Precise Impedance Based Fault Location Algorithm with Fault Resistance Separation

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***Abstract*— The reactance method with fault resistance separation has been developed in order to determine as precisely as possible the impedance of a fault loop in a transmission or distribution power system line. This method has commonly been used for impedance calculation in case of a single phase-to-earth fault in diverse power system protection applications. New developments in this area have shown that the extension of the method to multi-phase faults is not only possible but also of practical relevance. However, all previous investigations focused on impedance calculation using data from one single side of the power system line. Due to missing data from the remote end, the determined impedance value can deviate from its real value. This research consists in an improvement of this calculation method using data from both the own and the remote line end. This approach uses communication between two measurement units e.g. protection relays, which have the advantage of not requiring a precise synchronization with each other. The additional time invariant parameters of the power system, acquired by each device and transferred to the remote end, allow an exact computation of the fault reactance and fault resistance. In this paper, the derivation of this novel approach as well as experimental results in a fault location application are presented.**

***Index Terms*—Fault Location, Impedance Measurement, Power System Protection, Transmission / Distribution Line**

I. Introduction

Fault location algorithms give an estimation of the distance between the point of measurement at the device (mostly protective relay) and the point of a short circuit (fault) in a transmission or distribution line. The maintenance effort of the line after an already cleared temporary fault and the recovery time of the line after a permanent fault both depend on the accuracy of the fault location. As a result, the fault location function contributes indirectly to an improvement in quality and availability of electrical energy. Accuracy of the fault location depends on the chosen algorithm and hypothesis for the calculation itself, as well as on the complexity of the power system and on fault conditions.

This paper focuses on the double-ended impedance based fault location algorithm, which is derived from the reactance method with fault resistance separation [1]. The adapted algorithm for a double side supplied network is presented for each fault type. The influence of different factors such as load flow, fault resistance and system non-homogeneity are considered. Moreover, it is shown in this paper that the reactance based impedance calculation method allows a precise calculation of the fault location when the appropriate data from the remote side is supplied.

II. Background of the Method

A. Main Equations of the Reactance Method

The fault location method described in this paper is based on the computation of the faulty loop's reactance, which is linearly proportional to the distance to the fault.

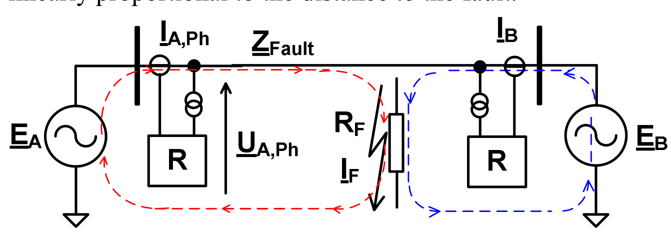

Figure 1. Fault with transition resistance in a double side supplied line

A faulty doubly in-fed line is first considered in the form of a single-phase system (Fig. 1). For the short circuit, a purely resistive fault is adopted. If the faulty loop includes a fault resistance R_F, it is not possible to calculate the exact reactance value using only the measurements from one side A or B. Indeed, the unknown fault current $\underline{I}_F$ is necessary for the calculation. Applying Kirchhoff's Voltage Law (KVL) to the system from the point of view of side A results in (1), which is the base to extract the fault reactance and resistance:

$$\underline{U}_{A,Ph} = \underline{Z}_{Fault} \cdot \underline{I}_{A,Ph} + R_F \cdot \underline{I}_F \quad (1)$$

In order to eliminate from (1) the unknown voltage drop on the transition resistance, which depends on the fault current, the so called load decoupled compensation quantity $\underline{I}_{A,Cmp}$ and compensation factor $\underline{\delta}_{A,B}$ are introduced. $\underline{I}_{A,Cmp}$ corresponds to the fault current as it is seen from side A, and $\underline{\delta}_{A,B}$ is an extension factor for the double in-fed line. The factor $\underline{\delta}_{A,B}$ corresponds to the phase shift due to the consideration of the remote end and is therefore the most influent term of the compensation. The product of these two quantities gives an estimation of the fault current $\underline{I}_F$. Therefore, it is considered that this term has the same electric phase angle and magnitude as the fault current $\underline{I}_F$. Equation (1) is multiplied by the conjugate of these combined quantities. The term reflecting the resistive voltage drop in (1) becomes a pure real number and can be eliminated by considering only the imaginary part.

$$\begin{aligned}&\mathrm{Im}[\underline{U}_{A,Ph}\cdot\underline{I}^{*}_{A,Cmp}\cdot\underline{\delta}^{*}_{A,B}]=\\&\mathrm{Im}[\underline{Z}_{Fault}\cdot\underline{I}_{A,Ph}\cdot\underline{I}^{*}_{A,Cmp}\cdot\underline{\delta}^{*}_{A,B}]\end{aligned}\tag{2}$$

Introducing the line's angle φ and thereby isolating the reactance X_{Fault} from the fault impedance $\underline{Z}_{fault}$, equation (3) is obtained. This result is proportional to the fault location.

$$X_{Fault}=\frac{\sin\varphi\cdot\mathrm{Im}[\underline{U}_{A,Ph}\cdot\underline{I}^{*}_{A,Cmp}\cdot\underline{\delta}^{*}_{A,B}]}{\mathrm{Im}[e^{j\varphi}\cdot\underline{I}_{A,Ph}\cdot\underline{I}^{*}_{A,Cmp}\cdot\underline{\delta}^{*}_{A,B}]}\tag{3}$$

The compensation quantity and extension factor can further be used to determine the fault's resistance R_F. Replacing the fault current by the product of these two quantities in (1), and multiplying by the conjugated product of the fault impedance and phase current $\underline{Z}_{Fault}^{*}\,\underline{I}_{A,Ph}^{*}$, the voltage drop on the fault impedance can be eliminated and the fault resistance can be extracted:

$$R_F=\frac{\mathrm{Im}[\underline{U}_{A,Ph}\cdot e^{-j\varphi}\cdot\underline{I}^{*}_{A,Ph}]}{\mathrm{Im}[\underline{I}_{A,Cmp}\cdot\underline{\delta}_{A,B}\cdot e^{-j\varphi}\cdot\underline{I}^{*}_{A,Ph}]}\tag{4}$$

B. *Application to each fault type*

Each fault type in the symmetrical electrical power system can be described with symmetrical components. The zero-, negative- and delta-positive- sequence components are independent from the load flow. This property is used to introduce compensation quantities and thereby to eliminate the voltage drop on the fault resistance in order to achieve a precise reactance value. The previously introduced extension factor is calculated based on the symmetrical components equivalent circuit as well.

The phase voltage $\underline{U}_{A,Ph}$ and phase current $\underline{I}_{A,Ph}$ respectively represent the voltage and current in the considered single-phase fault loop. In the case of a phase-to-earth fault, the earth compensation factor $\underline{k}_0$ is introduced, similarly to the conventional fault location algorithm, to take into account the earth return path, as shown in (5)-(6).

$$X_{Fault}=\frac{\sin\varphi\cdot\mathrm{Im}[\underline{U}_{A,Ph-E}\cdot\underline{I}^{*}_{A,Cmp}\cdot\underline{\delta}^{*}_{A,B}]}{\mathrm{Im}[e^{j\varphi}\cdot(\underline{I}_{A,Ph}-\underline{k}_0\underline{I}_{A,E})\cdot\underline{I}^{*}_{A,Cmp}\cdot\underline{\delta}^{*}_{A,B}]}\tag{5}$$

$$R_F=\frac{\mathrm{Im}[\underline{U}_{A,Ph}\cdot e^{-j\varphi}\cdot(\underline{I}_{A,Ph}-\underline{k}_0\underline{I}_{A,E})^{*}]}{\mathrm{Im}[\underline{I}_{A,Cmp}\cdot\underline{\delta}_{A,B}\cdot e^{-j\varphi}\cdot\underline{I}^{*}_{A,Ph}]}\tag{6}$$

In Fig. 2, the single phase to earth fault in symmetrical components is represented. It can be concluded that the fault current $\underline{I}_F$ can be reflected by positive, negative or zero sequence current. Since the negative and zero sequence currents are independent from the load flow, both these components can be used as compensation quantities. In order to estimate the fault current $\underline{I}_F$ using the sequence current measured on one network side, appropriate compensation factors must be introduced.

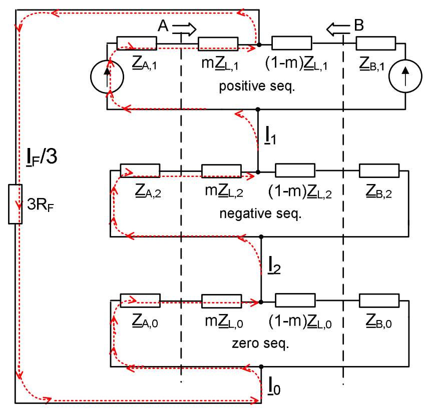

Figure 2. Single phase-to-earth fault with fault resistance (representation in symmetrical components – double side supplied line)

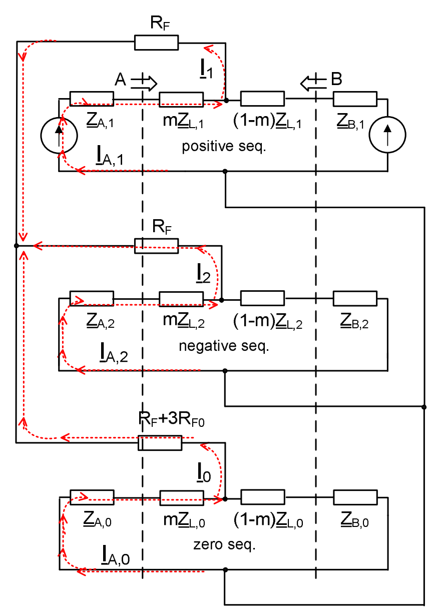

Figure 3. Phase-phase-to-earth fault with fault resistance (representation in symmetrical components)

This compensation factor can be derived from the system impedances. Applying the KVL for the zero sequence circuit, the following expression can be obtained:

$$\left[\underline{Z}_{A,0}+m\cdot\underline{Z}_{L,0}\right]\cdot\underline{I}_{A,0}=\left[(1-m)\cdot\underline{Z}_{L,0}+\underline{Z}_{B,0}\right]\cdot\underline{I}_{B,0} \tag{7}$$

From the sequence equivalent circuit one can conclude:

$$\underline{I}_F=3\cdot(\underline{I}_{A,0}+\underline{I}_{B,0}) \tag{8}$$

Describing the unknown current $\underline{I}_{B,0}$ of the opposite side with the measured current $\underline{I}_{A,0}$ of the own side (7) and substituting it into (8), the following expression can be written:

$$\underline{I}_F=3\underline{I}_{A,0}\cdot\left(\frac{\underline{Z}_{A,0}+m\cdot\underline{Z}_{L,0}}{(1-m)\cdot\underline{Z}_{L,0}+\underline{Z}_{B,0}}+1\right) \tag{9}$$

$$\underline{I}_F=\underline{I}_{A,Cmp}\,\underline{\delta}_{A,B}$$

As a result, the compensation factor $\underline{\delta}_{A,B}$ and compensation current $\underline{I}_{A,Cmp}=3\underline{I}_{A,0}$ can be identified. An analogue consideration can be carried out for the negative and delta-positive components.

For phase-to-phase faults, the voltage and current to take into account consist in the voltage (respectively current) difference between the two concerned phases. This method can be generalized for phase-to-phase faults with earth. The corresponding reactance and resistance are given in (10) and (11).

$$X_{Fault}=\frac{\sin\varphi\cdot\mathrm{Im}[\underline{U}_{A,Ph1-Ph2}\cdot\underline{I}^*_{A,Cmp}\cdot\underline{\delta}^*_{A,B}]}{\mathrm{Im}[e^{j\varphi}\cdot\underline{I}_{A,Ph1-Ph2}\cdot\underline{I}^*_{A,Cmp}\cdot\underline{\delta}^*_{A,B}]} \tag{10}$$

$$R_F=\frac{\mathrm{Im}[\underline{U}_{A,Ph1-Ph2}\cdot e^{-j\varphi}\cdot\underline{I}^*_{A,Ph1-Ph2}]}{\mathrm{Im}[\underline{I}_{A,Cmp}\cdot\underline{\delta}_{A,B}\cdot e^{-j\varphi}\cdot\underline{I}^*_{A,Ph1-Ph2}]} \tag{11}$$

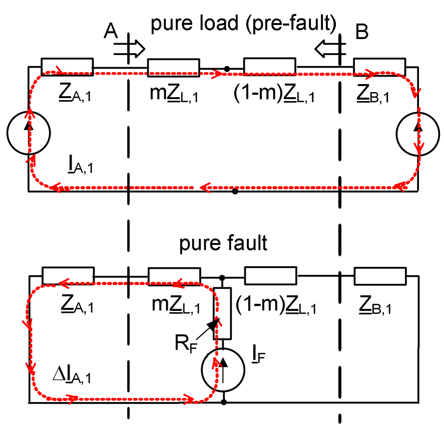

Figure 4. Three phase fault with symmetrical fault resistance (superposition principle)

Fig. 3 presents the phase-to-phase fault with earth in symmetrical components. It is assumed that the fault resistance between phases $2R_F$ is split symmetrical by the earth fault resistance R_{F0}. Expressing the fault current as the difference between both phase currents flowing into the fault, the following generalization can be made:

$$\underline{I}_{F,Ph1}-\underline{I}_{F,Ph2}=\underline{I}_F=\left[\underline{I}_{A,Cmp,2}\quad -\underline{I}_{A,Cmp,0}\right]\cdot\begin{bmatrix}\underline{\delta}_{A,B,2}\\ \underline{\delta}_{A,B,0}\end{bmatrix} \tag{12}$$

Since in case of a phase-to-phase fault, the zero sequence current is zero, the formulation from (12) is still valid.

For three phase faults, the positive sequence current and voltage are used:

$$X_{Fault}=\frac{\sin\varphi\cdot\mathrm{Im}[\underline{U}_{A,1}\cdot\underline{I}^*_{A,Cmp}\cdot\underline{\delta}^*_{A,B}]}{\mathrm{Im}[e^{j\varphi}\cdot\underline{I}_{A,1}\cdot\underline{I}^*_{A,Cmp}\cdot\underline{\delta}^*_{A,B}]} \tag{13}$$

$$R_F=\frac{\mathrm{Im}[\underline{U}_{A,1}\cdot e^{-j\varphi}\cdot\underline{I}^*_{A,1}]}{\mathrm{Im}[\underline{I}_{A,Cmp}\cdot\underline{\delta}_{A,B}\cdot e^{-j\varphi}\cdot\underline{I}^*_{A,1}]} \tag{14}$$

For the calculation of the compensation factor, the approach with superimposed components must be used (Fig. 4). The compensation quantity is the difference between the current in pre-fault and fault condition, in positive sequence. This current will further be called delta current. It is also assumed that the fault is symmetrical, with a resistance R_F between each phase and the star point.

C. *Calculation of the Compensation Quantity*

Fault Type	Compensation current and extension factor
Phase to earth	$\underline{\delta}_{A,B}=\left(\frac{\underline{Z}_{A,0}+m\cdot\underline{Z}_{L,0}}{(1-m)\cdot\underline{Z}_{L,0}+\underline{Z}_{B,0}}+1\right);\ \underline{I}_{A,Cmp}=3\cdot\underline{I}_{A,0}$ or $\underline{\delta}_{A,B}=\left(\frac{\underline{Z}_{A,2}+m\cdot\underline{Z}_{L,2}}{(1-m)\cdot\underline{Z}_{L,2}+\underline{Z}_{B,2}}+1\right);\ \underline{I}_{A,Cmp}=3\cdot\underline{I}_{A,2}$ (15)
Phase to Phase without earth	$\underline{\delta}_{A,B}=\left(\frac{\underline{Z}_{A,2}+m\cdot\underline{Z}_{L,2}}{(1-m)\cdot\underline{Z}_{L,2}+\underline{Z}_{B,2}}+1\right);\ \underline{I}_{A,Cmp}=2\cdot\underline{I}_{A,2}\cdot\left(\underline{a}-\underline{a}^2\right)$ (16)
Phase to Phase with earth	$\underline{\delta}_{A,B,2}=\left(\frac{\underline{Z}_{A,2}+m\cdot\underline{Z}_{L,2}}{(1-m)\cdot\underline{Z}_{L,2}+\underline{Z}_{B,2}}+1\right);\ \underline{I}_{A,Cmp,2}=2\cdot\underline{I}_{A,2}\cdot\left(\underline{a}-\underline{a}^2\right)$ $\underline{\delta}_{A,B,0}=\left(\frac{\underline{Z}_{A,0}+m\cdot\underline{Z}_{L,0}}{(1-m)\cdot\underline{Z}_{L,0}+\underline{Z}_{B,0}}+1\right);\ \underline{I}_{A,Cmp,2}=\underline{I}_{A,0}\cdot\left(\underline{a}-\underline{a}^2\right)$ (17)
Three Phase	$\underline{\delta}_{A,B}=\left(\frac{\Delta\underline{Z}_{A,1}+m\cdot\underline{Z}_{L,1}}{(1-m)\cdot\underline{Z}_{L,1}+\underline{Z}_{B,1}}+1\right);\ \underline{I}_{A,Cmp}=\Delta\underline{I}_{A,1}$ (18)

TABLE I. Equivalent fault current for each fault type

The compensation term can be summarized as an equivalent of the fault current, which is given for each fault type in Table I. Depending on the type of fault and implicated phases, the quantity and compensation factor can be determined using the adapted symmetrical components. The following notations are used in Table I: $\underline{Z}_{A,2}$ is the negative sequence, $\underline{Z}_{A,0}$ the zero sequence and $\Delta Z_{A,1}$ the delta-positive sequence impedance of source A. The impedances of the remote end are noted with the index B. $\underline{Z}_{L,2}$, $\underline{Z}_{L,0}$ and $\underline{Z}_{L,1}$ denote the line impedance for negative, zero and positive sequence respectively. $\underline{a}$ is the well known 120° shift factor used in three phase systems. Moreover, the introduced compensation quantities in Table I. are valid for the following fault types: AG, BC, BCG, ABC, ABCG – as reference, the phase A was chosen. For the other fault types, an appropriate phase shift or change of the phase reference is necessary.

The line data used in the computation of the compensation factors is available in the relay device. However, the source impedances are not parameterized in common protection devices. These network parameters can be computed using the measurements made by the protection relays during the fault transient. Considering the equivalent circuits in symmetrical components, it can be concluded that based on the measured voltages and currents, in case of the fault on the line, the real source impedance can be simply calculated:

$$\underline{Z}_{A,0} = -\frac{\underline{U}_{A,0}}{\underline{I}_{A,0}}, \underline{Z}_{A,2} = -\frac{\underline{U}_{A,2}}{\underline{I}_{A,2}}, \quad \underline{Z}_{A,1} = -\frac{\Delta \underline{U}_{A,1}}{\Delta \underline{I}_{A,1}} \tag{19}$$

This method can also be used in meshed networks, however in that case, the calculated impedances do not reflect the real source impedances. As a proof, the power system from Fig. 5a can be used. Each meshed system can be replaced by the system given in Fig. 5a, so that this network can be considered as an equivalent for any meshed power system. Taking this network into account in a symmetrical or superimposed component representation, each sequence network can be considered separately like shown in Fig 5b. As presented in Fig. 2-5 the connection type of the sequence network depends on the fault type only. The meshed system can be reduced to the system from Fig. 5c. with two busbars using the commonly known wye-delta transform. During the reduction process, a fictive parallel line without mutual coupling appears between busbar A and B. In order to prove that this parallel line does not impact the calculation procedure for the compensation factors and compensation quantities, the wye-delta transform can be used. It can be noted that the calculated impedances applied to compute the compensation factors depend on the fault location. This does not limit the approach presented in this paper. However, using the estimated source impedances presumes that the fault occurs on the line between busbars A and B.

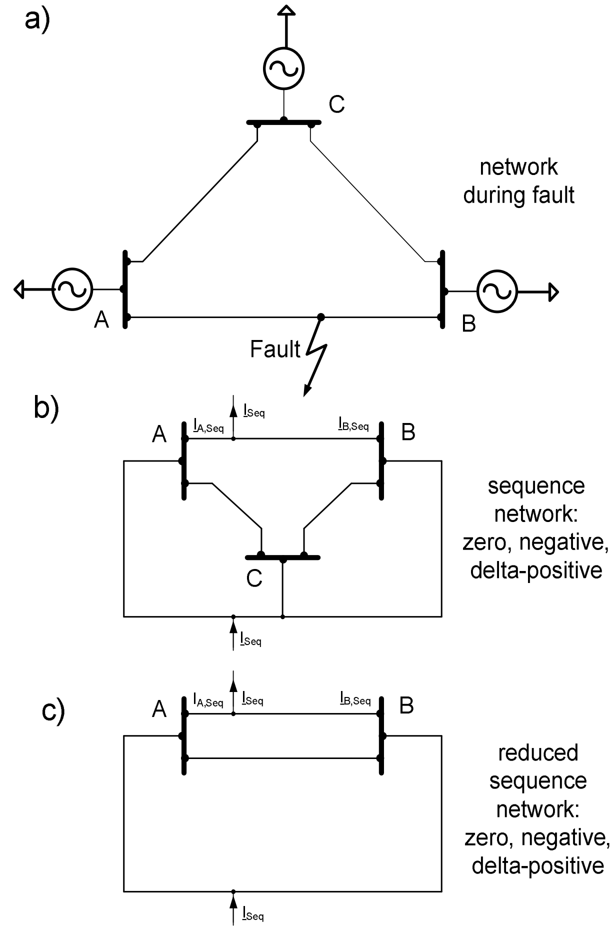

Figure 5. Meshed power system with fault on the line between busbars A and B a) network during fault; b) sequence network; c) reduced sequence network

D. Accuracy Improvement

The compensation quantity introduced in section *A-C* corresponds to the fault current seen from side A and is deduced from the measured values on this side ($\underline{Z}_{A,0}$, $\Delta\underline{Z}_{A,1}$ or $\underline{Z}_{A,2}$). However, the compensation factor depends on the network homogeneity degree as well as on the fault location *m*. Therefore, the equations in Table I require an equivalent of source impedance from side *B* in symmetrical components ($\underline{Z}_{B,0}$, $\Delta\underline{Z}_{B,1}$ or $\underline{Z}_{B,2}$), and the fault location *m*. The impedance parameters are a priori unknown because they depend on the short circuit power of the remote side and on the network configuration, which are not available to the relay. However, they can easily be obtained by implementing data exchange between both devices. This data exchange procedure offers several advantages:

- It makes network states available to each relay in order to calculate the fault current.
- It only requires the exchange of a limited number of parameters.
- It does not require synchronization of the exchanged data, as opposed to other two-side based algorithms.

Data exchange makes it possible to determine the system's state. Moreover, the parameter m (fault location) can be calculated using an iterative procedure. Equation (5) is divided by the reactance per unit length x', which is a constant parameter of the line, in order to obtain the fault location. Introducing Gauss' method, (20) is obtained:

$$m_{n+1} = \frac{\sin\varphi \cdot \mathrm{Im}[\underline{U}_{A,Ph} \cdot \underline{I}^{*}_{A,Cmp} \cdot \underline{\delta}^{*}_{A,B}(m_n)]}{x' \cdot \mathrm{Im}[e^{j\varphi} \cdot \underline{I}_{A,Ph} \cdot \underline{I}^{*}_{A,Cmp} \cdot \underline{\delta}^{*}_{A,B}(m_n)]}, \qquad (20)$$
$$m = m_{n+1} \quad if \quad |m_{n+1} - m_n| < \varepsilon$$

where ε is a condition for the last iteration step. With this condition, if iterations do not contribute to any improvement of the result, the fault location m is adopted. Considering the (20), it can be noted that after some reformulations, a quadratic form for almost all fault types can be derived as well. An analytic equation of the third order only appears in the case of a phase-to-phase fault with earth. The analytical solution of such an equation is much more complex than the iterative approach. As a result, the iteration approach was chosen as general solution for the implementation of each fault type. After a successful estimation of the fault location, the fault resistance as minor product is computed.

III. EXPERIMENTAL RESULTS

After implementing the algorithm in protection devices, tests were performed for different network structures and fault types represented by simulation models. The parameters used for the network model are typical for high voltage overhead lines. The test environment, shown in Fig. 6, is made of two test devices to which three phase currents and voltages are provided by current and voltage amplifiers. A communication interface without synchronisation was implemented between the two devices, enabling the data exchange. The fault locator function was triggered after the pick up of the protection function, for which distance protection was used.

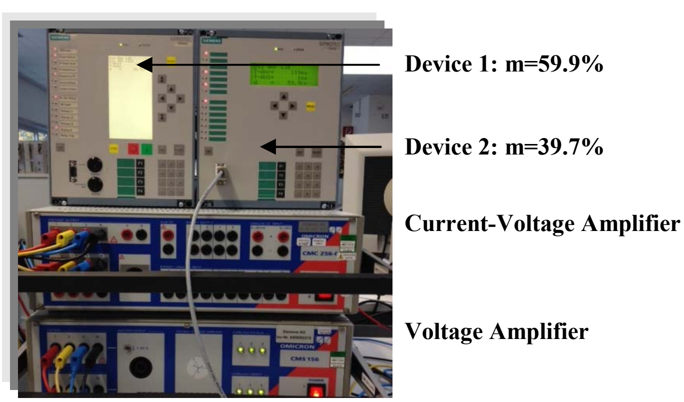

Figure 6. Test environment

The behavior of the fault locator algorithm for various fault locations has been tested for each fault type. As an example, the calculated fault location for a phase-to-earth, phase-to-phase (without and with earth) and a three-phase fault are plotted in Fig. 7 for locations every 5% of the fault line. The fault resistance is equal to 5Ω. The representation focuses on several points, which present the greatest observed deviance. As shown in Fig. 7, the maximum error attained is of 0.8%, although the simulated system contains significant load flow (different short circuit power and phase shift between both voltage sources from Fig. 1) and inhomogeneous network.

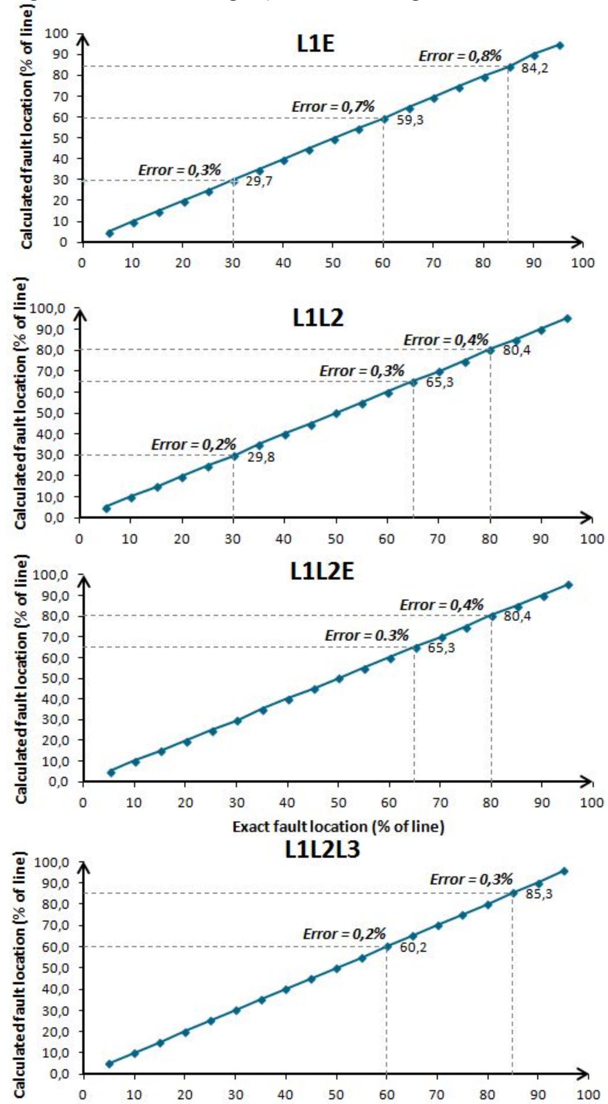

Figure 7. Calculated fault location determined with protection devices as a function of the exact fault location for each fault type L1E, L1L2, L1L2E and L1L2L3 respectively

The implemented algorithm shows very satisfying results, as it calculates precise values not only for the fault location but also for the fault resistance. The tests have been performed for various fault resistance values ranging from 1Ω to 100Ω, giving similar results as the ones presented in Fig. 7. The results showed no influence of the fault resistance on the fault location as opposed to the conventional impedance method.

Moreover, tests with meshed networks also provided accurate results for faults located on the line between the two bus bars, as the impedances calculated with the measurements from the protection relays gave an equivalent of the meshed network.

Adding a delay between the calculations of both protection relays also had no influence, as long as the data could be exchanged. This data exchange takes place as long as the fault location algorithm is in use in both devices simultaneously. If no data is recieved after a given time (which can be set as a parameter), the fault location can still take place, but without using the data of the remote end.

In case of the absence of communication between the two protection devices, different assumptions can be adopted: the compensation factors can be assumed to be equal to 1, or the source impedance of the remote side can be assumed to be the same as the one of the own side. However, without data exchange, any assumption made could be false, and lead to deviation from the correct value of the fault location. This would lead the fault locator back to a single sided fault location algorithm, with a precision depending on whether the assumption corresponds to the state of the system. In that case, a notification on whether the data exchange took place or not should be made, in order to inform the user on the reliability of the result.

IV. SUMMARY

This paper focuses on the explanation of the method and its theoretical background. It has been shown that the developed algorithm efficiently calculates the faulty loop's impedance in fault location applications. Successful experimental results were obtained, also when considering typical influent factors such as load flow, fault resistance and system homogeneity degree. A significant improvement in precision of fault location is therefore achieved. The advantage of the algorithm is an elimination of the numerous aspects regarding synchronization accuracy and availability of the stable communication interface between devices. The weakness of the method is its dependency on the line parameters, which can show through the residual factor $\underline{k}_0$ or the mutual coupling of the parallel line $\underline{k}_M$. Moreover, the faulty loop must be provided to fault location algorithm in order to calculate the correct fault location and fault resistance. The further investigations of robustness of the proposed method focus on considerations of the power system line in its transposed or un-transposed form. In addition, two main aspects must be considered in fault locating application: line parameters are distributed and electric arcs cannot be fully replaced by a primitive fault resistance.

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