of the neighbor lines.

Fig.7.a presents the connecting mode (principle) of a distance protection, with current transformers and voltage transformers, for a high-voltage line. Fig.7.b presents the protection characteristic Z depending on U_p with the three distinct zones: normal operation, operation in maximum load regime and operation in shortcircuit regime. The protection characteristics of the distance relay are presented in fig.7.c where the relay's acting zone is presented. The protection acts for $Z_1 < Z_2$.

The constructive principles based on which distance protections are different.

One of the most used distance protections is the impedance protection [1].

The operation principle of one of the most simple impedance relays of "electromagnetic balance" type is presented in fig.8.

The "electromagnetic balance" is composed from two electromagnetic relays of which mobile armatures are fixed each at one end of a lever that can rotate around an axis; one of the relays being supplied by the voltage:



Fig.7. Distance protection: a. Connecting mode;
b. Protection characteristic Z depending on U_p;
c. Protection's drive characteristic



Fig.8. Impedance relay of "electromagnetic balance" type

 U_1 being the line's voltage between phases, in the protection's installation's point; n_{VT} –transformation ratio of the voltage transformer), and the other relay is supplied by the secondary line current:

$$I_r = \frac{I_l}{n_{CT}} \tag{6}$$

 I_1 being the line's current and n_{CT} – transformation ratio of the current transformer. The forces exerted on the armatures of these realys create some moments that act in oposite senses upon the lever.

Because the relays being are electromagnetic, the moment exerted by the relay exerted by the current transformer has the expression:

$$M_{I} = K_{I} \cdot I_{r}^{2} = K_{I} \cdot I_{L}^{2} / n_{TC}^{2}$$
(7)

where K_I is a proportionality coefficient, and the moment exerted by the relay supplied by the voltage transformer has the expression:

$$M_{U} = K_{U} \cdot U_{r}^{2} = K_{U} \cdot U_{L}^{2} / n_{TC}^{2}$$
(8)

As can be seen from fig.6, the moment M_U trends to keep open the contacts of the impedance relay, and the moment M_I trends to close them. One can notice that the contacts' closing and, therefore, the activation of the line's switch is produced when M_I $\ge M_{IL}$.

$$K_I I_r^2 \ge K_U U_r^2 \tag{9}$$

respectively:

$$\frac{U_r}{I_r} \le \sqrt{\frac{K_I}{K_U}} \tag{10}$$

Noting by $Z_r = U_r/I_r$ the impedance seized by the relay (sometimes called also measured impedance, respectively relay constant impedance), and by:

$$Z_{pr} = \sqrt{\frac{K_I}{K_U}} \tag{11}$$

the relay's start-up impedance, the drive condition (10) becomes:

$$Z_r \le Z_{pr} \tag{12}$$

The drive characteristic on the diagram R-X is a circle with the centre in origin and radius equal with the adjusted impedance Z_r .

In normal regime, when voltages U_l and U_r are close to the their nominal values, and currents I_l and I_r correspond to the line load, the relay is adjusted not to act, resulting in this case $Z_r > Z_{pr}$.

3.2. The electric arc's influence at the shortcircuit place on the distance protection's operation

By describing of different constructive types of impedance relays and the by actuation characteristics, has resulted that their operation is determined by their distance up to the fault's place, if the short-circuit loop's impedance between the installation place of the relay and the fault's place is strictly proportional with this distance. The proportionality is, however, valid only in case of firm short-circuits. In case of short-circuit with resistance to fault, the short-circuit loop's impedance does not depend exclusively on the line's characteristics, but also by the value of this resistance, so it's not anymore a measure of distance.

At electric lines, especially the aerial ones, the major part of short-circuits are not metallic but by electric arc. Therefore, exactly in major part of the cases, determination of the impedance by the impedance relays is miscounted. The electric arc's resistance that intervene in determining the shortcircuit loop's impedance does not have a constant value, but varies by its length and by the value of the short-circuit current.

4. The distance relay RD 110

4.1. Relay's characteristics

The distance relay RD 110 is part of the family of classic (analogue) distance protections, built during 1975-1980. They are still used today for the protection of high-voltage electric grids. The relay was built by the EAW-Treptov Berlin Company, in DDR. It's a newer model of the versions RD 7 and RD10, the improvements brought to the model RD 110 being in the oscillations blocking part [11].

Increasing of the installed power, of the volume of transport and distribution lines and the multitude of events in the system made that the version RD 110 to support some adaptations in the part of selecting a

voltage of defect, of the internal angle (directional relay).

In Hunedoara area (Romania), in the last century, once with development of the steel industry, took place also the development of the power distribution grids on the part of 110kV, fact which imposed the utilization of the distance relays.



Fig.9. The distance relay RD 110

The distance relay RD 110 has more elements [11]: - start-up elements of maximum current;

- start-up elements of minimum impedance;

- start-up elements of minimum impedance,

- measuring element - a very sensitive relay with rotating coil, of magneto-electric type - in electric balance assembly;

- directional element - a sensitive relay with mobile coil;

- d.c. motor of which rotating speed is kept constant even at great voltage variations, due to a centrifugal regulator that acts in the electric circuit. This motor, together with the cam axle provided with contacts and driven by an electromagnetic coupling, ensures the protection's delay. There are 5 time steps which can be adjusted independently and continuous from 0.3, ..., 10 s, as well as on the value ∞ ;



Fig.10. Distance protection front panel RD 110 – detail



Fig.11. Constructive detail of the distance protection RD 110

- auxiliary relays which, by their contacts, ensure the selection of the defect phase for supplying the voltage circuit of the measuring relay;

- the contacts of the final intermediary relays, is control the activation of the protected element's switch and signalizing the protection's operation;

- relay that signals the power's reverse sense of circulation, thus blocking the distance protection by its directional element;

- auxiliary relay for bringing the defect in the drive area;

- the LED for signalling the presence of the continuous voltage;

- auxiliary relays that condition the measuring relay's operation by a previous operation of the start-up element;

- 5-digit counter, where the number of start-ups can be read;

- oscillations blocking relay; blocking against wrong

drive at oscillations; enters in operation if the startup relays from the 3 phases are acting (without driving the homopolar current relay) and the activation command is not sent in 100 ms from start-up;

- auxiliary relays with two windings (working and reclosing), and a locking-in contact having the role to prevent the relays' contacts from wear;

- signal LED for indicating the existence of threephased voltages; at the disappearance of one or two phases, as well as at the reverse succession, the LED goes off;

- commutation device (straps) that helps at modification of the impedance brought by the relay and can be established for the values 1 or 0.5;

- strap by which can be modified the reaction depending on the line's angle 0° , 60° , 70° , 80° ;



Fig.12. Fine tuning of the protection's adjustment domains



Fig.13. Rough tuning of the protection's adjustment domains



Fig. 14. Maximal current relays from the distance protection RD 110 for the three phases (minimum 4A, maximum 10 A) and null (minimum 2A, maximum 5 A)

- resistances (shunts) connected in the current circuit (star-connection). On these resistances the voltage drops which go to the selection diagram are collected;

- separation transformer provided with plugs, that allows the earth factor's adjustment from 45% to 155%;

- strap that makes possible the commutation of the selection diagram for the cyclic system preferential (R before S and T) or acyclic (T before S, S before R), necessary in the protection's operation at double groundings in compensated grids, thus ensuring the disconnection of only one of the two lines;

- strap by which the positive drive sense of the directional relay is modified;

- strap that conditions or not the drive in 4th step from the power's circulation sense;

- strap that has the role to remove the blocking t oscillations from the diagram's circuit, by shunting a contact;

- fix resistances, staggered in steps, provided for the loop impedance's adjustment.

4.2. Adjustment of the RD 110 protection for an electric grid of 110 kV

The analyzed line's characteristics (110kV) are [12]: - line's electric length: 23.069 km;

- number of pillars: 82 out of which 61 for supporting the double circuit and 21 pillars for anchoring the double circuit;

- soil's quality: dry earth, stone, sterile;
- there are no overcrossings and parallelisms.
- The electric measures that feature the analyzed line:
- current transformers type TECU 600/5/5/5;
- voltage transformers type TEMU 110/0.1/0.1/0.1;
- earth factor kg = 80%;

- line's short-circuit angle: 70°;

- maximum power that can be transported on the line P_{max} =60 MW;

- maximum angle of the maximum load in normal regime 38° inductive regime;

- short-circuit power with connected autotransformer: 2105.634 MW;

- short-circuit power with disconnected autotransformer: 1845.877 MW.

Adjustments of the related protections LEA 110kV: *Distance protection*:

- primary impedance on phase: $X_1=4 \Omega$;

- delaying steps:

 $X_{3}=22 \Omega.$ $t_{1}=0 s;$ $t_{2}=0.5 s;$ $t_{3}=1 s;$ $t_{4}=3.5 s.$

 $X_2 = 13 \Omega;$

- adjustment resistances' values:

 $R_1 = 0.65 \Omega;$

 $R_2 = 1.95 \Omega;$

 $R_3 = 1.9 \Omega_{.}$

passing voltages from one step to another:single-phased short-circuit:

U₁₀= 4.0 V; U₂₀=13.2 V;

- $U_{20} = 13.2 \text{ V},$ $U_{30} = 22.2 \text{ V}.$
- bi-phased short-circuit:
 - $U_1 = 4.3 \text{ V};$
 - $U_2 = 14.3 \text{ V};$
 - $U_3 = 23.9 \text{ V}.$

Another protection used for the line's protection is the *delayed directional homopolar protection* (*with current cutting*), which is the reserve of the distance protection, achieved with static directional relay, type RDC-3, with internal angle adjusted for 110° capacitive, and two current relays type RC-2 accompanied by two time relays type Rtpa 5, with the following adjustment values:

- step I (rapid): I_{pp} = 1500 A; I_{pr} =12.5 A; t= 0.5 s;

- step II (delayed): I_{pp} =400 A; I_{pr} = 3.33 A; t=1 s. Automation of the *rapid automatic reactivation protection (RAR)* is achieved with a relay type OZ 33, manufactured in DDR by the EAW Company, the relay operating adjusted as follows:

- RAR break cycle I $t_{pRAR} = 0.8$ s;

- blocking break (time in which RAR does not operate, this period is necessary to blow-out the arc at the defect location) $t_{pbl} = 15$ s.

The synchronism's control at connecting by RAR is achieved with *synchronism relay* type RCS produced by ICEMENERG, Romania, adjusted at 35° and bar voltage of 60 V, line voltage of 100 V. The protection is supplied by a measuring group, and on the line exist only voltage transformers for the voltage's presence and supplying the synchronoscope from the control room.

The RAR controls are also achieved by two minimal relays, type RT 4S, manufactured at IRME, Romania, that monitor "lack of line's voltage" and "lack of bars' voltage". The two minimal relays are adjusted at $U_{min} = 15$ V.

The distance protection has also, the operation blocking at the voltage's disappearance achieved by a null flux relay, relay which, by its normal closed contact does not allow the distance relay's supply in case of burnt fuses.

Blocking at oscillations lasts t=0.4 s, and has as logic the three-phase start-up without null.

From studies and statistic calculations, from exploitation, results that in proportion of 85-90 % from the faults on the distribution lines where of single-phased short-circuit type (grounding).

5.Conclusion

The analog protections in the high-voltage grids are still used in practice. Careful analysis is imposed of the protection's utilization and adjustment modes. Commissioning of an analog protection is achieved much harder than of a digital protection, which is more flexible in operation. The personnel that uses and adjusts the analog protections should handle the complex phenomena from the high-voltage grids.

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