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Influence of phase shift transformer on distance protection's operation

***Abstract**. In the paper, the model, as simplified as possible, with which the influence of the phase shift transformer (PST) on the impedance's measurement carried out by the distance protection has been proposed. Referring to a single case, the idea of the model's mathematical description has been briefly presented. The formulas obtained have been interpreted in graphical way. Consistency regarding the adequate protection settings has been underlined. The results have been verified using a digital model.*

Streszczenie.** W artykule zaproponowano maksymalnie uproszczony model pozwalający badać wpływ przesuwnika fazowego (sterownika PST) na pomiar impedancji przez zabezpieczenie odległościowe. Na pojedynczym przykładzie w sposób skrócony przedstawiono ideę opisu matematycznego tego modelu. Przeprowadzono graficzną interpretację otrzymanych wzorów. Zwrócono uwagę na konsekwencję odnośnie prawidłowych nastaw zabezpieczeń. Wyniki zweryfikowano na modelu cyfrowym. (Tytuł: **Wpływ przesuwnika fazowego na pracę zabezpieczenia odległościowego)

Keywords: FACTS, PST, distance protection
Słowa kluczowe: FACTS, PST, zabezpieczenia odległościowe

Introduction

In 220kV and 400 kV transmission grid systems, the preferred principal protection is differential protection whilst the reserved one is the distance protection. In the elder network sections, where no optical fiber is carried in the line, the distance protections play role of both the principal and back-up ones. The hallmark of the distance protections is they function not only as the local back-up but also as the remote one; also, it has an impact on the reserve of the circuit-breakers. That was the reason to choose such a protection as the research subject.

In 70s of the XX century, the EPRI (*Electric Power Research Institute*) in US started the research and, in1986, presented the idea of the Flexible AC Transmission System (FACTS), the controllers making the AC transmission more flexible. Research works on these controllers are still developed worldwide. The FACST as such permit to control the active and passive power flow and, finally, contribute to limit the losses and to improve the transmission stability. Referring to the published results of the research conducted for PSE S.A. (Transmission System Operator in Poland), the FACTS is going to be implemented also in Poland [1,2] as the great expenses for grid investments are the alternative. Recently, the papers concerning the planned application of the phase shifters on the Polish-Germany border have appeared. [3].

Majority of the elaborated FACTS controllers have already been implemented (long-distance transmission in US, Brazil, Canada, RPA and China) and the controllers are mounted in the center of transmission line and affects mainly the line's protections. In Europe, the transmission lines are strongly linked, the transmission is for shorter distances; therefore, regarding the infrastructure costs, the FACTS-equipped substations will be built in vicinity of existing electric power substations. In effect, the controllers will affect the protections of some adjacent lines.

The controllers connected in parallel with the network affect only negligibly the operation of the automatic protections during the short-circuit (the current they introduce is of 5% the short-circuit current vale), although their influence on the post-short-circuit process of the maintaining the voltage stability i.e. on the breakdown development process is great. The controllers connected in series to the network seriously contribute to the impedance measurement's falsification by the distance protection, even if not but slightly affect the short-circuit current. From the controllers, the Phase Shift Transformer (PST) has been chosen for continued research.

The PST controller introduces an additional series voltage shifted by 90^0 (obtained from two other phases) into the actual phase. During short-circuits, the controller is still working. However, if the short-circuits are non-symmetric, the added voltage value in percents increases due to the introduction of voltage of the non-broken phase. For a distance protection, it results in a very high falsification of the impedance measurement during short-circuit in the remotely reserved line.

System model and mathematical description

A system's section, which the influence of any FACTS controller on the operation of protections is possible to observe, can be modeled as the Y-configuration of three subsystems (Fig.1).

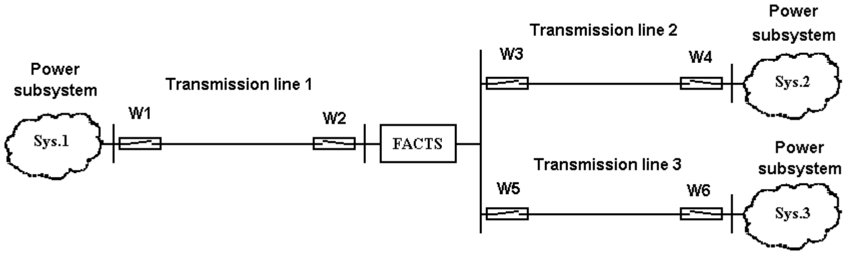

Fig.1 System for investigation of influence of any FACTS controller on the protections' operation

In a one of transmission line, the considered distance protection present, a short-circuit occures in the next line, and another transmission line co-supply short-circuit.

The PST phase shifter is the set of two transformers that introduces an added voltage shifted by 90^0in series to the actual phase (Fig.2); in effect, the set can be modeled as an ideal voltage source (assuming the low-leakage reactance toroidal series transformers).

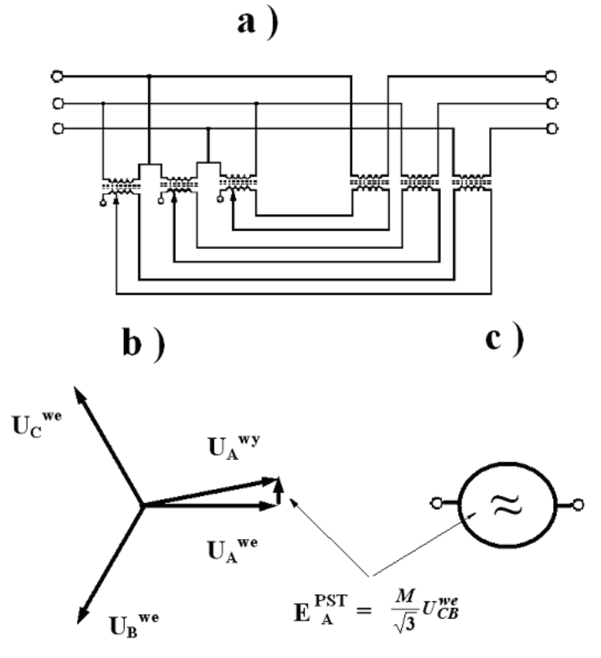

Fig.2 PST phase shifter: a) principal networks; b) voltage vector configuration; c) equivalent model

Thus, when the task of the protection by the W1 circuit-breaker is to evaluate the impedance during the short-circuit in the transmission line 2, the theoretical considerations can be conducted using the circuit shown in figure 3.

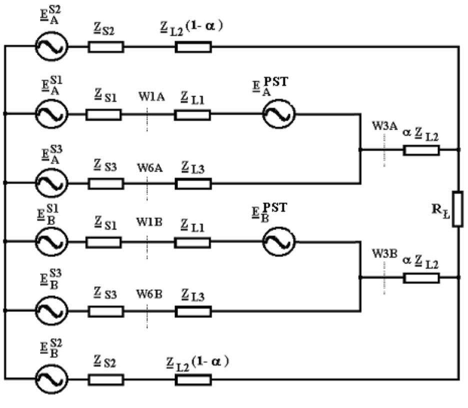

Fig. 3 Network for finding the error of impedance measurement by the distance protections under the arc short-circuit in the transmission line 2

Electric power subsystems (Fig.1) marked as *Sys.1*, *Sys.2*, *Sys.3* are replaced by the ideal voltage sources connected in series with the impedance corresponding to the short-circuit impedance. In the lines, only longitudinal impedance is considered, and the α coefficient determines the short-circuit location – the line section. Unfortunately, in such a scheme, the arc resistance is not constant. Assuming the constant voltage value across the arc column (depending on the column length), the arc resistance can be found from the formula (1) using the node potential method.

$$\frac{R_Ł}{K_Ł} = \frac{1}{\sqrt{\frac{\left[\sum_{sys}\frac{\underline{E}_{AB}^{sys}}{\underline{Z}_{sys}^{ZW}} - \frac{\underline{E}_{AB}^{FACTS}}{\underline{Z}_{1}^{ZW}}\right]_{Im}^2 + \left[\sum_{sys}\frac{\underline{E}_{AB}^{sys}}{\underline{Z}_{sys}^{ZW}} - \frac{\underline{E}_{AB}^{FACTS}}{\underline{Z}_{1}^{ZW}}\right]_{Re}^2}{U_Ł^2}} - \left[\sum_{sys}\frac{1}{\underline{Z}_{sys}^{ZW}}\right]_{Im}^2 - \left[\sum_{sys}\frac{1}{\underline{Z}_{sys}^{ZW}}\right]_{Re}}$$

(1)

Where: $K_Ł$ coefficient depends on the short-circuit type, and for two-phase short-circuit KŁ=2 (half length) for three-phase short-circuit KŁ=3 (□ - Y replacement)

The values of $\underline{Z}_{sys}^{ZW}$, in formula (1), for short-circuit in the transmission line 2 (see Fig.1) and all subsystems are given by the formulas (2).

$$\underline{Z}_1^{ZW} = (\underline{Z}_{S1} + \underline{Z}_{L1}) + (\alpha \underline{Z}_{L2}) + \frac{(\underline{Z}_{S1} + \underline{Z}_{L1})(\alpha \underline{Z}_{L2})}{(\underline{Z}_{S3} + \underline{Z}_{L3})}$$

(2) $$\underline{Z}_2^{ZW} = \underline{Z}_{S2} + \underline{Z}_{L2}(1-\alpha)$$

$$\underline{Z}_3^{ZW} = (\underline{Z}_{S3} + \underline{Z}_{L3}) + (\alpha \underline{Z}_{L2}) + \frac{(\underline{Z}_{S3} + \underline{Z}_{L3})(\alpha \underline{Z}_{L2})}{(\underline{Z}_{S1} + \underline{Z}_{L1})}$$

The impedance measured by the distance protection is given by the formula (3)

(3) $$\underline{Z}_P = \frac{\underline{U}_P}{\underline{I}_P} = \frac{\underline{U}_{AB}}{\underline{I}_A - \underline{I}_B}$$

Therefore, taking into account the chosen currents and voltages used in formula (3), the mathematical description for the circuit shown in figure 3 takes a form of the relationship (4)

$$\left(\underline{U}_A^{W1} - \underline{U}_B^{W1}\right)\left\{1 + \frac{\alpha \underline{Z}_{L2}}{\underline{Z}_{S3} + \underline{Z}_{L3}}\left(1 - e^{-j\delta_{13}}\right) + \frac{R_Ł}{K_Ł}\left(\frac{1 - e^{-j\delta_{12}}}{\underline{Z}_{S2} + (1-\alpha)\underline{Z}_{L2}} - \frac{K_2}{K_1}\right)\right\} =$$

(4) $$= \left(\underline{I}_A^{S1} - \underline{I}_B^{S1}\right)\left\{\underline{Z}_{L1} + \alpha \underline{Z}_{L2}\left(1 + \frac{\underline{Z}_{S1} e^{-j\delta_{13}} + \underline{Z}_{L1}}{\underline{Z}_{S3} + \underline{Z}_{L3}}\right) + \frac{R_Ł}{K_Ł}\left(\frac{\underline{Z}_{S1}(K_3 + K_2)}{K_1}\right)\right\} +$$

$$+ \left(\underline{I}_A^{S1} - \underline{I}_B^{S1}\right)\left\{\frac{R_Ł}{K_Ł}\left(\frac{K_4 + K_5 + K_6}{K_1}\right)\right\} +$$

$$+ \left(\underline{E}_A^{PST} - \underline{E}_B^{PST}\right)\left\{1 + \frac{\alpha \underline{Z}_{L2}}{\underline{Z}_{S3} + \underline{Z}_{L3}} + \frac{R_Ł}{K_Ł}\left(\frac{\underline{Z}_{S2} + \underline{Z}_{L2} + \underline{Z}_{S3} + \underline{Z}_{L3}}{K_1}\right)\right\}$$

where

$$K_1 = \left(\underline{Z}_{S2} + (1-\alpha)\underline{Z}_{L2}\right)\left(\underline{Z}_{S3} + \underline{Z}_{L3}\right)$$

$$K_2 = \left(e^{-j\delta_{13}} - 1\right)\left(\underline{Z}_{S2} + \underline{Z}_{L2}\right)$$

$$K_3 = \left(e^{-j\delta_{12}} - 1\right)\left(\underline{Z}_{S3} + \underline{Z}_{L3}\right)$$

$$K_4 = \left(\underline{Z}_{S1} + \underline{Z}_{L1}\right)\left(\underline{Z}_{S2} + \underline{Z}_{L2}\right)$$

$$K_5 = \left(\underline{Z}_{S2} + \underline{Z}_{L2}\right)\left(\underline{Z}_{S3} + \underline{Z}_{L3}\right)$$

$$K_6 = \left(\underline{Z}_{S3} + \underline{Z}_{L3}\right)\left(\underline{Z}_{S1} + \underline{Z}_{L1}\right)$$

A voltage introduced by the PST controller can be described by the formula (5)

$$\left(\underline{E}_A^{PST} - \underline{E}_B^{PST}\right) = -\sqrt{3}M\left(\underline{K}_C^{S1}\underline{E}_C^{S1} + \underline{K}_C^{S2}\underline{E}_C^{S2} + \underline{K}_C^{S3}\underline{E}_C^{S3} - \underline{K}_C^{PST}\underline{E}_C^{PST}\right)$$

(5)

where coefficients KCS1, K_C^{S2}, K_C^{S3}, K_C^{PST} will take a form given by the relationships (6) and (7) below for the two-phase short-circuit and the three-phase short-circuit, respectively

$$K_P = \frac{1}{\underline{Z}_{S1} + \underline{Z}_{L1}} + \frac{1}{\underline{Z}_{S2} + \underline{Z}_{L2}} + \frac{1}{\underline{Z}_{S3} + \underline{Z}_{L3}}$$

$$\underline{K}_C^{S1} = \frac{1}{(\underline{Z}_{S1} + \underline{Z}_{L1})K_P}$$

(6) $$\underline{K}_C^{S2} = \frac{1}{(\underline{Z}_{S2} + \underline{Z}_{L2})K_P}$$

$$\underline{K}_C^{S3} = \frac{1}{(\underline{Z}_{S3} + \underline{Z}_{L3})K_P}$$

$$\underline{K}_C^{PST} = -\underline{K}_C^{S1}$$

$$\begin{gathered}
K_{P1}=\frac{R_{\text{Ł}}}{K_{\text{Ł}}}\left(\underline{Z}_{S2}+\underline{Z}_{L2}\right)+\alpha\underline{Z}_{L2}\left(\underline{Z}_{S2}+(1-\alpha)\underline{Z}_{L2}\right)\\
K_{P2}=\frac{R_{\text{Ł}}}{K_{\text{Ł}}}+\underline{Z}_{S2}+(1-\alpha)\underline{Z}_{L2}\\
\underline{K}_C^{S1}=\frac{1}{\left(\underline{Z}_{S1}+\underline{Z}_{L1}\right)\left(\frac{1}{\underline{Z}_{S1}+\underline{Z}_{L1}}+\frac{K_{P2}}{K_{P1}}+\frac{1}{\underline{Z}_{S3}+\underline{Z}_{L3}}\right)}\\
\underline{K}_C^{S2}=\frac{\frac{R_{\text{Ł}}}{K_{\text{Ł}}}}{\frac{K_{P1}}{\underline{Z}_{S1}+\underline{Z}_{L1}}+K_{P2}+\frac{K_{P1}}{\underline{Z}_{S3}+\underline{Z}_{L3}}}\\
\underline{K}_C^{S3}=\frac{\left(\underline{Z}_{S1}+\underline{Z}_{L1}\right)}{\left(\underline{Z}_{S3}+\underline{Z}_{L3}\right)}\underline{K}_C^{S1}\\
\underline{K}_C^{PST}=-\underline{K}_C^{S1}
\end{gathered}\tag{7}$$

Thus, for the symmetrical short-circuits (three-phase) we obtain formula (8)

$$\begin{gathered}
\underline{Z}_P=\frac{\underline{Z}_{L1}\left(1-\underline{K}_1\right)+\alpha\underline{Z}_{L2}\left(1+\frac{\underline{Z}_{S1}e^{-j\delta_{13}}+\underline{Z}_{L1}\left(1-\underline{K}_1\right)}{\underline{Z}_{S3}+\underline{Z}_{L3}}\right)}{1-\underline{K}_1+\alpha\underline{Z}_{L2}\frac{1-\underline{K}_1-e^{-j\delta_{13}}}{\underline{Z}_{S3}+\underline{Z}_{L3}}+\frac{R_{\text{Ł}}}{K_{\text{Ł}}}\frac{-\underline{K}_2-\underline{K}_1\underline{K}_3}{K_5}}+\\
+\frac{\frac{R_{\text{Ł}}}{K_{\text{Ł}}}\frac{\underline{Z}_{S1}\underline{K}_2-\underline{Z}_{L1}\underline{K}_1\underline{K}_3+\underline{K}_4}{K_5}}{1-\underline{K}_1+\alpha\underline{Z}_{L2}\frac{1-\underline{K}_1-e^{-j\delta_{13}}}{\underline{Z}_{S3}+\underline{Z}_{L3}}+\frac{R_{\text{Ł}}}{K_{\text{Ł}}}\frac{-\underline{K}_2-\underline{K}_1\underline{K}_3}{K_5}}
\end{gathered}\tag{8}$$

where

$$\begin{gathered}
\underline{K}_1=\frac{M\,e^{-j\frac{\pi}{2}}}{1+M\,e^{-j\frac{\pi}{2}}}\\
\underline{K}_2=\left(\underline{Z}_{S3}+\underline{Z}_{L3}\right)\left(e^{-j\delta_{12}}-1\right)+\left(e^{-j\delta_{13}}-1\right)\left(\underline{Z}_{S2}+\underline{Z}_{L2}\right)\\
\underline{K}_3=\left(\left(\underline{Z}_{S2}+\underline{Z}_{L2}\right)+\left(\underline{Z}_{S3}+\underline{Z}_{L3}\right)\right)\\
\underline{K}_4=\left(\underline{Z}_{S1}+\underline{Z}_{L1}\right)\left(\underline{Z}_{S2}+\underline{Z}_{L2}\right)+\left(\underline{Z}_{S2}+\underline{Z}_{L2}\right)\left(\underline{Z}_{S3}+\underline{Z}_{L3}\right)+\\
+\left(\underline{Z}_{S3}+\underline{Z}_{L3}\right)\left(\underline{Z}_{S1}+\underline{Z}_{L1}\right)\\
K_5=\left(\underline{Z}_{S2}+(1-\alpha)\underline{Z}_{L2}\right)\left(\underline{Z}_{S3}+\underline{Z}_{L3}\right)
\end{gathered}$$

whilst for the two-phase short-circuits we obtain formula (9)

$$\begin{gathered}
\underline{Z}_P=\frac{\underline{Z}_{L1}\left(1-\underline{K}_6\right)-\underline{Z}_{S1}\underline{K}_7}{K_9+\frac{R_{\text{Ł}}}{K_{\text{Ł}}}\frac{-\underline{K}_3+\underline{K}_5\left(\underline{K}_7-\underline{K}_6\right)}{K_8}}+\\
+\frac{\alpha\underline{Z}_{L2}\left(1+\frac{\underline{Z}_{S1}\left(e^{-j\delta_{13}}-\underline{K}_7\right)+\underline{Z}_{L1}\left(1-\underline{K}_6\right)}{\underline{Z}_{S3}+\underline{Z}_{L3}}\right)}{K_9+\frac{R_{\text{Ł}}}{K_{\text{Ł}}}\frac{-\underline{K}_3+\underline{K}_5\left(\underline{K}_7-\underline{K}_6\right)}{K_8}}+\\
+\frac{\frac{R_{\text{Ł}}}{K_{\text{Ł}}}\frac{\underline{Z}_{S1}\underline{K}_3-\underline{K}_5\left(\underline{Z}_{S1}\underline{K}_7+\underline{Z}_{L1}\underline{K}_6\right)+\underline{K}_4}{K_8}}{K_9+\frac{R_{\text{Ł}}}{K_{\text{Ł}}}\frac{-\underline{K}_3+\underline{K}_5\left(\underline{K}_7-\underline{K}_6\right)}{K_8}}
\end{gathered}\tag{9}$$

where

$$\begin{gathered}
\underline{K}_1=e^{j\frac{\pi}{2}}\left(\frac{1}{\underline{Z}_{S1}+\underline{Z}_{L1}}+\frac{e^{-j\delta_{12}}}{\underline{Z}_{S2}+\underline{Z}_{L2}}+\frac{e^{-j\delta_{13}}}{\underline{Z}_{S3}+\underline{Z}_{L3}}\right)\\
\underline{K}_2=\frac{1+M^2}{\underline{Z}_{S1}+\underline{Z}_{L1}}+\frac{1}{\underline{Z}_{S2}+\underline{Z}_{L2}}+\frac{1}{\underline{Z}_{S3}+\underline{Z}_{L3}}\\
\underline{K}_3=\left(\underline{Z}_{S3}+\underline{Z}_{L3}\right)\left(e^{-j\delta_{12}}-1\right)+\left(e^{-j\delta_{13}}-1\right)\left(\underline{Z}_{S2}+\underline{Z}_{L2}\right)\\
\underline{K}_4=\left(\underline{Z}_{S1}+\underline{Z}_{L1}\right)\left(\underline{Z}_{S2}+\underline{Z}_{L2}\right)+\left(\underline{Z}_{S2}+\underline{Z}_{L2}\right)\left(\underline{Z}_{S3}+\underline{Z}_{L3}\right)+\\
+\left(\underline{Z}_{S3}+\underline{Z}_{L3}\right)\left(\underline{Z}_{S1}+\underline{Z}_{L1}\right)\\
\underline{K}_5=\left(\left(\underline{Z}_{S2}+\underline{Z}_{L2}\right)+\left(\underline{Z}_{S3}+\underline{Z}_{L3}\right)\right)\\
\underline{K}_6=\frac{M^2}{\left(\underline{Z}_{S1}+\underline{Z}_{L1}\right)\underline{K}_2}\qquad\underline{K}_7=\frac{M\,\underline{K}_1}{\underline{K}_2}\\
K_8=\left(\underline{Z}_{S2}+(1-\alpha)\underline{Z}_{L2}\right)\left(\underline{Z}_{S3}+\underline{Z}_{L3}\right)\\
K_9=1-\underline{K}_6+\underline{K}_7+\alpha\underline{Z}_{L2}\frac{1-\underline{K}_6+\underline{K}_7-e^{-j\delta_{13}}}{\underline{Z}_{S3}+\underline{Z}_{L3}}
\end{gathered}$$

Graphical interpretation of formulas

At first glance, the formulas (8) and (9) seem too complex for driving the conclusions; thus, the corresponding graphical interpretation has been carried out for some defined network parameters and powers interchanged between systems.

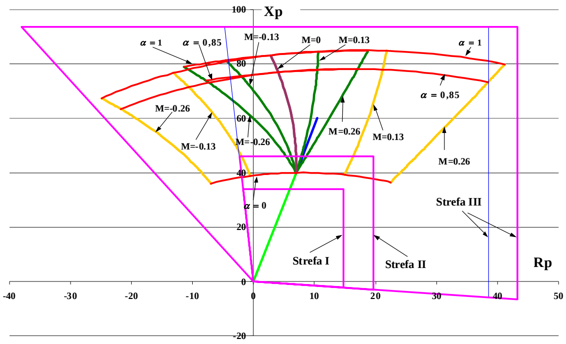

Fig. 4 Impedances measured by distance protection at W1 circuit-breaker during the 2- or 3-phase metallic short-circuit in the transmission line 1 or transmission line 2 when the PST controller is on and δ_{13} angle value is strongly negative

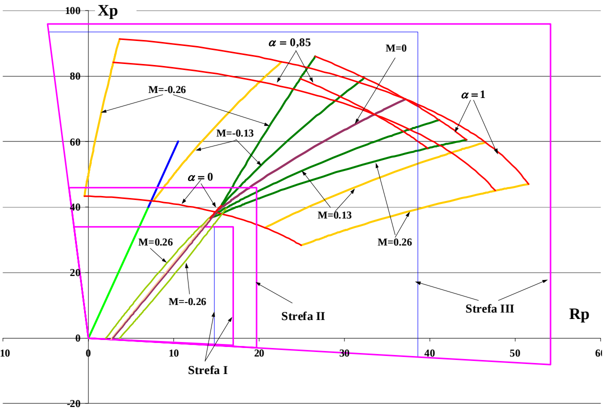

Fig. 5 Impedances measured by distance protection at W1 circuit-breaker during the 2- or 3-phase arc short-circuit in the transmission line 1 or transmission line 2 when the PST controller is on and δ_{13} angle value is strongly positive

Many figures have been obtained, and two of them are selected for presentation in the paper as especially distinctive ones. The case with the highest measuring error towards the negative resistances, i.e. the metallic short-circuit at the negative angle δ_{13} , is shown in figure 4. Whilst that with the highest measuring error in the range of positive resistance values (i.e. an arc short-circuit at the positive angle δ_{13} is presented in figure 5).

The first thing one can see in the both figures is the difference in the impedance measured for the 3-phase and 2-phase short-circuits. Such a case does not occur not only when the PST controller is missing but also for any other FACTS controller. It results from the specific features of the PST controller, which introduces, to the actual phase, a voltage proportional to the difference of voltages in the other phases. In the distance protection, the difference of voltages introduced in two phases is taken into account; thus, in practice, the value proportional to the voltage in the third phase is taken for the measurement. When the three-phase fault occurs nearby the controller, the value of the voltage introduced by the controller is low, whilst, for the two-phase fault, the value of voltage introduced to the measurement does not change and, due to the lowering of voltages in the damaged phases, causes a much higher shift. That way, the difference between impedances measured for the three-phase and two-phase short-circuits can be explained. For three-phase short-circuits, the results at different PST settings are similar to those obtained with no controller at the different angles between systems [4]. However, for two-phase short-circuits, the PST controller introduces higher errors to the measurements. Thus, the two-phase faults will decide on the choice of range of the distance protection zones.

During the arc-type faults, the very low influence of the PST controller on the impedance measurement in the line close to the protection is also observed. If the first zone of the distance protection is chosen regarding the boundary conditions, it can require a slight expansion as to the resistance. However, in general, it is not necessary. At the excessive resistance reserve in this zone, under the two-phase fault conditions, the fault at the initial point of the successive line can sometimes penetrate into the first zone; in such a case, the first zone shall be slightly shortened to block the possibility of an unselective operation of distance protections.

Settings of the second zone of the protection do not require any manipulation.

The controller very intensively affects the measured impedance value (especially resistance) during the two-phase faults in the line on its side opposite to the protections; then, the protections operate in the third zone as the remote back-up. When the δ_{13} angle value is negative, the controller only slightly affects the reactance measurement. When the δ_{13} angle value is positive (especially for the arc-type short-circuits), the relevant errors in the reactance measurements start to appear; however, regarding their specifics, the changes in the zone setting as to the reactance are not required. When choosing the negative resistance in third zone, the case of the maximum power flow from the *Sys 3* to *Sys.1* just before the short-circuit (the highest negative value of the angle δ_{13}) as well as the two-phase metallic short-circuit are to be taken into account. When choosing the positive resistance in third zone, the case of the maximum power flow from the *Sys 1* to *Sys.3* just before the short-circuit (the highest positive value of the angle δ_{13}) as well as the two-phase arc-type short-circuit are to be taken into account.

Verification of results

A series of simplifications has been introduced when deriving the formulas. The subsystem models have been developed from the voltage source of the nominal value and phase shift corresponding to the transmitted active power and of the impedance corresponding to the short-circuit capacity of the actual substation with disconnected line not included in the model of subsystem. In electric power lines, not but the longitudinal components have been considered.

To asses if the assumptions do not go too far resulting in the conclusions far from the true, i.e. if the formulas can be used when choosing the protections, the decision has been taken to verify the results applying the platform proposed Jiang for investigation of the FACTS models [5]. The verification has been carried out in the PS CAD environment (Fig.6).

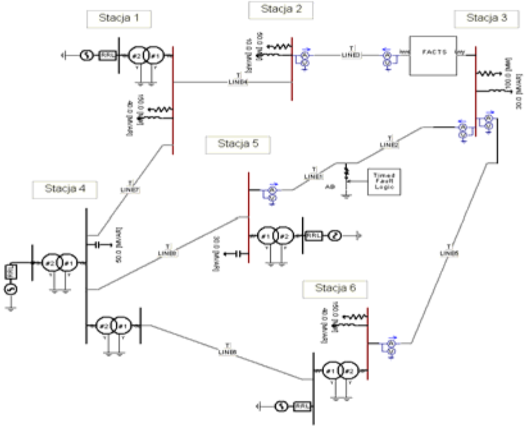

Fig.6 Section of the network investigated using PS CAD program.

First, the initial simulations have been carried out to obtain the equivalent model for calculations as described above (Fig.1), Then, the equivalent subsystems (Fig.6) on the second, fifth and sixth substations have been found and the calculations were conducted. Independently, the short-circuits have been simulated using PS CAD (Fig.6) with no simplifications for lines and transformers. In the same environment, the currents and voltages have been measured and impedances have been found out. For different short-circuits, the obtained results have been superposed on the common diagrams. One of the diagrams constructed for the arc-type short-circuit between the substation 1 and substation 3 and the negative angle between voltage vectors between substation 2 and substation 6 (Fig.6) is presented in figure 7.

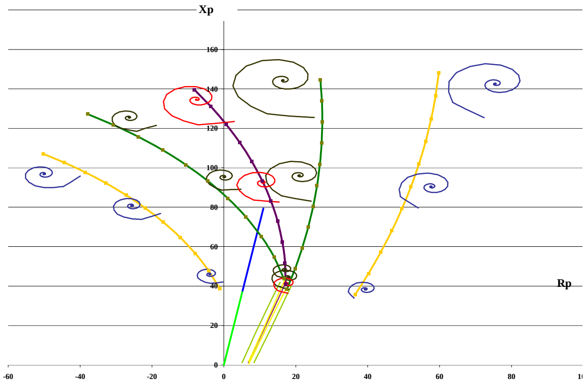

Fig.7 Impedances measured by the protection at W1 circuit-breaker (Fig.1) obtained from the formulas and measured at substation 2 (Fig.6) in turn of the simulation.

The plots of impedances obtained from the formulas (8) and (9) and presented in figure 7 are similar to those in figures 4 and 5; the differences result from other parameters of lines, systems and short-circuit type. From the time waveforms of the measured impedances obtained in the digital simulation the sections just preceding the reaching of the steady state have been cut out (spiral lines). We can see that there is no ideal matching between the results obtained by simulation and those found analytically using the formulas. The differences result from the simplifications assumed for calculation purposes. However, regarding the fact that the safety and sensibility coefficients are considered when choosing the protections, the results obtained from the formulas are sufficiently accurate for the protections' choice. Therefore, we can state that the verification of results has been run successfully

Conclusions

Influence of the PST controller on the impedance measurement during the short-circuits in the line nearby the protection is low and appears not but the arc-type faults.

When the protection is located on the controller's side opposite to the fault, the PST intensively affects the impedance measurement (especially for –two-phase short-circuit). Thus, the change in the protections third zone settings is required. The feature of the measuring errors introduced by the controller decides on the necessity of the zone's expansion for both the positive and the negative resistances. In very few cases, the shortening of the first zone (only at the minimum leakage reactance of the series transformer) can be required.

There is no problem to separate the areas of measured impedances for the faults in the particular lines by using the protections with known characteristics.

During digital verification it has been found that to obtain the full profit of the PST controller's control properties, the assumed series transformer has to be that with the minimum leakage reactance (three single-phase toroidal transformers). From the other side, if we are interested in the limitation of the power transmitted in the frame work of the investment on the Poland –Germany border (with no planned power transmission increase in the future), the small leakage reactance is not necessary resulting in the higher measured reactance value behind the controller and facilitates the selective operation of protections.

Distance protections are able to work properly in vicinity of the PST controller, and not but the change in settings is required.

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