VERIFICATION OF THE EARTH FAULT LOCATION METHOD BASED ON EVALUATION OF VOLTAGE SAG IN REAL DISTRIBUTION NETWORK

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ABSTRACT

The main aim of the contribution is verification of designed principle for earth fault location in real distribution network which is based on evaluation of voltage sags recorded on secondary side of distribution transformers MV/LV. For this purpose, series of experimental measurement in real compensated MV distribution network were carried out. During the experiments, different types of earth fault (solid, arcing and impedance earth fault) were artificially ignited and all important waveforms (secondary voltages of distribution transformer, fault currents, voltages and currents at supply substation) were recorded for further analyses. These fault records were used for verification of described method. The result of the analyses is answer to question, if it is possible to use the idea of earth fault localization method in real conditions of compensated distribution network operation.

INTRODUCTION

The requirement to monitor the characteristic parameters of electrical energy and the evolution of distribution networks towards the concept of “SmartGrids” requires the installation of measuring and recording equipment in individual distribution transforming substations (DTS). If such equipment is installed in the majority of DTSs in a given distribution network and all the recorded data are appropriately centralised and time-synchronised, it can bring new possibilities for the optimisation, control and protection of by this way monitored networks.

Just an earth fault localization problem can be solved with mentioned advancement, because due to low level of earth fault current it is very difficult to localize a fault point in wide distribution networks especially in resonant earthed system. This is the reason why lots of different methods have been proposed for earth fault location in such systems, for example these transient or passive methods can be used [1-5]. A few methods are focused on calculation of the reactance between supply substation and earth fault point [6]. The reactance corresponds to fault distance which can match more than one fault place in the network. Therefore additional principle has to be used for selection of correct fault place. Another group of methods is based on comparison of voltage sags recorded in supply substation with Voltage Sags Database (VSD) [7] or evaluation of secondary voltage patterns [8].

METHOD PRINCIPLE

The presented method is based on voltage sag evaluation, where voltage sags are measured on LV side of distribution transformers MV/LV with Dy winding connection. Monitored voltage sag is caused by short-time connection of auxiliary resistor during earth fault in compensated network. The auxiliary resistor (R_p) is commonly used for increasing of active part of residual current for earth fault protection sensitivity improvement in resonant earthed (compensated) Czech distribution systems. Auxiliary resistor is typically connected to the power winding of arc-suppression coil (Fig. 1) and is switched on automatically in 2 seconds after EF ignition for short-time circa 1 s, as shown in Fig. 2. This time setting is sufficient for indication of EF direction by an earth fault protection located at outgoing feeder.

When solid earth fault occurs in an ideally compensated network (Fig. 1), an earth fault current is flowing through the faulty line to the fault point. This residual I_W current causes voltage sag on faulty line impedances which contributes to unbalance of line to line MV voltages towards the fault point and can be proportionally measured on LV sides both transformers DTS2 and DTS1. However this voltage unbalance on MV side or voltage sag on LV side is hardly detectable in common compensated networks due to the very low level of residual currents.

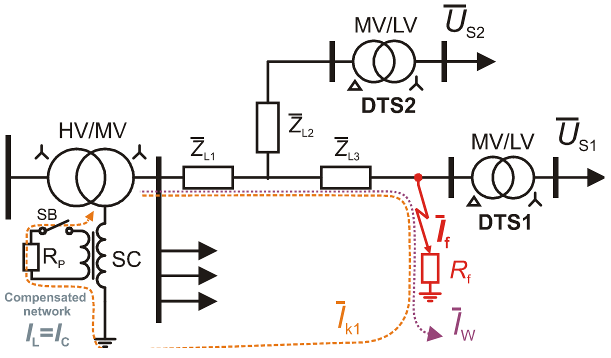

Fig. 1: Currents during a persisting ground fault

Significant voltage sag arises when auxiliary resistor is switched on by switcher SB. In this case the initial residual current $\overline{I}_{\mathrm{W}}$ is for short-time increased by single-phase fault current $\overline{I}_{\mathrm{k1}}$, which is limited by the value of the auxiliary resistor R_p. Again this current flowing through line impedance causes L-L voltage unbalance along the faulty line that is measurable on the LV side of distribution transformers as voltage sags of phase to neutral voltages. This voltage unbalance is increased in the direction of the fault current to the fault point, where it reaches its maximum. This principle can be used for delimitation of faulty area as is described.

Fault Area Delimitation Principle

If protected distribution network is equipped by the voltage monitors which measure RMS values of phase to neutral voltages on LV sides of most of distribution transformers placed in affected network, then it is possible to calculate voltage change ΔU_{SM} evoked by auxiliary resistor connection at all measuring points as is described below.

Let´s assume that earth fault occurred, the three phase voltage RMS values ($U_{S\,L1}$, $U_{S\,L2}$, $U_{S\,L3}$) are recorded and collected. Then voltage change of each phase $\Delta U_{S\,L1}$, $\Delta U_{S\,L2}$ and $\Delta U_{S\,L3}$ is calculated, as is shown in Fig. 2. The figure presents sample of RMS phase voltages recorded on secondary side of real distribution transformer (DT) during solid EF which was ignited in time 0 s and in time 2,5 s was connected auxiliary resistor. A voltage change waveform ΔU_S is calculated as moving difference of values given by Frame 1 and Frame 2, where both frames calculate ten periods moving average of recorded phase voltages. The Figure 1 and Figure 2 are time-shifted by a time interval Δt which is 0,5 s (half period of auxiliary resistor connection).

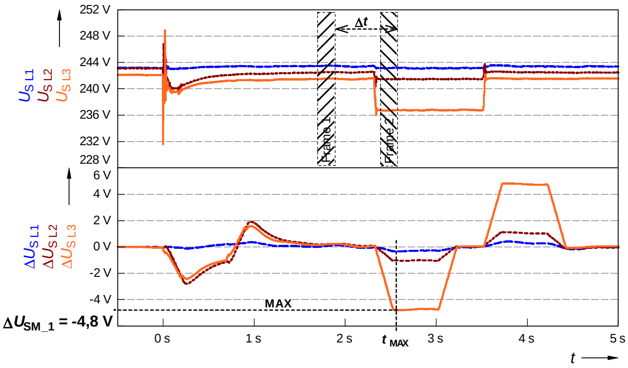

Fig. 2: Example of maximal voltage sag determination for selected DTS during real earth fault

Then, the voltage change waveforms of each phase ΔU_{SL1}, ΔU_{SL1} and ΔU_{SL1} are processed to determinate maximal value of voltage sag $\Delta U_{SM\,x}$ for particular measuring point, where index x is a number of respective DTS where the RMS voltage waveforms were recorded ($x = 1$ for the example in Fig. 2. If it is possible to monitor ΔU_{SM} for the majority of the distribution transforming substations on the affected line, the section of the line affected by the earth fault can be determined as is presented in Fig. 3.

Considering the earth fault in marked spot in Fig. 3 and also short-time connection of auxiliary resistor during the fault, the maximal voltage sag on LV side is measurable with comparable level in the stations DTS1, DTS2, DTS3 and also in DTS placed behind the fault, because the fault current passes through the longest part of its feeding line, in this case line $a + b + c + d + e$. Lower voltage sag is measurable in DTS4 and DTS5 where the fault current flows through the shorter part of their feeding line, in this case sections $a + b + c + d$. Similarly, DTS6 and DTS7 are fed by shorter part of faulty line which is section $a + b + c$. Hence the voltage sag at these stations is smaller. Analogously voltage sag recorded in DTS9 and DTS8 is proportional to section $a + b$. The minimal voltage sag can be measured at DTS10 and DTS11 which are fed only by faulty section a. All stations located on unaffected feeders or directly connected to the supply substation HV/LV.

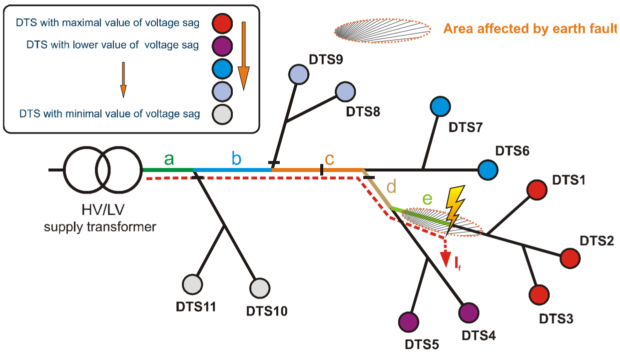

Fig. 3: Principle of ground fault location in a compensated distribution network

Base on above mentioned, the fault area can be delimited by points where highest values of voltage sag was recorded (DTS1, DTS2 and DTS3) and where second highest value of voltage sag was recorded (DTS4, DTS5), respecting measurement error. Correct delimitation of faulty area can be done only if least one DTS behind the fault point is equipped by voltage monitor.

THE PRINCIPLE VERIFICATION USING FAULT RECORDS

To verify above mentioned principle, measurements in a real distribution network were performed. The purpose of this measurement was recording of phase to ground voltages on LV side of selected distribution transformers which can be used for calculation of maximal values of voltage sag to verify earth fault location principle. Disposition of all monitored distribution transformers is depicted in Fig. 4. Earth fault was artificially ignited inside the switching station 22kV/22kV. As it can be seen in Fig. 4, totally four DTs were monitored, where three of all are placed before fault point (between earth fault and supply substation) and last one DT4 behind fault.

Detailed configuration of performed test and all quantities which were recorded during experimental measurement are shown in the Fig. 5.

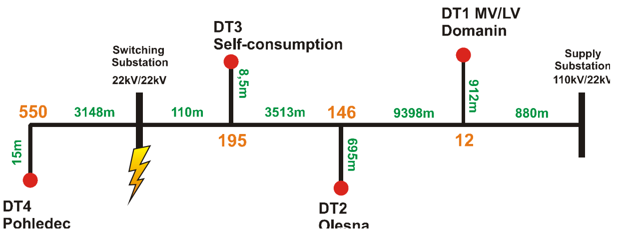

Fig. 4: Topology of faulty feeder and placement of monitored distribution transformers

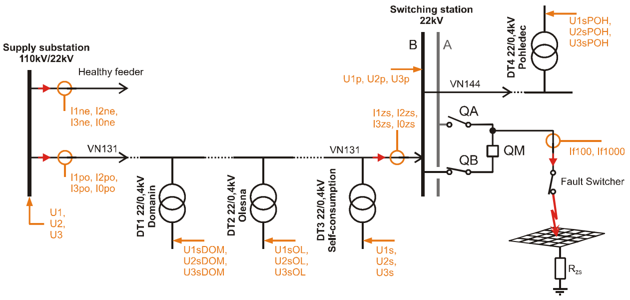

Fig. 5: Detailed configuration of the tested system and quantities recorded during experimental measurement

The experiments were performed for several states of the tested based on compensation state of the network, type of simulated earth fault. In total, eleven faults were simulated; the configuration and parameters of the experimental measurements are shown in Table 1.

Table 1: Characteristics of performed tests

Test No.	Type of EF	Compensation state	Capacitive current
1	solid	compensated (I_L=267 A)	I_C=267 A
2	solid	compensated (I_L=267 A)	I_C=267 A
3	solid	compensated (I_L=267 A)	I_C=267 A
4	solid	undercompensated (I_L=220 A)	I_C=267 A
5	solid	overcompensated (I_L=305 A)	I_C=267 A
6	impedance (300Ω)	compensated (I_L=267 A)	I_C=267 A
7	impedance (1250Ω)	compensated (I_L=267 A)	I_C=267 A
8	impedance (3000Ω)	compensated (I_L=267 A)	I_C=267 A
9	impedance (7500Ω)	compensated (I_L=267 A)	I_C=267 A
10	arcing	compensated (I_L=267 A)	I_C=267 A
11	arcing	undercompensated (I_L=220 A)	I_C=267 A

For verification of described location principle, all recorded voltage sags have to be sorted proportionally to distance of faulty line which is monitored by particular voltage monitor. As follows from network topology (Fig. 4), the highest value of voltage sag has to be recorded on LV side of transformer DT4 and other values has to be met following condition

$$\Delta U_{\mathrm{SM}\,DT4} < \Delta U_{\mathrm{SM}\,DT3} < \Delta U_{\mathrm{SM}\,DT2} < \Delta U_{\mathrm{SM}\,DT1}, \qquad (1)$$

where $\Delta U_{\mathrm{SM}\,DT4}$ is maximal voltage sag calculated from RMS phase to neutral voltages recorded on LV side of distribution transformer DT4 according to described principle (Fig. 2), similarly $\Delta U_{\mathrm{SM}\,DT3}$, $\Delta U_{\mathrm{SM}\,DT2}$ and $\Delta U_{\mathrm{SM}\,DT1}$ are maximal voltage sags recorded on LV side of DT3, DT2 and DT1. Examination of this condition is done individually for each type of earth fault (solid, impedance and arcing) because type of EF especially fault resistance has significant effect to method sensitivity. Since voltage taps of selected transformers were set to the same position over whole experimental measurement, it is not necessary to correct the recorded values of voltage sags.

Solid EF in ideally compensated system

Effective phase to neutral voltages recorded on the LV side of DT4 during solid earth fault in ideally compensated network are shown in Fig. 6. This figure shows that maximal voltage sag arise in faulty phase L3 which is similar for all voltage records. This is given by R/X ratio of characteristic impedance of MV line and also by phase displacement of fault current which causes voltage drop in the same direction as is phasor of phase to phase voltage, therefore maximal voltage sag arises in adequate phase L3 on the LV side.

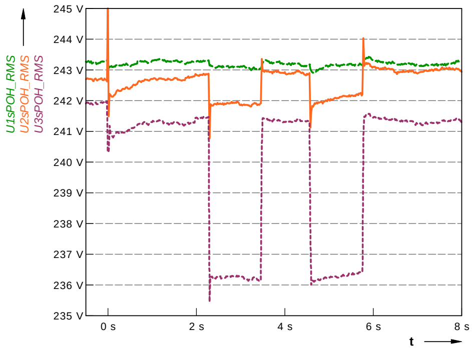

Fig. 6: Effective value of phase to neutral voltages recorded during solid EF in compensated system on LV side of DT4

For this reason, only phase voltages recorded in faulty phase L3 are presented in the next sections.
Comparison of RMS voltages recorded on LV sides in the phase L3 of all monitored DT for test no. 3 is shown in Fig. 7.

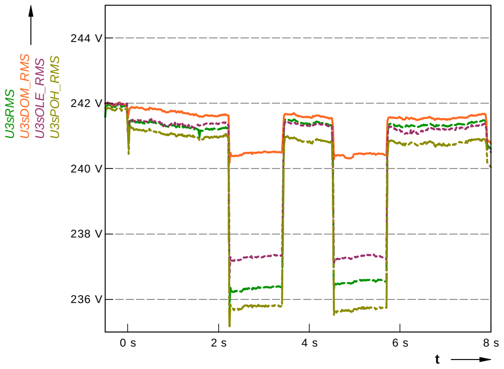

Fig. 7: Effective value of phase to neutral voltages recorded on LV side in phase L3 during solid EF in compensated system for all DTs

As shows in Fig. 7, the maximal voltage sag arise in DT4 as was supposed and also voltage sags recorded in DT1, DT2, DT3 and DT4 met defined condition (1).

$$\Delta U_{\mathrm{SM}\,DT4} = -5{,}26\mathrm{V} < -4{,}98V < -4{,}18V < -1{,}25V$$

All values of maximal voltage sags calculated for all measuring points are listed for solid earth faults in Table 2.

Solid EF in undercompensated and overcompensated system

Similarly during this test, maximal voltage sags were recorded in phase L3 for both tests no. 4 (undercompensated) and 5 (overcompensated). Effective value of phase to neutral voltages recorded on LV side of particular DT during solid EF inside of undercompensated system is shown in Fig. 8 and for case of overcompensated system is depicted in Fig. 9.

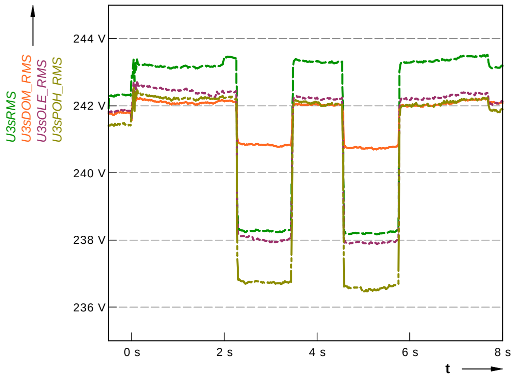

Fig. 8: Effective value of phase to neutral voltages recorded in phase L3 during solid EF in undercompensated system for all DTs

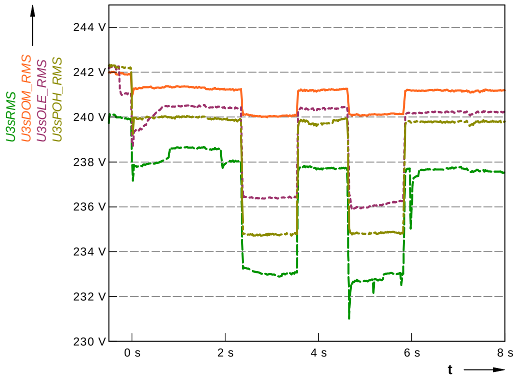

Fig. 9: Effective value of phase to neutral voltages recorded in phase L3 during solid EF in overcompensated system for all DTs

The condition (1) was also met for solid EF in both undercompensated and overcompensated states as calculated values of maximal voltage sags shows. These values are for undercompensated state as follows:

$$\Delta U_{\mathrm{SM}\,DT4} < \Delta U_{\mathrm{SM}\,DT3} < \Delta U_{\mathrm{SM}\,DT2} < \Delta U_{\mathrm{SM}\,DT1}$$

$$-5{,}55\mathrm{V} < -5{,}22V < -4{,}36V < -1{,}32V$$

and for overcompensated state

$$-5{,}09V < -4{,}82V < -4{,}00V < -1{,}15V$$

As it can be seen from these results, the higher sensitivity of proposed method was reached during undercompensated operation of distribution system with respecting of consistent fault impedance. The recorded voltage sag in undercompensated system is around 9 % higher than is voltage sag during over compensated system and roughly 5 % higher than voltage sag recorded inside correctly compensated network.

Impedance EF in compensated system

Four values of fault resistance 300 Ω, 1,25 Ω, 3 Ω and 7,5 Ω were selected for impedance earth fault tests in correctly compensated distribution system.

In case of 300 Ω fault resistance, the residual current reached 9 A and after connecting of auxiliary resistor this value increased up to 28 A. Proportionally to this fault current change, bellow depicted voltage sags were calculated.

$$\Delta U_{\mathrm{SM}\,DT4} < \Delta U_{\mathrm{SM}\,DT3} < \Delta U_{\mathrm{SM}\,DT2} < \Delta U_{\mathrm{SM}\,DT1}$$

$$-0{,}28\mathrm{V} < -1{,}03V < -1{,}24V < -1{,}37V$$

These results support the theory flowing from equation (1), but sensitivity of discussed method is lower then in the case of solid EF due to lower value of fault current, as expected.

Similarly in the case of 1,25 Ω impedance EF, where residual current reached 5 A and 9 A after connection of auxiliary resistor, the monitored voltage sags were minimal, as it can be seen in Fig. 10.

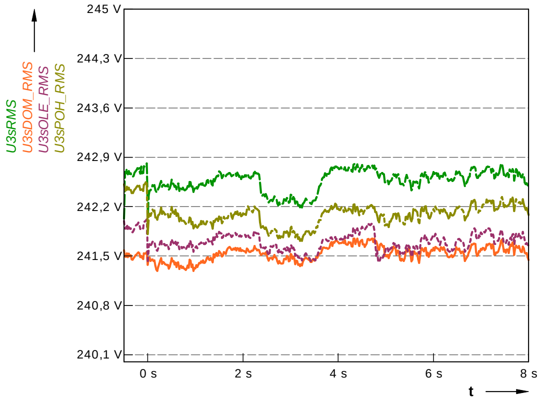

Fig. 10: Effective value of L-N voltages recorded on LV side in phase L3 during 1,25k Ω impedance EF in compensated system for all DTs

The voltage sags caused by auxiliary resistor connection are hardly recognizable in this case. Therefore it may not be possible to recognize differences between individual voltage sags due to voltage measuring error and faulty area can be delimited incorrectly. The results of monitored voltage sags for 1,25 Ω impedance EF in correctly compensated network are listed in Table 2. Base on these results, the condition (1) is not met for this case, because voltage monitors placed at DT3 and DT4 recorded the same value of voltage drop as follows

$$\Delta U_{\mathrm{SM}\,DT4} < \Delta U_{\mathrm{SM}\,DT3} < \Delta U_{\mathrm{SM}\,DT2} = \Delta U_{\mathrm{SM}\,DT1}$$

$$-0{,}13\mathrm{V} < -0{,}25V < -0{,}35V = -0{,}35V.$$

Base on described principle and these results, the fault area can be incorrectly delimited between distribution substation DT3 and DT2. Therefore it is not possible to use this method for location of high impedance EF or It is necessary to extend line impedance (line length), between the monitored stations to increase method´s sensitivity.

In case of 3 Ω and 7,5 Ω impedance EF, it is not possible to delimited any faulted area, because auxiliary resistor wasn't automatically switch on. That is why the voltage sags couldn´t be determined.

Arcing EF in compensated system

The results of recorded maximal voltage sags obtained from experimental measurement of arcing EF (Experiment no. 10 and 11) are very similar to results from solid EF tests, see Table 2. This similarity is given by stabilization of arcing when auxiliary resistor is switched on.

Summary of results

All results of calculated voltage sags for all experimental measurements are summarized in table 2.

Table 2: Results of maximal voltage sags recorded during tests

Ex.No.	Type of an earth fault		Compensation state	DT1	DT2	DT3	DT4
				$\Delta U_{SM\ DT1}$	$\Delta U_{SM\ DT2}$	$\Delta U_{SM\ DT3}$	$\Delta U_{SM\ DT4}$
				[V]	[V]	[V]	[V]
1	Solid EF		comp.	-0,99	-3,93	-4,70	-5,02
2			comp.	-1,13	-4,10	-4,86	-5,17
3			comp.	-1,25	-4,18	-4,98	-5,26
4			underc.	-1,32	-4,36	-5,22	-5,55
5			overc.	-1,15	-4,00	-4,82	-5,09
6	Impedance	300 Ω	comp.	-0,28	-1,03	-1,24	-1,37
7		1,25 kΩ	comp.	-0,13	-0,25	-0,35	-0,35
8		3 kΩ	comp.	Without auxiliary resistor			
9		7,5 kΩ	comp.	Without auxiliary resistor			
10	Arcink EF		comp.	-1,01	-3,68	-4,37	-4,80
11			underc.	-1,26	-4,27	-5,08	x

CONCLUSION

According to results, the designed principle can be used for delimitation of faulty area during solid, arcing and low impedance EF, where level of monitored voltage sags is sufficient for its evaluation with respecting measurement error. In case of high impedance EF, where over 1 kΩ fault resistance is respected, it is not possible to accurately delimited faulty area due to low sensitivity of the method - low value of voltage sags is obtained. The sensitivity can be increased by line impedance extension, but in this case delimited fault area can be also extended. The next possible way how to improve sensitivity of the method is to operate the network in undercompensated state. As experiment showed, the sensitivity of the method is higher for undercompensated system then is for over or correctly compensated network, which is given by characteristic line impedance and by phase displacement of earth fault current.

Acknowledgments

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