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

PRESENT PROBLEMS OF POWER SYSTEM CONTROL

3

Wrocław 2013

Cover design
Piotr PIERZ

Printed in the camera ready form

Institute of Electrical Power Engineering
Wrocław University of Technology
Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland
phone: +48 71 320 26 55, fax: +48 71 320 26 56
www: http://www.ie.pwr.wroc.pl/; e-mail: Inst.Energ@pwr.wroc.pl

OFICYNA WYDAWNICZA POLITECHNIKI WROCŁAWSKIEJ
Wybrzeże Wyspiańskiego 27, 50-370 Wrocław
http://www.oficyna.pwr.wroc.pl
e-mail: oficwyd@pwr.wroc.pl
zamawianie.ksiazek@pwr.wroc.pl

ISSN 2084-2201

Drukarnia Oficyny Wydawniczej Politechniki Wrocławskiej. Order No. 295/2013.

Dynamic Thermal Line Rating,
distance protection,
power swing, third zone

Łukasz STASZEWSKI*, Waldemar REBIZANT*

THERMAL CALCULATION FOR DISTANCE PROTECTION ENHANCEMENT

Worldwide analysis of recent wide area cascading failures has shown that very often their main cause was the mal-operation of the distance protection relay third zone. The load encroachment and power swing phenomena are the two dire problems to solve when dealing with the third zone of distance protection. The vast number of blackouts could have been avoided or the consequences lowered if the distance relay had not operated due to impedance encroachment while there was no risk of further, continuous operation.

This paper proposes a way to improve operation of the distance protection relay by introducing a new blocking algorithm that uses the Dynamic Thermal Line Rating (DTLR) to restrain relay from tripping when conditions in electrical power system allow for it.

1. DISTANCE PROTECTION RELAY

A high speed protection for transmission and distribution circuits is under continuous development. It considers the most important fact for protection devices that is to meet the requirements of combining fast fault clearance with selective tripping. Thus for many years distance protection relay has been one of the most commonly used devices amongst electrical protection equipment. Distance protection is comparatively simple to apply and can be fast in operation for faults located along the majority of protected circuit. It can also provide both primary and remote back-up functions in a single device [1].

The basic principle of operation of the distance protection relay is based on impedance calculation seen by the relay. Since the impedance of a transmission line is proportional to its length, for distance measurement it is appropriate to use a relay able to

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

measure the transmission line impedance to a predetermined point. Such a 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. The ratio between voltage and current phasors measured at the relay installation point is calculated. The impedance calculations are based upon the following relationship:

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

with: $\overline{Z}_R$, $\overline{V}_R$ and $\overline{I}_R$ being impedance, voltage and current phasors, respectively, whereas the detailed algorithms can be found in [2, 3].

The reach point of a relay is the point along the line impedance that corresponds to a certain distance from the relay. As 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 figure 1b) below.

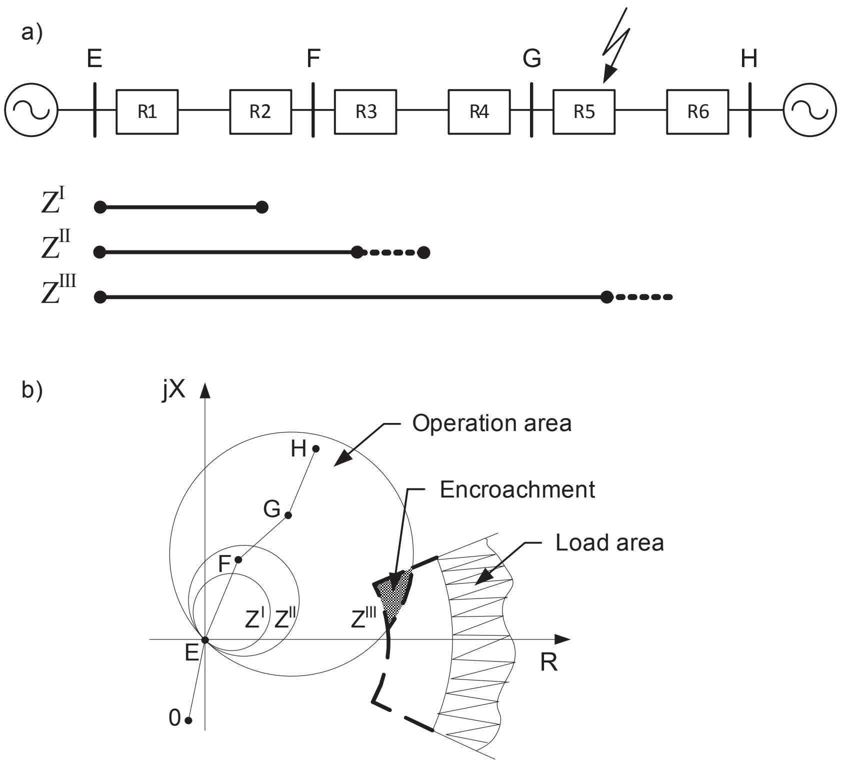

Fig. 1. a) Structure of a test transmission network,
b) distance relay zones 1, 2 and 3 vs. load area

The EF, FG and GH sections in figure 1a correspond to respective impedances of line sections seen by relay R1. The position of power system impedances as seen by the relay during faults, power swings and load variations may be plotted on the same diagram. In this manner the performance of the relay in the presence of system faults and other disturbances may be studied. This fact will be used in this paper for Zone 3 operation investigation of distance relay. Especially the third zone encroachment phenomena will be shown in situations of high load and power swing and its influence on the distance relay operation.

Careful selection of the reach settings and tripping times for the various zones of protection enables correct co-ordination of the distance relays in 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 are given as follows.

Zone 1 is set up to 85% of the protected line impedance, Zone 2 must cover the remaining 15% of the first line section and, to ensure full coverage of the line, is set to cover 120% of the protected line or the protected line section +50% of the shortest adjacent line [4]. Remote back-up protection for all faults on adjacent lines can be provided by a third zone 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 120% of the impedance presented to the relay for a fault at the remote end of the second line section (Fig. 1a) [5]. However due to the effect of interconnected power systems (Fig. 2), 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 like in equation (2). As the third zone of impedance relays with mho-characteristic covers significant part of the network and thus the impedance characteristic area is big, it is the most vulnerable to abnormal conditions zone in the electrical power system configuration and operation.

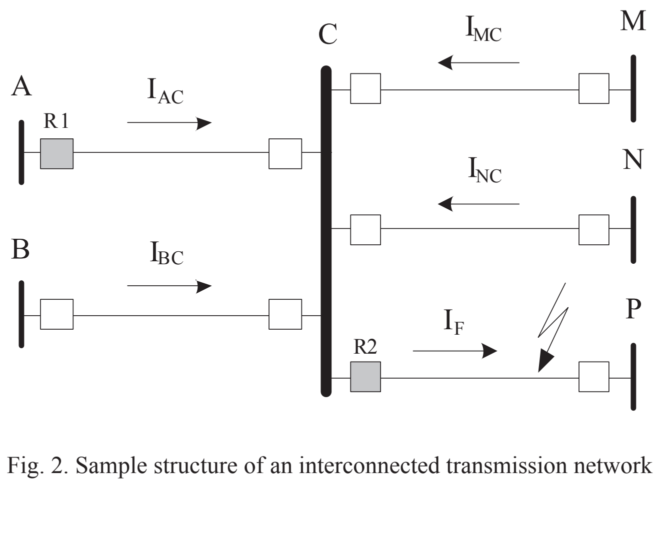

Fig. 2. Sample structure of an interconnected transmission network

Considering the problem of backing up the protection system of line CP (relay R2, Fig. 2) by the distance relay R1 it must be taken into account that because of the currents contributions from the lines BC, CM and CN, the third zone setting will be equal to:

$$Z^{III} = Z_{AC} + 1.2 Z_{CP} \left(1 \frac{I_{BC} + I_{MC} + I_{NC}}{I_{AC}} \right) \tag{2}$$

where: Z^{III} is apparent impedance seen by the relay R1 in case of the other lines current contribution.

In case of an extreme situation of equal contribution to the fault current from all the remaining lines the third zone relay setting will be:

$$Z^{III} = Z_{AC} + 4.8 Z_{CP} \tag{3}$$

Therefore the third zone is especially exposed to load encroachment and power swing – all these situations can lead to the measured impedance encroachment into the Zone 3 area. This results in relay mal-operation and can be a leading factor to a large scale blackout occurrence, as it was seen, e.g. in Germany on November 4th, 2006 [5].

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

There are 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 currents) [1–3]. However, it is very difficult to predict all possible situations in power system and all possible operating conditions, thus none of them is perfect. This paper is focused on the possibility of Dynamic Thermal Line Rating 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 monitoring weather conditions and calculating the overhead conductor temperature and actual for ambient weather conditions conductor current limit as well as the time left to reach this thermal limit.

2. DYNAMIC THERMAL LINE RATING BASICS

The Dynamic Thermal Line Rating technique aims at real time calculation of an overhead bare conductor ampacity dependent on the ambient weather conditions. The DTLR algorithm cooperates with standard distance protection devices to fully utilize the transmission line by calculation of temporary current-carrying capability.

The conductor temperature is calculated from the heat balance equation [6, 7]:

$$q_c + q_r = q_s + q_i \tag{4}$$

where: q_c, q_r are heats dissipated due to convection and radiation and q_s, q_i are heat gain due to solar radiation and heating due to Joule's law, respectively.

Each of above heat balance components are calculated in numerical way. Specific formulas the calculations are based on can be found in [6]. However, at this point, it is worth mentioning that the most significant factors for the heat balance are the convective cooling (due to wind) and Joule's heating (due to current flow and conductor resistance change).

Basing on the heat balance it is possible, using numerical solutions, to compute the current conductor temperature as well as the time needed for the conductor to reach its thermal limit according to the actual current value and ambient weather conditions. The solution is given by the following:

$$\frac{dT_C}{dt} = \frac{1}{mC_p}[R(T_C)I^2 + q_s - q_c - q_r] \tag{5}$$

where m is mass of conductor and C_p is specific heat of conductor material.

3.ENHANCED DISTANCE PROTECTION SCHEME

During the high load and power swing phenomena there is a high risk of the measured impedance encroachment into the Zone 3 area. Both these situations correspond to current values higher than the values during the normal operating conditions thus the measured impedance is sometimes even much lower than during the normal operating conditions (Eq. 1). The standard way of designing protection devices usually does not take into consideration the Joule's law, i.e. the fact that higher currents evoke higher conductor temperatures and each conductor has its thermal limit that due to the safety reasons cannot be exceeded.

The Dynamic Thermal Line Rating application introduces an additional algorithm into a standard distance relay, that is based on real-time conductor temperature calculation. The aim is to restrain the relay from tripping until the conductor temperature reaches its thermal limit. The block scheme of DTLR supported distance relay operation is presented in figure 3 below:

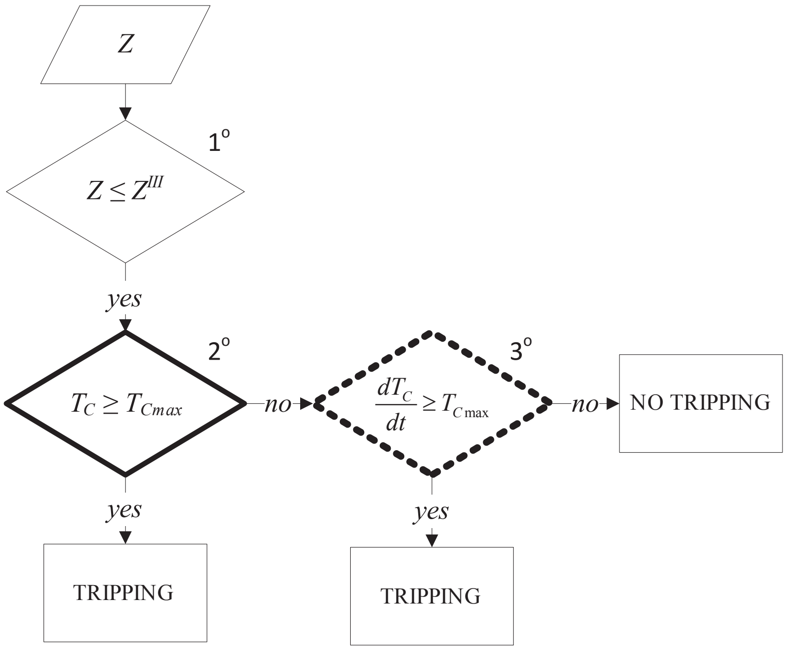

Fig. 3. Block diagram of a distance relay with new blocking algorithms

The block diagram above presents the idea of a standard distance relay enhancement based on temperature calculation. The relay acquires current samples and then using standard Fast Fourier Transform (FFT) computes the magnitudes of phase current signals, which is followed by computation of the conductor temperature [8].

Block 1 of the new protection scheme is a standard solution applied commonly in impedance relays. Its task is to compare the measured (seen by the relay) impedance with Zone 3 setting and operate if the impedance encroaches on the operation area (Fig. 1b). However, as it was mentioned earlier, there are some possible situations during which impedance encroachment occurs when the relay decision of tripping is unnecessary and even highly unwanted. Therefore there is a need for introducing additional blocks 2 and 3 to the relay logic, as described below.

Block 2, presented in figure 3, is responsible for the conductor temperature monitoring and ensures that it will not exceed the designed, for particular conductor, maximum operating temperature. Thus in case of heavy load and power swing it allows the transmission line to be operated safely, without tripping, when sufficient cooling conditions are met.

However as in some cases the temperature itself is not a sufficient factor to decide an additional algorithm (Block 3) is needed. Here a ratio of a conductor temperature change is observed. As the fault causes faster change in current magnitudes than power swings or heavy load situations, it is reasonable to use the information about the speed of change to determine whether the situation met is safe for further operation or if it should be stopped.

Figures 4a and 4b below show the impedances seen by the relay in case of some faults and power swing conditions. From the relay point of view there is no difference between these two phenomena. In each of presented situations the third zone setting area was encroached. The standard relay would operate in all five situations and that is why the additional algorithms, based on the Dynamic Thermal Line Rating, are proposed to be implemented into a distance relay. If introduced, a hope is justified that the relay would restrain itself from tripping in Power Swing situations, when it is not desired.

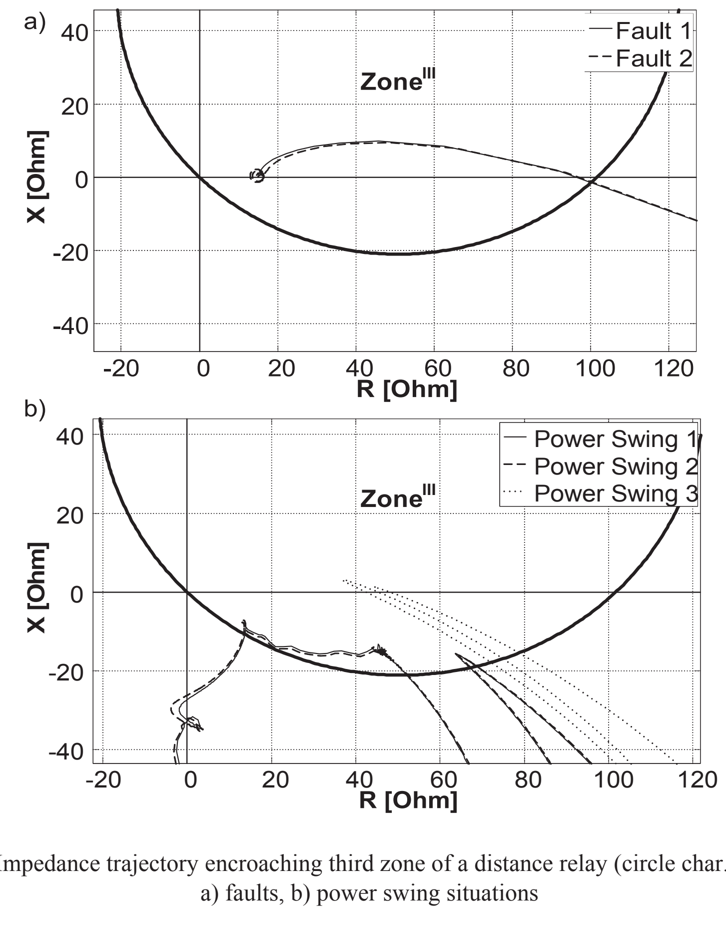

Fig. 4. Impedance trajectory encroaching third zone of a distance relay (circle char.) during: a) faults, b) power swing situations

4. PROTECTION TESTING RESULTS

During the tests AFL 6 240 conductor with rated current of 645 [A] and its thermal limit of 60 [°C] was used at nominal transmission line voltage of 110 [kV], protected line length was 70 [km] which corresponds to 29.96 [Ω]. Fault and power swing situations were simulated and examined and the testing results will be presented below. The most important signals from the point of view of introducing the new algorithm were taken into account. Thus the current magnitude (as a factor highly responsible for the conductor temperature), the conductor temperature (as in the Block 2) and the ratio of change of the conductor temperature were examined (as in the Block 3).

During the simulated situations the current flowing throughout the conductor in cases of faults and power swings was as presented in figure 5 below.

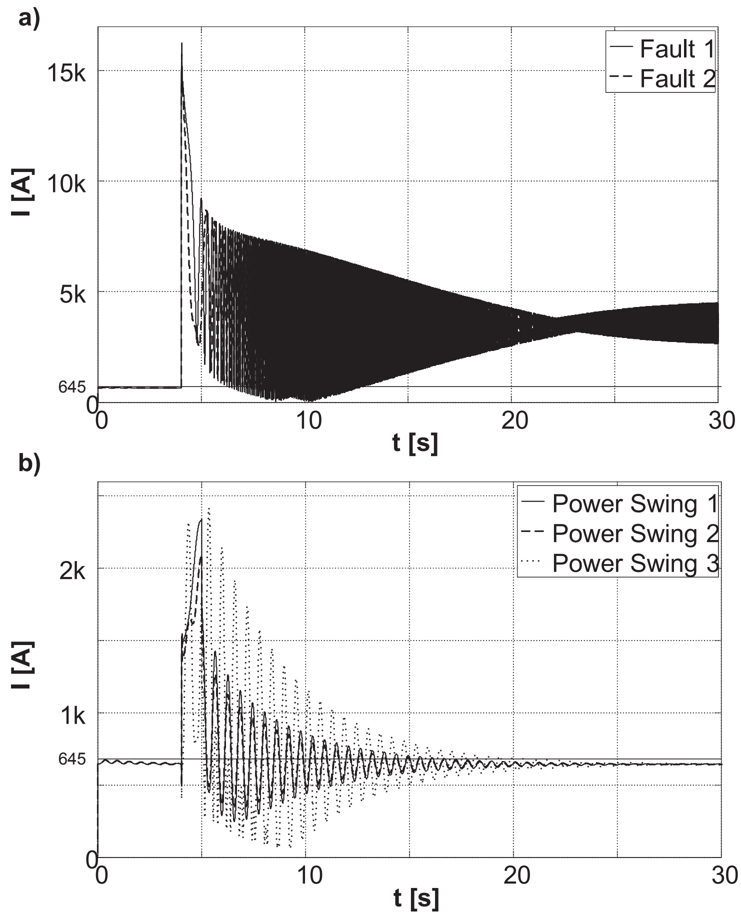

Fig. 5. Current magnitudes during a) faults, b) power swing situations

As it can be noticed in figure 5a the current magnitudes in both fault and power swing cases were much higher than the nominal conductor rating value of 645 [A]. In fault causes the values were of course much higher, momentarily over 15 [kA], than in cases of power swings were the values not even reached 2.5 [kA]. However in all the power swing situations the current magnitudes returned to their normal values after the time from 15 to 20 seconds and in both fault situations currents stabilized over 4 [kA]. Of course the thermal impact on the conductor in so different situations was also altered. The conductor thermal behaviour is presented in figure 6 below.

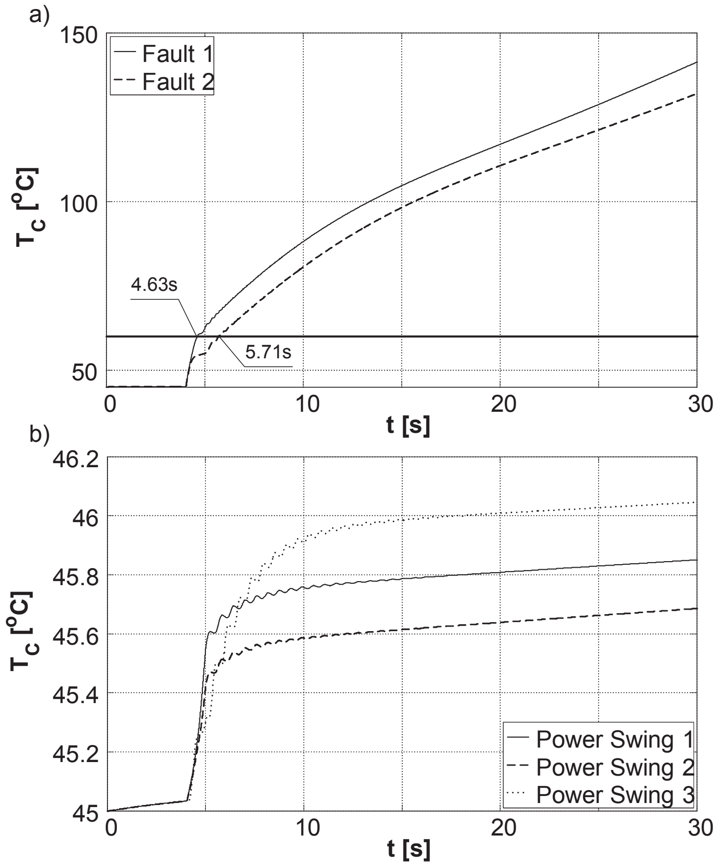

Fig. 6. The conductor temperatures during a) faults, b) power swing situations

As seen in figure 6a, much higher and longer lasting current magnitudes in case of faults cased much faster and higher temperature exceeding the conductor thermal limit at 4.63 [s] and 5.71 [s] of simulation which is respectively 0.595 [s] and 1.675 [s] after the fault happened. This situation highlights the need for fast protection because less than two seconds are enough for the fault currents to permanently destroy the conductor. However, all three situations of power swing phenomena proven the fact, that during sufficient weather conditions the continuous transmission line operation is safe and allowable.

Despite the fact, that the temperature monitoring is usually a sufficient factor to determine whether the situation met by the relay is a fault or a power swing the decision time can still be shortened by additional algorithm (Block 3 in Fig. 3). The conductor temperature change ratio (calculated as a derivative of conductor temperature over time) limit value was determined experimentally as 1, however was set to 2 due to safety reasons. The results of the ratio values examinations can be seen in figure 7 below.

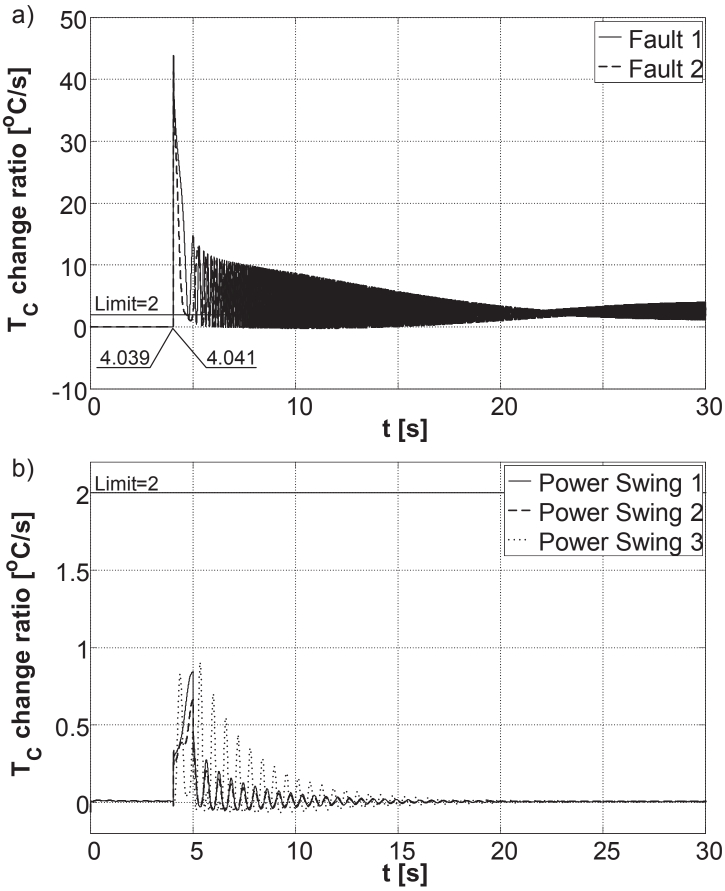

Fig. 7. The conductor temperature change ratios during a) faults, b) power swing situations

As it was seen in figure 7, the additional algorithm responsible for conductor temperature change ratio monitoring also perfectly determined between the fault and power swing situations and as expected operated much faster than the algorithm monitoring the conductor temperature. The reaction time for the Block 3 was 0.004 [s] and 0.006 [s] instead of the longer Block 2 reaction times of 0.595 [s] and 1.675 [s] respectively. The Block 3 reaction times are shorter by the time the conductor needed to reach the temperature of its thermal limit.

Despite the fact that the Block 3 presented reaction times are shorter than in case of Block 2, there is a risk that during unstable power swing situation or long-lasting ones the conductor limit temperature can be exceeded with simultaneously low ratio of temperature increase causing the conductor damage. That is why for the best performance both Block 2 and 3 should co-operate with standard protection relay.

5. CONCLUSIONS

This paper presented the examination of a standard distance protection relay enhanced with two additional algorithms based on the Dynamic Thermal Line Rating. The examination, considering the most important factors: current magnitudes, conductor temperature and conductor temperature change ratio has proven that the proposed algorithms improved the distance relay operation reaction times and reliability.

Despite the Dynamic Thermal Line Rating application high weather dependency, in vast number of cases it is very efficient and reliable tool making it worth considering for the standard distance protection improvements.

The DTLR can also introduce much better transmission line utilization and increase of the transmission system efficiency, bringing additional profits for operators. It can also improve the system reliability and safety avoiding unnecessary relay operations.

REFERENCES

[1] WISZNIEWSKI A., UNGRAD H., WINKLER W., *Protection techniques in electrical energy systems*, New York 1995.

[2] REBIZANT W., SZAFRAN J., WISZNIEWSKI A., *Digital Signal Processing in Power System Protection and Control*, Springer Verlag, Series: Signals and Communication Technology, London 2011.

[3] SZAFRAN J., WISZNIEWSKI A., *Algorytmy pomiarowe i decyzyjne cyfrowej automatyki elektroenergetycznej*, 2001.

[4] HOROWITZ S.H., PHADKE A.G., *Third zone revisited*, IEEE Transactions on Power Delivery, Vol. 21, January 2006, pp. 23–29.

[5] YAMASHITA K., LI J., ZHANG P., LIU C.-C., *Analysis and Control of Major Blackout Events*, IEEE, 2009.

[6] *IEEE Standard for Calculating the Current-Temperature of Bare Overhead Conductors*, IEEE Std. 738-2006 (Revision of IEEE Std. 738-1993).

[7] SAMANMIT U., CHUSANAPIPUTT S., PUNGPRASERT V., *Increasing of Dynamic Thermal Rating of Transmission Line*, International Conference on Power System Technology, 1–4, 2006.

[8] SMITH S.W., *Digital signal processing: A practical guide for engineers and scientists*, 2003.