Łukasz STASZEWSKI[1], **Waldemar REBIZANT**[1]

Wrocław University of Technology (1)

Distance protection with thermal blockade

***Abstract**. 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 the thermal limit reach.*

***Streszczenie.** Artykuł przedstawia algorytm oparty na Dynamicznej Obciążalności Linii usprawniający pracę zabezpieczenia odległościowego, czyniąc je mniej wrażliwym na powszechnie występujące zjawisko wkraczania widzianej przez przekaźnik impedancji w nastawę trzeciej strefy podczas wysokiego obciążenia oraz kołysania mocy. Przedstawione wyniki przeprowadzonych symulacji i analiz wskazują na poprawę pracy zabezpieczenie odległościowego. (**Zabezpieczenie odległościowe z blokadą termiczną**)*

Keywords: distance protection, third zone, conductor temperature, Dynamic Thermal Line Rating
Słowa kluczowe: zabezpieczenie odległościowe, trzecia strefa, temperatura przewodu, Dynamiczna Obciążalność Linii Przesyłowej

Introduction

For many years distance protection relay has been one of the most commonly used devices amongst electrical protection equipment. To meet the requirements of combining fast fault clearance with selective tripping, high speed protection for transmission and distribution circuits is under continuous development. 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 measure the transmission line impedance to a predetermined point (the reach 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:

$$\overline{Z}_R = \frac{\overline{V}_R}{\overline{I}_R} \quad (1)$$

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). 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.

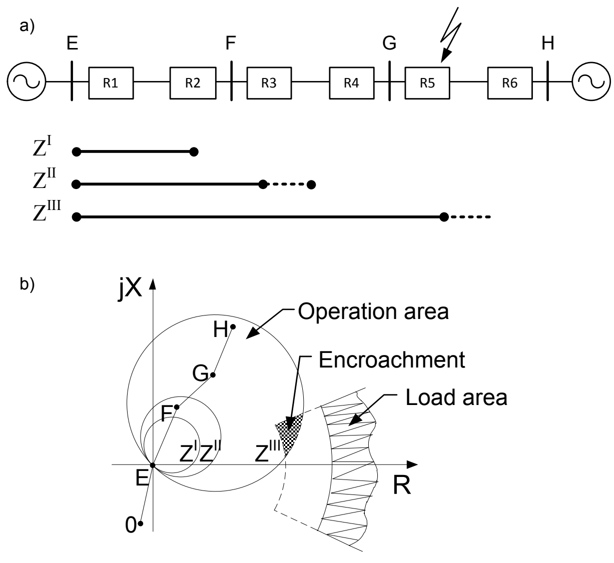

Fig. 1a) Structure of a test transmission network, b) distance relay zones 1, 2 and 3 vs. load area

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. The resulting 15% 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.

Zone 2 of the distance protection must cover the remaining 15% of the first line section and to ensure full coverage of the line. It is commonly accepted that the reach of the Zone 2 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 [4].

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 (Fig.1a) [5].

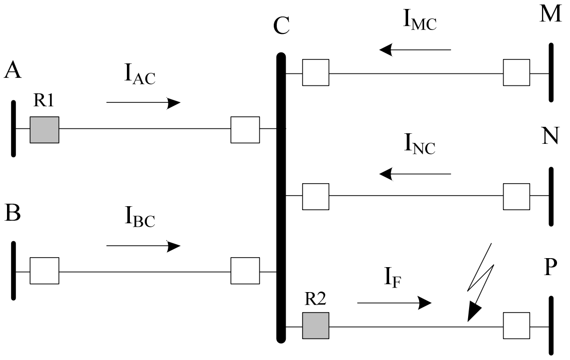

Fig. 2. Sample structure of an interconnected transmission network

On 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 zone to abnormal conditions in the electrical power system configuration and operation.

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:

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

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:

(3) $$Z^{III} = Z_{AC} + 4.8Z_{CP}$$

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) [1,2,3]. 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.

DTLR 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 standard heat balance equation [6,7]:

(4) $$q_c + q_r = q_s + q_i$$

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.

The first of these factors, heat dissipated due to convection, is calculated in a way that equations (5) and (6) are determined simultaneously and the higher of the two values is chosen:

(5) $$q_{c1} = \left[1.01 + 0.0372\left(\frac{D\rho_f v_w}{\mu_f}\right)^{0.52}\right] k_f K_{angle}\left(T_c - T_a\right)$$

(6) $$q_{c2} = \left[1.0119\left(\frac{D\rho_f v_w}{\mu_f}\right)^{0.6} k_f K_{angle}\left(T_c - T_a\right)\right]$$

where: ρ_f density of air, v_w air stream velocity at a conductor, k_f thermal conductivity of air and T_c and T_a conductor and ambient air temperature, respectively.

Cooling due to radiation is calculated with:

(7) $$q_r = 0.0178D\varepsilon\left[\left(\frac{T_s + 273}{100}\right)^4 - \left(\frac{T_a + 273}{100}\right)^4\right]$$

where: D is external diameter of the conductor and ε is emissivity factor.

Heating due to solar radiation is presented by:

(8) $$q_s = \alpha Q_{se}\sin\left(\theta\right)A'$$

where: α is solar absorptivity, Q_{se} is the total solar and sky radiated heat flux elevation corrected, Θ is effective angle of incidence of sun rays and A' is projected area of conductor per unit length.

The last is the heating due to the Joule's law (9), that takes into account not only the flowing current (I) but also the change of resistance (R) due to conductor temperature:

(9) $$q_i = I^2R\left(T_c\right)$$
$$q_i = I^2\left(\left[\frac{R\left(T_{high}\right) - R\left(T_{low}\right)}{T_{high} - T_{low}}\right]\left(T_c - T_{low}\right) + R\left(T_{low}\right)\right)$$

where: $R(T_{high})$, $R(T_{low})$ are the resistance values for high and low conductor temperatures, respectively.

According to above equations it is possible, using numerical techniques, to calculate the current conductor temperature from the equation (10) as well as the time needed for the conductor to reach its thermal limit according to the actual current value and weather conditions:

$$\frac{dT_C}{dt} = \frac{1}{mC_p}\left[R\left(T_C\right) I^2 + q_s - q_c - q_r \right] \tag{10}$$

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

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) [8]. 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:

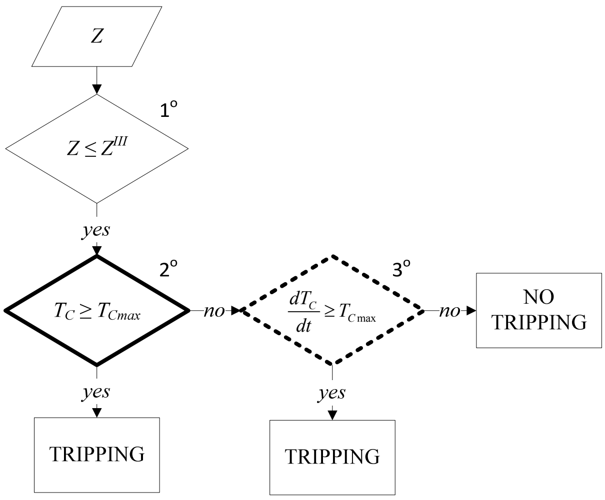

Fig. 3. Block diagram of a distance relay with new blocking algorithms

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 [9].

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 an additional algorithm (Block 3) was introduced. 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 4 a) and b) 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.

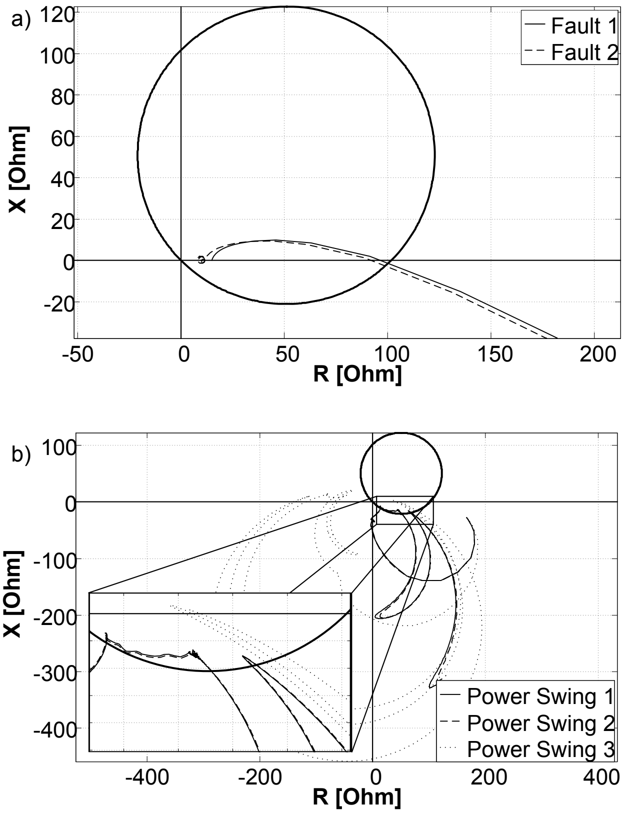

Fig. 4. Impedance trajectory encroaching third zone of a distance relay (circle char.) during: a) faults, b) power swing situations

Protection testing results

The calculated temperature is compared with the maximum allowable one and then the decision is made. Figures 5 a) and b) present the fault current magnitude flowing throughout the conductor, like in case of situation in figure 4a), along with corresponding conductor temperature and the enhanced relay decision.

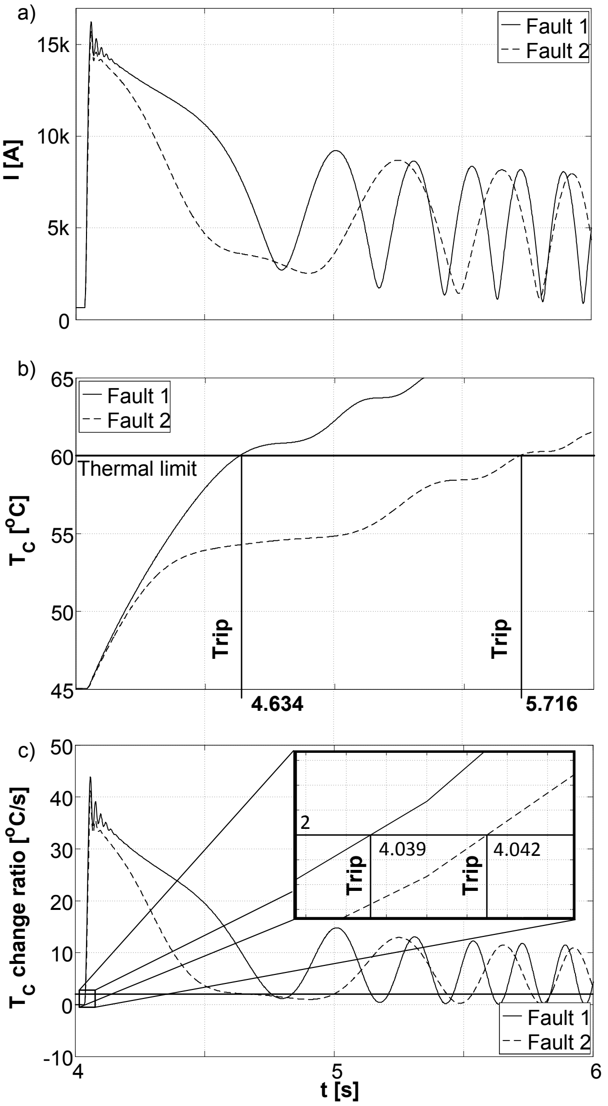

Fig. 5. Sample fault cases: a) magnitude of currents, b) conductor temperature, c) conductor temperature change ratio

As it can be seen in figure above, presenting two fault situations incepted at *t*=4.035[s], the current magnitudes are up to about 15[kA] causing the conductor to quickly reach its thermal limit of 60^{o}C. These situations are highly dangerous and further operation of this transmission line is not allowable. In both cases the relay has to make instant decisions to trip the transmission line as quick as the thermal limit is reached. However, the tripping decision times are different. In the first situation the relay made the decision at 4.634[s], which is 0.599[s] after the fault happened. In the second case the relay operated at 5.716[s], which is 1.681[s] after the fault inception. In both cases the time of operation is sufficient because the third zone tripping of distance protection itself has to be delayed by 1.8 [s] (90 cycles for 50[Hz]) due to selectivity of protection (third zone is a back-up protection, it cannot operate before zone one or two). However, in some cases, especially high impedance faults, there is a possibility that the conductor will reach its thermal limit far later than 1.8 [s] and that would be unsafe situation for the public safety and electrical power system to operate under fault conditions. Figures 6 a), b) and c) below present three selected cases of power swings with signals measured and quantities computed by the relay.

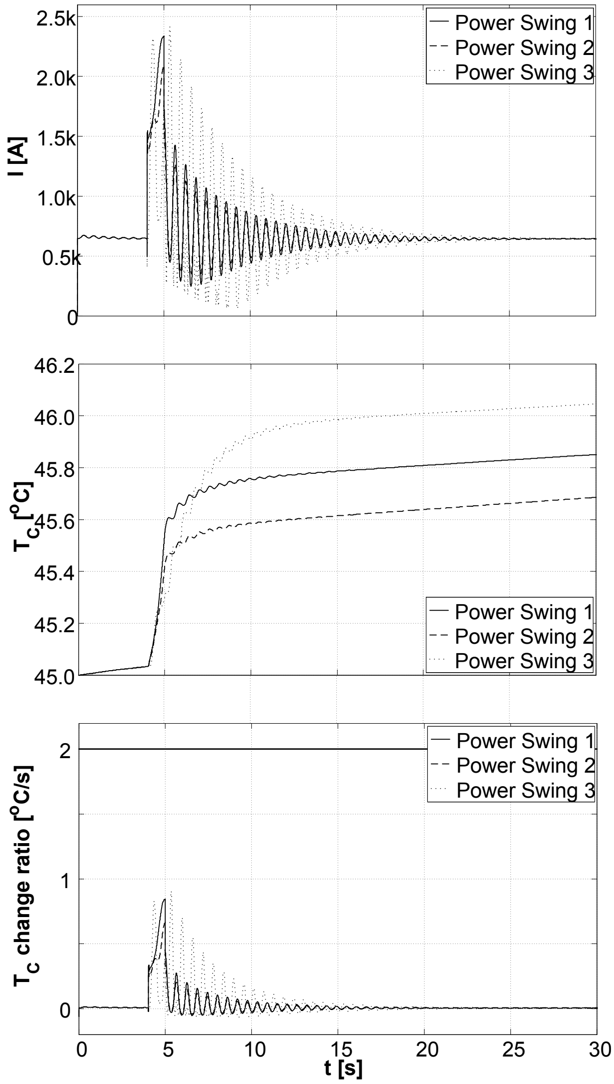

Fig. 6. Selected power swing situations: a) magnitude of currents, b) conductor temperature, c) conductor temperature change ratio

From the figures presented above it can be concluded that despite significant temporary current increase the relay decisive parameters (conductor temperature and conductor temperature change ratio) remained within their limits for all cases of considered stable power swings. This caused the relay to allow for continuous operation of the line under the conditions met.

It is worth mentioning that for the AFL 6 240 conductor used in simulation the nominal allowable current is 645[A]. This means that, according to the met weather conditions, the relay allowed to operate the line under about three times nominal current for about 10[s], preventing the power system protection from unnecessary line tripping and possibly also from wide area events or blackout. This could never take place with standard protection devices, and that is why it is worthy to use additional algorithms based on Dynamic Thermal Line Rating to enhance operation of the protection/control schemes.

Summary

During some conditions met in power system it is necessary to trip the protected transmission line when the impedance encroaches the third zone setting area and the currents values are higher than nominal, as in cases of permanent faults. However, as presented in this paper, in other situations – like power swings or heavy load conditions – it is not. With application of additional algorithms, based on Dynamic Thermal Line Rating, it is possible to monitor and operate transmission lines under conditions that will cause the standard distance protection operate.

Restraining the relay from tripping in situations in which it could be avoided gives to the operator great benefits – continuous load distribution helps satisfy the market demand bringing profits and does not cause dangerous tripping of overloaded transmission lines. Tripping of heavily loaded line can cause loss of power system stability which, therefore can lead to wide area events, like blackouts, system splitting or cascaded events.

REFERENCES

[1] Wiszniewski A., Ungrad H., Winkler W., Protection techniques in electrical energy systems, Marcel Dekker Inc., New York, 1995.

[2] Rebizant W., Szafran J., Wiszniewski A., Digital Signal Processing in Power System Protection and Control, Series: Signals and Communication Technology, Springer Verlag, London, 2011.

[3] Szafran J., Wiszniewski A., Algorytmy pomiarowe i decyzyjne cyfrowej automatyki elektroenergetycznej, WNT, Warszawa, 2001 (in Polish).

[4] Horowitz S. H., Phadke A. G., Third zone revisited, IEEE Transactions on Power Delivery, Vol. 21, No. 1, January 2006, pp 23–29.

[5] Yamashita K., Li J., Zhang P., Liu C-C, Analysis and Control of Major Blackout Events, Power Systems Conference and Exposition, 2009. PSCE '09. IEEE/PES, Seattle, WA, USA, pp. 1-4. DOI: 10.1109/PSCE.2009.4840091.

[6] IEEE Standard for Calculating the Current-Temperature of Bare Overhead Conductors, IEEE Std 738-2006, IEEE, New York, NY, USA, Jan. 30, 2007, DOI: 10.1109/IEEESTD.2007.301349.

[7] Samanmit U., Chusanapiputt S., Pungprasert V., Increasing of Dynamic Thermal Rating of Transmission Line, International Conference on Power System Technology, Chongqing, China, 22-26 Oct. 2006, pp. 1-4, DOI: 10.1109/ICPST.2006.321536.

[8] Kremens Z., Sobierajski M., Analiza systemów elektro-energetycznych, WNT, Warszawa, 1996 (in Polish).

[9] Smith S. W., Digital signal processing: A practical guide for engineers and scientists, Newnes, Elsevier Science, Burlington, MA, USA, 2003.

***Authors**: mgr inż. Łukasz Staszewski, Politechnika Wrocławska, Instytut Energoelektryki, ul. Janiszewskiego 8, 50-370 Wrocław, e-mail: lukasz.staszewski@pwr.wroc.pl;*

prof. dr hab. inż. Waldemar Rebizant, Politechnika Wrocławska, Instytut Energoelektryki, ul. Janiszewskiego 8, 50-370 Wrocław, e-mail: waldemar.rebizant@pwr.wroc.pl,