Fault Point Location Method, Based on Harmonics Analysis of a Distribution System

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Abstract: To increase the reliability of energy distribution, it is necessary to shorten the downtime. It is very important to determine the location of a fault as accurately and as quickly, as possible. Than the maintenance service team can rectify the fault as soon as possible. Determining the distance of the fault (from the relevant power station) with the greatest possible accuracy, in the event of a short circuit on the external power line, is an important information that affects the time to find the actual location, thus eliminating the cause of the fault and the overall downtime. At present, we can most accurately determine the location of the fault using a wave locator - impedance principle. The main disadvantage of existing fault locators is that they are based on the assumption of ideally faults takes into account the consideration of symmetrical components of the line. These locators do not take into account the topology of the line, i.e. that the impedances of the individual phases, resp. fault loops are different. This paper proposes, an innovative method of symmetrical components or the Fourier thesis, by using modern informatics and communication tools, which provide opportunities to set new standard in finding the location of the fault on overhead lines in distribution network. Armed with a more precise determination of the failure location, we can reduce the time needed to eliminate the failures and thus, achieve improvements in the reliability of the power distribution system.

Keywords: symmetrical components; fault location

1   Introduction

In a case of power outages, localization of the fault point is the most important task. In most cases, until the fault location is determined, electricity service can only be partially restored. This can lead to customer dissatisfaction and economic damage.

Today, this damage is becoming more critical with the increasing demand for continuous electricity. In the future, distribution networks are expected to be more smart to handle that problems. This means that various new detection methods will need to be developed to increase the reliability of electricity supply.

Gudzius S. et al [1]. point of view is that the smart grid is the vision of the electric power network which integrates the electro-technical, communication and informatics technologies. This integration allows developing new fault location technologies which are based on methods of fast transient's analysis. Muhammad U. U. et al. [2] presents a novel approach to classify and locate different types of faults in a smart distribution network. The method is based on artificial neural networks pattern recognition which uses data from µPMUs/smart meters placed at different locations in a distribution system. Shafiullah, Md et al. [3] refers about that the most of the CMLs (grids causes customer minute loss) are caused due to different types of faults sustained for a longer period of time. Therefore, rapid fault location techniques are very necessary in order to restore the power supply quickly by reducing outage durations and revenue losses. That means it is necessary to find new and fast location methods. Lot of paper present different location methods and technics, such as Trindade F. C. L. et al. [4] proposes to combine the voltage monitoring capability of smart meters with impedance-based fault location methods to provide an efficient fault location approach improving service restoration. Another method is presented by Lotfifard S. et al. [5] present fault location method based on matching calculated voltage sag data and data gathered at some nodes in the network. This method is developed for characterization of voltage sags to reduce amount of transferred data. Sensitivity analysis of voltage sag based fault location with distributed generation is presented by Po-Chen Chen et al. [6]. Kezunovic M. [7] present a smart localization method for smart grids. This method is associated with improving accuracy of fault location methods in smart grids using an abundance of IED data. As alternative methodology of statistical nature based on finite mixtures for solution to the problem of power service continuity associated to fault location is proposed by Mora-Flórez J. et al. [8]. In this paper the statistical model is obtained from the extraction of the magnitude of the voltage drop recorded during the fault condition together with the network parameters and the topology. Other publications define a different approach to fault location, for example S. Lotfifard et al. [9] present the two-step approach and discussed for ranking available fault location methods that takes into account application requirements and modeling limitations and uncertainties. Other paper use direct three-phase circuit analysis-based fault location for Line-to-Line fault. Simulation results show a high degree of accuracy and robustness to load uncertainty. A Direct Three-Phase Circuit Analysis-Based Fault Location for Line-to-Line Fault methodology was presented by Choi M-S et al. [10]. Dong Y. et al. [11] proposed fault-location method for radial distribution systems. The proposed method uses voltage and current phasors from feeder root and voltage sags measured at sparse nodes along the feeder, and pinpoints faults to the nearest node. Other articles refer to other methods of locating faults such us Goudarzi M. et al. [12], also Adeyemi Ch. A. et al. [13], or Livani H.

and Evrenosoglu C. Y. [14]. R. Jalilzadeh Hamidi et al. [15] presents a novel recursive method for detecting the first arrival time (AT) of traveling waves (TWs) in power grids to enhance the fault-location methods relying on TWs. Also B. Ravindhranath Reddy et al. [16] using traveling wave theory for localization of fault on power transmission lines. Hang C. et al. [17] proposes HVDC transmission line fault localization algorithm based on radial basis function (RBF) neural network with wavelet packet decomposition (WPD). Xing L. et al. [18] publish results of experimental studies on the rtEthernet-based centralized fault management system for smart grids. Wanshui L. et al. [19] Use IEC 61850 communication protocol for Distributed Fault Localization, Isolation, and Supply Restoration. A method to identify and localize failures in smart grids, based on a carefully designed Petri Net (PN), is presented by Calderaro V. et al. [20]. Kasperowicz R. et al. [21] offers a preview of Economic growth and energy consumption: comparative analysis of V4 and the "old" EU countries. This is important for further analysis of energy management system. Balitskiy, S. et al. [22] deals with Energy security and economic growth in the European union. Sabishchenko, O. et al. [23] present the Ukraine energy sector management using hybrid renewable energy systems. Hussain, H.I. et al. [24] An investigation of an adaptive neuro-fuzzy inference system to predict the relationship among energy intensity, globalization, and financial development in major ASEAN economies is presented it this paper. Haseeb, M. et al. [25] [26] deals with the natural resources curse-economic growth hypotheses and Impact of economic growth, environmental pollution, and energy consumption on health expenditure and R&D expenditure of ASEAN countries. Škare, M. et al. [27] deals with Energy consumption and Green GDP in Europe: A panel co-integration analysis. Tvaronavičienė, M. et al. [28] present the Cyber security management of critical energy infrastructure in national cybersecurity strategies: cases of USA, UK, France, Estonia and Lithuania. Insights into Regional Development. Nasr, A. et al. [29], Dudin, M. N. et al. [30] and Zhelykh, V. el al. [31] deals with barriers and innovative technologies of renewable energy sources. Ulewicz, R. et al. [32] deals with Sustainable development and knowledge management from the stakeholders' point of view.

The work herein, first presents the description of the symmetric component in Chapter 2. This method makes possible, the modelling of asymmetric 3-phase electrical networks. In Chapter 3, the modelling of the earth fault location using this procedure will be presented.

In Chapter 4 an electrical equivalent diagram of a transmission line will be presented, followed by a model with three branches, since the final model in this paper is based on a model with three branches where one branch is earth-barred. In this final model can be seen, the 5th harmonic of the zero-sequence current flows in the reverse direction from the faulty branch, relative to the fault-free line (The theoretical background is given in Chapter 5.)

In Chapter 7, it is shown that if we can measure this zero-order 5th harmonic at the junctions, we can see exactly at which junction the fault location is located.

By placing such a meter at all or at the highlighted junctions, fault clearance time can be radically reduced. Finally, in Chapter 8, our conclusions and possible future research is presented.

2   Symmetric Component Description

The passive three-phase network can be called symmetric if in the way of current all the three-phases self and mutual-impedances are equal. Additionally, the isolation in all the three-phases and impedances relating to each other the ground and the zero wires are equal. Analyzing the symmetrical network operating is simple. By substitution the three-phase network for one-phase network in proper way. In asymmetrical cases which mean the real network models, it can be seen from the strict conditions of the symmetrical network these methods cannot be applied [33].

Analyses of asymmetrical cases of multi-phase system can by realized by dividing into symmetrical components [33].

These three phasors and their time-functions are the following:
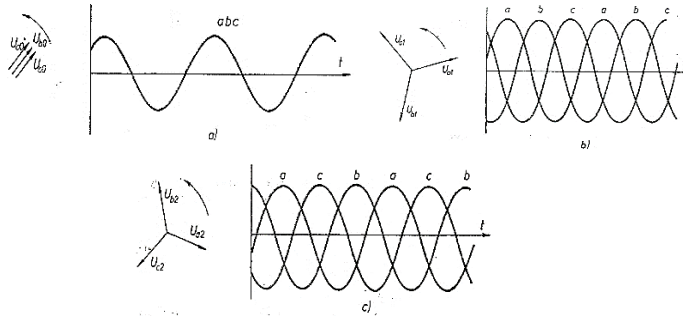

Figure 1

The phasors and time functions of the three-phase asymmetrical voltage system, a) Zero sequence b) Positive sequence c) Negative sequence [34]

Introducing $\bar{a}$ and $\bar{a}^2$ operators, whose values are:

$$\bar{a} = -\frac{1}{2} + 3j\frac{\sqrt{3}}{2} = e^{j120^0} \tag{2.1}$$

$$\bar{a}^2 = -\frac{1}{2} - 3j\frac{\sqrt{3}}{2} = e^{j240^0} \tag{2.2}$$

in which j is the complex unit-phasor.

Can be deduced:
$$\begin{bmatrix} \bar{I}_a \\ \bar{I}_b \\ \bar{I}_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \bar{a}^2 & \bar{a} \\ 1 & \bar{a} & \bar{a}^2 \end{bmatrix} \begin{bmatrix} \bar{I}_{a0} \\ \bar{I}_{a1} \\ \bar{I}_{a2} \end{bmatrix}$$ (2.3)

that is:
$$\bar{I}_{AS} = A\bar{I}_S$$ (2.4)

The symmetrical components of the phase A:
$$\begin{bmatrix} \bar{I}_{a0} \\ \bar{I}_{a1} \\ \bar{I}_{a2} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \bar{a} & \bar{a}^2 \\ 1 & \bar{a}^2 & \bar{a} \end{bmatrix} \begin{bmatrix} \bar{I}_a \\ \bar{I}_b \\ \bar{I}_c \end{bmatrix}$$ (2.5)

That is:
$$\bar{I}_S = A\text{-}1 \, \bar{I}_S$$ (2.6)

With this method asymmetrical cases can be transformed into symmetrical once, in case of three-phase the original – not symmetrical – phasors can be divided into three symmetrical phasor-system [35] [46].

3   Modelling Fault Location of Ground Fault, Modelling of Ground Fault by the Method of Symmetrical Components

Modelling fault location of ground fault an impedance-free branch from the three phase conductor (h) can be made. This is just a theoretical, non-exist branch, but that is necessary for taking the flowing out currents from the fault location into account [47] [48].

The impedance-free recirculation of the different sequenced single-phase models are signed with n_1, n_2, n_0 and the fault location is h_1, h_2, h_0:
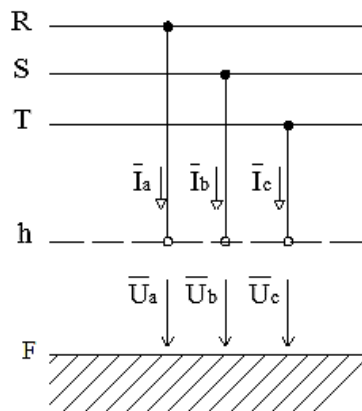

Figure 2
Theoretical figure of the fault location in which R-S-T is the phase A-B-C and the F is the ground [35]
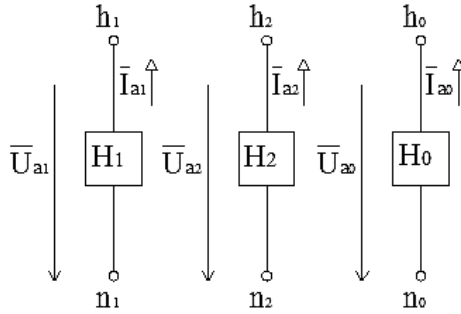
Figure 3

Symbolic figure of the positive-, negative- and the zero sequences network [35]

The current and voltage components in the figured network are all the quantities of the phase A. Phase A is the chosen reference phase, the sequence components of B and C can be expressed by the sequence components of A.

Model of the ground fault location, the connection of the symbolic figures of the sequenced networks:
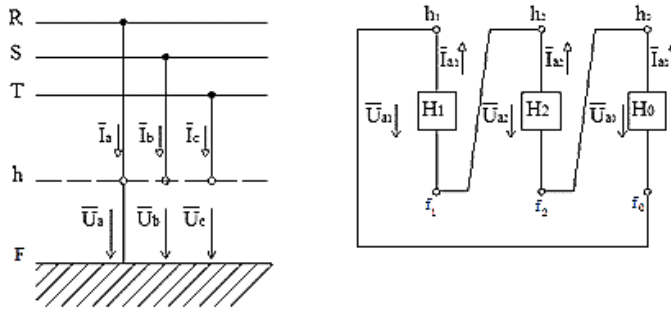

Figure 4

Theoretical figure of the fault location (left fig.),

the connection of the symbolic figures of the sequenced networks (right fig.) [35]

Verified for the fault location its voltage and current equations:

$$\bar{U}_a = 0; \bar{I}_b = 0; \bar{I}_C = 0 \tag{3.1}$$

The symmetrical components of the fault location current, based on chapter 1:

$$\begin{bmatrix} \bar{I}_{a0} \\ \bar{I}_{a1} \\ \bar{I}_{a2} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \bar{a} & \bar{a}^2 \\ 1 & \bar{a}^2 & \bar{a} \end{bmatrix} \begin{bmatrix} \bar{I}_a \\ 0 \\ 0 \end{bmatrix} \tag{3.2}$$

That is:
$$\bar{I}_{a0} = \bar{I}_{a1} = \bar{I}_{a2} = \frac{\bar{I}_{a3}}{3} \tag{3.3}$$

Therefore, in case of a single-phase ground fault, all three components of the network at fault location (h) the outgoing currents are equal.

Considering that:

$$\bar{U}_{a0} + U_{a1} + \bar{U}_{a2} = 0 \tag{3.4}$$

That is, the sum of the three-component network fault location voltage components is zero, it can be determined the positive, negative and the zero sequence network component connection mode: the three networks must be in series in the fault location (h) [35] [49].

4 Modelling of an Overhead Line Junction

For modelling the overhead lines, the π connection is available which consists of the following components.

- Serial elements:
    - Inductive reactance of the line system (X_L)
    - The resistance of the wire (R)
- Parallel (shunt) elements:
    - Calculated capacitive reactance from the ground capacity of the line system (X_C)
    - Calculated reactance from the leakage current of insulators and the corona-loss of the phase conductor wires (R_{SZ})
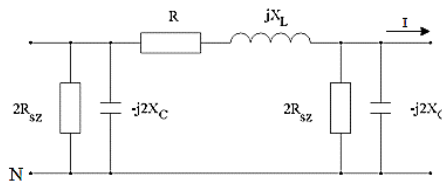

Figure 5

Single-phase circuit diagram of the three-phase overhead lines [42]
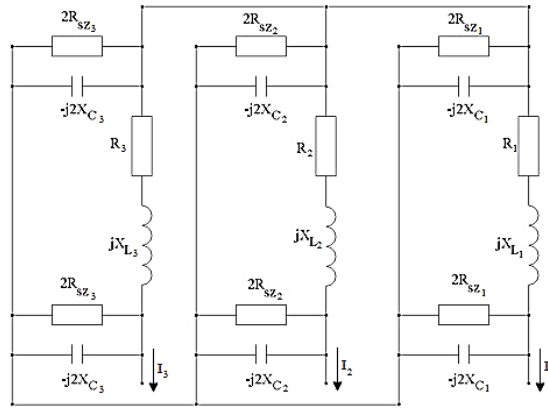
Extending this to an overhead line junction:

Figure 6

Single-phase circuit diagram of an overhead lines junction

Figure 6, clearly shows the connection point (top horizontal line) that connects the three transmission line sections to one pole. An overhead junction will be shown later using the symmetric components method. In this latter figure, the current directions of the harmonics will also be plotted. The most suitable tool for introducing harmonics is the Furier thesis [36] [37] [50].

5   Modelling of the Harmonics in Three-Phase Systems

One part of the consumers are linear consumers. They consume sinusoidal current and voltage (for example iron, heater). The other part of the consumers are non-linear, who do not use clear sinusoidal power (for example the switched-mode power supplies,SMPS) [38] [39] [51]

In the three-phase systems the harmonics are three-phase quantity with the corresponding frequency to the number of harmonics. They can be represented in a rotating coordinate system, where the phase order determines the order of modelling asymmetrical systems when they are disassembled to symmetrical components [39] [52].

If we analyze a three-phase system which is symmetric but contains some harmonics, deduced for i_a, i_b, and i_c current:

$$i_a = \sqrt{2}\left[I_1 e^{j\omega t + a_2} + I_2 e^{2j(\omega t + a_2)} + I_3 e^{3j(\omega t + a_3)} + \cdots\right] \tag{5.1}$$

$$i_b = \sqrt{2}\left[I_1 e^{j\omega t + a_2 + 240} + I_2 e^{2j(\omega t + a_2) + 240} + I_3 e^{3j(\omega t + a_3) + 240} + \cdots\right] \tag{5.2}$$

$$i_c = \sqrt{2}\left[I_1 e^{j\omega t + a_2 + 120} + I_2 e^{2j(\omega t + a_2) + 120} + I_3 e^{3j(\omega t + a_3) + 120} + \cdots\right] \qquad (5.3)$$

in which: I_1, I_2 and I_3 is the effective value of each harmonic; ω is the angular velocity of the basic harmonic, t is the time, a_1, a_2, and a_3 is the phase shift of each harmonics [53].

Transforming the right side of the 5.1 – 5.3 equation by expressing all harmonics with the power of the $\bar{a}$ operator:

$$i_a = \sqrt{2}\left[I_1 e^{j\omega t + a_2} + I_2 e^{2j(\omega t + a_2)} + I_3 e^{3j(\omega t + a_3)} + \cdots\right] \qquad (5.4)$$

$$i_b = \sqrt{2}\left[\bar{a}^2 I_1 e^{j\omega t + a_2} + \bar{a} I_2 e^{2j(\omega t + a_2)} + I_3 e^{3j(\omega t + a_3)} + \cdots\right] \qquad (5.5)$$

$$i_c = \sqrt{2}\left[\bar{a} I_1 e^{j\omega t + a_2} + \bar{a}^2 I_2 e^{2j(\omega t + a_2)} + I_3 e^{3j(\omega t + a_3)} + \cdots\right] \qquad (5.6)$$

Can be derivable from the equation if the base harmonics has positive order that means the following order of the phasors in a, b, and c phases 1, $\bar{a}^2$, $\bar{a}$ than in the second harmonics is 1, $\bar{a}$, $\bar{a}^2$ whitch equivalent to the negative sequence.

In symmetric (static) systems even-order harmonics are not presented. It is verifiable for the uneven-order harmonics that $(6n+1)$[th] harmonics has positive, $(6n-1)$[th] has negative, and the $(6n-3)$[th] has zero sequence [33] [54].

Based on measurement results [41], the 5th has the highest amplitude from the reverse rotational direction harmonics. It is verifiable for the 5th harmonics, if the rotation direction of the base harmonics is A-B-C - the phase B delayed by $\frac{2\pi}{3}$ angle compared to A - than the phase delay for 5th harmonics between phases A and B:

$$(6n - 1)\frac{2\pi}{3} = 4n - \frac{2\pi}{3} \qquad (5.7)$$

Consequently in the phase B, the $(6n-1)$[th] harmonics hurries with $2\frac{\pi}{3}$ angles compared to the $(6n-1)$[th] harmonics in phase A, therefore, the phase sequence reverses: A5-C5-B5 [40].
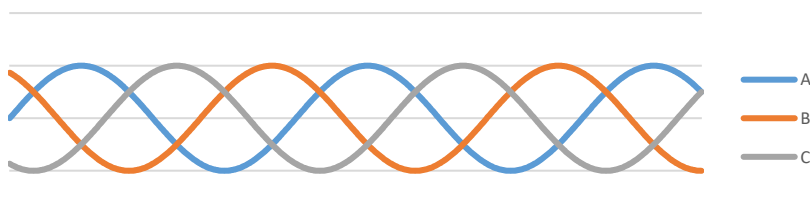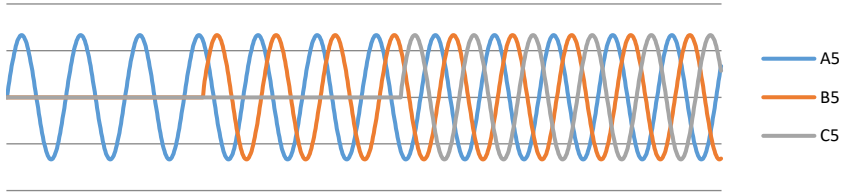
Figure 7

A three-phase system (top) and his fifth harmonic initial waveform (bottom)

Y: Amplitude; X: Period time $\left[\frac{1}{2\pi} = \frac{1}{360^0}\right]$

As a result of this phase tracking order the 5th harmonic can be modelled by the harmonics generator in the negative sequence.

6   Determination of Earth Fault Direction by Analyzing Harmonics in Overhead Line Networks

Based on the theory described in Chapter 2-5, can be modelled a junction of three compensated ($Z_{Choking-coil}$) overhead lines in case of ground fault. The serial RL and the parallel RC components are replaceable with their impedance in the following way [43] [55] [56]:

$$Z_{RL_n} = R_n + jX_{L_n} \tag{6.1}$$

$$Z_{RC_k} = R_k \times \left[-j2X_{C_k}\right] \tag{6.2}$$

The single-phase model, which is valid for the reversed phase order compared to the base harmonics (the negative sequenced harmonics generated by the non-linear consumer substituting with a harmonics generator in the negative sequence network):
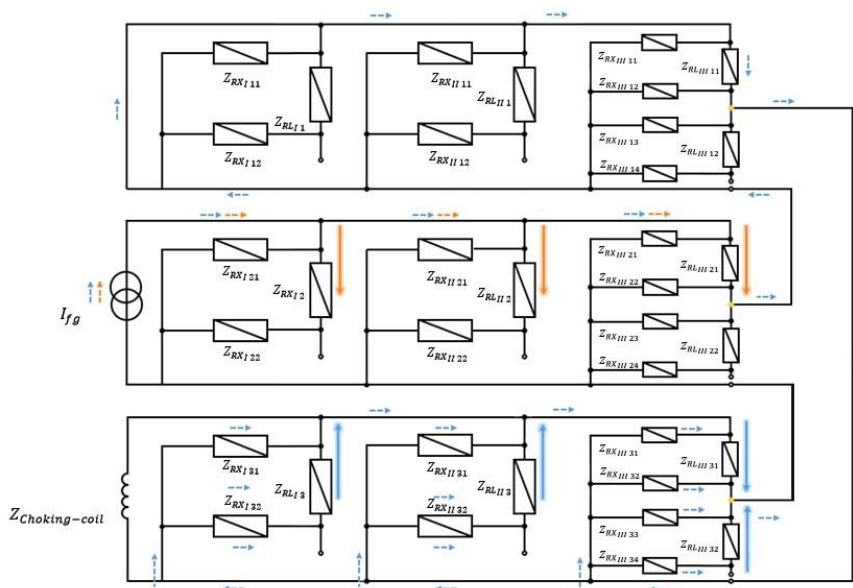
Figure 8

Single-phase model of ground faulted overhead lines junction supplied by 5th harmonics,
where 5th harmonic of the zero-sequence current is blue arrow,
the 5th harmonic of negative-sequence current is orange arrow,
the fault points are the yellow dots

Following the current directions all the way it could be seeable the 5th harmonic of the zero-sequence current flows in the reverse direction from the faulty branch, relative to the fault-free line.

7   Zero Sequence Impedances of Overhead Lines

The direction and the size of zero phase sequence components are the same in all the three phases, namely three-phase conductors – in terms of excitation – can be defined as one single conductor. Which means, that the zero phase sequence current loop flows only in one direction between feeding points and consumers. The path for current to return happens under the ground on medium voltage (in some cases with a guard-conductor or a neutral-conductor or with both) [57] [58]. Grounding plays a significant role in the zero sequence impedances of three-phase conductors.
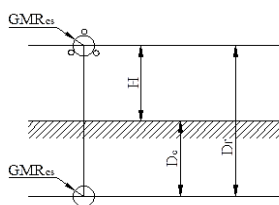
Figure 9

The path of zero sequence current to return [35]

The deep of the zero sequence current return:

$$D_e = 659 \sqrt{\frac{\rho_{ground}}{f}} \, [m] \tag{7.1}$$

in which f: frequency; ρ_{ground}: ground resistivity

The reactance value of ground:

$$X_f = 0{,}435 \cdot lg \frac{D_e}{GMD} \left[\frac{\Omega}{km}\right] \tag{7.2}$$

The group of phase conductors surrogate thin pipe radius:

$$GMR_{CS} = \sqrt[9]{GMR^3 D_{ab}^2 D_{ac}^2 D_{bc}^2} \tag{7.3}$$

The degree of geometric distance conductors:

$$GMD = \sqrt[3]{D_{ab} D_{ac} D_{bc}} \tag{7.4}$$

In case of AC the least impedance is the reference. The W component keeps the current fibers away and holds them along a straight line. The farther the center of gravity of the current fibers in the ground is, the higher the reactance of the circuit is. If ρ is high, it is not the ground resistance that will rise, but the depth of earth return and also the X_f reactance due to the bigger surface area current can flow on. If the current flowing in ground diverged from the path of its the overhead lines, and would flow in a straight line connecting the inflow and outflow – similarly as in DC - large current loop would be created in the part of flows against the line and the ground return. As result of this the reactance in alternating current circuit would highly increase. This is the reason why ground current – in case of AC network - follows the path of its overhead line to shorten the distance of the current flow to the minimum (theory of energy minimization) [35] [59] [60].

Conclusions and Future Research Directions

If the zero sequence component of the 5th harmonic and the direction can be measured, we can identify the general location of the fault and eliminate the causes of the problem.

Today, operation controls – for life saving reasons – less commonly allow for ground faulted operation [44]. However, under protective operation, applying

modern technology – installed measuring devices, quick and efficient communication – measurements cannot only be carried out, but also evaluated.

The type of measuring instrument used, is based on the comparison of two signals of the roll, excited by the positive and zero sequence currents. Accordingly, the quotient of the excitation of the two roll rotated 90^0, will provide the measured signal. If this quotient is negative, the measuring device "looks" toward the location of the fault, if it is positive, it searches the other direction. Using a signal processor and transmitter, with more sensors, would make measurement possible in all directions, simultaneously.

The installed data processor and transmitter could be suitable for evaluating future results. The provided data might enhance such areas, in the future, as the implementation of branch selection, without FÁNOE (earth fault current raising resistor) [45]. This includes the further theoretical elaboration of these measurements, the selection of the potential sensors and measured quantity, the development of signal processors and transmitter devices, the central processing of the results and their broader exploitation – all under the umbrella, of applying Smart Grid Philosophy.

Acknowledgment

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