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## PROBABILISTIC ANALYSIS FOR A ROBUST ZERO-SEQUENCE FAULT LOCATION METHOD FOR MV DISTRIBUTION FEEDERS

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### ABSTRACT

This paper is an upgrade of a previous work on an impedance-based fault location method (FLM) designed for medium voltage (MV) distribution feeders using zero-sequence (ZS) components and distributed voltage measurements [1]. This paper proposes to estimate ZS voltage probability density functions (PDFs) instead of amplitude and phase. Indeed, impedance-based FLMs are sensitive to measurement errors as well as line impedance value uncertainties, which tend to be higher at the distribution level. Thus, this paper presents a probabilistic formulation for fault location which is robust to both measurement and line impedance values errors with as few as possible additional voltage measurements needed on some secondary substations. A series of Monte-Carlo simulations enable us to fit two 4-dimensional Gaussian PDFs for ZS current and voltage and perform robust fault location by computing the volume inside the intersection of the two 2-dimensional marginal voltage PDFs estimated along a path of nodes on the feeder. This probabilistic formulation comes at the expense of an increase in the size of the fault location area with respect to the previous formulation. However, in most cases, this formulation offers a high increase in robustness while leading to a minor diminution of locating precision. The proposed algorithm has been validated with simulated faults on the CIGRE MV benchmark network (CIGRE network).

### 1. Introduction

Efficient fault location algorithms are more and more needed at the distribution level. Indeed, the value of the lost load is increasing more and more with the rampant electrification of the industry and the rise in electricity costs. That is why distribution system operators (DSOs) should try to reduce the fault-clearing time on MV feeders. However, most of the FLMs already deployed at the distribution level are adaptations of the ones used at the transmission level, which try to locate the fault precisely. In a MV feeder, the busbar in the primary HV/MV substation is usually the only instrumented node, leading to a major decrease in locating performance of traditional algorithms. While a highly precise fault location algorithm can be valuable, it is less required at the distribution level. Indeed, the reliability can be greatly increased – compared to manual inspection of the whole area between automatic breakers – with the fault's location inside an area between two manual switches.

The FLMS can be divided into two main categories. First, transient-based methods mainly investigate the transient

travelling waves induced by the fault inception and try to locate the fault based on the estimation of the propagation time of such waves [2]. While they are said to be the most accurate methods with a higher locating potential, these methods need measurement devices with very high sampling frequencies, which are not widely deployed at the distribution level. The cost of such massive deployment might be too important for DSOs with respect to the potential gains from better reliability. Secondly, the methods which study the fundamental phasors of the measured signals are called impedance-based methods [3], [4]. They are said to be efficient with regard to their cost of implementation, which is much less expensive. However, since distribution feeders have a radial topology, it is not possible to differentiate between two possible solution nodes located at the same electrical distance (apparent impedance) on different ramification branches: this is the multiple estimation problem. In order to solve this problem, the most studied way in the literature is to add measurements following the “1-bus spaced placement strategy” [5], which aims to achieve observability of the voltage across the whole feeder. This technique would enable DSO to perform state estimation, for example, but comes at the expense of a need for a very high number of additional measurements. This would represent an investment which is not economically viable at the distribution level.

Besides, DSOs appear to be more and more inclined to deploy a few additional measurements for some complex feeders. A FLM has been presented in a previous work [6], further studied and explained in [1] and reposes on the estimation of two zero-sequence voltage and current sets along a path between the busbar and a given additional voltage measurement. Unfortunately, while not being sensitive to neither load current value nor fault resistance values, this method proves to be very sensitive to measurement errors. It would need errors inferior to what the standard voltage transformer (VT) or current transformer (CT) accuracy classes provide us with. That is why there is a need to develop a method that can handle those potential errors: measurement errors and ZS line impedance estimation errors. In the literature, there are few probabilistic methods that take these coupled errors into account. While [7] deals with erroneous measurements by proposing an area around the solution of the FLM as a robust fault location, [8] uses synchronized measurements from both ends of a transmission line to compensate for line impedance misestimation while being robust to measurement errors. Deploying such techniques is difficult to imagine at the distribution level since it would need to be robust to both sources of errors with a small

number of additional measurements in order to be economically acceptable by DSOs.

This paper is structured as follows. Section 2 presents the deterministic formulation and the motivations for the probabilistic formulation of the FLM dealing with both measurement and line impedance value errors, which is presented in section 3. Then, section 4 shows some simulation results obtained on the CIGRE network. The conclusions and perspectives are given in section 5.

## 2. Deterministic fault location method

### 2.1. Non-robust location algorithm

In the non-robust fault location algorithm, we consider a MV grid with some additional voltage measurements on some remote end secondary substations (there is no ZS current on transformers in a secondary substation). The ZS voltages and currents are estimated as if there was no fault occurring on the grid [6], leading to accurate estimates for the nodes upstream of the fault during the Top-Down (from the busbar to a considered measurement) estimation and symmetrically inaccurate estimates for the upstream nodes of the fault in the Bottom-Up estimation (c.f. Figure 5). So, the two zero-sequence voltage estimates agree on the node which is the projection of the fault onto the path between the busbar and a considered additional measurement node. This means that the fault is located laterally of this node - called the projection node - in which the distance between the two sets of estimates is minimal. This method enables us to locate all types of earth faults in an area whose size depends on the number and location of the additional voltage measurements. An optimal placement algorithm for the additional measurements has also already been developed and presented.

### 2.2. Motivations for a probabilistic method

A sensitivity analysis has been carried out on the CIGRE network with a single-line-to-the-ground (AG) fault occurring at node ten and considering the instrumentation of the three end nodes, as shown in Figure 4. A Monte-Carlo process is used to compute the mean success rate of the method - which is how many times in average a measurement is able to locate the projection node of the fault. Different measurement errors for different accuracy classes - as defined by the standard [9] and extended by us (the 0.01% accuracy class has been built by interpolation) - of voltage transformers are chosen uniformly distributed within the margin of each class. This represents a more challenging case than the gaussian distribution widely used in the literature. A total of  $N_{MC} = 100$  simulations have been carried out for each measurement and for each considered accuracy class. Figure 1 shows the mean success rate across all tested cases. It appears that with this method all measurements always succeed to exhibit the real projection node of the fault when there are no measurement errors (the mean success rate is 1 in the ideal case). However, we observe that the method would be

statistically wrong 55% of the time with a 0.1% VT accuracy class, which is the most deployed today (using synchronized measurements). Moreover, considering a 0.5% accuracy class would lead to projection nodes being close to always wrong (mean success rate is inferior to 15%, even 10% with unsynchronized measurements), meaning that the faulty node would never be located in the solution area. Nevertheless, it should be said that the success rate is set to 0 if the method fails to exhibit the right projection node. It has been observed from the simulation results, that even though the success rate can be very low, the method exhibits in most cases one of the neighboring nodes of the real projection node. That is calling for a method that would be able to select more than one projection node if the two set of ZS voltage estimates are close enough to each other on more than one node. This is the aim of the presented method.

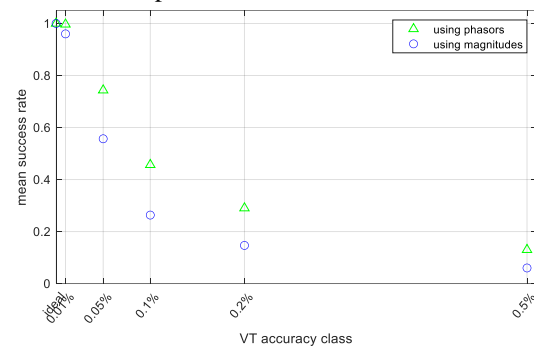


Figure 1: The success rate of the FLM when considering voltage measurement errors

## 3. Probabilistic fault location method

### 3.1. Dealing with measurement errors: Estimation of a Gaussian PDF of the ZS voltage and current

The possible errors coming from measurement devices are bounded by their accuracy class. In this paper, it has been chosen to consider the worst-case scenario, being uniformly distributed and independent errors in amplitude and angle displacement on voltage and current measurements. To compute the ZS component, there is a need for three measurement devices, one on each phase of the system. We made the hypothesis that the errors of each measurement transformer are independent, which seems reasonable given that they are coming from different devices. Considering a uniform PDF for each measurement implies that the PDF of the ZS component is piecewise quadratic. This PDF is approximated by a joint 4-dimensional Gaussian PDF of the zero-sequence voltage (real and imaginary parts) and current (real and imaginary parts) and is estimated with a Monte-Carlo process. The PDF parameters: the 4-dimensional mean  $\mu \in \mathbb{R}^{4 \times 1}$  and covariance matrix  $\Sigma \in \mathbb{R}^{4 \times 4}$  are estimated by a random sampling of  $N_{MC} = 5 \times 10^3$  (arbitrarily chosen) samples of the three voltages (and current at the busbar). From this inferred PDF, we sample  $N_{MC}$  values of the zero-sequence voltage and current for the next step of the FLM described

in subsection 3.2. Finally, a 2-dimensional marginal PDF is extracted to represent the PDF of the ZS voltage only, which will be used in the proposed fault location algorithm. An example is presented below considering a 0.1% accuracy class for measurements with a measured ZS voltage  $V_0^{mes} = -8,967 + 821j V$ . Figure 2 shows the histogram obtained from Random sampling (RS) with uniformly distributed measurement errors (white), the inferred 2-dimensional marginal voltage PDF (black) and the histogram obtained from RS with the inferred PDF (red).

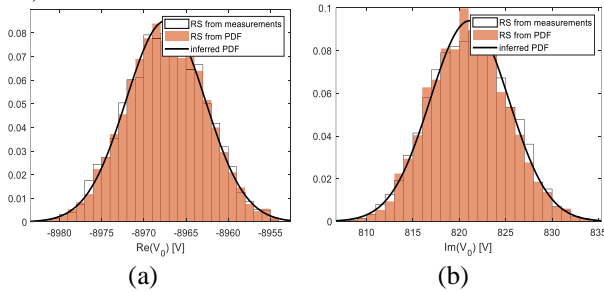


Figure 2: real part (a) and imaginary part (b) histograms of the measured zero-sequence voltage

We observe that, for this value of  $N_{MC}$ , the inferred PDF fits well the PDF histogram obtained with the Monte Carlo simulations. In order to verify that, a statistical study over 500 estimation processes has been carried out. It appears that the total vector error (TVE) – defined as the ratio between the magnitude of the error vector and the magnitude of the real vector – remains inferior to 0.01% in all cases. This means that the convergence of the estimation of  $\mu$  by Monte-Carlo process is guaranteed. Moreover, the variances of such estimates are very low ( $0.0043 V^2$  for the real part and  $0.0034 V^2$  for the imaginary part) meaning that there is very little risk to obtain an estimation far away from the real value. To estimate this risk, we computed the cumulative distribution function (CDF) of the TVE over the 500 performed estimations.

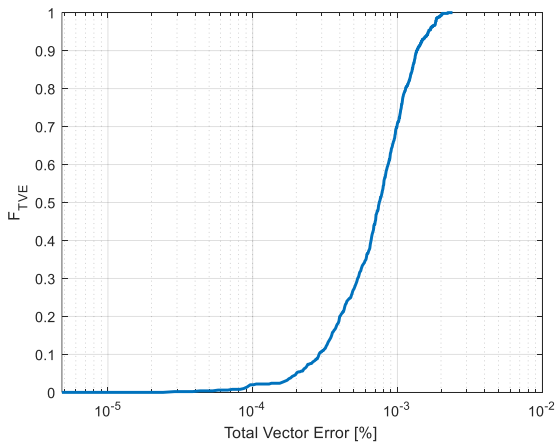


Figure 3: CDF of the TVE of the zero-sequence mean voltage estimation

In Figure 3, we see that in all performed estimations, there is never a TVE greater than 0.01%. Besides, the estimation TVE is in 70% of the cases inferior to 0.001%. All these

observations led us to affirm that the inferred PDF is well extracted from the observed probabilities. Finally, we observe that the random sampling obtained using the inferred PDF is a good representation of the first random sampling, as shown by the value of the intersection surface between the two histograms (white and red) in Figure 2. The intersection surface is defined as the relative surface under both histograms. On this statistical study, the intersection is in average 95%, meaning that the inferred PDF parameters  $\mu, \Sigma$  are sufficient to describe the probability repartition of the ZS voltage.

### 3.2. Dealing with line impedance errors: Progression along the path

Once the 4-dimensional ZS PDF is obtained for every measurement node, the zero-sequence voltage needs to be estimated for every node along the path between the busbar and each additional measurement, as shown in [6]. To design a FLM which is robust to misestimation of line impedance parameter values, the estimation of the 4-d PDFs along the path is obtained by Monte Carlo simulations. A PI-lumped parameter model is chosen for the lines, as used by most DSOs. A uniform distribution within relative margins is chosen for the impedance parameters. For example, the results presented in this paper are obtained considering that real line resistances, reactances and capacitances are within  $\pm 10\%$  of the ones stored in the database.

To estimate the PDF of node  $m$  while knowing the PDF of voltage and current at node  $k$  and the  $m-k$  line parameters, we draw  $N_{MC}$  samples of the voltage and current at node  $k$  and of the line parameters. Then, the corresponding voltage and current mean and covariance matrix at node  $m$  are computed. It is possible to extract the marginal 2-dimensional gaussian corresponding to the voltage – as shown on Figure 6 (a), (b) – so that the intersection probability  $\mathbb{P}_\cap(p)$  can be computed for all nodes  $p$  along the path. When using synchronized measurements,  $\mathbb{P}_\cap(p)$  is the volume located below the intersection of the two surfaces and is computed with the rectangle method. When using unsynchronized measurements,  $\mathbb{P}_\cap(p)$  is the surface located below the two curves describing the 1-dimensional PDF of the ZS voltage amplitude. In this paper, we chose to focus on synchronized measurements.  $\mathbb{P}_\cap(p)$  corresponds to the probability of the fault occurring in a node which is located laterally of the considered node  $p$ . To perform a robust FLM, we need to define a probability threshold  $\tau$  and for a given measurement node  $m_i$ , we select as solution area all the nodes which are lateral to one of the nodes with an intersection probability higher than  $\tau$ , this area is defined as  $\Omega_{m_i}(j)$ , with  $j$  being the faulty node. Then, for every node  $n$  of the feeder, we count the number of times  $N_\Omega(n)$  that it appears in a fault location area to produce the solution area, given by (1).

$$\Omega_{sol}^k(j) = \{n, N_\Omega(n) \geq k\} \quad (1)$$



## 4. Simulation results

### 4.1. Use case

We first implemented the proposed fault location scheme onto a simulated benchmark grid which is a modified version of the CIGRE network [3] with compensated neutral grounding, as shown in Figure 4. In this simple case, there is only the need for 3 additional measurements (at the three extremities of the feeder 6,7,11) for the method to be able to exactly locate the fault if the measurement were ideal and the impedances exactly known. However, the fact that the feeder is small reduces the distance between the two sets of estimates since the voltage drops are low due to the compensated earthing among others. In this paper, a single-line-to-the-ground fault on phase A (A-G) is simulated with MATLAB/Simulink at node 10 with fault resistance being  $R_f = 150 \Omega$ . Measurement devices are considered compliant with the 0.1% accuracy class and line impedances are supposed within  $\pm 10\%$  of the stored ones.

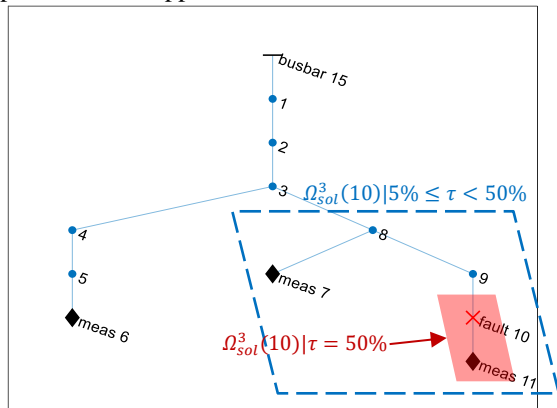


Figure 4: topology of the CIGRE network with measurements (meas 6,7,11) and fault position (fault 10)

### 4.2. Accuracy of the estimates along the path

To ensure that the number of iterations of the Monte Carlo process provides us with an accurate estimation of the voltage along the path, we compared the means of the marginal 2-dimensional PDFs with the results obtained using the non-robust version of the algorithm with the real impedance values and exact measurements, this represent the estimates that would be obtained in the ideal case. In Figure 5, this comparison is shown for the path between node 15 et node 6. It shows that there is no divergence between the 2 sets of estimates meaning that there is no accumulation of errors along the path. In average, this probabilistic robust method behaves the same way as the non-robust one using phasors. We can also see the impact of the unknown impedance values with the  $\pm \sigma$  interval shown in shaded area. We observe that the variance of the Top-Down estimate is increasing when going from the busbar to the remote measurement while it is the opposite for the Bottom-Up estimation.

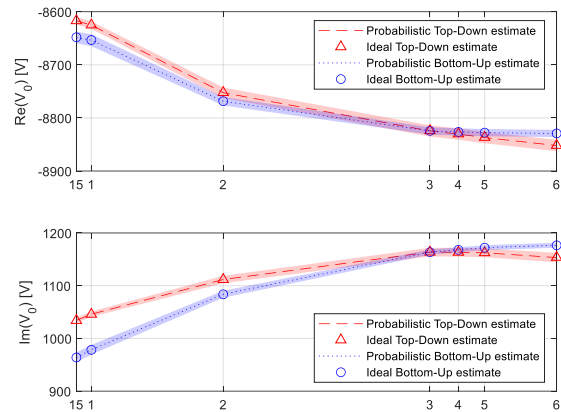


Figure 5: Comparison of the mean of the PDFs (with the  $\pm \sigma$  intervals shaded) and accurate estimates of ZS voltage along the path to measurement node 6

### 4.3. Intersection Volume

From the estimation of the two marginal gaussian distributions (Figure 6 (a),(b)), the volume inside their intersection  $\mathbb{P}_\cap$  is computed along the path with the rectangle integration method. The fault is occurring in node 10 which is lateral to node 3 – which is the node with the highest intersection probability  $\mathbb{P}_\cap = 69\%$  (Figure 6 (c)). However, small measurement errors might lead to a misestimation of the projection node with node 4 which also presents a very high intersection probability ( $\mathbb{P}_\cap = 56\%$ ).

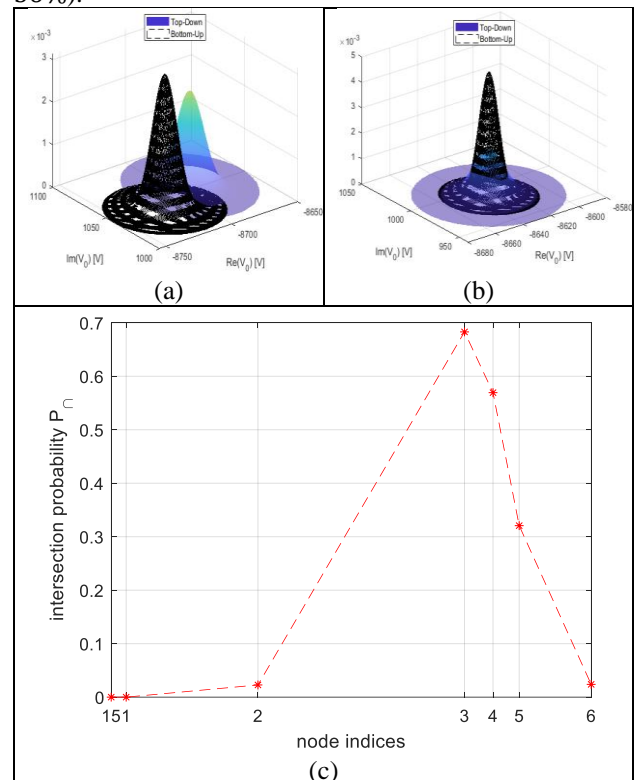


Figure 6: 2 ZS voltage PDFs estimated at node 2 (a) and 3 (b) with the intersection probability along the path (c)

#### 4.4. Length of solution area with respect to thresholding

The robust FLM has been implemented on the three paths corresponding to the three additional measurements and the evolution of the solution area – which can be seen in Figure 4 - with respect to the value of  $\tau$  is presented in Table 1. The first row shows the result obtained by selecting only the node with maximal intersection without any uncertainties, which corresponds to the behavior of the non-robust FLM with ideal measurements and knowledge of grid impedances. Given that all extremities are instrumented, it is theoretically possible to locate exactly the fault provided that the measurements are ideal.

In reality, if we consider measurement errors up to 0.1% and exact knowledge of the impedance values, we observe over 100 simulations that node 10 is located in  $\Omega_{sol}^3(10)$  only 9 times, while node 11 is present 11 times. Moreover,  $\Omega_{sol}^3(10)$  is not void in only 26% of the cases. This means that for all other cases (in three quarter of them), the best fault location area available is  $\Omega_{sol}^2(10)$ . This means that in practice, the non-robust method would not be able to locate the fault accurately and with precision since  $\Omega_{sol}^{m-1}$  is way larger than  $\Omega_{sol}^m$  on a more realistic distribution feeder [6].

Besides, we can see that with the chosen level of uncertainties and considering the nodes three times in a solution area, there is more than 50% of probability that the fault is occurring in node 10 or 11, without possible further discrimination. It appears that to be sure that the nodes excluded from the solution area have a fault probability inferior to 5%, we should select a large part of the feeder as the solution area. On this feeder, it appears that the enlargement of the solution area with respect to the ideal case is very important given the size of the robust solution area for  $\tau = 5\%$  compared to the non-robust method. Nevertheless, on longer and more ramified feeders, the voltage drops should be larger, and the relative enlargement of the solution area should not be as important as in the presented example. That is why we think that this robust formulation would have a lesser impact on the size of the solution area when applied to larger and more ramified feeders.

Table 1: Evolution of the solution area with the probability threshold value  $\tau$

Threshold value $\tau$	$\Omega_6(10)$	$\Omega_{sol}^3(10)$
$\max(\mathbb{P}_\rho)$	{3,7,8,9,10,11}	{10}
50%	{3,4,7,8,9,10,11}	{10,11}
25%	{3,4,5,7,8,9,10,11}	{7,8,9,10,11}
5%	{3,4,5,7,8,9,10,11}	{7,8,9,10,11}

## 5. Conclusion

This paper presents a probabilistic robust FLM designed for MV distribution feeders. While the non-robust formulation is very sensitive to measurement errors and line impedance estimation, this method enables DSO to

deal with the uncertainties faced at the distribution level. This paper shows the first simulation results of the method on a benchmark grid, which demonstrate that it can precisely estimate the zero-sequence voltage. A comprehensive study of the impact of the number  $N_{MC}$  on the performances of the algorithm needs to be carried out so that an optimal value for this parameter is defined. Besides, the method should be tested on more complex and ramified feeders, on which we expect it to reveal its relevance even more. Finally, research on the behavior of the method when considering larger measurement errors need to be carried out.

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