Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania

Transient based Single Phase to Ground Fault Distance Computation

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***Abstract*—The subject of this work is location of single phase to ground fault in medium voltage distribution network. The considered distribution network can be grounded or isolated and normally is in radial operation. The fault location is based on the fault generated low frequency transient signals of current and voltage of faulty phase measured in the supply substation. In the aim of calculating the fault distance, differential equation algorithm is applied to the fault charge transient.**

***Index Terms*—single phase to ground fault location, medium voltage distribution network, charge transients**

I. Introduction

FAULT location in distribution system based on measured values in supplying substation is applied on 10 kV or 20 kV networks and is more discussed in the last time. The majority of the former studies are concerned on the transmission network. The reason for it is greater impact on power system and large length of transmission lines. The development of power system and appearance of world market of electrical energy increases importance of fast fault location in distribution network too. The aim is to reduce time in which customers are without electrical energy. In the conditions of electrical energy market it can accomplish additional expenses. Also s lot of network is overground in medium voltage distribution system. Neutral point can be isolated, low-resistance grounded or compensated. The largest number of faults in distribution network is single phase to ground faults. The fault statistics show that single phase to ground fault is almost of 80 % of all types of faults in medium voltage distribution network. Particularly single phase to ground faults are often in mainly overground distribution network. The current of single phase to ground fault, especially if neutral point is isolated, is small and fault location is complicated. The aggravating circumstance during single phase to ground fault location is possibility of high value of fault resistance. Generally, distance to the fault in the case of other fault types can be easier calculated. In practice, two phase faults are more often than three phase faults. Furthermore, fault resistance during two phase fault without ground usually has smaller value than in the case of single phase to ground faults. Also, fault location methods based on fundamental components of currents and voltages and reactance estimation can obtain accurate results in the great number of phase two phase faults. During this work, for accurate single phase to ground fault location is examined transient based method. The charge transient component has a lower frequency and higher amplitude in compare to discharge component. Therefore, the charge transients are more applicable for the fault distance calculation.

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978-1-4244-2235-7/09/$25.00 ©2009 IEEE

II. Transient Based Method

The fault signal which can be used in the aim of fault location covers a wide frequency spectrum. Generally, it can be noted that transients with higher frequencies usually attenuate faster than transients with lower frequencies. During this examination, it is considered single phase to ground fault location based on fault generated transient signals in the case of isolated and low-resistance grounded distribution 10(20) kV network. The transients of currents and voltages are based on the charging of the network capacitances of the two healthy phases and the discharging of the faulted phase's capacitance. For instance, in the case of single phase to ground fault in isolated distribution system, the voltages of the two sound phases rapidly increase, what creates transients. Also, the charge stored in the earth capacitance of the faulty phase is removed during a fault and discharge transients are appeared. The discharging of the earth capacitance has frequencies determined by the speed of the traveling wave on the feeder. The fault generated traveling waves are reflected between the fault place and the supplying substation (x/10(20) kV). The example of the isolated distribution system is shown on the figure 1. The connected feeders in supplying substation without fault are presented by equivalent sum of parameters. The charge transient is of a higher amplitude and relatively low frequency and consequently more applicable for fault location. In the case of medium voltage distribution network, the charge transient frequencies are usually in the range of 100 – 800 Hz. The transient signals of currents and voltages for fault location are measured in the supplying substation. In the case of single phase to ground fault it is necessary to take over current and voltage of phase with fault. In general the possibility of fault location depends on amplitude of the transients generated during fault. The substantial influence to amplitude of fault transients has fault resistance. For certain distribution network it is needed to evaluate fault resistance limit for accurate transient detection and fault distance calculation. Also spectrum of fault transients can be affected by the type of neutral grounding of network but in finally this have no greater impact in accuracy of fault distance calculation.

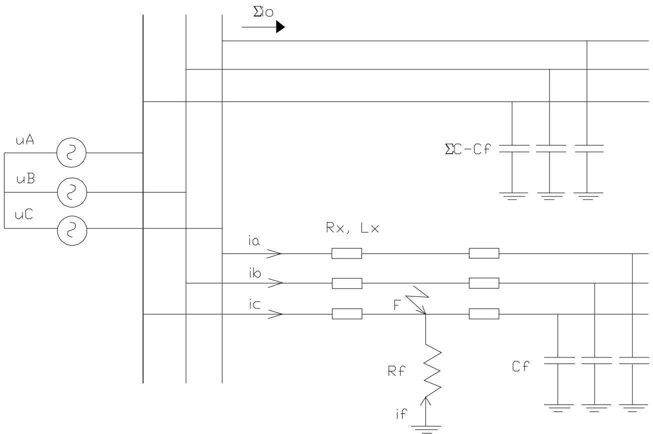


Fig. 1. Single phase to ground fault in distribution network. All feeders belong to supplying substation without faults are comprised in one.

A. Signal pre-processing and spectrum analysis

Basically the measured current and voltage signals contain fundamental, harmonic components and the transient components. In this way the current signal contains the following components:

- fundamental (50 Hz) component of the load current and its harmonics,
- fundamental (50 Hz) component of the fault current and its harmonics,
- charge transient component,
- discharge transient component,
- DC transients.

For extracted important frequencies of the current and voltage signal it can be used Discrete Fourier Transform (DFT). In that way, the spectrum of the non stationary fault signal can be calculated according to the following relation;

$$DFT[k] = \frac{2}{N} \sum_{n=1}^{N/2} f[n] \cdot e^{-j\frac{2\pi kn}{N}} \tag{1}$$

where: $f[n]$ is a discrete function of the samples, k and n are integer variables and N is number of samples. The spectrums of the fault signals contain numerous component but charge and discharge components need to be easily identified. In the aim of fault current spectrum examination and with regard to operation speed of distribution protection, it was used time period of 100 ms (from the instance of fault occurrence). After identification of important frequencies (or frequency band) it is necessary to obtain appropriate filtering of fault current and voltage. Removing of the 50 Hz component can be done by filtering as;

$$y[n] = f[n] - f[n + N_{50}] \tag{2}$$

Where: $y[n]$ is output of the filter, $f[n]$ is measured and sampled signal and N_{50} is number of samples in one period of signal with fundamental frequency. In the next filtering it was used frequency band from 100 Hz to 800 Hz. For the component with the highest amplitude in this frequency band is assumed that correspond to charge transient component.

III. Estimation of the Fault Distance by the Differential Equation Algorithm

In this work, the principle of fault location in distribution network is based on the estimation of the fault path inductance using the charge transients. The fault path inductance is calculated using differential equation algorithm which solves the line inductance directly in the time domain. It is consider concentrated model of distribution section as shown on the figure 1.

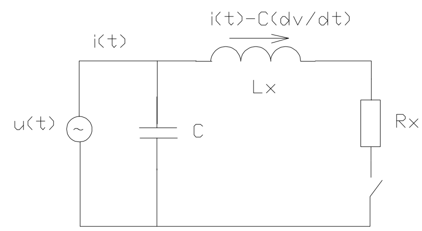


Fig. 2; Single phase model of distribution sections with shunt capacitances

A. R-L model of distribution sections

In the case of first order model, which includes only the series connection of the line resistance *R* and inductance *L* (in this approach shunt capacitances are neglected), the voltage and current of the faulty phase, seen by the protection relay, satisfy the following relation;

$$u(t) = R_x \cdot i(t) + L_x \frac{di(t)}{dt} \tag{3}$$

where; u and i are the measured voltage and current of the transient in the faulty phase, R_x and L_x are the resistance and inductance of the faulty path and t is time. By using numerical integration in two consecutive intervals and applying trapezoidal rules it follows;

$$\int_{t_0}^{t_1} u(t)dt = R_x \int_{t_0}^{t_1} i(t)dt + L_x [i(t_1) - i(t_0)] \tag{4}$$

$$\int_{t_1}^{t_2} u(t)dt = R_x \int_{t_1}^{t_2} i(t)dt + L_x [i(t_2) - i(t_1)] \tag{5}$$

$$\int_{t_0}^{t_1} u(t)dt = \frac{\Delta t}{2} [u(t_1) - u(t_0)] = \frac{\Delta t}{2} (u_1 - u_2) \tag{6}$$

For samples *k*, *k*+1 and *k*+2, the above equations can be written as;

$$\begin{bmatrix} \frac{\Delta t}{2}\left(i_{k+1}+i_k\right) & \left(i_{k+1}-i_k\right) \\ \frac{\Delta t}{2}\left(i_{k+2}+i_{k+1}\right) & \left(i_{k+2}-i_{k+1}\right) \end{bmatrix} \cdot \begin{bmatrix} R_x \\ L_x \end{bmatrix} = \begin{bmatrix} \frac{\Delta t}{2}\left(u_{k+1}+u_k\right) \\ \frac{\Delta t}{2}\left(u_{k+2}+u_{k+1}\right) \end{bmatrix} \tag{7}$$

For three equally spaced samples of voltage and current, from the above equation, it can be calculated the fault path inductance L_x. The fault path inductance L_x is proportional to the fault distance according to the following equation;

$$L_x = \frac{1}{3}\left(L_1' + L_2' + L_0'\right)\cdot x \tag{8}$$

where: x is the fault distance, L_1', L_2' and L_0' are the positive, negative and zero sequence inductances of the line per km at the frequency concerned. The previous relation is a result of series connection of circuits of symmetrical components in the case of single phase to ground fault (fig. 3). On the fig. 3, the next marks were used; M and F are measurement and fault point, respectively; Z_f is the fault impedance, Z_g is the ground impedances, Z_{0x}, Z_{1x} and Z_{2x} are faulty path impedances of zero, positive and negative sequences (composed by parameters R_x and L_x).

In the case of real distribution network, the values of L_1', L_2' and L_0' usually are not explicitly known. Actual distribution network is almost always connected from numerous sections with different electrical parameters. In the case of branchy and complex distribution network simply calculating distance from supplying substation to the fault place can not be preferred choice. Usually it is needed to convert the calculated L_x to corresponding reactance value and after that make comparison with results of fault calculations of all nodes of considered feeder. Thereby the fault place can be determined according to the names of the network model or distance from the specified places or objects close to the faulted region.

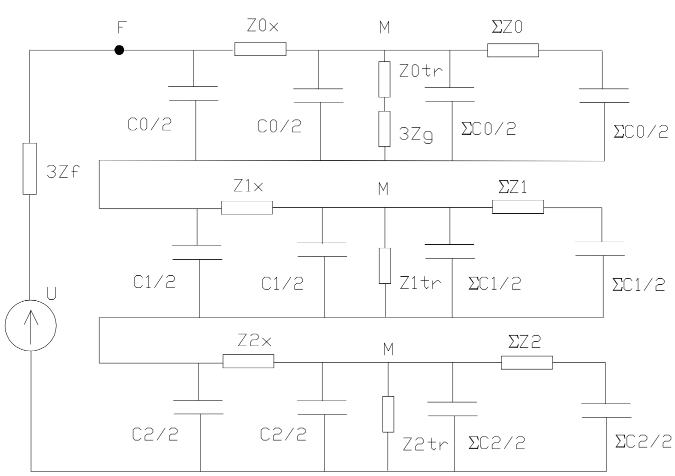


Fig. 3 – Equivalent circuit of symmetrical component in the case of single phase to ground fault.

B. A possible improvement in fault distance calculation

In the aim of improving above access in solving fault location, here is considered second order line model where the earth capacitances are also included. In this case, the next differential equation is valid;

$$v(t) = R_x i(t) + L_x \frac{di(t)}{dt} - R_x C \frac{dv(t)}{dt} - L_x C \frac{d^2 v(t)}{dt^2} \tag{9}$$

As in previous case, the integration of this equation can be done. In that way the next matrix equation is obtained;

$$\begin{bmatrix} I_{11} & V_{12} \\ I_{21} & V_{22} \end{bmatrix} \cdot \begin{bmatrix} X \\ CX \end{bmatrix} = \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} \tag{10}$$

where;

$$I_{11} = \begin{bmatrix} \frac{\Delta t}{2}\left(i_{k+1}+i_k\right) & \left(i_{k+1}-i_k\right) \\ \frac{\Delta t}{2}\left(i_{k+2}+i_{k+1}\right) & \left(i_{k+2}-i_{k+1}\right) \end{bmatrix}$$

$$I_{21} = \begin{bmatrix} \frac{\Delta t}{2}\left(i_{k+3}+i_{k+2}\right) & \left(i_{k+3}-i_{k+2}\right) \\ \frac{\Delta t}{2}\left(i_{k+4}+i_{k+3}\right) & \left(i_{k+4}-i_{k+3}\right) \end{bmatrix}$$

$$V_{12} = \begin{bmatrix} -\left(v_{k+1}-v_k\right) & -\frac{1}{\Delta t}\left(v_{k+1}-2v_k+v_{k-1}\right) \\ -\left(v_{k+2}-v_{k+1}\right) & -\frac{1}{\Delta t}\left(v_{k+2}-2v_{k+1}+v_k\right) \end{bmatrix}$$

$$V_{22} = \begin{bmatrix} -\left(v_{k+3}-v_{k+2}\right) & -\frac{1}{\Delta t}\left(v_{k+3}-2v_{k+2}+v_{k+1}\right) \\ -\left(v_{k+4}-v_{k+3}\right) & -\frac{1}{\Delta t}\left(v_{k+4}-2v_{k+3}+v_{k+2}\right) \end{bmatrix}$$

$$X = \begin{bmatrix} R_x \\ L_x \end{bmatrix}, V_1 = \begin{bmatrix} \frac{\Delta t}{2}\left(v_{k+1}+v_k\right) \\ \frac{\Delta t}{2}\left(v_{k+2}+v_{k+1}\right) \end{bmatrix}, V_2 = \begin{bmatrix} \frac{\Delta t}{2}\left(v_{k+3}+v_{k+2}\right) \\ \frac{\Delta t}{2}\left(v_{k+4}+v_{k+3}\right) \end{bmatrix}$$

In this case it is needed to take five subsequent samples of current and voltage. The estimation of the value of inductance and resistance to the fault place can be done by the next equation;

$$\begin{bmatrix} R_x \\ L_x \end{bmatrix} = \left(I_{11} - V_{12}V_{22}^{-1}I_{21}\right)^{-1}\left(V_1 - V_{12}V_{22}^{-1}V_2\right) \tag{11}$$

IV. VERIFICATION

Transient simulations, for distribution system shown on the figure 4, were carried out by using MATLAB PSB. At first, the sampling frequency was 100 kHz (sampling time = 10^{-5} s). It was used pi-section representation of distribution sections. The instance of the fault occurrence was 0.05 s. Spectral analysis was done by using DFT. The maximum amplitude of components in frequency spectrum was at the frequencies about 100 Hz. It was examined single phase to ground fault at the distance of 15 km from supplying substation. The fault resistance was 50 ohms. It was observed isolated and low reactance distribution network. The concerned low-reactance distribution network is grounded with resistance of 20 ohm and limitation of single phase fault current on the value of 300 A.

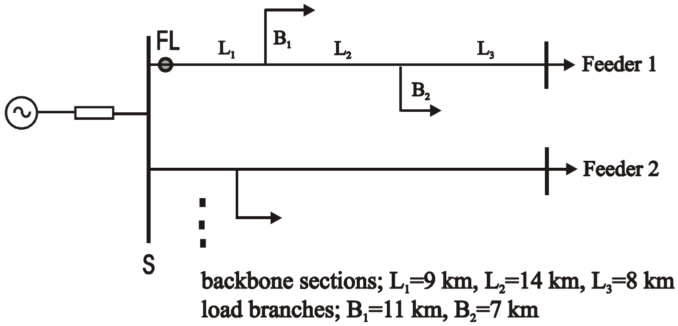
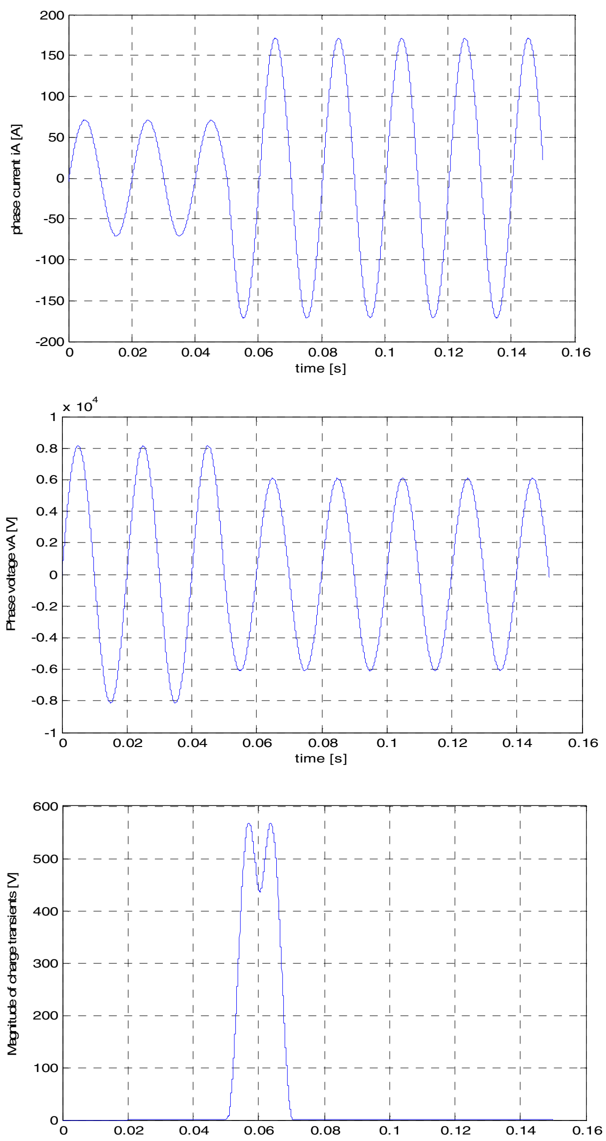


Fig. 4 - Example of the studied distribution system

On the fig. 5, current and voltage during 100 ms after the fault instance in low-reactance grounded network are presented. The diagram of transient magnitudes and fault distance (fig. 5) shows that charge transient lasts about 20 ms after the fault occurence.



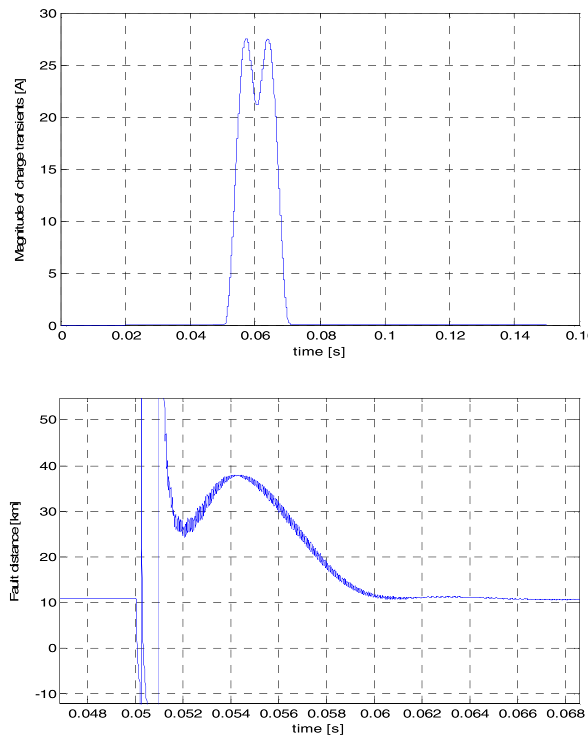
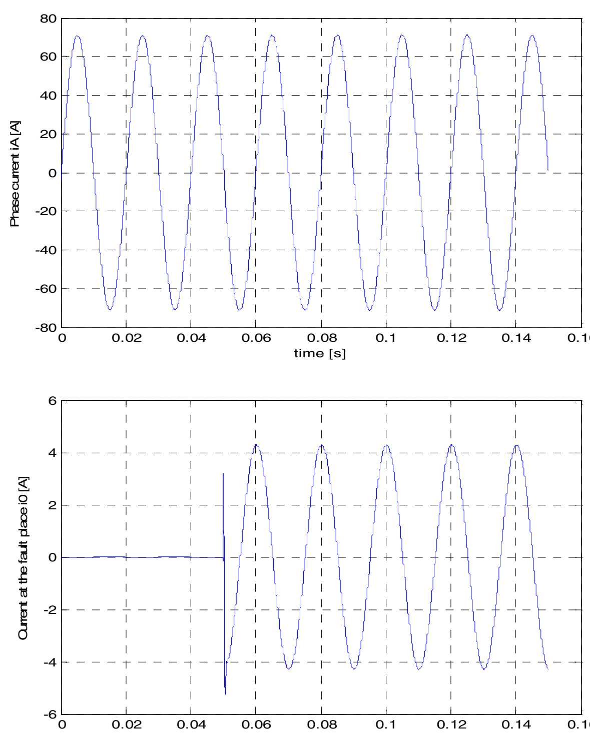


Fig. 5 – Diagrams of faulty current and voltage, charge transient magnitudes and fault distance during single phase to ground fault in low-reactance network

On the figure 6, faulty current and voltage and current at the fault place in isolated network are presented. The duration of charge transient is almost same as in low-resistance grounded network (fig 6). The fault distance has convergence to value of 14.46 km (fig. 6).



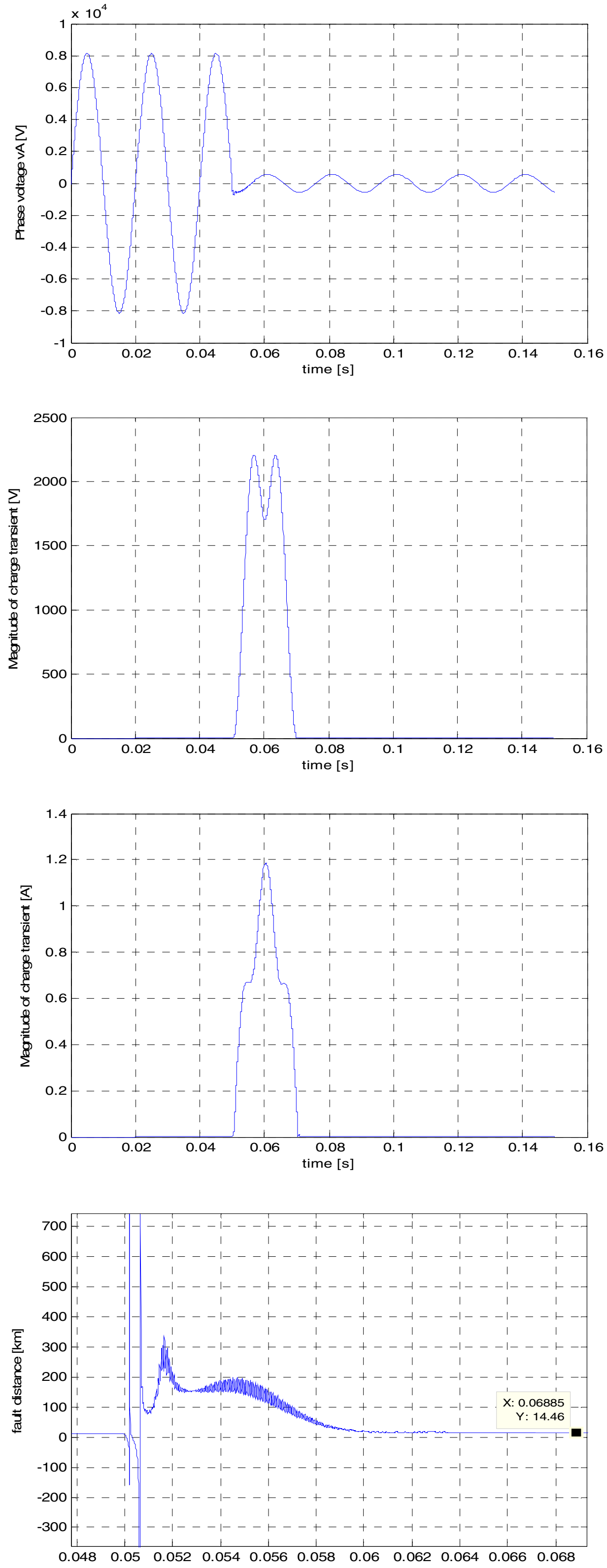


Fig. 6 – Diagrams of faulty current and voltage, charge transient magnitudes and fault distance during single phase to ground fault in isolated distribution network

It can be seen that charge transients disappeared quite fast. The duration of charge transient for considered distribution network was about 20 ms. It is valid for isolated and low-reactance grounded network. The maximal value of fault resistance for acceptable accuracy was about 100 ohms. The sampling frequency in the case of transient based methods can be lower the used frequency of 100 kHz. The examination is shown that enough accurate results can be obtained for sampling frequency in the range of a few kHz. Also, during this examination it was made attempt of using discrete wavelet transform in the aim of filtering charge transients. But no one checked type of wavelets that provided discrete wavelet transform (available in MATLAB Wavelet Toolbox) didn't obtain convergence in fault location process.

V. CONCLUSION

The fault path inductance is calculated from the transient components of the voltage and currents in the time domain. It can be concluded that fault location based on charge transient is acceptable in isolated as so as low-reactance distribution network. For obtaining more accurate result it is needed to examine more suitable identifying and filtering charge transients for considered distribution network. The advantage of transient based method is that the sampling frequency needed for fault location can be considerably lower than in the traveling wave methods. The problem in real distribution network can be multiple fault locations and reliable identification the fault place from the calculated inductance.

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VII. BIOGRAPHIES

Šeila Gruhonjić Ferhatbegović (M'2003.) was born in 1969. in Bijeljina, Bosnia and Herzegovina. She received the B.Sc. and M.Sc. degrees from the Faculty of Electrical Engineering, University of Tuzla, in 1994 and 2001, respectively. She is working toward Ph.D. degree at the Faculty of Electrical Engineering and Computing, University of Zagreb. She is interested in power system protection.

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