Operation Experience with a New Fault Location System for MV Networks

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Abstract--**The first part of this paper contains a short review on problems related to distribution system operators' (DSOs) current practice regarding earth fault location and sustained faulty operation of compensated networks. A new device and method are then presented that have been implemented recently at Hungarian DSOs. This technique uses current injection parallel to the Petersen coil for fault location, and the same device is further used to decrease the harmonics in the residual fault current during sustained earth-fault operation. First field test results are presented. It is also shown that the CTs installed along with the proposed device eliminate the need for the additional resistor that was necessary to select the faulted feeder.**

***Index Terms*--** **Power distribution control, Power distribution faults, Power distribution protection, Power distribution reliability, Power quality, Power system harmonics, Power system measurements**

I. Introduction

An excellent overview on the advantages and disadvantages of different star-point treatment strategies is given in [1]. Because the majority (above 90 %) of the faults in a distribution system (comprising mainly overhead lines) is a single phase to ground fault, the star-point strategies are often compared from the point of view of such faults.

One major advantage of compensated networks is that the rms of the fault current is small (typically below 20 A) and therefore it can be allowed to persist for several hours. The continuous operation of the system can be sustained during a single-phase to ground fault in order to continuously supply the consumers if some requirements are fulfilled. The residual current at the fault location has to be kept securely below 12 A in order to ensure, that the touch voltage remains below 65 V during the steady state faulty operation. (This assumption considers a 5 Ω grounding resistance of the pole.)

Measurements are carried out regularly at the substations in order to check the above condition. In recent years these measurements showed, that in spite of having set the compensation to some 1-2 A fundamental residual current, the RMS of the residual current is in some substations greater than the allowed value. The analysis of the Fourier spectrum of the residual current shows that in these cases the harmonic content of the residual current is several times greater than the fundamental component. The circumstances resulting in the increasing of the harmonic content of the arc current and the possible solutions of the problem were outlined in [2] and [3].

A great disadvantage of compensated networks however is the complicated way a single phase to earth fault can be located.

The first step includes the selection of the faulted feeder. In case of a single phase to ground fault the rms of the compensated fault current is small, therefore the feeder selection using an overcurrent relay will be unreliable. Present Hungarian DSO practice overcomes this problem by temporarily switching a resistor in parallel to the Petersen coil in order to increase the fault current.

The next step is finding the location of the fault along the selected feeder. This is done by first isolating the faulted section using remote-controlled switch-gear, which involves a number of switching on and tripping sequences – and therefore disturbance of the consumers – before the faulted section is found. (Pole-mounted fault indicators can also be used for this purpose.) The exact location is then found

- in case of overhead lines: by using a mobile sensor that usually measures harmonic magnetic fields under the line
- in case of cables: current injection on both ends of the section and measuring reflections of travelling waves.

Fault location is thus a time-consuming procedure that usually causes additional consumer disturbance.

This paper addresses

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– the selection of the faulted feeder without using an additional resistor, followed by
– the determination of the location of the fault on that feeder in a "quick and clean" way, and finally
– the sustained operation during single phase to ground faults.

New methods will be proposed for these problems and field measurement results will be shown.

II. Selection of the Faulted Feeder

Instead of the procedure described in Section I the proposed method uses the fundamental component of the zero sequence voltage (U_0) and the fundamental components of the zero sequence feeder currents (I_0).
It can be shown that the active power computed from these quantities

$$P_0 = Re\{U_0 I_0^*\} \quad (1)$$

is negative for the faulted feeder and positive for all other feeders (with positive consumed power reference).
Since the phase angle error of the CTs cannot be neglected, it can be stated that the zero sequence active power computed from (1) is the largest negative for the faulted feeder.

Field measurement results for two sites are summarized in Tables shown below. In both cases artificial single phase to ground faults have been established in several kilometers distance from the substation, and the faulted feeder was correctly identified using the above algorithm.

TABLE I Measurement Results at Site #1

feeder	P_0 (W)	Q_0 (VAr)	S_0 (VA)	angle, °
A	-1014	-13823	13860	-94,2
B	-2694	-59042	*59104*	*-92,6*
C	-2066	-30456	30526	-93,9
D	**-13011**	-60177	**61568**	**-102,2**
E	-1169	-13820	13870	-94,8
F	802	-50321	50327	-89,1
G	-728	-44344	44350	-90,9
H	-850	-27727	27740	-91,8
I	-39	-11	41	-164,9

In the first case it can be easily computed that a -5° error in the phase angle of the feeder current *B* and a +5° error in the phase angle of the feeder current *D* would have yielded wrong results (i.e. selection of feeder *B* instead of *D*).
In the second case a -1° error in the phase angle of the feeder current *N* would have yielded wrong results (i.e. selection of feeder *N* instead of *O*).

TABLE II Measurement Results at Site #2

feeder	P_0 (W)	Q_0 (VAr)	S_0 (VA)	angle, °
J	4353	4749	6443	-132,5
L	-2608	6959	7432	-69,5
M	-2104	-28261	28339	-94,3
N	-2482	-143609	143630	-91,0
O	**-4013**	-45149	**45327**	-95,1
P	-66	105	124	-57,9

It can be stated, that the proposed method for faulted feeder selection is appropriate, convenient and eliminates the need of the additional resistance.
It is, however, only reliable if the phase angle accuracy of the zero sequence current measurement is within 1° for the fundamental harmonic component.
In the substations investigated this was not the case, therefore additional zero sequence CTs had to be installed.
(The usage of Rogowski coils has not yielded acceptable results either, because the measurement error was too sensitive to the placement of the coil.)

III. Fault Location

Several solutions have been elaborated for determining fault locations and fault resistance in a more convenient and consumer-friendly way than described in the Introduction [8], [9]. These methods can usually be categorized into
– fundamental harmonic methods
– traveling wave reflection methods
– transient evaluation methods
– pole-mounted fault indicators.

An overview on several of these methods has been presented in [10]. To the knowledge of the authors none of these methods has gained wide popularity among DSOs due to either their cost or their lack of reliability.

In the present paper a new method is proposed, where fault location is performed by injecting current in parallel to the Petersen coil (Fig.1). (See further [11].)

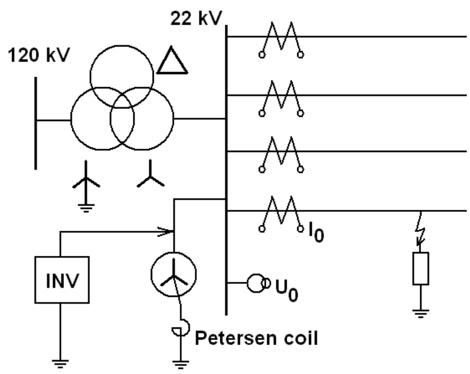

Fig.1. Result of fault location in a MV network field test

The frequency of the injected current is chosen so that it does not coincide with any of the harmonic or ripple control frequencies that are present at the network. (The injected current can be composed of multiple frequencies.) Therefore this method is independent from the disturbing effects of external circumstances to a great degree.

For the sake of continuous power supply, this method is implemented economically, employing a simple design, adapted to the substation protection automation system; it is more accurate than the known solutions, employing real-time measurements of relatively short duration. (The measurement takes approx. 1.5 s, which is smaller than the time allowed before the resistance is usually switched parallel to the Petersen coil.) Zero sequence voltages and currents measured in the substation are the input signals to the calculation procedure.

The zero sequence current signals are – for the sake of accuracy – those yielded by the CTs mentioned in the previous section.

The base idea of the fault location algorithm can be seen in Fig.2 where the zero sequence impedances are shown for the faulted line for a 40 km overhead line and for fault resistances between 1 to 5000 Ω. The zero sequence impedance depends on the fault location and the fault resistance, as it can be observed in the figure.

These possible Z_0 locations on the complex plane have to be calculated in advance for the whole line and for a large range of fault resistances. The resolution of the calculations has to be fine enough (e.g. 50 meters and 0.1 Ω). In case of a fault, the zero sequence impedance is measured, and this value is matched to the a priori calculated impedances. The calculated impedance nearest to the measured one yields the fault location and also the fault resistance. (The accuracy can be increased using interpolation between the a priori calculated values.)

Simulation results and sensitivity analysis has been reported on in [4].

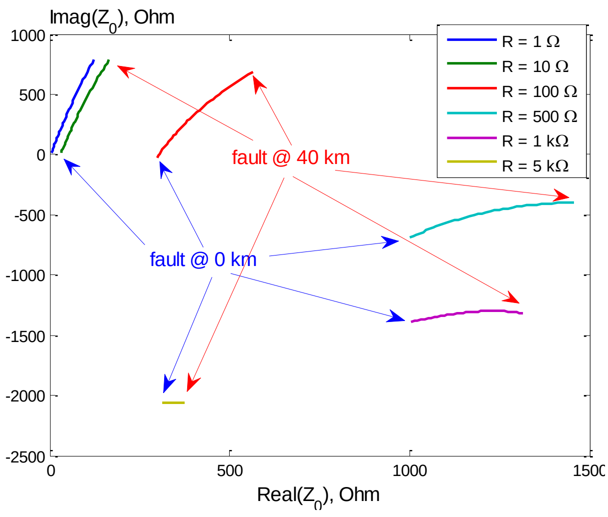

Fig.2. Calculated zero sequence impedances for various fault locations and fault resistances at a 40 km line

As the fault resistance increases towards infinity, there will be less and less difference between the zero sequence impedances for different fault locations. At a given accuracy and resolution of the measurements, this results in a decreasing accuracy of the fault location method.

The result of a field test is shown in Fig.3

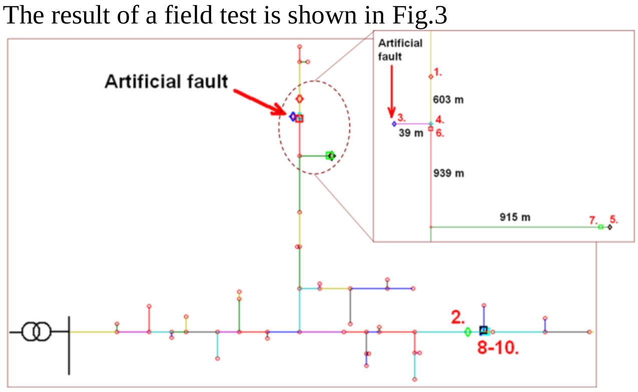

Fig.3. Result of fault location in a MV network field test

The method provides several possible fault locations (e.g. because it cannot distinguish between electrically identical side-lines based on substation measurements). Possible fault locations are shown in a simplified network scheme, prioritized by their probability (the best results have been found to be very close to the artificial fault location). Using a small number of fault indicators could eliminate these uncertainties.

IV. OPERATIONAL EXPERIENCE WITH THE FAULT LOCATION SYSTEM

The fault location results yielded by the first installed device are shown in Fig.4, Fig.5 and Fig.6.

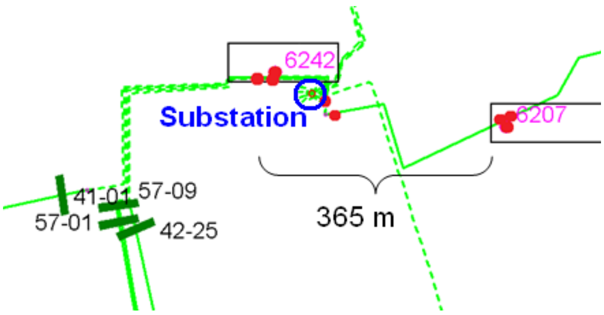

Fig.4. Result of fault location during operation (case I)

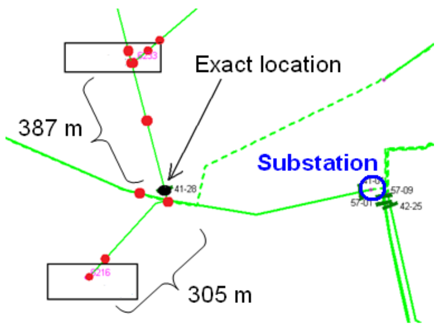

Fig.5. Result of fault location during operation (case II)

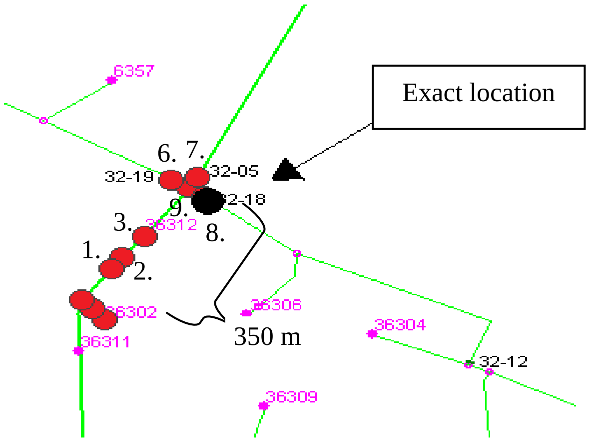

Fig.6. Result of fault location during operation (case III)

It can be observed that the accuracy is acceptable. In the first case (Fig.4) the fault was located somewhere between the points marked by “6207” and “6242”. This means that in this case the accuracy of the result was not worse than 365 m. In the second case (Fig.5) the accuracy was not worse than 387 m. In the third case (Fig.6) the majority of the results was within 350 m of the exact fault site (worst guesses were as far as 950 m).

The fault location system was able to detect not only permanent faults, but also very short faults (lasting at least 100..200 ms). If such faults are starting to accumulate over time at a certain point of the network, then it is advisable to have the place inspected by a maintenance team.

In such a way several problems were detected:

- tree trimming problems (Fig.7)
- loose wiring at a transposition pole (Fig.9)
- contaminated insulators (Fig.10)
- broken insulators (Fig.11)

It is important to note, that these problems could be detected based on temporary faults, before they even caused a permanent fault.

Fig.7. Tree trimming problem detected by temporary faults

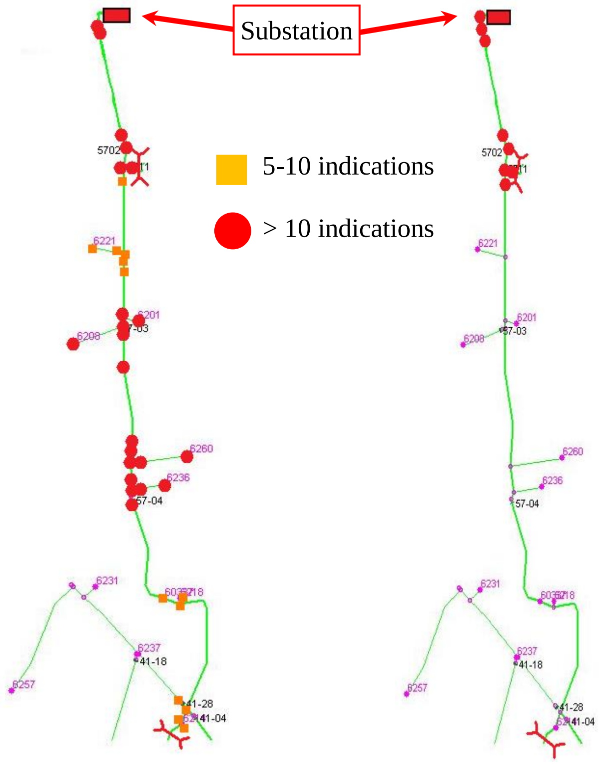

Fig.8. Number of earth fault indications a) Aug.2010-Mar.2011 (before trimming) and b) Mar.2011-June 2011 (after trimming)

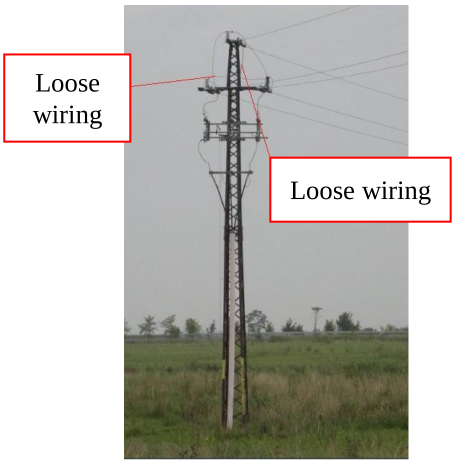

Fig.9. Loose wiring detected by temporary faults

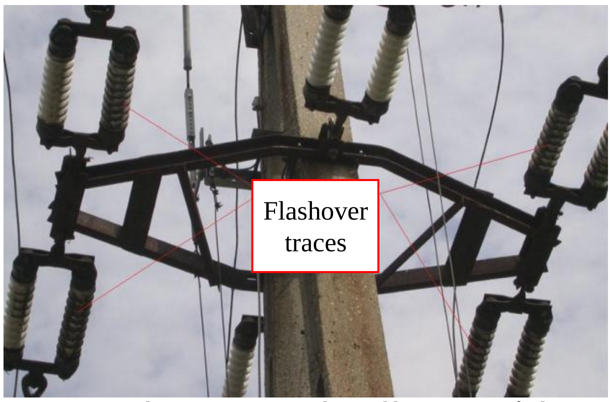

Fig.10. Insulator contamination detected by temporary faults

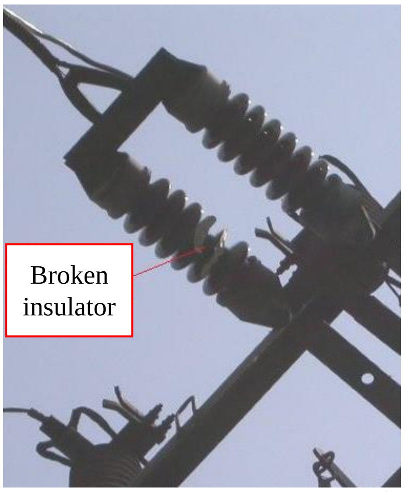

Fig.11. Broken insulator detected by temporary faults

In Fig.8 the effect of tree trimming can be observed. Part a) of the figure shows a large number of fault indications before trimming along the line, and part b) shows a significantly decreased number of fault indications after trimming.

V. SUSTAINED OPERATION DURING THE FAULT

In [5] the authors discussed the possible solutions for compensating the harmonic content of the residual current based on computer simulations. Zero sequence active filtering has been proven to be an appropriate method for decreasing the harmonic content of the fault current near to zero [6]. In [7] and [8] the authors discussed the control algorithm of the zero sequence active filter.

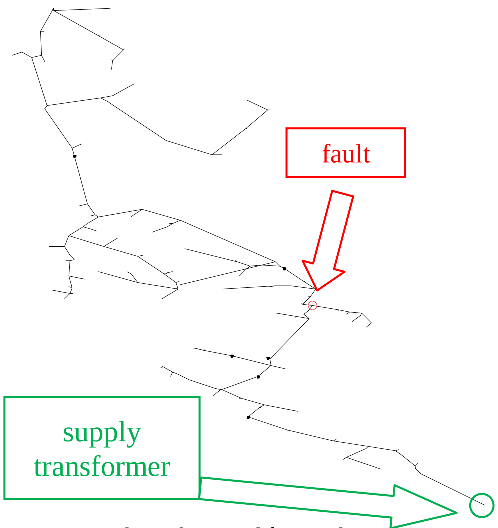

Fig.12. Network topology used for simulations

The proposed algorithm was tested using computer simulation. The simulated network was a 20 kV network, consisting of 6 km cables and 37 km of various types of overhead lines. The network was divided into line sections not longer than 300 m, for each line section a three-phase PI-model was used. The network topology along with the fault location is shown in Fig.12.

The dominant harmonic voltages and currents of this network have a frequency of 250 Hz, therefore the simulation was carried out for this frequency only.

The initial value of U_{1G} was set to 20 V/70°, and initial value of U_{1G} was set to 100 V/-130°. These values change over time, the change between simulation time steps $10 \le k \le 24$ was simulated as

$$U_{1G}(k)=U_{1G}(k-1)\cdot(1+(k-10)/200)\cdot exp(j\ (k-10)/5°)$$
$$U_{2G}(k)=U_{2G}(k-1)\cdot(1+(k-10)/200)\cdot exp(-j\ (k-10)/5°) \quad (2)$$

After simulation time step $k > 35$ $U_{1G}(k) = 40\ V / -80°$.
After simulation time step $k > 50$ $U_{2G}(k)=140\ V /-170°$.

The initial value of the fault resistance was set to $R_F = 0.1\ \Omega$, but after simulation time step $k > 70$ it was changed (*randn* represents a random number having a standard normal distribution):

$$R_F(k) = |randn \cdot 300|\ \Omega \quad (3)$$

A voltage measurement error was also simulated using a random noise having a mean of 0, a standard deviation of 10 V and 10° (independent of each other).

With such assumptions the result of the simulations are shown in Fig.13.

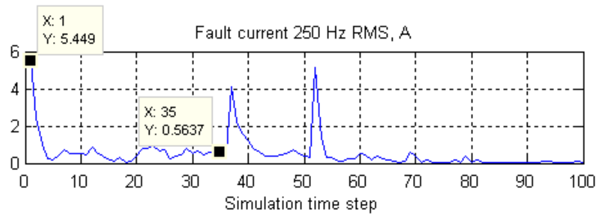

Fig.13. Simulation results

Based on the results it can be stated that the algorithm is efficient and robust.

Field tests have also been carried out, one of the results is shown in Fig.14.

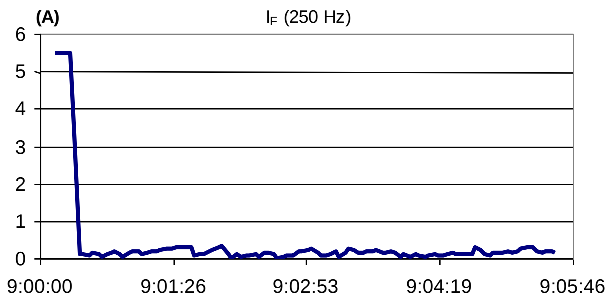

Fig.14. Field test results for 5th harmonic fault current compensation

Another field measurement has shown that it is possible to decrease the 5th harmonic content of a single phase to ground fault residual current from **8.3 A to 0.3 A** using the proposed device.

VI. CONCLUSIONS

Fault location and continuous operation of compensated networks is an important but difficult task.

The proposed method and equipment has proven its efficiency in selecting the faulted feeder without any additional device (e.g. no resistance parallel to the Petersen-coil is necessary).

It is also capable of determining the fault location in case of single-phase to earth faults on compensated networks. The average accuracy was between 300 and 400 meters. (In case of a 40 km line this is smaller than 1 % of the total line length.)

A very important feature of the presented method is that it is acting as an expert system: by accumulating information on temporary faults the personnel can be advised where to take preventive measures (tree trimming, maintenance etc.) to avoid permanent faults and consequent outages.

The device is further able to decrease the harmonic content in the residual current, thus the RMS current can be reduced and the faulty operation can be sustained.

The method was also tested on cable networks. Pure cable networks in Hungary are operated with a resistive star point. (Thus a sustained faulty operation is not an option due to the high fault currents.) There are two major difficulties regarding the application of the presented fault location method to cable networks.

On the one hand, the cables are connected to the busbar via a short circuit limiting reactor. The voltage transformers, however, are placed at the busbar-side of the reactor, so that the exact values of the three inductances (together with the coupling inductances) have to be known. This requires a measurement of each of these reactors in a substation, since they may differ significantly.

Another difficulty is the lack of exact knowledge of the cables' electric parameters. Especially the zero sequence parameters depend strongly on actual values of ground resistivity and ground return path.

These factors result in an insufficient accuracy for cable networks. Options to overcome the above problems are being analyzed.

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VIII. BIOGRAPHIES

Dr. András M. Dán (SM'90) received MSc degree from Budapest Technical University in 1966, PhD and DSc degrees in Electrical Engineering from the Hungarian Academy of Sciences in 1983 and 2005 respectively. He has been at Budapest Technical University since 1970 where he currently holds the rank of professor and acts as a consultant for local industry. His expertise is in power electronics, power quality, reactive power compensation especially associated with power system harmonics. Dr Dán is a member of the Hungarian Electrotechnical Association and Senior Member of IEEE.

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