Marek HÖGER, Pavol RAFAJDUS, Peter BRACINÍK, Lukáš KANKULA

University of Žilina

The specification of data needed for fault location in medium voltage distribution networks based on triangulation principle

Abstract. *The paper will introduce the basic idea of fault location method based on triangulation principle. At the beginning, the summary of weaknesses of known methods for fault location in medium voltage networks with tree topology will be presented. Then the basic principle of proposed method will be described, together with the analysis of critical factors influencing its usability. The last part of the paper will be focused on the investigation of voltage transformer as a source of data needed for fault location by triangulation principle application.*

Streszczenie. *Artykuł wprowadza koncepcję metody lokalizacji zakłócenia na podstawie zasad triangulacji. Na początku zaprezentowano podsumowanie słabych stron znanych metod lokalizacji zakłóceń w sieci średniego napięcia z przestrzenną topologią. Następnie została opisana podstawa proponowanej metody razem z analizą krytycznych czynników wpływających na jej użyteczność. Ostatnia część artykułu skupia uwagę na badaniu transformatora napięciowego jako źródła danych potrzebnych do lokalizacji zakłócenia przez aplikację wykorzystującą zasady triangulacji* ***(Specyfikacja danych potrzebnych do lokalizacji zakłócenia w sieciach dystrybucyjnych średniego napięcia na podstawie reguły triangulacji).***

Keywords: Fault location, Medium voltage networks, Triangulation, Voltage transformer.
Słowa kluczowe: lokalizacja zakłócenia, sieci średniego napięcia, triangulacja, transformator napięciowy

Introduction

The control of electric power system is very complex process. This control is realized through dispatching control centres, which are organized in hierarchical structure. Each level in this structure is responsible for the control of different part of electric power system. The general principle of dispatching control is common for all levels. Nevertheless, each of them has some particularity.

Dispatching control of medium voltage networks is typical for the biggest number of manipulations, which must be done in order to ensure its efficient and reliable operation. These dispatchers' interventions are mainly caused by the need to solve faults occurring in these networks. The reason of the fault could be human activity, nature intervention or just the failure of network components. Even the application of sophisticated distribution automation cannot ensure the elimination of faults' occurrence.

The strong dependence of modern society on electricity has resulted in demand on uninterrupted energy supply. So the distribution utilities are forced, by the customers, to increase the reliability of supplies and decrease the duration of faults. Therefore a fault restoration process plays very important role in the control of any distribution power network. Our analysis showed that fault location in medium voltage networks with tree structure has bigger influence on total length of fault's restoration process than fault identification. Therefore each method reducing the time of fault location can significantly improve the quality of dispatching control.

Fault location methods

There are many methods for fault location based on different principles e.g. measuring of fault circuit impedance or high frequency voltage and current components analysis. Transmission lines in 400 kV and 220 kV networks (and most of 110 kV distribution lines) have a point – to – point topology, so the fault location is relatively simple. There are no branch lines, in most cases there is measurement on both ends of line, so it is possible to compute the fault location from both ends. Therefore it is possible to use methods based on fault circuit impedance with relative high accuracy for fault location.

The situation in medium voltage distribution networks is completely different. Medium voltage lines have a tree structure with many branches, the line is fed from a single point and there is only one point equipped with measurement (this is not true for modern networks, where remote controlled switching devices are used). These networks are operated as compensated networks with transformer node grounded over a coil or a resistor.

All this attributes make the fault location in a medium voltage network a difficult task. Methods based on fault circuit impedance measurement are useless – most of failures in this type of network are ground faults, where the fault current is independent from the location of fault. By other types of fault, the tree structure of network makes the information about fault circuit impedance useless too, because there are many points with the same fault impedance. At least, the network is made from different types of wires, so it would be necessary to know the type of wire for every segment of the network. This method is also very sensitive to changes of loads connected to the network.

Adaptation of triangulation principle

The fault location in transmission networks, or more precisely on point to point power lines, is from geometrical point of view a problem of finding a point on an abscissa – we are working in a one dimension space, where the only dimension is length or distance from a base point.

The situation in distribution network is different. By networks with tree structure it isn't possible to solve the problem in a one dimension space. We must add another parameter representing the branching of the network. Now we are solving the problem in a two-dimensional space and the problem is similar to finding a point on a plane. This comparison is not exact from the electrical point of view, but leads to an idea to use principles used to locate points on a plane (something like an electrical triangulation). Principle is similar to location of a mobile phone using a network of BTS-stations.

The adaptation of triangulation principle is based on fallowing idea. If a fault occurs on one segment of power line, there will be a response to this fault in form of an electro-magnetic wave spreading from point of fault to all directions. The propagation of this electromagnetic wave could be monitored. If monitoring devices are placed at different location of faulted power line, each of them will detect electro-magnetic wave in different time, because it takes the wave some time to travel along the power line. If we know wave's propagation speed and times of its propagation from the place of the fault to monitoring devices, we will be able to calculate the distance of fault from each monitoring device.

Factors influencing electro-magnetic wave propagation

The adaptation of triangulation principle is based on premise that the wave propagation speed is constant in every point of the network. This assumption is key factor for the adaptation of triangulation principle to fault location, because the knowledge of the value of wave propagation speed is essential input for the calculation of fault's position. Considering the propagation speed to be constant will significantly simplify calculation algorithm. On the other hand, it will also add some inaccuracy to obtain results. Therefore some analyses were done in order to identify factors, which might have impact on the change of propagation speed along the power line.

Analyses were done on a simple model of distribution power line created in Matlab Simulink. The topology of the model is shown in Fig. 1. The length of the main line (sections **a**, **b**, **c**) is about 25 km. Branches **d** and **e** have 5 km and 4 km. There are three loads representing distribution transformers 22/0.4 kV with overall load about 6 MV.A (cos φ = 0.95). The cross-section of wires in each section was chosen according to load and allowed voltage drop.

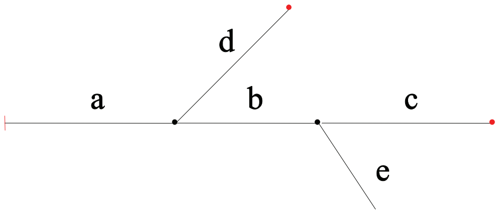

Fig. 1. Topology of created model

Propagation speed of electromagnetic wave in lossless line can be calculated as

$$v_i = \frac{1}{\sqrt{LC}}, \tag{1}$$

where *L* and *C* are parameters of the line. Equation (1) doesn't respect the change of conductor's resistance, which is caused by the change of conductors' cross-section within the power line, so typical for medium voltage networks. The influence of conductor's resistance on propagation speed can be evaluated through specific phase constant. Its value can be calculated by the help of line parameters as

$$a = \sqrt{0,5 \cdot \left(\omega^2 L_1 C_1 - R_1 C_1\right) + 0,5 \cdot \sqrt{\left(R_1^2 + \omega^2 L_1^2\right) \cdot \left(G_1^2 + \omega^2 C_1^2\right)}}. \tag{2}$$

Table 1 shows values of specific phase constant calculated for different conductor's cross-sections. Selected conductors are very often used for medium voltage power lines. The speed of wave propagation decreases with smaller value of conductor's cross-section.

Table 1. The parameters of different conductors

S(mm^2)	95	50	35
R_1 (Ω)	0,28445	0,4663	0,68717
L_1 (mH)	0,97166	0,97317	0,97414
C_1 (nF)	12,08	12,08	12,08
a (rad.km^{-1})	1,170174.10^{-3}	1,27881.10^{-3}	1,41561.10^{-3}

Other factor influencing wave propagation speed is changing of line's geometry (distance between wires, distance of wires from ground …), because it influences line's electrical parameters. The change of geometry is very often in medium voltage power lines, so it's important to know how the wave propagation speed is affected by these changes. This verification was made on the same model as before. Wave propagation speed was computed for two typical line configurations and for a 110 kV line, which served as an example of extreme configuration change. Results are shown in Table 2, where v_{EM} is calculated propagation speed of electro-magnetic wave. The last column shows how much slower the electro-magnetic wave is comparing to speed of light (c).

Table 2. Wave propagation speed for various geometry of line

Configuration	L_k (H.km^{-1})	C_k (nF.km^{-1})	v_{EM} (km.s^{-1})	v_{EM}/c (%)
22 kV flat	0,00114	10,112	294529	98,2
22 kV triangle	0,00112	10,264	294939	98,4
110 kV	0,00113	10,300	293117	97,8

Medium voltage networks have a tree structure with many branches, so it is important to know how the propagation speed is affected with networks topology. To verify the effect of topology changes, some test were done on the simulation model. First, an additional branch was added to different points of the model and the propagation speed was evaluated. Then multiple additional branches were added. Results confirmed that even massive changes in network topology didn't affect the propagation speed.

The change of load at network branches is another factor that influences the accuracy of method based on the measurement of fault circuit. To verify the impact of load changes to wave speed propagation, a few simulations were done on the simulation model. The load in network's branches was being changed from 0 to 100 % with 20 % step. Obtained results didn't prove any influence.

The results of simulation confirmed the change of conductor's type as the biggest factor influencing propagation speed of electromagnetic wave. The worst situation is in networks with both overhead and cable sections because cable lines have much greater capacitance and so the propagation speed is much lower and longer cable sections can cause serious errors in computation of fault location. Nevertheless, if we take one value of propagation speed and use it as average value respecting all above mentioned factors, we can use it for the calculation of fault location. Obtain results will be burden with some error, of course. The error will be the biggest in networks with the ratio of the length of overhead to cable sections close or equal to one. But the principle of triangulation itself eliminates this inaccuracy a little bit.

Data specification

The wave propagation detection can be realized as a voltage measurement. The data acquisition system detects the time of beginning of rapid voltage sag. The advantage of under voltage wave detection is the fact, that the wave is generated by all most recent failures occurring on 22 kV lines, including the earth fault.

The figure 2 illustrates detail of voltage waveforms of one phase of modeled 22 kV line by an earth fault. Waveforms were acquired from three different measuring points. A clear difference between times of voltage drops' beginning detected in different points can be clearly seen on Fig. 2. These time differences are caused by different distances between measurement points and point of fault, which has the under voltage wave to overcome.

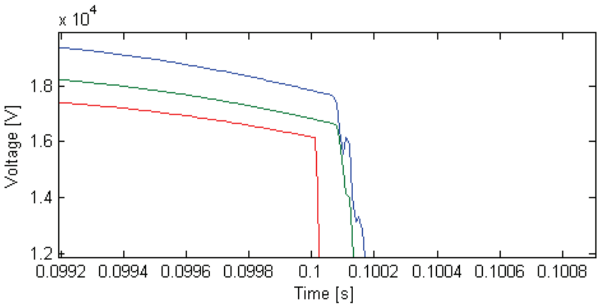

Fig. 2. Detail of voltage drops measured at different parts of faulted power line

The biggest advantage of this method is that it doesn't need digital detection of voltage drop, what significantly reduces hardware requirements. It can be done by analogue measuring devices. Only information needed for fault location computation is the time of voltage drop. And this information can be easily obtained by readily available GPS modules.

To make this idea workable, we need some device, which will transform power line's voltage to values suitable for measuring analogue devices. Therefore, the analysis of commonly used voltage transformer was done, in order to check its ability to transform the voltage drop correctly.

Voltage transformer investigation

As it is known, voltage transformer (VT) works on the base of classical transformer principle. VT is very hard voltage source and the output terminals have to be loaded by very high impedance and no short circuit state is possible [2].

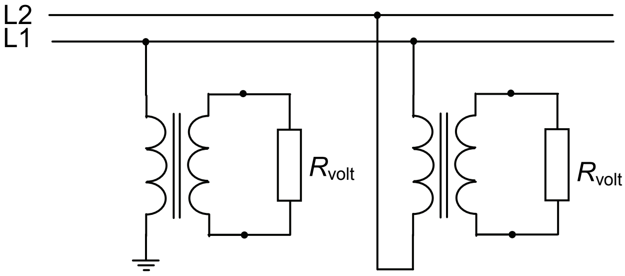

Fig. 3. The basic scheme of voltage transformer connection

Fig. 4. A real investigated voltage transformer

The basic scheme of VT is shown in the Fig. 3 and a real investigated VT is in the Fig. 4 with following nameplate:

- nominal primary voltage: U1 = 10000/√3 V,
- nominal secondary voltage „S1“ :U2S1 = 100/√3 V,
- nominal secondary voltage „S2“: U2S2 = 100/3 V,
- input power of secondary windings „S1“: SS1 = 10 V·A,
- input power of secondary windings „S2“: SS2 = 30 V·A,
- frequency: f = 50 Hz,
- ratio between „P – S1“: pS1 = 100,
- ratio between „P – S2“: pS2 = 100·√3.

Mathematical model of VT

The mathematical model of voltage transformer is very close to the classical transformer under no load conditions. The operating of VT is with very high secondary load impedance, what is theoretically equals to infinity. Then, the mathematical model is simpler, because the secondary current is approximately equal zero. This secondary current depends on the value of R_{volt} and as it has been mentioned above it is proportional to infinity. The next simplification is to neglect resistance, which represents iron losses and then, no-load current is equal to magnetizing current. The equivalent circuit of VT is shown in the Fig. 5.

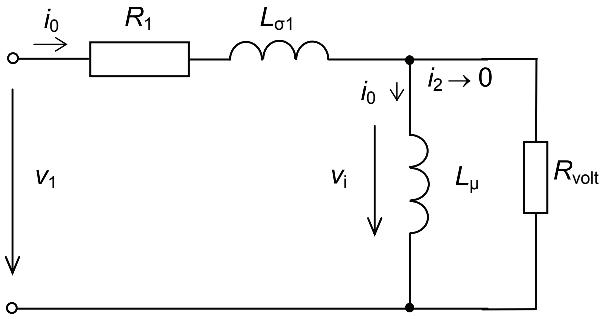

Fig. 5. The equivalent circuit of VT

For equivalent circuit shown in the Fig. 5, the equation on the base of Kirchhoff's law, can be written as follows:

(3) $$v_i = v_1 - R_1 i_\mu - L_{\sigma 1}\frac{di_\mu}{dt},$$

where v_1 is instantaneous value of primary voltage, R_1 is resistance of primary winding and $L_{\sigma 1}$ is leakage inductance of primary winding.

Induced voltage v_i is given on the base Faraday's law [2] for the winding with N turns is as follows:

(4) $$N\frac{d\Phi}{dt} = v_1 - R_1 i_\mu - L_{\sigma 1}\frac{di_\mu}{dt}.$$

Induced voltage v_i can be given also as by means of inductance and current derivation

(5) $$v_i = N\frac{d\Phi}{dt} = L_\mu \frac{di_\mu}{dt}.$$

Magnetizing inductance can be also expressed by means of magnetic conductivity or reluctance of iron transformer core as follows:

(6) $$N\frac{d\Phi}{dt} = N^2 \frac{A}{l}\frac{dB}{dH}\frac{di_\mu}{dt},$$

where *A* is cross-section area of transformer core, *l* is average length of magnetic flux, *B* is flux density and *H* is intensity of magnetic field.

Combining of equations (4) and (6) the following equation is given to derive magnetizing current of VT:

$$\frac{di_\mu}{dt} = \frac{1}{L_{\sigma 1} + N^2 \frac{A}{l}\frac{dB}{dH}}\left(v_1 - R_1 i_\mu\right) \tag{7}$$

or it could be derived in simpler form by means of magnetizing inductance L_μ:

$$\frac{di_\mu}{dt} = \frac{1}{L_{\sigma 1} + L_\mu}\left(v_1 - R_1 i_\mu\right). \tag{8}$$

As it can be seen from derived equations of voltage transformer, the equivalent circuit parameters are needed. There are many methods to investigate these parameters: analytically, by means of Finite Element Analysis or by measurements. The last method has been used and it is described in the next chapter to simulate VT under steady state or transient conditions.

VT parameters measurement

This measurement is similar as for classical transformers. The resistances of primary and secondary parts have been measured by Ohm's method. The primary resistance R_1 = 1100 Ω and secondary resistance are: R_{22} = 0.16 Ω and R_{21} = 0.187 Ω.

Very important parameter is magnetizing inductance. As it is known from transformer theory, it is not constant value, but it depends on magnetizing current. This parameter has been measured from no-load measurement from secondary side and the dependence of L_μ= f(I_μ) is shown in the Fig. 6.

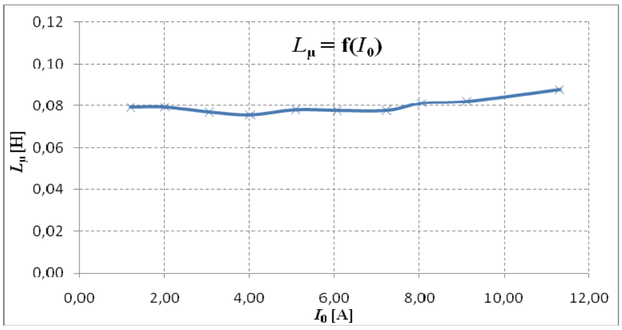

Fig. 6. The dependence of magnetizing inductance versus magnetizing current

From the Fig. 6 it is clear, that VT works in linear area because, the magnetizing inductance is approximately constant and the saturation is neglected.

The leakage inductances of primary and secondary windings have been measured from short-circuit measurement also from secondary side as a total leakage inductance L_k = 0.003 H and primary leakage inductance $L_{\sigma1}$ = 0.0015 referred to the secondary winding or 15.26 H from the primary side of transformer. These parameters of VT equivalent circuit have been used in the mathematical model and simulated under Matlab - Simulink program.

Transient analysis of VT

To create simulation model of VT, the equation (8) is used and solved. The simulation model of voltage transformer is created from secondary side and it can be seen in the Fig. 7. It is also possible to make a simulation model from primary side, but all input parameters of mathematical model have to be recalculated and referred to the primary side, because they have been investigated from secondary side of transformer. In real operation is very important to know the behavior of VT not only under normal operation, but also under fault network operation (short circuit, sudden voltage dip). The voltage waveform obtained from some cases of fault operation can be used for better localization of network fault as it is described in this paper.

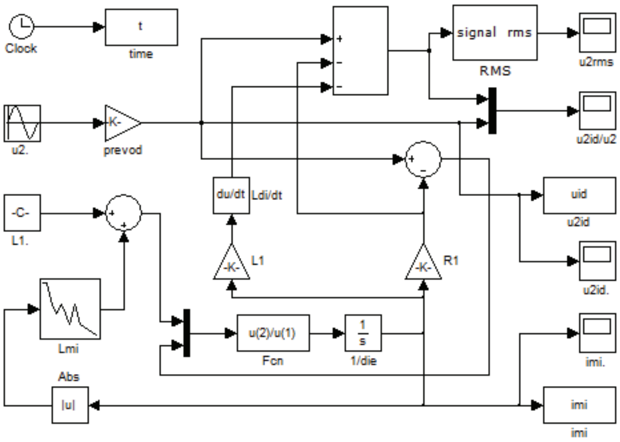

Fig. 7. Transient simulation model of VT under Simulink

The VT mathematical model has been used also for transient analysis of sudden voltage dip of 22 kV distribution network. The simulated case is following: from time 0 to 0.024 there is normal operation, from time 0.024 some sudden voltage dip has occurred to time 0.032. From time 0.032 starts regenerated voltage. There can be seen the transient state. This simulated case is shown in the Fig. 8 for primary voltage and in the Fig. 9 for secondary side of VT.

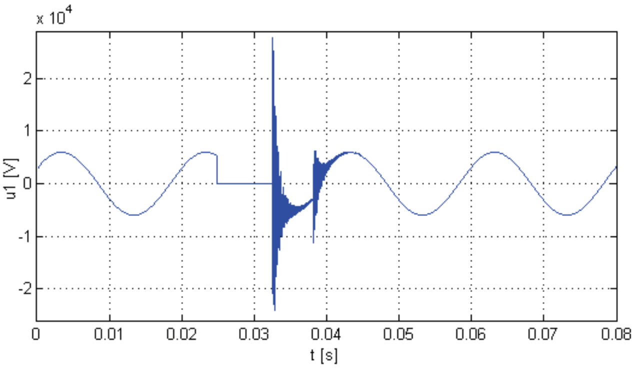

Fig. 8. Transient voltage waveform of VT primary side

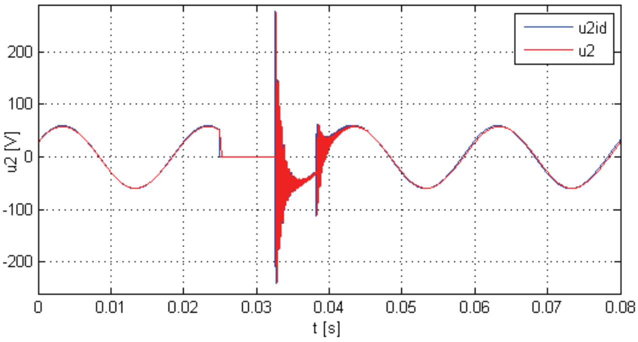

Fig. 9. Transient voltage waveform of VT secondary side

In Fig. 9 can be seen the secondary voltage transformed from primary side during fault operation. There can be seen two waveforms: ideal (u2id) – it means, voltage transformer works without internal error [2], and it is compared with a real waveform (u2), if the influence of transformer error is taken into account. The difference is very low and it means, that this model and simulations can help to identify and to localize the network fault.

Conclusions

Fault location in medium voltage networks with power lines with tree structures can be solved through the adaptation of triangulation principle. If a fault occurs on one segment of power line, there will be a response to this fault in form of an electro-magnetic wave spreading from point of fault to all directions. If monitoring devices are placed at different location of faulted power line, each of them will detect electro-magnetic wave in different time, because it takes the wave some time to travel along the power line. If we know wave's propagation speed and times of its propagation from the place of the fault to monitoring devices, we will be able to calculate the distance of fault from each monitoring device.

The accuracy of proposed method depends strongly on electro-magnetic wave propagation. The results of simulation confirmed the change of conductor's type as the biggest factor influencing propagation speed of electromagnetic wave. Nevertheless, if we take one value of propagation speed and use it as average value respecting all investigated factors, we can use it for the calculation of fault location. Obtain results will be burden with some error, but the principle of triangulation itself eliminates this inaccuracy a little bit.

The biggest advantage of this method is that it doesn't need digital detection of voltage drop, what significantly reduces hardware requirements. It can be done by analogue measuring devices. Only information needed for fault location computation is the time of voltage drop. And this information can be easily obtained by readily available GPS modules.

To examine if commonly used voltage transformers can provide correct input signal for analogue measuring devices, the investigation of voltage transformer behaviour under transient conditions was done. Simulations result confirmed the ability of such a transformer for measuring and detection purposes. It means that also remote controlled section switches, which are already installed in power lines and use voltage transformers for their operation, could be used for the adaptation of triangulation principle for fault location, without big investments.

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REFERENCES

[1] Kolcun M. et al., *Prevádzka elektrizačnej sústavy (The Operation of Electric Power System),* TU Košice (2007), 306 pp., ISBN 978-80-8073-837-2

[2] Tziouvaras D.A., McLaren P., Alexander G., Dawson D., Esztergalyos J., Fromen C., Glinkowski M., Hasenwinkle I., Kezunovic M., Kojovic L., Kotheimer B., Kuffel R., Zocholl S., Mathematical models for current, voltage, and coupling capacitor voltage transformers, *International Journal of Electric Engeneering Education* 15/1

[3] Rafajdus P., Braciník P., Hrabovcová V., The current transformer parameters investigation and simulations, *The journal Electronics and Electrical Engineering*, 2010, No.4 (100), pp.: 29 - 32, ISSN 1392 - 1215

[4] Bo Z.Q., Weller G., Jiang F., Yang Q.X., Application of GPS Based Faul Location Scheme for Distribution System. *POWERCON `98*, Bejing, 1998

[5] Lehtonen M., Novel Techniques for Fault Location in Distribution Networks. *Power Quality and Reliability Conference,* Parnu, 2008

[6] Sluis L., *Transients in Power Systems*. John Wiley & Sons Ltd, Chichester, England, 2001

***Authors**: Ing. Marek Höger, marek.hoger@kves.uniza.sk; Ing. Peter Braciník, PhD., peter.bracinik@kves.uniza.sk; assoc. prof. Ing. Pavol Rafajdus, PhD. Pavol.rafajdus@kves.uniza.sk; Lukáš Kankula, lkankula@gmail.com, University of Žilina, Faculty of Electrical Engineering, Department of Power Electrical Systems, Univerzitná 1, SK 010 26 Žilina, Slovakia*