LOCALIZATION OF SHORT-CIRCUITS ON A MEDIUM VOLTAGE FEEDER WITH DISTRIBUTED GENERATION

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ABSTRACT
The paper deals with localization of phase-to-phase short-circuits on a medium voltage (MV) feeder with distributed generation (DG). Fundamental frequency currents and voltages are utilized for estimating the distance to the fault location. Loads and DG connected to the feeder cause errors in the estimated distance. Two methods to compensate for these errors are presented in the paper. In compensation method A, pre-fault measurements from the DG-unit are utilized for estimating the DG-current during fault. In compensation method B, the magnitude of the DG-current and voltage during fault is measured. A method for utilizing the DG-node measurements to discriminate between faults on the main and on a lateral branch is also presented. The goal is to obtain sufficiently accurate fault localization with limited information from the feeder available.

1 INTRODUCTION
With an increased focus on power quality, a fast and efficient fault handling is becoming more important. Today, sectioning of faults in distribution networks is time-consuming, but remote control of breakers is becoming more common. This paper looks into possibilities for automated localization of phase-to-phase faults in networks with DG, utilizing fundamental frequency measurements. The presented solution is based on impedance relays. The purpose is to correct for errors due to load and DG in the measured impedance in a simple way. Measurements from the DG-unit before fault occurrence is required (method A and B), and preferably also during fault (method A).

Fault localization in MV networks without DG is extensively reported in the literature [1], [2]. The challenge in this case is to minimize the impact from loads and fault resistance. When fundamental frequency measurements in the substation are used for fault localization, pre-fault measurements can be utilized for minimizing the impact from load on the distance estimate. This approach seems to work well for feeders without DG. Fault localization in networks with DG is treated in e.g [3]. [4]-[7] deals with more advanced methods based on fault transients, adaptive protection schemes and relay agents.

2 SIMULATION MODEL
A simple medium voltage (MV) feeder with DG, shown in Figure 1, is modelled in PSCAD. The feeder is operating at 22 kV.

The DG-unit is a synchronous generator, generating 3 MVA at unity power-factor. High load (HL) for the feeder is 6 MVA (2 times the DG-power). Low load (LL) is 1.5 MVA (0.5 times the DG-power).

The “during fault” voltage and current values are read 40 ms (2 periods) after the fault inception.

3 DISTANCE TO FAULT ESTIMATION BASED ON IMPEDANCE

The following equation can be used for estimating the location of a phase-to-phase fault involving phase B and C:

\[ d = \frac{1}{X_l} \text{Im} \left( \frac{U_{\text{B}} - U_{\text{C}}}{I_{\text{B}} - I_{\text{C}}} \right) \]

\[ d \]: distance from substation to fault location
\[ X_l \]: line reactance per unit of length
Superscripts B and C denote phase quantities.

The distance \( d \) obtained from (1) is used as a starting point for the calculations in both compensation methods described later in the paper.

Load and DG connected along the feeder will cause errors in the distance estimate. This is shown in Figure 2, where the fault is located at the end of the feeder (30 km from the substation, on the main branch) in all cases. 2-ph. means two-phase short-circuit, 3-ph. means three-phase short-circuit. The connection point of the DG-unit is varied along...
the main branch. The distance estimate error is defined as estimated distance minus real distance.

Figure 2. Distance estimate error with short-circuit at the end of the feeder.

The DG cause a positive error in the distance estimate, while the load cause a negative error. For most of the cases shown, the impact from the DG is larger than the impact from the load, and there is a net positive error. Thus the fault appears to be located farther away than it is in reality. The worst-case (largest distance estimate error) is a two-phase short-circuit at low load, with the DG connected at the beginning of the feeder (5 km from the substation). The DG has negligible impact on the distance estimate for faults located before the DG connection point, on the main branch. The distance estimate error is defined as estimated distance minus real distance.

The DG voltage and current, which have been decomposed to the d- and q-axes, can be estimated based on pre-fault measurements from the DG-unit. Only magnitude values of voltage and current and the phase-angle are assumed to be available (|U|, |I|, φDG). The advantage of not requiring phasors, is that the measurements from the DG-unit does not need to be time-synchronized with the substation measurements. In the transient state, the generator can be represented by constant d- and q-axis transient emfs E'd and E'q behind the transient reactances x'd and x'q, respectively. The rotor flux linkages in both axes can be assumed to remain constant during the transient state. The internal emfs corresponding to these linkages can also be assumed to remain constant, and equal to the pre-fault values [10]. This property is utilized for calculating the DG current during fault.

If the pre-fault value of the voltage magnitude in the DG connection point is known, the load between the substation and the DG, S1,0, can be estimated. The phase-angle of the load, φL,0, must be known or assumed. The estimated load also includes the load on the side-branch. The remaining load is put after the DG connection point, in S2,0.

S1,2,0 + S2,0 = S5,0 + S10,0 - S6,0 - S7,0
S1,0, S2,0: line losses in section 1 and 2.

Since only the magnitude of the DG voltage is measured, the phasor angle has to be estimated. This can be done using the following equation:

\[ U_{DG,0} = U_{5,0} - Z_{1,0} \left( I_{5,0} - \frac{U_{5,0}}{Z_{1,0}} \right) \]

The angle of estimated phasor is then combined with the measured DG-voltage magnitude.

A better distance estimate can be obtained if the impact from DG and load is compensated for. For a fault located after the DG-node the new estimate, \( d_c \), equals:

\[ d_c = \text{Im} \left[ \frac{Z_{1,0} + \frac{U_{DG}^B - U_{DG}^C}{I_{1}^B + I_{DG}^B - I_{1}^C}}{I_{1}^C + I_{DG}^C - I_{1}^B} \right] \frac{1}{X_{l}} \]

In this paper, the load current (I_l) is estimated in all cases using (5). The DG current is either estimated (comp. A) or measured (comp. B).

5 COMPENSATION UTILIZING PRE-FAULT DG-MEASUREMENTS (COMP. A)

The fault current contribution from the DG-unit can be estimated based on pre-fault measurements from the DG-unit. Only magnitude values of voltage and current and the phase-angle are assumed to be available (|U_{DG,0}|, |I_{DG,0}|, φ_{DG,0}).
to the transient reactances of the generator.
The DG-node voltage during fault can be estimated the same way as in (3), with the load calculated using (4).

5.1 Estimation of the DG-current
For a three-phase short-circuit, the DG can be represented by a positive sequence equivalent. The d- and q-axis components of the currents are estimated from:

\[ I_{DG,d}^+ = \frac{E_{dg}^+ - U_{DG,d}^+}{X_{DG,d}} \]
\[ I_{DG,q}^+ = \frac{E_{dg}^q - U_{DG,q}^+}{X_{DG,q}} \]  \hspace{1cm} (7)

For a two-phase short-circuit the current has to be represented by a negative sequence equivalent in addition to the positive sequence equivalent. The positive and negative sequence representations of the feeder are connected in parallel at the fault location. The phase voltages in the DG-node during fault are estimated in a similar way as in (3). The d- and q-axis components of the positive sequence DG-current are:

\[ I_{DG,d}^+ = \frac{E_{dg}^+ - U_{DG,d}^+}{X_{DG,d}} \]
\[ I_{DG,q}^+ = \frac{E_{dg}^q - U_{DG,q}^+}{X_{DG,q}} \]  \hspace{1cm} (8)

The negative sequence DG-current is:

\[ I_{DG}^- = \frac{-U_{DG}^-}{jX_{DG}} = \frac{-U_{DG}^-}{jX_{DG,d}X_{DG,q}} \]  \hspace{1cm} (9)

When the positive and negative sequence components of the DG-current are known, the phase currents can be calculated:

\[ I_{DG}^c = hI_{DG}^+ + h^2I_{DG}^- + I_{DG}^0 \]
\[ I_{DG}^c = hI_{DG}^+ + h^2I_{DG}^- + I_{DG}^0 \]  \hspace{1cm} (10)

Where \( h = e^{j2\pi/3} \) and the zero sequence current, \( I_{DG}^0 = 0 \).

5.2 Results with compensation A
Results with compensation A for faults 30 km from the substation, on the main branch, are shown in Figure 4.

For three-phase short-circuits, there is an overcompensation of the impact of the DG on the distance estimate, resulting in a negative distance estimate error when the compensation is applied. All estimated DG-current values are higher than the real values. This indicates that the transient reactance values used in the calculations are smaller than the actual reactance values of the generator 40 ms after fault inception. Still, the result is better than in Figure 2, without any compensation. For two-phase short-circuits the results with compensation is very good. The negative sequence reactance of the generator is constant throughout the short-circuit course, so the estimated negative sequence current is very close to the true value.

6 COMPENSATION UTILIZING DG-MEASUREMENTS DURING FAULT (COMP. B)
For this compensation DG-current and DG-node voltage magnitudes during fault (\( |I_{DG}|, |U_{DG}| \)) are assumed to be measured, together with the phase angle (\( \phi_{DG} \)). The phase angle of the DG-voltage is estimated in a similar way as in (3). Figure 5 shows the error in the distance estimate when compensation B is applied. Since the DG-current now is measured, instead of estimated, as in compensation A, the result is better, at least for three-phase short-circuits.

7 DECIDING THE FAULTED BRANCH
Distribution feeders generally have a tree structure, and one estimated distance might correspond to several possible fault locations. For each candidate location the corresponding \( |U_{DG}| \) is calculated, and compared to the measured value.

\[ \Delta U_{DG} = |U_{DG}| - |U_{DG,estimated}| \]  \hspace{1cm} (11)

The location where the calculated value is closest to the simulated value (smallest \( \Delta U_{DG} \)) is assumed to be the most probable fault location.

Table 1 shows the results for two faults located 20 km from the substation, on the main branch and on the side branch, respectively. The smallest value of \( \Delta U_{DG} \) is obtained when the correct location is assumed in both cases.
The two possible fault locations 20 km from the substation is shown in Figure 6.

![Figure 6. Two fault locations 20 km from the substation.](image)

For faults 25 km from the substation, the results were equally good.

Another possibility is to calculate a distance based on the DG-measurements, and compare with the distance estimate from the substation measurements to find the correct fault location. However, the estimated distance from the DG to the fault location will not be correct when the fault is located on the side branch or after the DG-node. This is due to the effect of side-infed from the substation in these cases. Thus this does not seem like a sufficient approach.

8 CONCLUSION

The paper presents two methods for correction of errors due to DG and load in the impedance measured by the substation distance relay. These errors are largest when the fault is located close to the feeder-end. DG-units connected close to the substation have the highest impact on the measured impedance. For a real feeder, measurement errors and inaccurate line data may contribute to additional errors in the distance estimate.

If an accuracy of +/- 1 km is required in the fault localization for the presented 30 km feeder, the conventional distance relay is good enough if the DG-unit is located 25 km or more from the substation for the low load case. For the high load case it is accurate enough only for the case when the DG is connected 15 km from the substation.

In method A, the pre-fault measurements from the DG are utilized for estimating the DG-current during fault. This method works well for two-phase short-circuits, and the accuracy of the fault localization is within 1 km in all cases. For three-phase short-circuits the estimated DG-current tends to be too high, resulting in over-compensation of the impact from the DG. The error in the fault localization is larger than 1 km in most cases.

In method B, the DG-current magnitude during fault is measured. This results in more accurate distance estimates, especially for three-phase short-circuits. The accuracy of the fault localization is within the limit of +/- 1 km for all cases.

The methods are not meant for protection, only for fault localization. Thus, communication speed is not critical. Only current and voltage magnitudes need to be communicated. Phase angles are estimated from the simplified equivalent circuit.

Measurements from the DG-node during fault can be utilized for deciding the most probable fault location when more than one candidate location is found. With more laterals or several DG-units connected to the feeder, it might be more difficult to distinguish between possible locations than for the presented feeder.

REFERENCES


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<td>0.21</td>
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<tr>
<td>Fault assumed on side branch</td>
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Table 1. $|\Delta U_{DG}|$ for two faults 20 km from the substation