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MV network earth fault parameters measurement as factor supporting quality of network operation in case of renewable sources presence

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Abstract. Security of supply and reliability of distribution network operation play the important role in power systems incorporating renewable energy sources. The requirements for reduction of SAIDI and SAIFI indexes imposed on distribution network operators result in intensive research being directed towards the development of modern methods able to ensure the improved continuity of customer supply. One of the effective ways to grant better network operation conditions is the improvement of earth fault current compensation adjustment and the correction of earth fault protection settings. The evaluation of network operating conditions and the proper selection of neutral point grounding parameters should be carefully conducted especially in the case of wind farm connections to the network. For this purpose, an innovative, non-invasive method of measuring network earth fault parameters has been developed. In result a portable device, named MPZ, able to measure the network earth-fault parameters was constructed. The measurement results conducted by use of the created meter form the solid base for proper selection of neutral point grounding ways and can effectively improve the quality of network earth fault current compensation and of earth fault current compensation coils adjustment. These improvements directly translate into increased reliability of the distribution network operation.

1. Introduction

The growing global demand for electricity and increasing environmental awareness translates into growing support of renewable energy sources development and in result in the fast grow of renewable energy industries. The number of new wind farms has grown significantly in recent years, forcing a dynamic and unpredictable development in medium voltage (MV) network structure. The farm internal network, located on the farm site, consists of cables connecting various generation systems to the site transformer station. Outer network infrastructure connecting the wind farm to the main substation of National Power System (GPZ), is often composed of several dozen kilometers of medium voltage lines. During the network development process for the wind farm connection several problems are encountered starting with the land acquisition and following the long time needed to obtain the construction permits. Apparently choosing the cable network for connecting several wind generators is a good solution that makes the line invisible and does not affect the aesthetic evaluation of the landscape, and has higher supply reliability comparing to overhead lines because it is not exposed to adverse weather conditions. Use of cables comparing to the overhead network impose one



major technical problem - much larger line to line and line to earth capacitance increasing with the length of cable lines. In effect the change of network zero sequence circuit parameters, and in particular of the earth fault compensation factor value, can result in a deterioration of earth fault protection operating conditions and, consequently, the deterioration of power supply continuity.

2. Supply continuity indicators

A major challenge for all distribution network operators is to ensure the high quality of supply expected by the power consumers and energy regulatory authorities. In Poland the continuity and reliability of power supply from MV power grid is expected to continuously improve. This is justified taking into account the differences between the average power outages duration and the frequency of these power outages taking place in Polish power distribution networks comparing to the leading European countries. The improvement of power supply continuity is now gaining importance as a decision factor that influence the investment variants of distribution and transmission networks. A large number of European regulators introduce instruments forcing power distribution system operators (DSO's) to maintain or improve power supply continuity. Typically this is done by setting the reference values of SAIDI (System Average Interruption Duration Index) for long lasting interruptions that should be reached by the network operators. The achievement of reference values guarantees the recognition of DSO operating costs at a reasonable level. Failure to meet the required indicator values has the consequence in lower tariff revenues, and achieving better values is rewarded by additional revenues comparing to the justified revenue level set in course of regulatory tariff verification process. The introduction of this type of quality regulation began in Poland in 2016.

Distribution network operators are therefore considering several solutions leading to effective reduction of SAIDI values. The proper strategy to achieve such goal should identify:

- specific reliability objectives,
- the most cost-effective ways to achieve them.

One of the effective ways to achieve the SAIDI value improvement is the proper selection of the operating conditions of the medium voltage network neutral point and the choice of effective earth fault protection equipment. This can be achieved by the application of new measurement methods and computer programs developed to support the design work and the maintenance process of network operators. The above mentioned measures proved to be helpful in limiting the development of earth faults by reducing the earth fault current value and overall power outage time, by reducing the time needed to identify the line with a ground fault. In result the lower values of SAIFI (System Average Interruption Frequency Index) and SAIDI are registered and also the value of ENS (Energy Not Supplied) is limited.

3. Earth-fault protection problems

The proper selection of earth fault protection is of major importance due to the fact that operating experience of Polish MV network indicates that earth faults have the share of 70-80% in all disturbances reported in these networks. The earth fault intensity is relatively large and the analysis conducted shows that during the year one can expect from a few to a dozen or sometimes several dozen of such events for 100 km of the MV line.

These faults are the cause of various phenomena that adversely affect the reliability and quality of electricity power supply for consumers. They result as well in network overvoltages and influence the level of electric shock risk. Earth faults, in the form of an unstable electric arc (intermittent faults), may cause dangerous overvoltages to ground, which may result in loss of insulation at other locations within the network. Earth faults can be a source of an electric shock hazard. This applies at the earth fault location, but it may also be transferred to other sites as well. In the case of earth faults occurring at MV/LV substation, the short-circuit currents flowing through the grounding installation of the substations may also cause dangerous voltages in the low voltage installations. Such disturbances often results in damage of electrical appliances or components if not identified and switched off in due time.

The most commonly used earth fault protection criteria in Polish medium voltage networks are based on the measured values of zero sequence current of the individual MV lines and on the zero sequence voltage of the network. The traditional protections are basing on zero sequence overcurrent criterion ($I_0 >$) or on directional zero sequence active or reactive power criterion ($->$). Modern protections are basing on admittance criteria that can be divided into basic ones (admittance $Y_0 >$, conductance $G_0 >$, susceptance $B_0 <$, admittance-comparative YY_0) and complex ones (YG_0 or $B_0 + G_0$). In all admittance protections the required conditions to actuate them are the minimal value of network zero sequence voltage and the exceeded values of the criterial value (for instance of zero sequence component of Y_0).

The performance of earth fault protection is determined by the range of resistances at the place of earth fault (RF) that can be detected. This range can be greatly reduced by incorrect selection of earth fault identification criteria and by erroneous protection setting values due to ignorance of network zero sequence parameters.

Ineffective protection operation can be also caused by:

- large short-circuit loop impedance values, resulting in low values of zero current signals,
- high number of high-resistance faults in overhead networks,
- decreased sensitivity of the measuring systems, limited by current errors generated by the earth fault current transformers and by the effect of the capacitive asymmetry of individual lines,
- different modes of network operation (neutral grounding method, switching off the auxiliary power transformer, temporary activation of systems forcing the flow of active or reactive zero sequence current component - AWSCz or AWSB, automatic switching of the standby power supply - SZR).

The following section of this paper presents selected aspects related to the correct determination of network earth-fault parameter values influenced by continuous change of topology of power supply network caused by the connections of new wind farms. The ongoing such new connections result in a significant increase in the value of line to line and line to ground capacities and in consequence of zero sequence capacitive currents of MW network. In the case of networks with earth fault current compensation the network parameter that the best presents the state of the relationship between the inductance of the compensating coils and the network zero sequence capacitance is the earth-fault current compensation coefficient s . The value of this coefficient reflects as well in the best way the operating conditions of earth fault protections. Figure 1 presents the effect of earth fault current compensation on the range of the earth fault resistances that can be detected by the network earth fault protection in the MV network having the parameters given in Table 1. In such way one can verify the effectiveness of protection operation. To illustrate this some analyses were carried out for earth fault protections installed on mixed overhead and cable line L6, having the share coefficient in network capacitance of 9.5% and as well for earth fault protections installed on the cable line connecting the wind farm (FW) having the share coefficient equal to 33%. The total capacitive earth fault current I_{cs} of MV network was 159 A. The ranges of detected earth fault resistances were verified for these lines equipped in protections based on the combined YGo admittance criterion and for comparison in zero sequence overcurrent criterion and in zero sequence directional active power criterion as well. For both lines, the most effective criterion was YGo (the graphs are overlapping), which loses its sensitivity due to unfulfilled zero sequence voltage condition. For this criterion, similarly to the directional criterion, the largest range of earth fault resistances detected coincides with the area of the best earth fault current compensation. The analysis were conducted for the starting value of the zero sequence voltage of 15 V. In figure 1 the characteristic sensitivity distribution of earth fault resistance values can be observed for the admittance and the directional criterions however, for directional criterion the smaller range of the detected resistances is observed across the whole range of coefficient “ s ” variation.

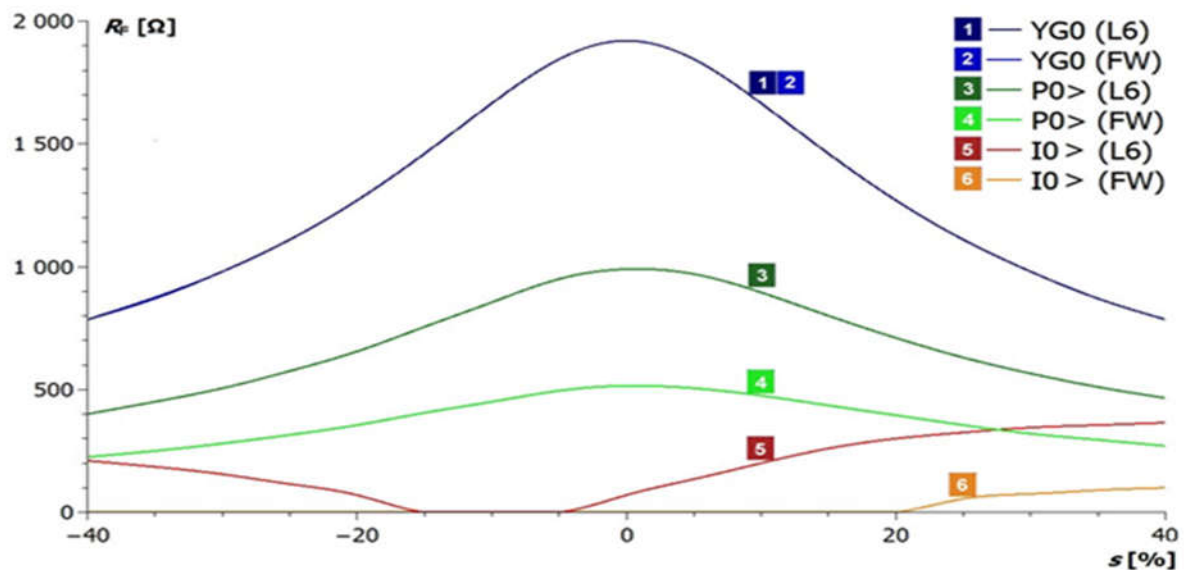


Figure 1. The ranges of detected earth fault resistances by selected earth fault identification criteria with variable degree of earth-fault current compensation for the considered MV network.

Sensitivity of the overcurrent criterion $I0>$ was the smallest and increases with the growing value of module of compensation coefficient s (in contrast to the other criteria). Due to the high value of the share coefficient in network earth fault capacitance current, the FW line does not provide the conditions for the correct functioning of the earth fault protections.

Table 1. Parameters of tested network.

Parameters	Values
Rated voltage U_N	15 kV
Network earth fault current value I_{CS}	159 A
Compensating choke current value I_L	179 A
Earth fault current compensation coefficient s	12,5%
Active zero sequence current forced	17,6 A
Number of lines	10
Earth fault current of L6 line I_{CL}	15,1 A
Share coefficient in network earth fault current a	9,5%
Earth fault current transformer	Zero sequence Holmgreen filter 200 A/5 A
Earth fault current of FW line I_{CL}	52,5 A
Earth fault current transformer	Zero sequence Holmgreen filter 300 A/5 A
Share coefficient in network earth fault current a	33%
Attenuation coefficient of the network d_0	2,4%

Table 1 presents the values of the network parameters after connecting the wind farm FW and after replacement of the compensating coil installed at the neutral point of the grid. The network earth fault parameters used in the analysis were obtained by measurements made with the meter described later in this article. These measured values are displayed on the meter operating screen (figure 3).

Prior to the wind farm connection, the network earth fault current I_{CS} was at the level of 106 A, and the network was overcompensated ($s = 12.7\%$) with a compensation coil operating at its maximum current range (120 A). Table 2 presents the changes in the degree of earth fault current compensation and the higher values of earth fault resistances possible to be detected in the tested lines by the overcurrent protection $I0>$, the directional zero sequence active power protection and admittance YG0 protection for the four network configurations. The network configuration before connecting the wind farm was described as K1, after connecting of wind farm and replacing the old compensation coil by

the larger one - as K2. In addition, the operation of the network was considered in two new configurations with the disconnected wind farm (K3) and with the disconnected one of the two HV/MV substation sections (K4).

Table 2. Highest values of earth fault resistance possible to be detected for different network configurations (N.A. means no action).

Configuration	I_{CS}	I_L	s	L6			FW			Y_G
				a	$I_{0>}$	$P_{0>}$	a	$I_{0>}$	$P_{0>}$	
	A	A	%	%	Ω	Ω	Ω	Ω	Ω	Ω
K1	106,5	120	12,7	14,2	175	870	1880	—	—	—
K2	159,0	179	12,5	9,5	230	845	1560	33,0	N.A.	435
K3	106,5	179	68	14,2	370	385	715	—	—	—
K4	126,5	179	41,4	11,9	355	505	930	15,8	255	300

In result of research conducted the admittance criterion was by far the most sensitive one and at the same time the least susceptible to changes in the way of neutral point operating mode as well to the changing network configurations. For network represented by K3 and K4 configurations, the significant detuning of earth fault compensation is possible in the absence of follower earth fault current compensation, what lowers the effectiveness of measures preventing the electric shock and deteriorate the conditions for extinguishing the arc present at the place of earth fault what may be the cause of intermittent earth faults. If auxiliary power transformed bay is switched off, for all considered network configurations the decrease of detected earth fault resistance range will take place or even the absence of protection operation can be expected with the exception of protection equipped in admittance criterion (the sure operation of $Y_{0>}$ module is maintained).

The above presented analyses were carried out on the assumption that the earth fault protection setting values were correctly calculated taking into account the actual values of the earth fault capacitive currents of the whole network I_{CS} as well earth fault current values in the individual lines I_{CL} .

4. Measurement of earth fault parameters of MV network

The analytical (calculation) or measurement methods are used to determine the capacitive currents I_{CS} and I_{CL} as well as such parameters as earth fault compensation factor s , network attenuation factor d_0 and residual current I_{res} . However, the analytical method requires comprehensive knowledge of the network structure, what is very difficult to achieve. In the past few years, the measurements of the earth fault current parameters of MV network were made only during the forced real earth fault [1]. For this reason, the frequency of performing such measurements and evaluating the capacitive current levels on this basis was quite rare. Measurements conducted during the forced experimental earth fault involve many disadvantages. The need to switch off the line with the fault causes a break in the power supply to consumers. In addition, during the measurements, the associated overvoltages can cause damage to the insulation of other network lines and, consequently, lead to emergency conditions. Therefore, since last few years, these measurements were replaced by indirect measurements using other methods. Their technical implementation is based mostly on analysis of network parameters and relationships listed below:

- the value of zero sequence voltage component caused by the natural asymmetry of the network,
- the phase angles between the vectors of the zero sequence voltage component and the zero sequence voltage component caused by the natural asymmetry of the network,

- the comparison of zero sequence voltage with the voltage value of the line phase grounded during the pure resistance fault,
- zero sequence line currents measured during earth faults caused by natural distortions,
- currents and voltages measured when switching the external low voltage sources into zero sequence circuit of the network.

Basing on the above enumerated data a number of new solutions for non-invasive determination of earth fault parameters of the MV network have been developed at the Institute of Electric Power Engineering of Poznań University of Technology. As a result of the research conducted, the measurement method [2,3,12] using the special measurement system MPZ was developed. The MPZ (earth fault network parameter meter) was constructed allowing to determine earth-fault parameters in MV network equipped with the earth fault current compensation. The advantage of this solution is the possibility to carry out the measurements during normal network operation, without performing any forced ground faults, and only the short-time switching off of individual lines is required to determine the share of these lines in the earth fault current of the network.

5. Measurement method

For the measurements execution, the access to low voltage winding of earth fault current compensation coil is required which is normally used to force the flow of zero sequence active current (AWSCz). The method of the MPZ measuring system operation is explained in figure 2. The signals measured during the temporary insertion of an additional voltage source into the zero sequence circuits of the network form the base for the proper operation of the MPZ meter. The voltage U_w of the forcing source is switched on for the measurement time to the secondary winding (forcing) of the earth fault current compensating coil and is transformed onto the operating voltage level of the network.

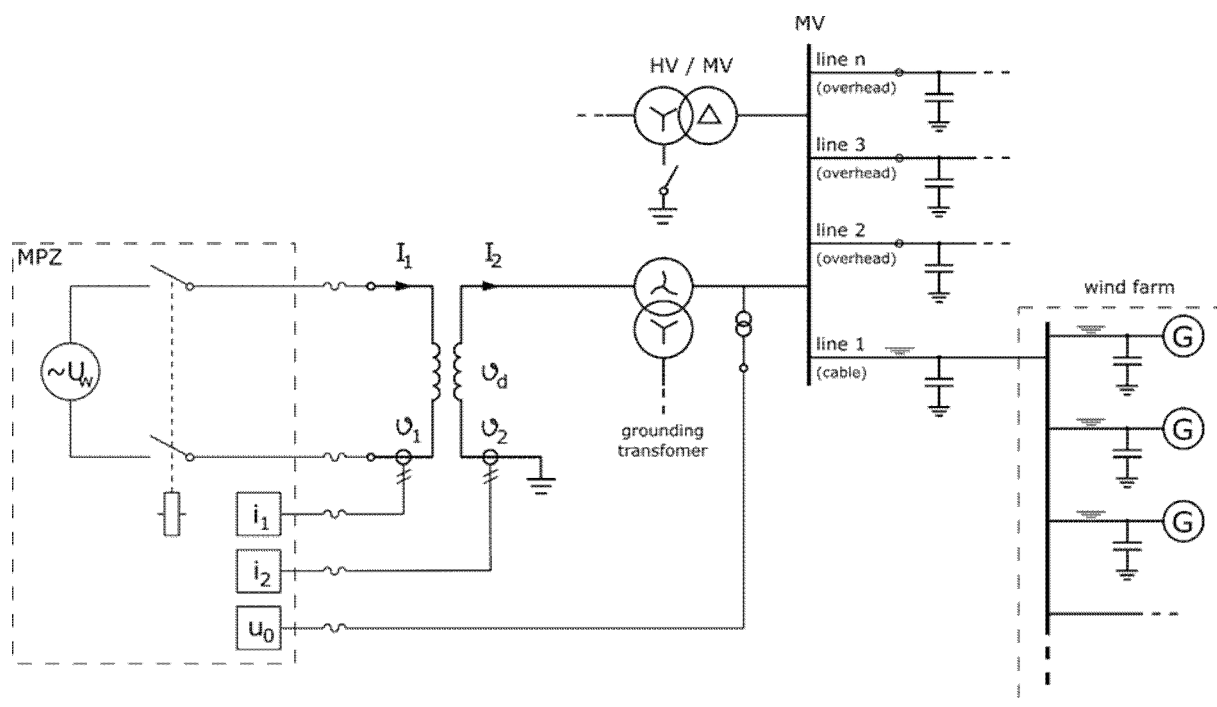


Figure 2. MPZ measuring system for determining earth-fault MV network parameters mining earth-fault MV network parameters.

Assuming that the longitudinal impedances in network substitution schemes can be neglected, is possible to express the currents I_1 and I_2 induced by voltage U_w , in accordance with figure 2, by the formula (1) and (2):

$$\underline{I}_1 = \mathcal{G}_d \left(\underline{I}_2 + \underline{U}_w \mathcal{G}_d \frac{1}{j\omega_N} \right) = \underline{U}_w \mathcal{G}_d^2 \omega C_{0s} (d_0 - js) \quad (1)$$

$$\underline{I}_2 = \underline{U}_w \cdot \omega \cdot C_{0s} (d_{0s} + j) \mathcal{G}_d \quad (2)$$

These currents flowing through the primary windings of measurement current transformers generate in measuring system the secondary currents $\underline{i}_1$ and $\underline{i}_2$ given by the relationships (3) and (4):

$$\underline{i}_1 = \underline{U}_w \cdot \omega \cdot C_{0s} (d_0 - js) \frac{\mathcal{G}_d^2}{\mathcal{G}_1} \quad (3)$$

$$\underline{i}_2 = \underline{U}_w \cdot \omega \cdot C_{0s} (d_{0s} + j) \frac{\mathcal{G}_d}{\mathcal{G}_2} \quad (4)$$

where:

- $\underline{U}_w$ – voltage value of the additional forcing source,
- C_{0s} – zero sequence network capacitance,
- $\mathcal{G}_1, \mathcal{G}_2, \mathcal{G}_d$ – winding ratios of measuring current transformers and of the compensation coil,
- d_0 – network and compensation coil attenuation coefficient
- d_{0s} – network and compensation coil attenuation coefficient with the conductance of neural point G_N omitted,
- L_N – compensation coil inductance,
- ω – network pulsation.

Current I_2 and voltage U_0 are the values that directly determine the earth fault capacitance of the network. On the other hand, by conducting the proper calculations the degree of earth fault current compensation can be determined. For this purpose, the procedures of determining the reactive power Q or the susceptance B for the circuits marked with indexes 1 and 2 are performed. The coefficient of earth fault current compensation s_p according to the power method is expressed by the relationship (5):

$$s_p = (-1) \frac{Q_1}{k_g Q_2} \quad (5)$$

When the susceptance method is applied, this coefficient is expressed by the equation (6):

$$s_p = (-1) \frac{B_1 k_g}{B_2 \mathcal{G}_d^2} \quad (6)$$

Factor (-1) corresponds to the operational practice, where it is often assumed that the state of network overcompensation should be designated by a positive sign and that the state of under compensation should be expressed by a negative sign.

Measurements conducted by such system may be subject to certain error due to the influence of voltage natural asymmetry U_{0as} . This effect can be reduced by using sources with sufficiently high voltage U_w . The U_w value must be however limited, since this voltage must not exceed the setting of the earth fault protection installed in the network. A more effective way of eliminating the effect of voltage natural asymmetry is to calculate the arithmetic average of s coefficient values from the data obtained in two successive measurements made at using the opposite phase of the U_w voltage. Such a method is used in the MPZ meter.

6. Meter construction

The MPZ is a portable measuring system and consists of voltage inducing device and a microprocessor measuring and control device connected via a USB communication link to a computer [11]. The U_0 zero sequence voltage from substation measurement bay and signals from Rogowski coil (I_{dl} in figure 3) are send to MPZ via suitable terminals and sockets. The suitcase is equipped with suitable inputs for connecting voltage inducing device to the secondary winding of compensation coil (U_w in figure 3). The power supply voltage of MPZ is 230 V AC. The basic version of MPZ meters is designed primarily to conduct measurements in 15 kV networks with a neutral point grounded by compensating coil equipped with additional winding used for zero sequence active current forcing

(AWSCz). In addition, specialized versions are constructed for 6 kV compensated networks and for MV networks with the neutral point grounded by resistor.

The measurement process is controlled by the appropriate software. In figure 3 the screen after performing the measurements for the above described test network is presented. Prior to performing the measurement, the correct operating voltage of the network, the number of compensation coils, and the ratio of compensation coil windings should be introduced using the special editing field. Other additional data are useful for final results editing. The calculated earth fault network parameters are displayed in the left panel. Meter support program allows for archiving them. Appropriate procedures allow for displaying and organizing the stored data. Additional tools facilitate the calculations in case of measurement series. In addition, the value of the compensation current of the coil is determined, taking into account the effect of auxiliary grounding transformer impedance (the value on the green plate in figure 3).

In the lower right corner of the screen, below the mean value of the forced zero sequence voltage asymmetry, the value of the zero sequence voltage component under normal network conditions is given. The measurement presented in figure 3 relates to an overcompensated network, where the earth fault current compensation factor $s = 12.5\%$ and the asymmetry of the zero sequence voltage is 0.63 V . The I_{d1} (or also I_{d2} in case of two coils in the substation section) is the value measured by Rogowski coil as a result of the forced 10-percent voltage asymmetry, while the value of the injected current I_w depends on the level of network earth fault current compensation. One of the parameters measured during the measurement is the network attenuation factor. It contains information about the active earth fault current. This information can help in verification of proper performance of zero sequence active current forcing equipment (AWSCz).

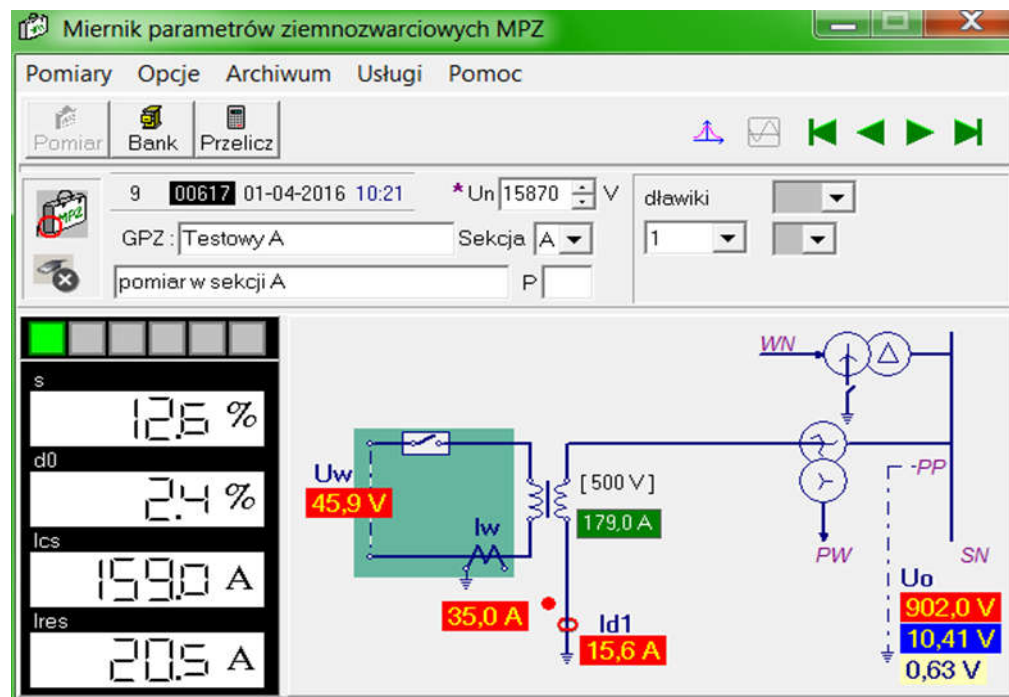


Figure 3. MPZ.EXE screen after measurement.

7. Summary

The main advantage of MPZ meter is the possibility to conduct the measurements during normal network operation, without the need to perform the earth faults. Only in order to determine the share coefficients of each line's contribution to the earth fault current of the network it is necessary to switch off individual lines. The functional range of the MPZ can be expanded with the stationary device for

automatic earth fault current measurement and earth fault current compensation evaluation that allows to conduct such operation remotely periodically or on demand [8,9]. Such a stationary solution (in the form of an integrated BS KKZ unit) allowed BEZPOL company to develop the automatic follower system for Petersen coil compensation adjustment that can replace the traditional criteria based on identification of voltage resonance [13].

The measurement method described in this article is also used in the RSB-MPZ [4,5] distributed wireless metering system, using a set of sensors to control the zero sequence current flow in all lines connected to the considered network. The detailed discussion of its accuracy is beyond the scope of this paper but it is satisfactory taking into account the accuracy of current and voltage measuring transformers accuracy being the base of protection devices operation. The adaptive control of protection settings can be the subject of further development studies concerning the MPZ application.

The possession of stationary MPZs also allows for the use of these devices forcing circuits to perform various verification tasks of protection automation. The authors of this paper attempted to use the changes of earth fault parameters of the power line, while forcing the additional asymmetry of the zero sequence voltage U_0 component at the neutral point of the network, to identify high resistance earth faults [6,7,10].

On the basis of the up to date experience of MPZ meter operation, many changes were implemented both in the construction of the device itself and in the way of measuring and interpretation of the obtained results as well.

The development of MPZ meter series continues and is focused on improvement of the measurement software performance and on increasing the functionality of the meter software. The new systems for earth fault MV network parameters evaluation are elaborated and verified and resulted in the development of a system enabling the earth fault parameters estimation even in networks with neutral point grounded by resistor.

The dynamic growth of MV cable networks, closely linked to the network connections of new distributed energy sources, necessitates reliable measurements of earth fault parameters in distribution networks to ensure higher continuity of their operation..

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