EARTH FAULT LOCATION IN COMPENSATED MV NETWORK USING A HAND-HELD MEASURING DEVICE

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ABSTRACT

Various papers and technical literature describe plenty of methods for locating the exact earth fault place in a compensated MV network. However, the usefulness of these methods is very questionable – from the perspective of achieved accuracy, as well as extreme investment demands. Information on practical experience and results from real operation are rarely published at all. Handheld earthfault location finder (device) is an innovative and highly functional alternative to static earth fault locators for overhead MV lines. The device provides a contactless determination of the relative earth fault location in relation to the specific place of measurement. It is possible to get to the fault location very quickly with sequential measurements in suitable positions. This paper describes the function and possibilities of the handheld device, as well as practical experience with locating both the real and experimental earth faults in the MV network.

LOCATING EARTH FAULTS IN MV NETWORKS

The recently growing pressure of regulatory bodies to increase the network reliability is reflected in the need to decrease the electricity supply reliability indicators SAIDI and SAIFI. This results in a pressing need for solutions which would enable faster locating of earth faults, and thus also a faster power restoration after a failure.

In 2009-2017, Západoslovenská distribučná, a.s. (DSO company) installed over 500 remotely controlled smart disconnectors on the overhead lines. If an earth fault occurs, simple protections (indicators) in these disconnectors will activate and send a signal to the SCADA system, indicating the section where the fault is located. The dispatch centre operator then remotely disconnects the affected section and restores power in the remaining part of the line. Sections divided by these switches are typically approx. 5-10 km long.

Until recently, exact determination of the fault within these sections used to be done only by using sequential manipulations with manually controlled switches and visual inspections of individual line sections. This was a time-consuming and physically demanding process – the network service employees often had to walk in a difficult terrain for a long time. The fault location is not always visible at the first glance. Finding the exact fault location could take even several hours.

To speed up and simplify the process, we developed a prototype of a handheld measurement device for finding the exact location of the earth fault. After verifying the prototype's functionality and design finalization, a serial production of the device started in cooperation with an external supplier – Elvac.

HANDHELD EARTHFAULT LOCATION FINDER (DEVICE)

Purpose of the device

Device provides a contactless determination of the relative earth fault position from anywhere under the overhead line, i.e. whether the fault is located *behind* the measurement place (toward the end of the line) or *before* the measurement place (toward the feeding substation).

All network service employees in Západoslovenská distribučná, a.s. are equipped with the device. If they are sent to find the earth fault location, they take sequential measurements at suitable places under the MV line and the device shows them which direction the fault is – where they must proceed in order to find it. Using this method, they can find the fault location quite quickly. Investment demands for this solution represent a fraction of the price of building a hardwired system for determining the exact earth faults location, and the time for finding the fault is ultimately comparable.

The device was primarily designed for compensated MV networks with switching the resistor to increase the active component of the fault current in the event of an earth fault. However, a version suitable for isolated MV networks and MV networks with a low-impedance grounded neutral point can also be supplied.

Device description

The device measures the electric and magnetic field under the electric line. Electric field is measured via the capacitive coupling between the measured electric line and the device's sensor, while the second pole of the measuring device requires a galvanic connection with the operator's body. For this purpose, there is a connector for the contact wrist strap on the front panel of the device. Magnetic field is measured via inductive coupling and requires no special arrangements.

The device is encapsulated in a durable plastic case, which fits in a hand (Figure 1). On the top, covered by a protective plastic sheet, there are four main large LEDs, a power button, a LED charge indicator and a LED indicator of battery status. The four main LEDs signal the actual status of the device and the measurement result. On the front side, there is a USB communication port and the connector for the contact wrist strap. The device can be connected to a PC through the USB port to set the parameters of the measurement algorithm and download the fault records.

Figure 1: Earth fault location finder

Measurement at a specific place

Stand in the axis of the MV line at the measurement place. It's convenient to choose places which are easily accessible. Connect the contact wrist strap to the connector on the front panel of the device. Put the wrist strap on so that it comes into direct contact with the skin (not through gloves or clothes). Switch on the device by pressing and holding the power button. The green LED READY will light up. Take the device and hold it as shown in Figure 2 so that its longitudinal axis is parallel with the axis of the line. Hold the device at eye level. It does not matter whether you face the feeding substation or away from it.

The device is now ready to detect and evaluate the earth fault. The next step is to contact the dispatch centre operator who will bring the affected section under voltage with a remotely controlled disconnector or circuit breaker – i.e. the voltage asymmetry caused by the earth fault will spread through the entire network. The device detects the voltage asymmetry, emits a short beep, the blue LED RUN lights up and the measurement process (standard duration is 3 seconds) starts. It is assumed that during this time, the resistor switching device also evaluates the occurrence of earth fault in the network, and after a 1 second delay it will switch on the secondary resistor to the auxiliary winding of the arc-suppression coil for 1 second, which will cause an increase of the active zero-sequence current component between the feeding substation and the earth fault location. It is also possible to change the duration of the measurement procedure in the device configuration and ensure its correct indication even with a different timing of secondary resistor switching.

During the measurement process, the device evaluates the electric and magnetic field under the line. Based on the electric field intensity and magnetic field induction the device evaluates the corresponding value of the voltage U_0 and current I_0 at the measurement place. After the measurement process is finished the device will determine the relative location of the earth fault.

If the fault location is *behind* the measurement place (toward the end of the line), the red LED RESULT will light up and the device will emit a sharp interrupted sound.

If the fault location is *before* the measurement place (toward the feeding substation), the yellow LED RESULT will light up and the device will emit an uninterrupted sound.

The concurrent visual and acoustic signalization enables correct evaluation of the measurement even in inconvenient light conditions. After the measurement is finished, the fault record (COMTRADE format) is saved and may be analysed later.

Figure 2: Measurement with device

Finding the earth fault

Detailed steps of finding the earth fault are shown in Figure 3. We assume an MV line section with several branches. Remotely controlled smart disconnector SW1 with protection is shown as the green circle, regular manually controlled disconnectors are shown as blue circles.

If the fault occurs at the marked place, the dispatch centre operator gets the signal of the earth fault behind the smart disconnector SW1. The operator remotely turns this smart disconnector off and sends out the network service employees. With sequential measurements at places 1-5, the network service employees get the information about the relative location of the earth fault. The red arrow means that the measurement result activates the red LED RESULT on the device. The yellow cross means that the measurement result activates the yellow LED RESULT. The network service employees proceed directly to the fault location and the earth fault is quickly found.

During each measurement, the smart disconnector SW1 is switched on to a fault for a while. Measurement places are primarily chosen so that the line section is divided approximately into halves, then into quarters, etc. This process is optimal from the perspective of speed of finding the fault location. Measurements are usually taken at places easily accessible by car.

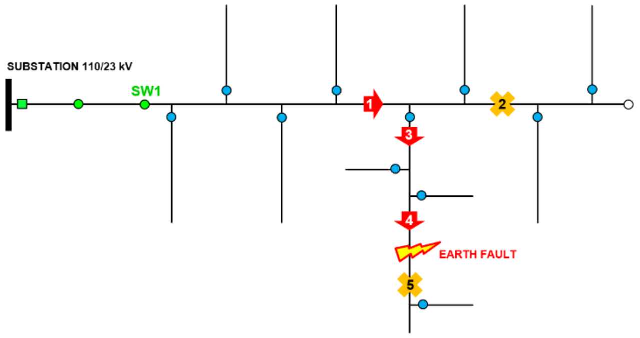

Figure 3: Example of a fault locating procedure

DEVICE DEVELOPMENT

The development of the evaluating part of device, as well as the calculation algorithm, had the following steps:

- determining the voltage and current conditions on the MV line during an earth fault,
- designing the measuring part of the device and the calculation algorithm,
- creating the mathematical model of the device,
- testing the mathematical model with experimental earth faults,
- complex testing of the device with real earth faults in the MV network.

Voltage and current conditions during earth fault

Voltage and current conditions at individual places in the MV network during an earth fault are described in detail in various papers, e.g. [1]. Device evaluates only the current component which is in parallel with the zero-sequence voltage component U_0. This current component will be labelled I_{MEAS}. We assume earth fault on the phase L1.

Zero-sequence current component in locations which are *not* between the feeding substation and the fault location is described in Figure 4. Capacitive and conductance currents of the power line part from the measurement place toward the end of the line flow jointly through the unaffected phases L2 and L3, labelled I_{CB} and I_{GB}. No current flows through the affected phase L1 (we assume unloaded line and compensated network). The capacitive current is perpendicular to U_0 voltage, and therefore the device does not consider it. In this case the resulting current measured by the device I_{MEAS} will be equal to the conductance current I_{GB} of the power line part from the measurement place toward the end of the line.

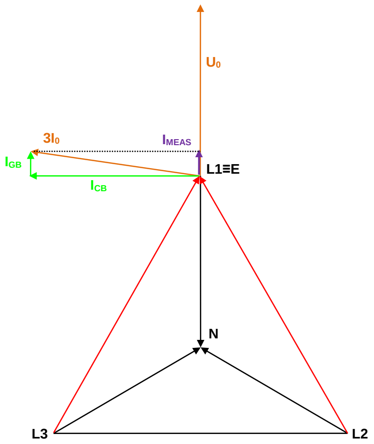

Figure 4: Current measured by the device at a location *not* between the substation and the fault

Zero-sequence current component in locations which *are* between the feeding substation and the fault location is described in Figure 5. Capacitive and conductance currents of the power line part from the measurement place toward the end of the line flow jointly through the unaffected phases L2 and L3, labelled I_{CA} and I_{GA}. Through the affected phase L1 flow: the sum of capacitive currents of the entire network, sum of conductance currents of the entire network, and the compensation current of the arc-suppression coil I_L. All capacitive currents, as well as the compensation current, are perpendicular to U_0 voltage, and therefore the device does not consider them. In this case the resulting current measured by the device I_{MEAS} will be equal to the conductance current of the entire network I_G minus the conductance current of the power line part from the measurement place toward the end of the line I_{GA}.

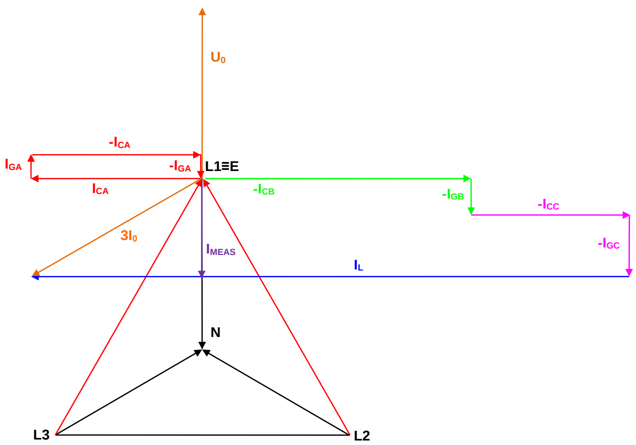

Figure 5: Current measured by the device at a location *between* the substation and the fault

Moreover, when the resistor is switched, additional current forced by the secondary resistor I_R will flow through the affected phase L1, parallel with U_0 voltage. When the resistor is switched, the resulting current measured by the device I_{MEAS} will increase by the current forced by the secondary resistor I_R. This situation is shown in Figure 6.

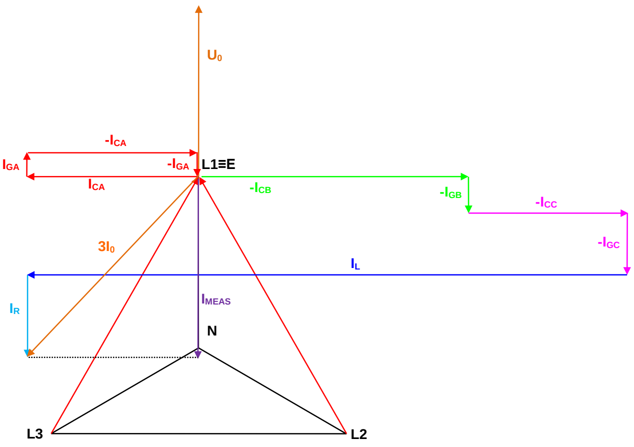

Figure 6: Current measured by the device at a location *between* the substation and the fault + resistor

The conductance current is in single-digit amperes. Secondary resistor values are set so that the resistor's current is approx. 37 A. Comparing individual situations, it is evident that the current measured by the device I_{MEAS} in locations between the feeding substation and the earth fault location will be at least an order of magnitude higher compared to the location *not* between the feeding substation and the earth fault location. Reliability of this method for determining the earth fault location is therefore sufficient despite the fact that the evaluation of individual electric quantities is performed by measuring the electric and magnetic field under the line.

Mathematical model of device

A complex model of device was created in MS Excel. Inputs for the mathematical model are:

- voltage conditions at the measurement place,
- current conditions at the measurement place,
- mutual position (geometry) of MV line conductors and the position of the device.

The mathematical model based on these input data calculates the intensity of the electric field E near the device and induction of magnetic field B near the device. These quantities are then calculated with sensor coefficients and entered into the mathematical model of the device evaluation algorithm. The result of the calculation is a differentiation of two final situations – earth fault *behind* the measurement place; earth fault *before* the measurement place. More than 500 combinations of conductor arrangement and voltage-current conditions at the measurement place were calculated with the mathematical model. Based on these results, sensor amplification coefficients and software parameters of the algorithm were set. They also determined the limits of device's capabilities in locating earth faults.

Experimental earth fault measurements

In order to verify the functionality and the mathematical model of the device, more than 60 of measurements were taken with experimental earth faults in the real MV network. The earth fault was created with switching a water resistor of own construction (Figure 7) to one phase of the overhead MV line; the value of resistance could be changed within a broad range.

Figure 7: Water resistor of own construction

Measurements were done so that they cover most situations which can occur in real operation, focused primarily on:

- measurement on various types of lines with different arrangement of phase conductors,
- measurement with metallic earth fault as well as resistive earth fault with various parameters,
- measurement on a MV double line,
- measurement near a HV line,
- measurement near the crossing of MV lines,
- measurement near large third-party conductive grounded objects,
- measurement very close to the earth fault location (both towards the substation and away from the substation),
- measurement with a detuned arc-suppression coil.

Experimental earth fault measurements verified the consistency of the used mathematical model with reality. Deviations between the mathematical model and the values actually measured by the device did not exceed 5%. Given the number of input quantities and the usage of electric and magnetic field measurements, the accuracy is fully satisfactory. Table 1 contains an example of experimental earth fault measurement result. The resistance of the earth fault in this case was 1.2 kΩ.

	MATHEMATICAL MODEL					ELF7 DEVICE					DIF
	AMP-1	PHA-1	AMP-2	PHA-2	VAL	AMP-1	PHA-1	AMP-2	PHA-2	VAL	[%]
1	46,73	-94,12	25,24	-65,30	13,90	48,60	-90,80	25,80	-57,80	14,43	-0,52
2	39,67	-66,54	28,25	-11,43	11,90	42,10	-70,80	29,80	-13,50	15,13	-3,24
3	40,89	-96,98	20,32	-99,46	1,63	42,70	-97,70	19,30	-99,90	2,40	-0,78
4	32,83	-65,45	13,97	-28,09	-1,32	34,50	-68,40	13,80	-25,70	-0,27	-1,05
5	51,18	-84,89	33,96	-52,01	16,34	53,80	-91,40	35,40	-60,30	18,85	-2,51
6	39,55	-104,07	18,95	-76,99	13,88	43,70	-110,50	21,10	-84,70	17,25	-3,37
7	42,55	-85,26	21,92	-79,24	0,57	47,00	-90,00	23,60	-88,00	0,82	-0,25
8	33,96	-107,00	18,03	-128,98	-1,41	37,90	-111,90	20,70	-133,20	-0,03	-1,38
9	42,70	-90,68	28,48	-53,26	17,54	49,90	-96,50	33,50	-62,00	21,38	-3,83
10	58,81	-96,45	45,36	-78,78	15,43	63,80	-99,60	49,30	-80,20	19,03	-3,61
11	35,31	-92,14	16,05	-92,83	0,53	41,80	-95,00	20,20	-94,40	2,09	-1,57
12	51,48	-97,17	34,12	-100,43	0,25	56,00	-100,00	36,40	-103,40	1,29	-1,04

Table 1: Experimental earth fault measurement result

All measurements taken with the device determined the relative location of the fault *correctly*. The parameters of the device were set according to the experimental earth faults measurement results and analysis of fault records, therefore it correctly evaluates the relative position of the earth fault location in all situations assumable in operation.

RESULTS OF USING THE DEVICE IN REAL OPERATION

All employees of the network service in Západoslovenská distribučná, a.s. were equipped with the device in the beginning of 2019 – 102 pieces of the device overall. Dozens of earth faults were located during the period of approximately 1 year and there hasn´t been any unexpected behaviour of the device observed yet. The process of fault locating took mostly about 20 minutes which is a significant decrease in comparison with the common method.

The algorithm of the device was tuned based on a long-term analysis of fault records acquired from real earth faults, thereby nowadays the device is capable to locate reliably even intermittent earth faults. It is important to note, that an intermittent earth fault is the most difficult case of a power system fault.

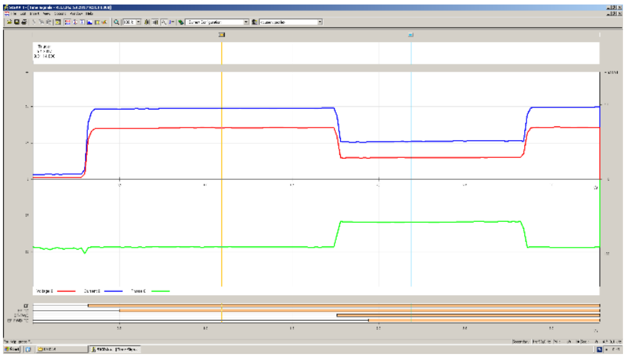

Figure 8: Fault record – fault *behind* device's measurement place

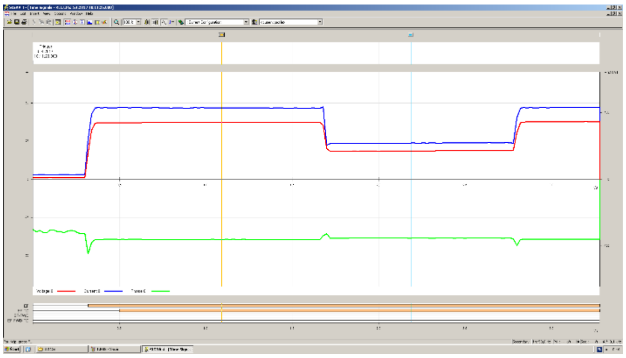

Figure 9: Fault record – fault *before* device's measurement place

Examples of fault records acquired with real faults in the MV network are shown in Figure 8 and Figure 9. In these records, red line means the measured voltage U_0, blue line means the measured current I_0 and green line means the phase angle between these two values.

CONCLUSION - DEVICE BENEFITS

The significant benefits of the handheld measurement device include especially the decreasing of time necessary to find the earth fault location, decrease of non-supply time in the event of earth faults, and decrease of the number of manipulations during the fault location. This also decreases the number of transient processes at the occurrence of earth faults, a phenomenon during which the voltage stress on insulation systems is the highest, often leading to a short-circuit.

An important aspect is the fact that during the common earth fault location with disconnector manipulations, it is often the incorrect section that is switched off. After reenergization of a power line, earth fault occurs in a network which is not correctly compensated. Additional capacitive current of the switched off section flows through the fault location, which can represent a safety risk when disconnecting longer cable sections. Using the device eliminates the possibility of such occurrences completely.

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