ACCURATE LOCALIZATION OF GROUND FAULTS IN NON-SOLIDLY EARTHED NETWORKS BASED ON TRANSIENTS ANALYSIS

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ABSTRACT

In this paper, we present a new approach for localizing ground faults, using transients in the currents and voltages. Our approach is based on the double sided estimation of the transient voltage at an unknown ground fault location. It is assumed that the calculated transient profile from both sides of the line is comparable for a known fault location. For better accuracy, an existing higher frequency spectrum is used, and through that, redundant information from each existing frequency is extracted. The precise idea, accuracy analysis, as well as further relevant benefits of our method will be thoroughly described in the paper.

INTRODUCTION

The increasing automation degree in distribution and transmission networks contributes to the improvement of energy quality. Monitoring and protection devices that support network automation are becoming increasingly flexible and powerful in order to serve the modern primary equipment. Their sampling rate is increasing, the gathered information has a higher bandwidth, and algorithms are growing in complexity as well as heuristic techniques becoming more sophisticated. However, in a lot of applications, the analysis of the network operation is still based on the consideration of the fundamental frequency [1], which, in a lot of cases, reaches its limits.

Also, in the area of fault location using the fundamental frequency, it seems that the boundary has already been achieved, especially if the short circuit duration is less than one fundamental period. Using modern devices with a higher sampling frequency, a new approach for fault location can be attempted. In this paper, we present a new possibility of locating a fault, using information delivered by transients generated by the fault.

In a non-solidly, earthed system, the transient earth faults have a very short duration [2]. These transient faults can develop into intermittent or permanent faults, and then the shutdown of the faulty line is obligatory. Inspection of the line after a transient fault can help to find weaknesses in the network. The exact location of the transient fault can contribute to reducing such a maintenance effort.

To date, the fault location in a non-solidly earthed network is evaluated only to an approximate result. In general, the computed direction result of transient faults only allows for the indication of the faulty feeder [3]. The conventional method, based on the fundamental frequency, does not provide a reliable result. The main reason for this is the short measurement window, the low level of the fundamental fault currents and voltages, as well as the distorted form of these measured quantities.

MOTIVATION AND GENERAL IDEA

The conventional methods for the fault location calculation are phasor based and operate at a single terminal. The fault location is determined from the calculated impedance of the short circuited loop. The basis of these methods leans on an assumption that overhead lines or cables are represented by generalized *PI*- or *T*- models with lumped parameters, often also with a neglected capacitive influence [1]. These models are satisfactory, if the computation approach takes place for the fundamental frequency only. The line length also introduces some limitation in the usage of the conventional method for the fault location. In order to improve the accuracy of the fault locator, the double-sided methods with a distributed parameter model were developed [4]. This method reduces the negative impact of the fault resistance as well as an uncertainty of some line parameters, like the parameters of the earth path. The vulnerability of all these methods is still the correct phasor calculation for the fundamental component. Especially in the case of the ground fault in non-solidly earthed networks, it can be a big challenge.

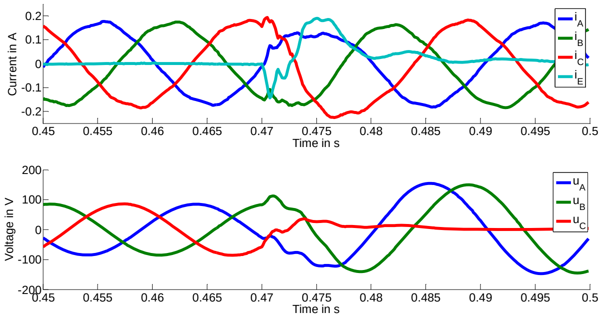

Figure 1: Typical behavior of the voltages and currents during a ground fault in a non-solidly earthed network

There are two particular cases which should be considered. On the one hand we can have permanent faults e.g. in a cable, which deliver a typical characteristic pattern for the faulty phase in the form of a very low voltage and almost steady load current for the fundamental component. Both of these quantities are not sufficient to calculate the fault location. On the other hand, emerging temporary faults, e.g. on the overhead line, are very short and characterized by the significant transients, with a very unsteady fundamental component. In this case, the models based on lumped parameters used in the calculation of the fault location are not sufficient.

Figure 1 presents an example of the measured quantities during the ground fault in a non-solidly earthed overhead line. The record was captured with a sampling frequency of 8 kHz. This example thoroughly covers two mentioned cases. Directly after the ground fault occurred, the transients with a relatively short duration can be recognized. In this time, the recharging of the capacity on the line is forced. After the capacitor has recharged, the line is in a steady state. At this time, we can observe that the current in the faulty phase is near to the load current. Concurrently, the voltage is unsteady and shifts to a certain value depending on the fault position.

Let's consider the voltage and current curves from figure 1 in the frequency domain for a very short measurement window, e.g. with half of the fundamental period. After a Fourier Transformation and elimination of the fundamental component in the currents and voltages, the occurred transients can be clearly observed.

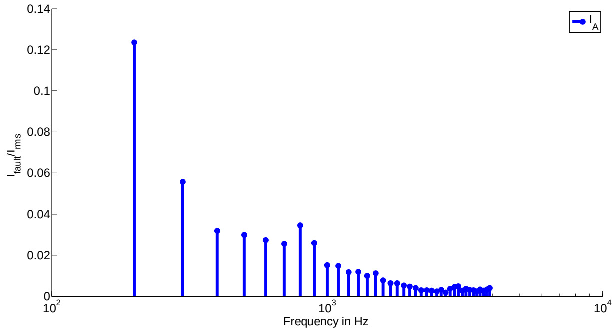

Figure 2: Phase current in the faulty phase

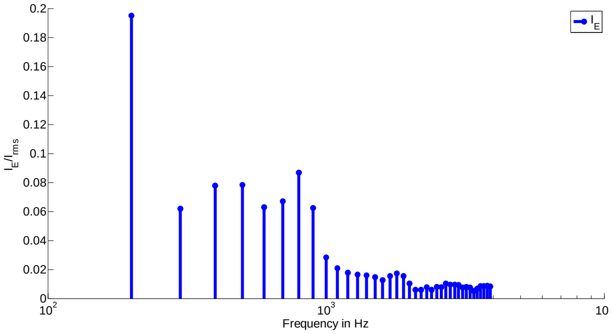

Figure 3: Earth current

It can be observed that in this case the transients lie between 100 Hz and 2 kHz. They can be better measured in a shorter window with higher sampling rate. According to practical rule, at least one period is needed to measure the frequency components with good accuracy. Because of that, the measurement window can be reduced by increasing the lower limit of the considered transient frequency. Another aspect is that the assumption of the wider frequency spectrum for the calculation introduces a certain redundancy that can be used to the improvement of the calculation result by applying error minimization methods. It is to be expected that each appearing frequency component in the current and voltage carries information applying to the fault location.

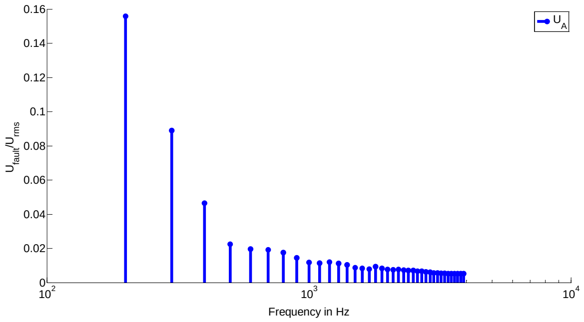

Figure 4: Phase-to-earth voltage in the faulty phase

For a better understanding of the concept, we first consider a single phase line. In addition, we assume that this single phase line is monitored from both sides. The fault occurs on this line. The electrical arc is represented by a simple fault resistance. This assumption does not limit the algorithm performance. Numerous investigations with different electrical arc models have resulted in the same quantitative results. As already explained, for a more precise calculation of the currents and voltages across the line, a line model with distributed parameters should be applied. Such a line model can be represented by a four terminal network as presented in figure 5.

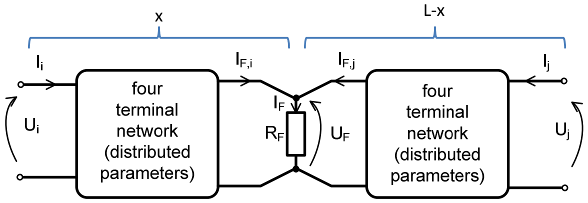

Figure 5: Four terminal representation of the line with fault

The mathematical description of the model in the frequency domain in the form of *ABCD* chain parameters is as follows (1):

$$\begin{bmatrix} \cosh \gamma l & -\underline{Z}_c \sinh \gamma l \\ -\dfrac{\sinh \gamma l}{\underline{Z}_c} & \cosh \gamma l \end{bmatrix} \rightarrow \begin{bmatrix} A & -B \\ -C & D \end{bmatrix} \tag{1}$$

This four terminal network can be described with the following expressions (2):

$$U_{F,i}(x, j\omega) = U_i(j\omega)\cosh \gamma(j\omega)x - Z_c(j\omega) \cdot I_i(j\omega)\sinh \gamma(j\omega)x$$

$$I_{F,i}(x, j\omega) = -U_i(j\omega)\frac{1}{Z_c(j\omega)}\sinh\gamma(j\omega)x + Z_c(j\omega)\cdot I_i(j\omega)\cosh\gamma(j\omega)x$$

$$U_{F,j}(x, j\omega) = U_j(j\omega)\cosh\gamma(j\omega)(L-x) - Z_c(j\omega)\cdot I_j(j\omega)\sinh\gamma(j\omega)(L-x)$$

$$I_{F,j}(x, j\omega) = -U_j(j\omega)\frac{1}{Z_c(j\omega)}\sinh\gamma(j\omega)(L-x) + Z_c(j\omega)\cdot I_j(j\omega)\cosh\gamma(j\omega)(L-x)$$

where Z_c is the characteristic impedance, and γ represents the propagation constant. Both parameters evidently depend on the frequency, however in the considered frequency spectrum they can be assumed as constant. This is a very important advantage of this method, because the line or cable parameters can be obtained by the conventional measurement approach and then used in the algorithm.

Since both terminals are monitored, the voltage U_F at the ground fault location can be estimated from both sides ($U_{F,i}$, $U_{F,j}$) separately. This voltage should be computed for each relevant frequency measured in the signal (Figure 2, 3 and 4). In order to obtain the fault location *x*, a one-dimensional optimization problem needs to be solved (3):

$$\min \left\| U_{F,i}(x, j\omega) - U_{F,j}(x, j\omega) \right\|^2 \qquad (3)$$

It is present in the minimization of the goal function, created by an error vector in the form of voltage differences between both sides at the frequencies that were analyzed. These error components are represented in the form of the complex numbers for each frequency separately.

In the case of the 3-phase systems, appropriate decoupling between the phases can be very useful. For this goal the well-known, linear Clarke transformation is recommended. The transformation matrix is defined in the following form (4):

$$T = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \rightarrow \begin{bmatrix} I_\alpha \\ I_\beta \\ I_0 \end{bmatrix} = T\cdot\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix}, \begin{bmatrix} U_\alpha \\ U_\beta \\ U_0 \end{bmatrix} = T\cdot\begin{bmatrix} U_A \\ U_B \\ U_C \end{bmatrix}$$

This matrix converts the phase quantities *A*, *B*, *C* into so called modal components (α, β, *0*). The advantage of this transformation is a relatively simple representation of any fault type in modal components. In the case of the single-pole-to-earth fault in phase *A*, only the α- and *0*-components reflect a fault contribution on measured quantities. The β component plays a passive role and is furthermore responsible for the load flow. From figure 6, it can be observed that each component can be considered separately. For the calculation of the fault location in this method, only the α– and *0*- components are applied. The single phase consideration described above (equations 1-3) is valid for each modal component separately.

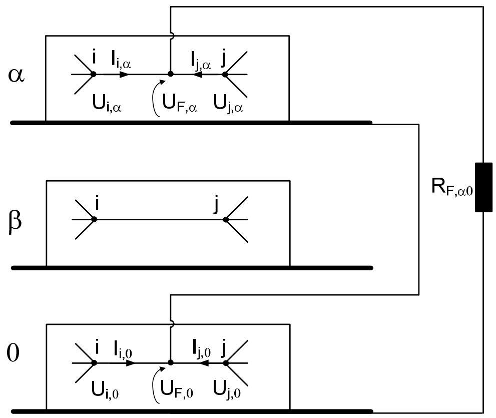

Figure 6: Single-pole-to-earth fault in modal components

The construction of the objective function and its optimisation takes place in the modal components α and *0*. Let us consider the 110 kV isolated distribution system with a fault on the line. The line is placed between nodes *i* and *j*. The length of the line is 50 km. Its parameters result from the common tower geometry applied for 110 kV systems. In order to achieve a better accuracy of the result, the data is sampled with 64 kHz. In order to have a secure gap between the signal and noise, the cutoff frequency is much lower than the antialiasing frequency. In this case, it is 15 kHz. From travelling wave theory, we know that transient signals are a superposition of step- or exponential functions, depending of the line's source impedance. Looking at spectrums of these signals, we can state that the signal magnitude will decrease at least by $1/j\omega$. A certain voltage drop at fault inception precedes a spectral magnitude drop of 60 dB at 20 kHz compared to the initial voltage drop. This damping of magnitudes in the frequency space limits the usable upper frequency, if 50 Hz signals should also be present in the used frequency band. If we want achieve an accuracy of 2 % at -60 dB, this will require a 16 bit *ADC* resolution. By using high pass filters before the *ADC* conversion, these 3 decades of used frequency bandwidth can also be shifted to higher frequencies. In this case, a separate *ADC* channel will be required for sampling these signals containing the nominal frequency.

Under the assumption that the ground fault position is known (in our case x=10 km), we can observe excellent overlapping between calculated voltages $U_{F,i,\alpha}$ $U_{F,j,\alpha}$ using quantities from the own (*i*-node) and remote (*j*-node) side in the frequency domain (Figure 9). It also results in an excellent overlapping in the time domain (Figure 10). Performing the comparison between the values obtained from both sides with an unknown fault location, the values of the objective function can be computed (Figure 11). The minimization of the objective function is carried out. This can performed using typical optimization methods.

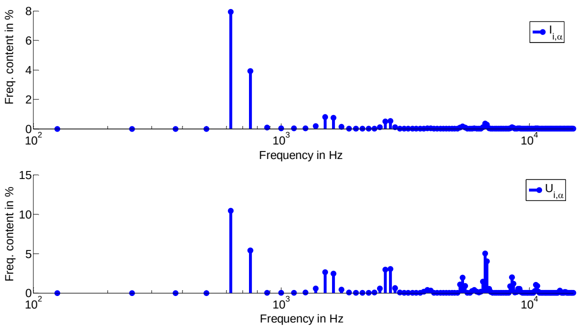

Figure 7: The frequency spectrum of the current and voltage as modal component α captured in the node *i*

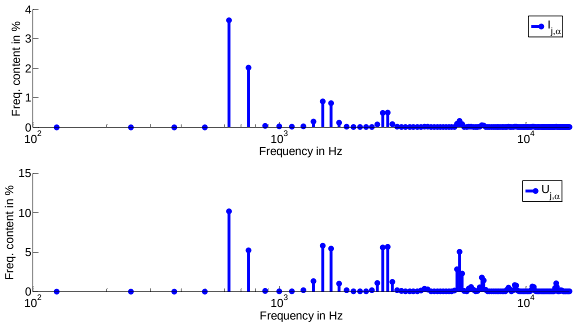

Figure 8: The frequency spectrum of the current and voltage as modal component α captured in the node *j*

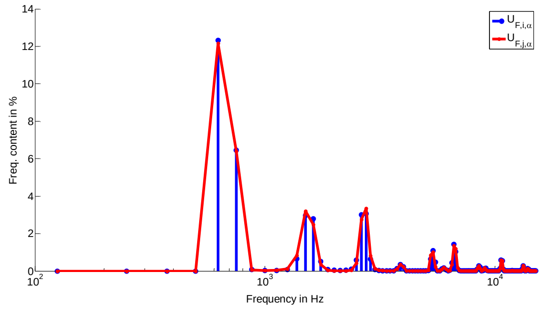

Figure 9: Comparison between voltages in α component calculated from quantities from both sides – frequency domain

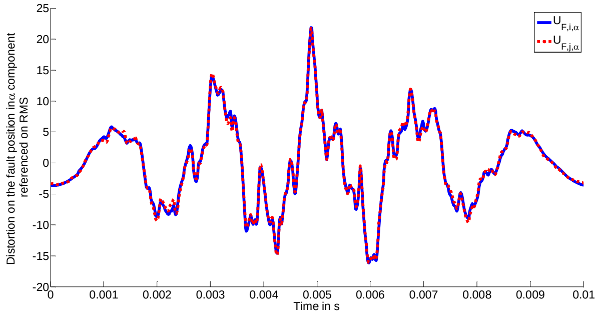

Figure 10: Comparison between voltages in α component calculated from quantities from both sides – time domain

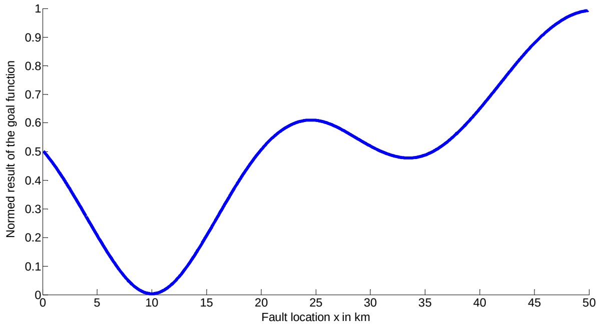

Figure 11: Objective function for fault localization

EXAMPLE RESULTS

In order to prove the validity of the method, a more complex network with a compensated star point is investigated. This network consists of an overhead line (50 km) and a cable (20 km). The overhead line is fed from both sides. The power in the cable is flowing into the passive load. For the simulation of the network, the distributed parameter models from MatLab® were used. The parameters of the models were calculated, based on the common parameters of the overhead line and cable on the 110 kV level. For the fault location calculation, node *i*, *n* and *m* are monitored. The results from two ground faults are presented. The goal is to show that independent of the medium of the power transfer, (cable or overhead line) the same methodology for ground fault localization can be used successfully.

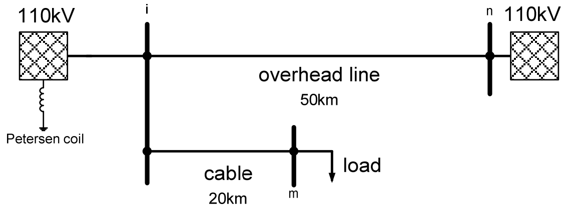

Figure 12: Compensated 110 kV network

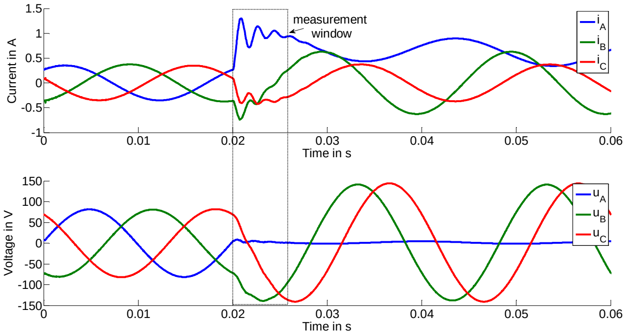

Figure 13: Current and voltage after transient ground fault in cable

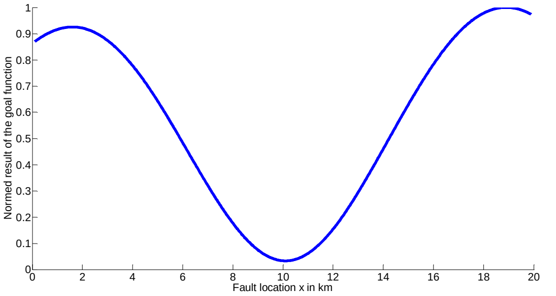

Figure 14: Objective function created for α component with the goal of fault localization – ground fault in the cable 10,2km (exact result 10km)

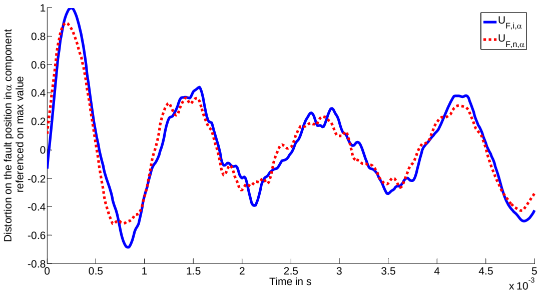

Figure 15: Comparison between voltages at fault location (cable) calculated from both sides in α component in time domain – measurement window 5ms

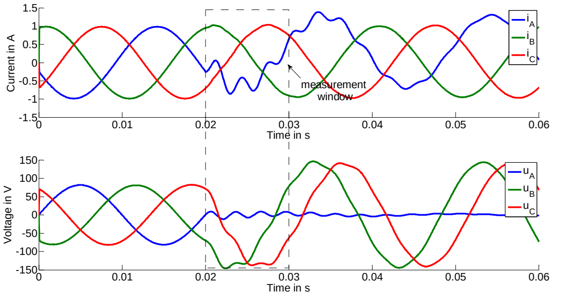

Figure 16: Current and voltage after transient ground fault in overhead line

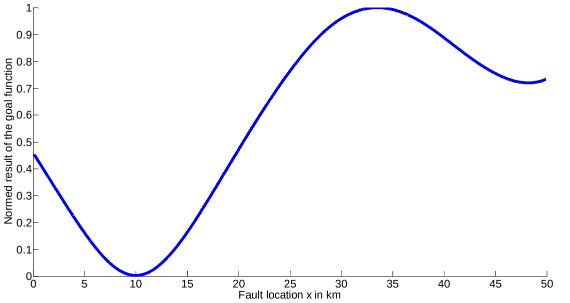

Figure 17: Objective function created for α component with the goal of fault localization – ground fault in the overhead line 10,5km (exact result 10km)

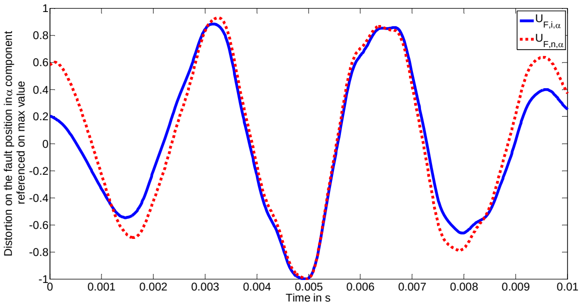

Figure 18: Comparison between voltages at fault location (overhead line) calculated from both sides in α component in time domain – measurement window 10ms (Signal differences at beginning and end of signal window arise from IFFT properties for non-periodic signals)

SUMMARY

In this paper, we have presented a method for the accurate fault location in isolated or compensated networks. Our investigations were based on theoretical considerations supported by the simulation result obtained from Power System – MatLab® models. From our point of view, the method presented in this paper is very promising and delivers very accurate results. Especially in isolated and compensated networks, due to the very short earth fault duration, a fault location using conventional methods is not possible. This idea could be a solution for a lot of applications. The advantage of the method is an usage of conventional measurement transformers. The possibility of calculating in the frequency domain allows for an appropriate correction of the measured quantities in order to achieve a better accuracy. From our point of view, this method can guarantee the fault location in networks with a high harmonic content. In this case, the active injected distortion can also be used for the fault localization. Nevertheless, the consideration presented in the paper should be confirmed on real measurements in the field. Only in this way can the validity of the method be confirmed.

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