

EVALUATION OF THE NEW METHOD Vdip FOR AN EARTH FAULT LOCATION

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ABSTRACT

The paper presents results from the first application of the new method "Vdip" for an earth fault location. The Vdip method is based on evaluation of the change of negative sequence voltage recorded on LV side of distribution transformers as described in the European patent EP2940483 (Evaluation method for determining of the probability of an asymmetrical fault location in a distribution network and a monitoring system for performing such method).

The fault records obtained from fifteen experimental tests in real compensated distribution 22 kV system were utilized as inputs for Vdip method. The main aim of the paper is to evaluate potential of the Vdip method in real systems and to determine its accuracy in the fault localization during different types of earth faults e.g. intermittent/arcing fault, low-impedance and 200 Ω - 1,2 k Ω resistance earth faults for two configurations of the MV network.

INTRODUCTION

Despite decades of experience with operation of resonant earthed MV distribution grids, there is still no universal method of single phase fault location in this type of network. The high difficulty of this task is caused especially by the low level of the earth fault current, the complexity of the distribution system topology, the limited number of reclosers or measuring points and the high rate of single-pole failures with different behavior (intermittent, arc, resistive, etc.) [1-4].

Despite many methods and presented studies, there are new opportunities that were not available few years ago. An example may be the new installation of voltage monitors into distribution transformer stations (DTS), which has been extensively installed under projects of Smart DTS in recent years. The primary purpose of these devices is to monitor the voltage and power conditions at the LV site of DTS or to monitor the voltage quality at these locations. Some monitors also support logical functions to indicate non-standard operation states in the LV network (e.g. VN fuse failure, over/under voltage etc.) or to remotely control LV circuit breakers or tap changer of OLTC transformer [5-6]. However, in order to maximize the benefits of these devices, it is necessary to gradually implement useful functions that would allow distribution system operator (DSO) to improve both the quality of the voltage and the continuity of the power supply. Just Vdip method is designed to utilize data

measured by voltage monitors for earth fault localization purpose what can significantly increase its benefit and thus satisfy investments to the monitoring system.

The nature of the method is based on monitoring of the change in negative sequence voltage at LV site of DTSs. Recorded value of this change is then used for estimation of the probability distribution of the unbalanced faults (L-N, L-L-N, double earth fault) in the affected network. The fault is in the node with the highest value of the probability. Detailed description is provided in European patent EP2940483 [7].

The subject of this paper is the basic assessment of the method function in the conditions of a real 22kV distribution network operated as compensated with the auxiliary resistor (connected to secondary winding of arc-suppression coil for 1 s). Evaluation of the method in this particular operation is crucial for its future application, because resonant earthed MV distribution network with the auxiliary resistor is the most widespread one in the central Europe Furthermore, locating of single phase faults in this type of network is difficult due to low fault current amplitude, and thus poses bigger challenge than other types of faults in other types of grids.

DESCRIPTION OF Vdip METHOD

Fault location algorithm is designed to determine the probability of unsymmetrical fault location base on evaluation of the maximal changes of negative sequence current $\Delta I_m^{(2)}$ and voltage $\Delta U_m^{(2)}$. Where values $\Delta U_m^{(2)}$ are monitored and recorded at the secondary side of selected MV/LV distribution transformers by means of voltage monitors NSVMs (negative sequence voltage monitors) and value $\Delta I_m^{(2)}$ is monitored and recorded at the faulty feeder in supply MV substation, as it is depicted in Fig. 1. The value $\Delta I_m^{(2)}$ can be determined from fault COMTRADE records of the feeder protection.

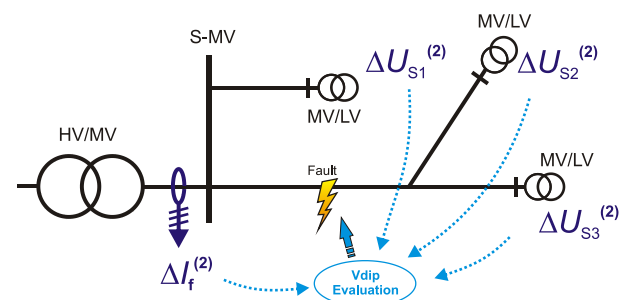


Fig. 1: Schematic principle of the Vdip method

Numerical model formulation for Vdip method

In the first step, each section of the network is divided into individual elements with maximal length Δ (optional value). It creates auxiliary nodes UP where the probability of fault is calculated by the method. The accuracy of the Vdip algorithm is higher for the shorter lengths of Δ element (fault point can be found with higher resolution). Then the method is applied to negative sequence scheme which is composed of UP nodes and measuring nodes UM, i.e. nodes where NSVMs are installed. Simplified negative sequence scheme created from the simple network in Fig. 1 is shown in Fig. 2.

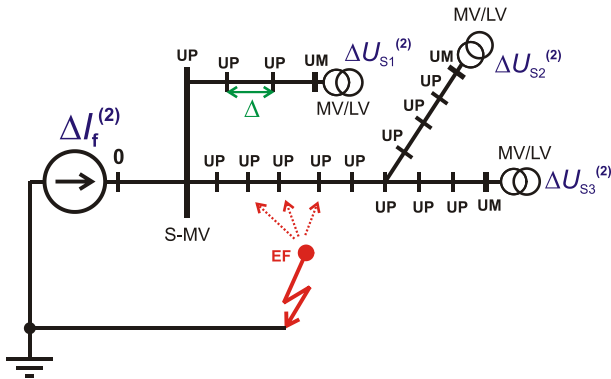


Fig. 2: Simplified negative sequence scheme for Vdip method

Then substitutive negative sequence admittance matrix $[\bar{Y}^{(2)}]$ can be created for negative sequence scheme of tested network. This matrix is used as an input parameter for calculation of the probability of the unsymmetrical fault.

Unsymmetrical fault probability calculation

The principal of the Vdip method is base on stepwise connecting of the fault point (node EF in Fig. 2) to the individual nodes numbered 1 to n , where n is total number of UP and UM nodes. Therefore the equation (1) is solved for $N = 1, 2, \dots, n$.

$$\begin{bmatrix} \Delta \bar{U}_n^{(2)} \end{bmatrix} = \begin{bmatrix} \Delta \bar{U}_{Sn}^{(2)} \end{bmatrix}^N = [\bar{Y}^{(2)}]^{-1} \cdot [-\Delta I_M^{(2)}]^N, \quad (1)$$

where N is node number with considered earth fault (EF), $[\Delta \bar{U}_n^{(2)}]$ is vector of calculated changes in negative sequence voltage when fault is considered in node N ($N = 1, 2, \dots, n$), $[-\Delta I_M^{(2)}]$ is vector of maximal change in negative sequence current assembled for fault in the node N , $[\Delta \bar{U}_{Sn}^{(2)}]$ is vector of calculated changes in negative sequence voltage in measuring nodes UM (its length is given by number of used NSVMs).

The next step solves the equation (2) for $N = 1, 2, \dots, n$, i.e.: it calculates the deviation (error), which is given by the difference between the calculated and measured values of change in negative sequence voltage for each

UM node considering earth fault in node 1 through n .

$$[\varepsilon]^N = \begin{bmatrix} \varepsilon_1^N \\ \varepsilon_2^N \\ \vdots \\ \varepsilon_i^N \end{bmatrix} = \begin{bmatrix} \Delta \bar{U}_{Sn}^{(2)} \end{bmatrix}^N - [\Delta U_{M-c}^{(2)}]^N, \quad (2)$$

where $[\varepsilon]^N$ is vector of deviations for all nodes UM in case of fault in node N , i is number of UM nodes, $[\Delta U_{M-c}^{(2)}]^N$ is vector of measured change in negative sequence voltage in respected UM nodes recalculated to MV side of distribution transformer.

In the next step, vector of total error $[E]$ is calculated based on deviations $[\varepsilon]^N$. The vector $[E]$ expresses total error/difference between measured and calculated values of the change in negative sequence voltage of monitored network for individual nodes $N = 1, 2, \dots, n$ as equation (3) shows.

$$[E] = \begin{bmatrix} E_1 \\ E_2 \\ \vdots \\ E_N \end{bmatrix} = \begin{bmatrix} \sum_{p=1}^i |\varepsilon_p^1| \\ \sum_{p=1}^i |\varepsilon_p^2| \\ \vdots \\ \sum_{p=1}^i |\varepsilon_p^N| \end{bmatrix}, \quad (3)$$

where i is number of UM nodes, N is number of node with respected fault.

Finally, percentage value of probability of fault presence F is calculated for each node N according to equation (4)

$$F_N = \frac{E_{\max} - E_N}{E_{\max} - E_{\min}} \cdot 100, \quad (4)$$

where E_{\max} and E_{\min} are maximal and minimal values of the vector $[E]$ respectively, E_N is value of total error for individual node N .

Node with the highest probability (100 %) is then selected as the faulty point. Analogically, based on the F values and its distribution, the probability of fault occurrence can be expressed for all nodes (UP and UM). That could be used for presentation of the results in dispatcher GIS systems or other user interface as graphical presentation of probability distribution in network scheme.

EXPERIMENTAL TEST DESCRIPTION

The verification of the Vdip method in real condition of resonant earthed system is important to uncover its real potential, therefore series of tests of earth faults was performed in cooperation with E.ON Distribuce a.s. in an overhead line network. During preparation of the experimental test, the three types of voltage monitors with implemented NSVM functionality (ability to automatically record $\Delta U_m^{(2)}$) were installed to DTSs. The first type was MEG44 (4 pcs. installed), the second one

MEG400 (11 pcs. installed) both from MEG company and the third one SMP133 (11 pcs. installed) designed by KMB company.

Then fault recorder Yokogawa DL850 was installed in the MV substation, which monitored the phase voltages and currents at the faulty feeder during all earth fault tests (Tab 1). The tests were carried out in resonant earthed network with auxiliary resistor connected for 1 s to increase active part of fault current. The value of auxiliary resistor R_p was 0.5 Ω on secondary winding of arc-suppression coil (i.e. 353 Ω primary) or 1 Ω (707 Ω) (Tab. 1). The capacitive current of the network was 80 A and the system was ideally tuned (without detuning). Thanks to the ring topology of the network, two configurations of the feeder were tested. The earth fault was 35 km from supply substation in case of the first configuration of the feeder and 23 km during the second one.

Totally 15 tests in three configurations were carried out within one day, where each configuration had different type of earth fault: resistive earth fault (fault resistance from 1,5 k Ω up to 200 Ω), arcing/intermittent earth fault or direct contact of phase conductor to earthing system of the pole (resistance of earthing system was 13 Ω) as Table 1 shows.

Tab. 1: Performed tests of earth fault

Test	EF character	Additional resistor/Configuration
1	1,2 k Ω	$R_p = 0,5 \Omega$ / 35 km to EF
2	430 Ω	$R_p = 0,5 \Omega$ / 35 km to EF
3	210 Ω	$R_p = 0,5 \Omega$ / 35 km to EF
4	arcing	$R_p = 0,5 \Omega$ / 35 km to EF
5	direct EF, 13 Ω	$R_p = 0,5 \Omega$ / 35 km to EF
6	1,1 k Ω	$R_p = 1 \Omega$ / 35 km to EF
7	440 Ω	$R_p = 1 \Omega$ / 35 km to EF
8	280 Ω	$R_p = 1 \Omega$ / 35 km to EF
9	arcing	$R_p = 1 \Omega$ / 35 km to EF
10	direct EF, 13 Ω	$R_p = 1 \Omega$ / 35 km to EF
11	1,1 k Ω	$R_p = 1 \Omega$ / 23 km to EF
12	430 Ω	$R_p = 1 \Omega$ / 23 km to EF
13	270 Ω	$R_p = 1 \Omega$ / 23 km to EF
14	arcing	$R_p = 1 \Omega$ / 23 km to EF
15	direct EF, 13 Ω	$R_p = 1 \Omega$ / 23 km to EF

Picture of the fault location during preparatory work is shown in the Figure 3.

EVALUATION OF THE TESTS

Just for illustration, only the results recorded by the monitors SMP133 (NSVM) are presented in this paper. These monitors were installed in the test network in the number of 11 pieces and have a sensitive setting for recording of change in negative sequence voltage, start value of $\Delta U_m^{(2)}$ was 0,2V.



Fig. 3: Preparation for an earth fault ignition

The Vdip method requires to determine maximal change in negative sequence voltage and current from records. For this purpose, the method of two shifted frames described in [8] were apply to time-course of negative sequence current/voltage phasor. The length of the frames was set up to 3 periods and time shift of the frames Δt is 0,36 s.

a) Maximal change in negative sequence current

Based on the analysis of phase currents and voltages stored in the fault records of the faulty feeder, the changes in negative sequence current $\Delta I_m^{(2)}$ were calculated for all tests. An example of the curve estimated from fault record of 5th test is shown in Figure 4. Then maximal change in negative sequence current $\Delta I_m^{(2)}$ (dl2m in Fig 4) and synchronization time t_{syn} , i.e. time when $\Delta I_m^{(2)}$ occurred, was determined for all records/tests, the summary of all determined values corresponding to test 1 up to 15 are listed in Tab. 2.

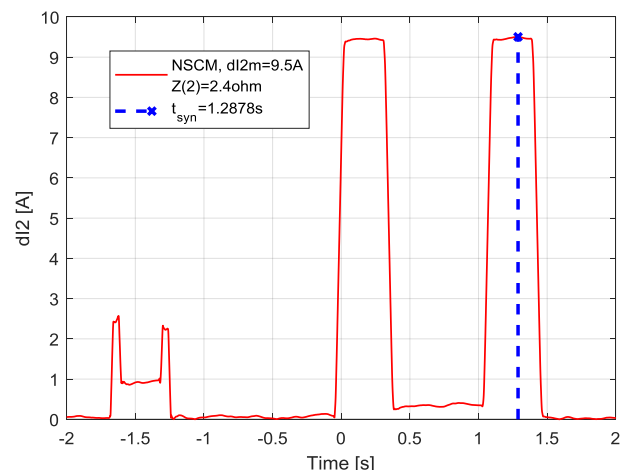


Fig. 4: Change of negative sequence current recorded at faulty feeder for test no. 5

c) Maximal change of negative sequence voltage

Maximal changes in negative sequence voltage $\Delta U_m^{(2)}$ were determined from synchronized records of all

available NSVMs. These maximal changes were determined as individual values $\Delta U^{(2)}$ in the moment of synchronization time as Figure 5 presents for example of the test No. 5 ($t_{syn} = 1,2878$ s). These values $\Delta U_m^{(2)}$ are listed in Table 2 as an example only for one monitor NSVM No. 3.

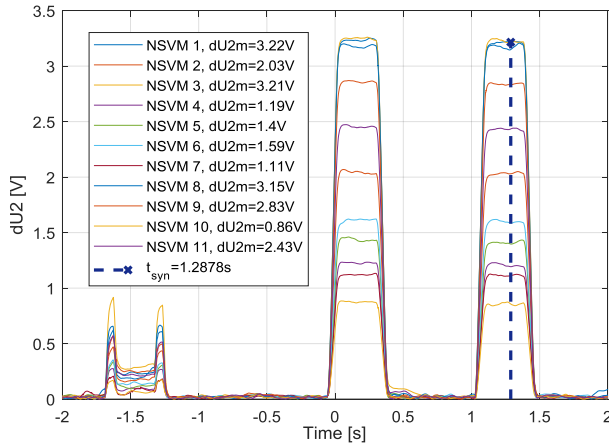


Fig. 5: Changes in negative sequence voltage recorded at LV side of DTS by NSVMs - automatically synchronized records

The second possible way, which was used for selection of $\Delta U_m^{(2)}$ and $\Delta I_m^{(2)}$ values, was manual estimation where synchronization time was not used. It enables to limit negative impact of DTS load variability to $\Delta U^{(2)}$ values and the imperfection of synchronization of the NSVM records. These manually selected values are also listed in Table 2. Both sets of data are used as input parameters for fault location estimation by the Vdip method (see Table 3). The negative sequence short circuit impedance to MV substation, which is necessary for admittance matrix arrangement, was calculated directly from fault records on the faulty feeder as the average value of all low-impedance earth faults (test 4,5,9,10,14 and 15) $Z^{(2)} = 2,33 \Omega$.

Tab. 2: Input values of change of negative sequence current and voltage for Vdip algorithm

Test	$Z^{(2)} [\Omega]$	NSCM, $\Delta I_m^{(2)} [A]$		NSVM 3, $\Delta U_m^{(2)} [V]$	
		Synchronized	Manual	Synchronized	Manual
1	2,33	1,99	1,85	0,68	0,58
2	2,33	4,49	4,40	1,50	1,47
3	2,33	7,34	7,30	2,45	2,43
4	2,33	9,53	9,40	3,22	3,19
5	2,33	9,50	9,45	3,21	3,25
6	2,33	1,53	1,50	0,53	0,52
7	2,33	3,06	3,00	1,00	1,01
8	2,33	4,25	4,20	1,44	1,46
9	2,33	5,36	5,10	1,77	1,75
10	2,33	5,26	5,00	1,77	1,76
11	2,33	1,59	1,55	0,33	0,35
12	2,33	3,33	3,12	0,69	0,67
13	2,33	4,62	4,55	0,98	0,99
14	2,33	5,84	5,50	1,21	1,20
15	2,33	6,26	5,00	1,25	1,14

EVALUATION OF THE METHOD

Based on the input values of $\Delta I_m^{(2)}$ listed in Table 2 and $\Delta U_m^{(2)}$ derived from eleven records of NSVM, the earth fault location was estimated according to Vdip method with used length of the element $\Delta = 200$ m for all fifteen performed tests. The accuracy of the method can be evaluated base on location error, expressed as difference between estimated distance to fault (node where the probability of the fault is 100%) and the real distance to fault. The location error is shown in Table 3 for all tests and both synchronized and manual data set. As shown in this table, the mean location error is 1,06 km (synchronized selection) and 0,81 km (manual selection). There are no significant differences in the localization error caused by different value of auxiliary resistor (0,5 Ω vs 1 Ω) or distance to earth fault (35 km vs 23 km). Higher accuracy of manual data set is achieved by more convenient selection of the moment for $\Delta U_m^{(2)}$ reading, which was manually chosen to reduce the impact of the load and any synchronization error.

Tab. 3: Error of an earth fault location estimated by Vdip method

Test	Location error [km]	
	Synchronized	Manual
1	-0,40	-3,38
2	-1,19	-1,19
3	-1,19	-1,39
4	-0,80	-0,60
5	-0,60	-0,20
6	-1,19	0,45
7	-2,19	-0,80
8	-0,60	0,45
9	-1,39	0,00
10	-0,80	0,84
11	-2,80	0,80
12	0,20	0,99
13	-0,64	0,20
14	-0,19	0,60
15	-1,75	-0,19
Average error [km]	1,06	0,81

Fig. 6 shows Vdip results of earth fault location for all tests, i.e. nodes with the 100 % probability of fault calculated by Vdip method for manual selected maximum of $\Delta U^{(2)}$ and $\Delta I^{(2)}$ values. The figure is drawn in the scale of the tested network.

The Vdip method always localize only one point with the 100 % probability as follows from the method principle. Therefore there is no problem with the multiple location in case of branched lines what is characteristic for feeder locators based on distance protection principle.

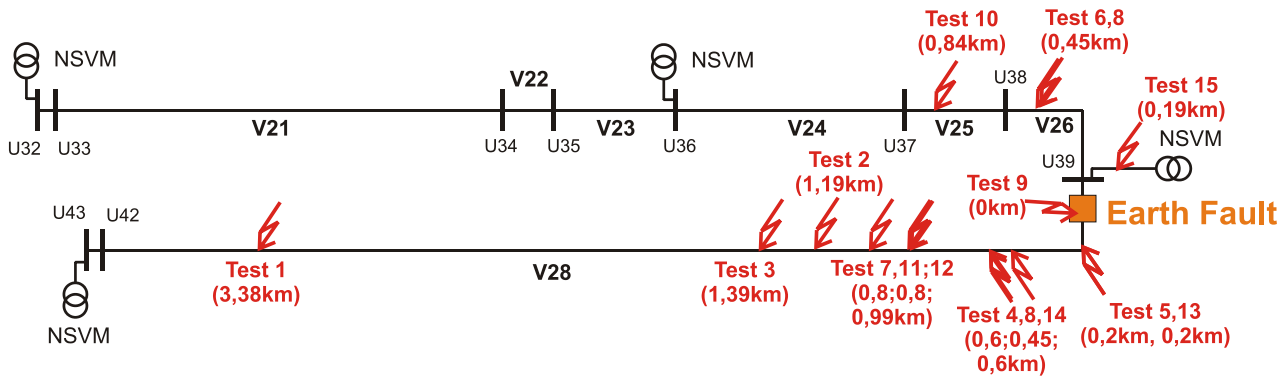


Fig. 6: Illustration of earth fault location results estimated by Vdip method for manual selected data

CONCLUSION

The experimental verification of the Vdip method in real distribution network shows, that first results of Vdip method are very promising, despite the relatively significant fault distances (35 km resp. 23 km) which was chosen for the pilot test. Due to a small average error (approximately 1 km), Vdip method can significantly reduce the time and switching operation or manipulation which are necessary for earth fault limitation and its clearing. However, all these results are related to initial parameters of the tested network (actual behaviour of the loads, fault distance, fault resistance, number of DTS etc.) and cannot be generalized.

Based on these first results and presence of areas for improving of Vdip system, the significant contribution can be expected especially in area of localization of earth faults with fault resistance up to 1,5 k Ω in resonant earth distribution network with auxiliary resistor. It should be noted, that the localization of an earth fault in compensated systems is an area where the Vdip method will achieve the lowest sensitivity (the lowest accuracy of localization). Significantly better results can be expected in resistor earthed systems (600A or 1kA nodal resistor) which are used in case of cable networks, or overhead networks characterized by too high capacitive current.

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