Scientific Papers of the
Institute of Electrical Power Engineering of
Wrocław University of Technology

PRESENT PROBLEMS OF POWER SYSTEM CONTROL

No 2

Wrocław 2012

dynamic thermal line rating,
*distance protection, overload, heat balance**

Łukasz STASZEWSKI*, Waldemar REBIZANT*

DISTANCE PROTECTION WITH DYNAMIC THERMAL LINE RATING ENHANCEMENT

As the worldwide analysis of recent wide area cascading failures have shown, very often the main cause of blackout was mal-operation of the third zone of a distance protection relay. The load encroachment and power swing phenomena are the two dire problems to solve when dealing with the third zone of distance protection mal-function. The vast number of blackouts could have been avoided or the consequences lowered if the distance relay had not operated due to controlled impedance encroachment.

This paper proposes a new approach to enhance the distance protection relay operation by introducing a new blocking algorithm. The algorithm is based on Dynamic Thermal Line Rating (DTLR) idea to restrain relay from tripping when conditions in electrical power system and weather conditions allow for it.

1. PRINCIPLES OF DISTANCE PROTECTION

The basic principle of distance protection involves the division of the voltage at the relaying point ($\bar{V}_R$) and the measured current ($\bar{I}_R$) phasors as it can be seen in (1). The apparent impedance calculated in this way is compared with the reach point impedance/characteristic.

$$\bar{Z}_R = \frac{\bar{V}_R}{\bar{I}_R} \tag{1}$$

If the measured impedance is lower than the relay reach, it is concluded that a fault exists on the line at a place between the relay and the reach point.

* Wrocław University of Technology, Institute of Electrical Power Engineering, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland.

A distance relay is designed to operate only for faults occurring between the relay location and the selected reach point, thus giving discrimination for faults that may occur in different line sections and making protection selectivity assured.

The reach point of a relay is the point along the line impedance that is intersected by the boundary characteristic of the relay. Since this is dependent on the ratio of voltage and current and the phase angle between them, it may be plotted on an R/X diagram as in Fig. 1. The loci of power system impedances as seen by the relay during faults, power swings and load variations may be plotted on the same diagram and in this manner the performance of the relay in the presence of system faults and other disturbances may be studied. This fact will be taken into account in this paper for zone 3 distance relay impedance characteristic encroachment to show the situations of power swing and load increase during particular system conditions and their influence on the distance relay operation.

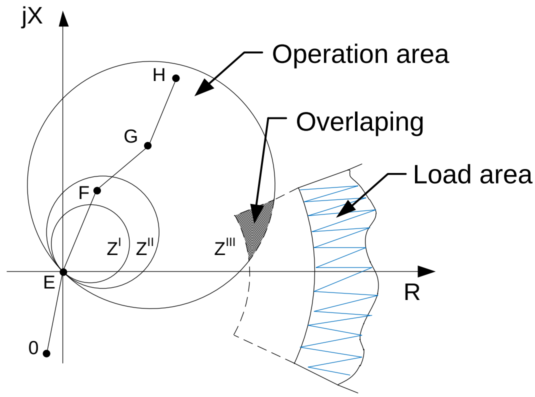

Fig. 1. Distance relay characteristic of operation for Zone 1, Zone 2 and Zone 3.

Careful selection of the reach settings and tripping times for the various zones of protection enables correct co-ordination of the distance relays on a power system. Main distance protection will comprise instantaneous directional Zone 1 and one or more time-delayed zones. Typical settings for three forward zones of basic distance protection are given as follows. Zone 1 settings of up to 85% of the protected line impedance. The resulting 15-20% safety margin ensures that there is no risk of the Zone 1 protection over-reaching due to errors in the current and voltage transformers, inaccuracies in line impedance data provided for setting purposes and errors of relay setting and measurement. Otherwise, there would be a loss of discrimination with fast operating protection on the following line section. Zone 2 of the distance protection must cover the remaining 15-20% of the line plus apart of following line section [5].

To ensure full coverage of the line with allowance for the sources of error already listed above, the reach setting of the Zone 2 protection should be at least 120% of the protected line impedance. In many applications it is common practice to set the Zone 2 reach to be equal to the protected line section +50% of the shortest adjacent line.

Remote back-up protection for all faults on adjacent lines can be provided by a third zone of protection that is time delayed to discriminate with Zone 2 protection plus circuit breaker trip time for the adjacent line. Zone 3 reach should be set to at least 1.2 times the impedance presented to the relay for a fault at the remote end of the second line section.

On interconnected power systems, the effect of fault current infeed at the remote busbars will cause the impedance seen by the relay to be much greater than the actual impedance to the fault and this needs to be taken into account when setting Zone 3. As the third zone of impedance relays with mho-characteristic covers significant part of the system and thus the impedance characteristic area is big, it is mostly vulnerable to abnormal conditions in the electrical power system operation.

The third zone is especially exposed to load encroachment, power swing and voltage instability – all three situations can lead to measured impedance entering into the Zone 3 characteristic what results in relay mal-operation and can be a leading factor causing a large scale blackouts, as it could be seen e.g. in Germany on November 4th in 2006 [6].

Despite the fact of Zone 3 setting encroachment, the system operational situation may not be dangerous and in case of load encroachment the load may be permissible due to the transmission lines loadability, and in case of power swing, after some time the system recovers to its normal operation not causing any danger during the restoration time. The important issue is to distinguish whether the encroachment is a result of fault and the relay should operate, or it is one from above-mentioned situations and the relay tripping decision should be restrained.

2. DYNAMIC THERMAL LINE RATING FOR LOAD ENCHROACHMENT

There are many various ways to avoid over-tripping due to unwanted impedance encroachment, both at the level of protection designing (characteristic shape shifting, adding restrictions) and during the relay operation (measuring additional criteria signals, e.g. zero sequence current). However, it is very difficult to predict all possible situations in a given system and all possible operation conditions, thus none of them is perfect. This paper is focused on the possibility of DTLR usage to prevent distance protection relay from tripping in situations of extreme load conditions and power swing by introducing an additional blocking signal into the standard distance relay. The blocking signal is based on the DTLR technique measuring weather conditions and calculating the overhead conductor temperature and actual conditions conductor current limit as well as the time left to reach the thermal limit.

The DTLR application aims at real time calculation of an overhead bare conductor ampacity dependent on the ambient weather conditions. The DTLR algorithm cooperates with standard protection devices (MHO distance protection relay) in order to fully utilize the transmission line by calculation of temporary current-carrying capability. The conductor temperature is calculated from the standard heat balance equation, according to the IEEE standard [3]:

$$q_c + q_r = q_s + q_i \tag{2}$$

where: q_c is a heat dissipation due to convection, q_r due to radiation, and q_s and q_r are heat gain due to solar radiation and due to Joule's law caused by the current flow, respectively. Considering the part of the total amount of heat gain and dissipation the biggest is Joule's heating and wind-forced convection cooling, the lesser are solar heat and radiated cooling.

Starting from Equations (2) and considering the conductor temperature change in time it is possible, using numerical solution, to calculate the current conductor temperature from the Equation (3) as well as the time needed for the conductor to reach its thermal limit – according to the actual current value and weather conditions:

$$\frac{dT_C}{dt} = \frac{1}{mC_p}\left[R\left(T_C\right)I^2 + q_s - q_c - q_r\right] \tag{3}$$

where: T_C is conductor temperature, m is mass of conductor and C_p is specific heat of conductor material, R is conductor resistance dependent on the conductor temperature and I is the magnitude of current flowing through the conductor.

Using the Dynamic Thermal Line Rating enhancement creates a possibility of reliability improvement of a standard distance protection relay in both load encroachment and power swing occurrences. The DTLR application introduces into a standard distance relay an additional algorithm, based on real time conductor temperature calculation, with the aim of blocking the tripping decision for some permissible time. Using Equation (3) computing there is a possibility to calculate that time and adjust the relay setting only for it. The scheme diagram of DTLR supported distance relay protection operation is presented in Fig. 2 with the new decision-restraining part. When the impedance seen by the relay encroaches the third zone of protection the restraining algorithm compares the current conductor temperature with the conductor's thermal limit and then restrain or not the tripping-decision.

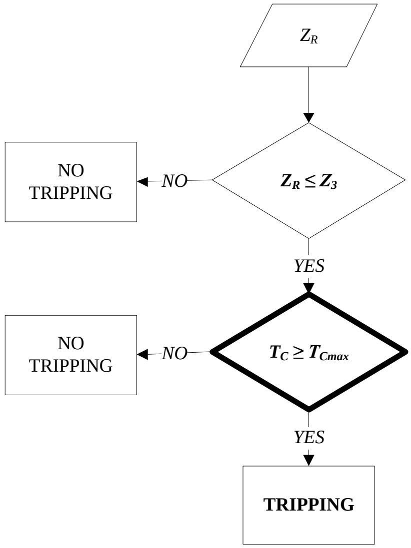

Fig. 2. Scheme diagram of a distance protection relay with additional DTLR support.

For the measurement of criteria signal of distance protection used in this study full-cycle fast Fourier transformation was applied [4].

Considering the problem of backing up the line protection from the distance relay located at one side of a multi-line terminal it must be taken into account the third zone setting would be much greater than in two-line terminal. For system arrangement as shown in Fig. 3, it is as follows:

$$Z_3 = Z_{AC} + 1.2 Z_{CP}\left(1 + \frac{I_{BC} + I_{MC} + I_{NC}}{I_{AC}}\right) \tag{4}$$

whereas in an extreme situation of equal contribution to the fault currents from all the lines the setting would be:

$$Z_3 = Z_{AC} + 4.8 Z_{CP} \tag{5}$$

This makes the third zone much bigger. For the study, taking into consideration the further case of 250km AFL 6 240 lines each, the Z_3 impedance settings for two-line terminal ($Z_{3(2)}$) and for multi-line one ($Z_{3(multi)}$) would be, respectively:

$$\begin{aligned} Z_{3(2)} &= Z_{AC} + 1.2 Z_{CP} = 235.752\Omega \\ Z_{3(multi)} &= Z_{AC} + 4.8 Z_{CP} = 621.516\Omega \end{aligned} \tag{6}$$

The multi-line substation for influence analysis of system topography on the third zone of impedance protection is illustrated below:

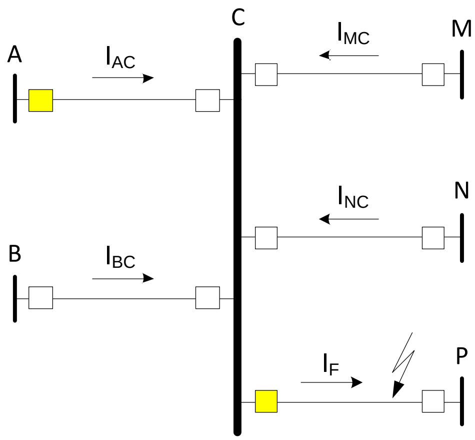

Fig. 3. Multi-line terminal (substation).

The described earlier issue has significant influence on both the system reliability and loadability. Increased zone 3 reach causes the distance relay characteristic approaching to the normal load impedance area, making possible the heavy load impedance to encroach it (Fig. 4).

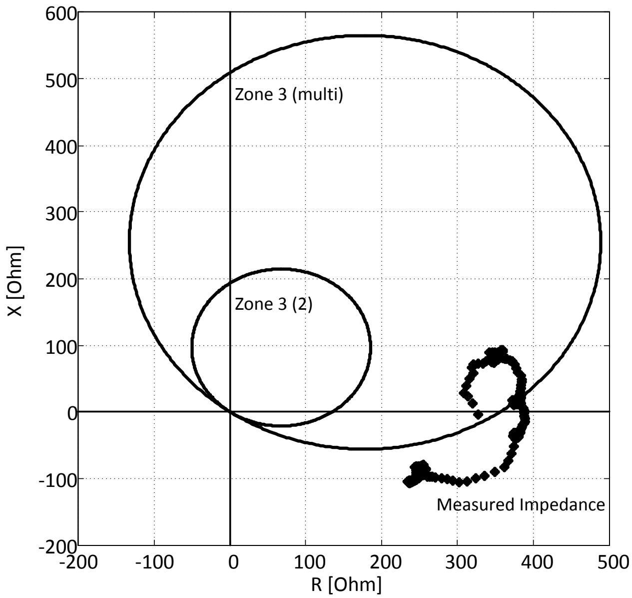

Fig. 4. Zone 3 settings for multiline and 2 lines terminal.

Allowance of the heavy load impedance to encroaching third zone and not restraining the tripping decision causes using the transmission lines not fully. The load limit lowered in comparison to the actual lines capability and also – which seems to be more dangerous – creates a possibility for the distance relay to trip the heavily loaded transmission line. This may lead to the cascading event development and maybe even lead to a blackout. This issue has been solved with use of DTLR algorithm application and the results of investigation are presented below.

The Dynamic Thermal Line Rating can be used for transmission optimization by temporary increasing current carrying capacity of transmission lines according to the weather conditions. This issue was also taken into account during the studies and therefore the simulation cases considered only the situations with both increase of load over the nominal rated level for transmission line overhead conductors and load encroachment of the third zone of the distance protection relay caused by the current increase [2].

For the sake of simulation the AFL 6 240 conductor was taken, at 110kV transmission overhead line. The AFL 6 240 conductor ratings are 645A and 745A, respectively for summer and winter, with 60 Celsius deg. of maximum allowable conductor temperature. The investigation on the load encroachment was carried out using simulation in MATLAB Simulink in a system configuration shown in Figure 3. The load changes in transmission line were simulated as follows: increase in transmission line during the summer time from about 606A to approximately 755A at 50th minute of simulation time, thus exceeding its summer rating by 110A (17%) and causing the load encroachment as in Fig. 4. The total time of simulation was 120 minutes.

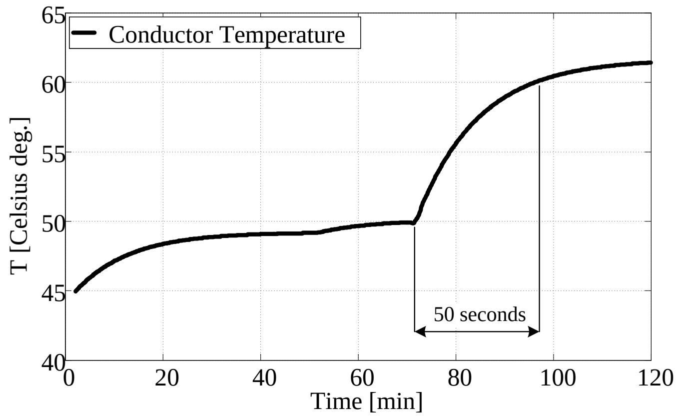

Fig. 6. Overhead transmission line conductor temperature during moderately favourable weather conditions.

In the first example, assuming moderately favourable weather conditions, the temporary conductor current rating was set to 748 A (for the 30 Celsius deg. ambient air temperature, 4.5 m/s wind speed and high solar radiation). As it can be seen in Fig. 6, the DTLR algorithm was able to handle the current increase, therefore lengthening the transmission operation time for over 25 minutes and restraining the distance protection relay from tripping the line, while still safely operated.

Despite the fact that after those 25 minutes the relay will still operate tripping the line, the DTLR algorithm can give the information to the system operator about the remaining time, thus allowing him/her to make appropriate decision about adapting the system configuration to the currents needs (e.g. turning off less important consumers).

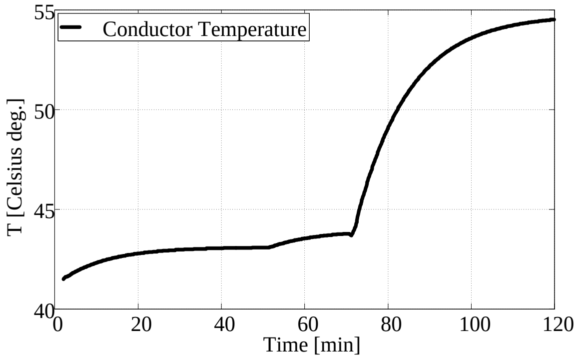

Fig. 7. Overhead transmission line conductor temperature during very favourable weather conditions.

The second example, presented in Fig. 7, is based on the same values of current, still with load encroachment occurring but with more favourable weather conditions than in the first case (for the 25 Celsius deg. ambient air temperature, 6.0 m/s wind speed and moderate solar radiation) with temporary rated current value of 791.5342A, thus allowing the transmission line to be operated continuously with the given high load. This is possible since for the given weather conditions and current values the conductor will never be able to reach its thermal limit of 60 Celsius deg.

Both described above situations show that the use of Dynamic Thermal Line Rating application makes possible the power system protection reliability and transmission efficiency to increase.

3. DYNAMIC THERMAL LINE RATING FOR POWER SWING

This section presents the DTLR application and impedance relay performance in case of a power swing. The power swing phenomenon occurs, in presented in Fig. 8 system, due to transmission line disconnection during the process of a fault clearance.

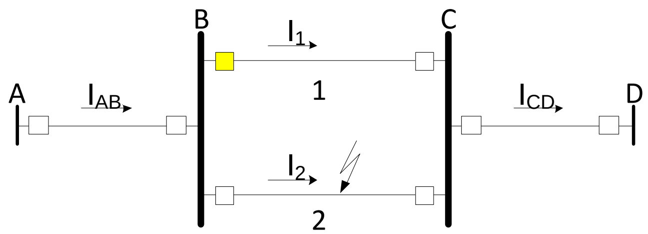

Fig. 8. Power system configuration for power swing investigation.

In a result of fault on line 2 the circuit breakers at both its ends operated and the relay impedance transients measurements occurred to be as seen in Figure 9 below:

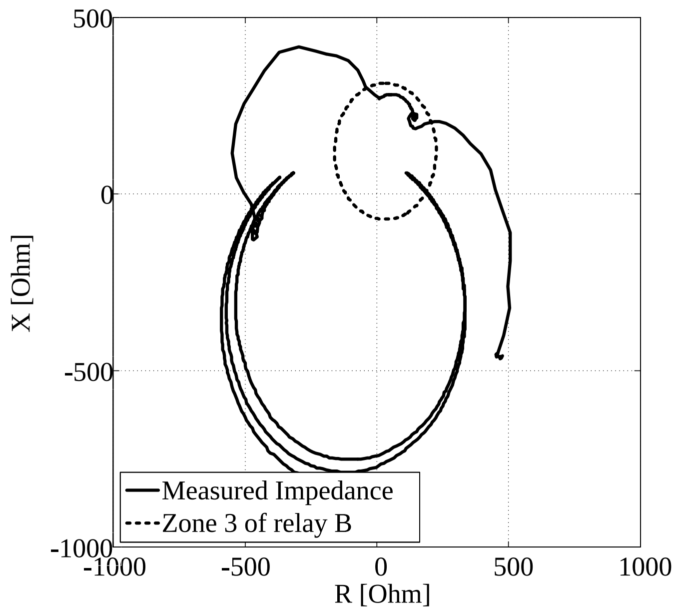

Fig. 9. Impedance during the power swing measured by the distance relay.

For the impedance trajectory as above, the standard distance relay without additional blocking would operate, tripping the line 1 and causing loss of power transmission in this area. However, application of the Dynamic Thermal Line Rating highly improves the system reliability also in this situation.

It is worth mentioning at this point that only three phase faults were considered here, because other faults can be easily distinguished from the load changes by the zero sequence presence in current and voltage signals. Thus in case of three phase faults the current ratio is very high in comparison to the normal load conditions (40 times higher or more) thus results in high value of a temperature change ratio per considered unit of time:

$$\frac{dT_C}{dt} \geq limit \tag{7}$$

where T_C is a conductor temperature, *dt* represents the temperature sampling time and *limit* stands for the value of change rate, which is different for every conductor, and its specific value will not be considered here.

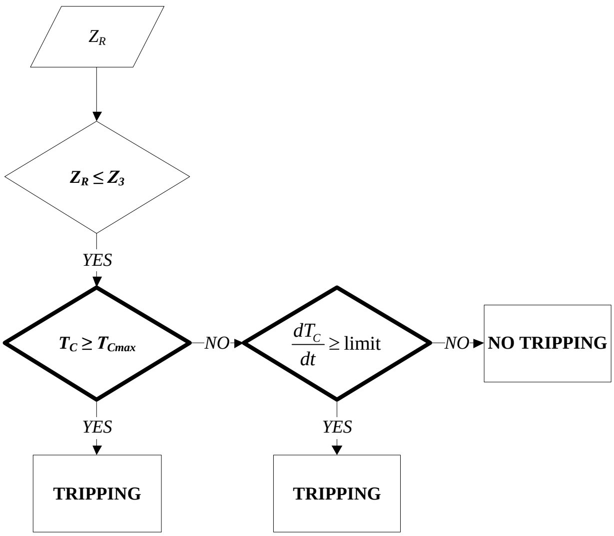

Fig. 10. Scheme diagram of improved algorithm of a distance protection relay.

Power swing problem is more complex than the previous one, and requires additional part of algorithm (Fig. 10) for the derivative calculation. First of all, combining the two facts of impedance encroachment and current values higher than the summer rating leaves no doubts that the standard relay would operate.

The standard time delay of the 3rd zone for the sake of protection selectivity is 90 cycles (50Hz – 1.8 seconds). In this case the additional algorithm which is based on a conductor temperature derivative was introduced. It can clearly distinguish the fault conditions from the load increase because of the rate of change in current values. It is well known that this value is totally different for power swing (rather low), and fault occurrence situations (rather high).

The DTLR algorithm, based on the conductor temperature calculation and the rate of its change is a way to avoid the relay operation what enables operating power system stably and safely despite of the transient situation. Figure 11 presents the thermal behaviour of the transmission line conductor during the favourable weather conditions.

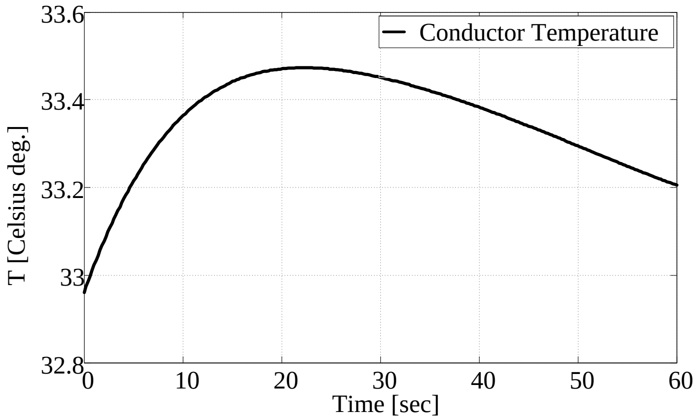

Fig. 11. Conductor temperature during power swing.

Because of the thermal time constant of a conductor, which is about 15 minutes, for the met conditions the conductor temperature does not change significantly, which results also in a low value of derivative from Equation (7). Thus, due to the favourable weather condition, the conductor does not exceed its thermal limit and because of the low temperature change ratio the presented DTLR algorithm allows safe operation.

4. CONCLUSIONS

The Dynamic Thermal Line Rating application may seem to be very good in performance, however not always. It is highly dependent on the weather conditions. When they are favourable the DTLR can perform very well and can introduce much better transmission line utilization and transmission system efficiency. It can also improve the system reliability and safety, and can sometimes act as an anti-blackout protection, avoiding unnecessary relay operation. Introduction of two additional parts of DTLR algorithm into the standard distance protection relay resulted in better performance and reliability of the relay which makes it worth considering for future transmission installation or upgrade of existing electrical power systems.

REFERENCES

[1] DOUGLASS D.A.,. EDRIS A.-A., *Field Studies of Dynamic Thermal Rating Methods For Overhead Line*", Transmission and Distribution Conference, volume 2, pp.:842–851, IEEE (1999).

[2] HOROWITZ S. H., PHADKE A. G., *Third zone revisited*, IEEE Transactions on power delivery, volume 21, pp. 23-29, (January 2006).

[3] *IEEE Standard for Calculating the Current-Temperature of Bare Overhead Conductors*, IEEE Std 738-2006 (Revision of IEEE Std 738-1993).
[4] REBIZANT W., SZAFRAN J., WISZNIEWSKI A., *Digital Signal Processing in Power System Protection and Control*, Springer Verlag, Series: Signals and Communication Technology, (London, 2011).
[6] WISZNIEWSKI A., UNGRAD H., WINKLER W., *Protection techniques in electrical energy systems*, (New York, 1995).
[4] YAMASHITA K., LI J., ZHANG P., LIU C-C., *Analysis and Control of Major Blackout Events*, IEEE (2009).