Localization of Phase-to-Phase Faults on a Medium Voltage Feeder with Distributed Generation

Jorun Irene Marvik, Hans Kristian Høidalen, Astrid Petterteig

***Abstract*—This paper presents a localization procedure for phase-to-phase short-circuits on a medium voltage (MV) feeder with distributed generation (DG). The distance from the substation to the fault location is estimated from the fundamental frequency voltage and current measured in the substation. Loads and DG-units connected along the feeder are shown to have opposite impacts on the estimated distance. The current drawn by loads cause the estimate to become too small. DGs feed current to the fault, and cause the estimate to become too large. The net impact of a DG is larger than that of an equally sized load, since the DG current increases in a fault situation while the load current decreases.**

Two methods to compensate for these errors are presented. 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 magnitudes of both DG-current and DG–voltage during fault are measured. The goal is to obtain sufficiently accurate fault localization, while taking into account that the use of measurements from other locations than the substation should be kept at a minimum.

***Keywords*: Fault localization, Medium Voltage Network, Distributed Generation, Three-phase short-circuit, Two-phase short-circuit, Fundamental frequency components**

I. Introduction

It has become more common to have generation units connected at distribution level. In Norway, a lot of small hydro power plants are being built, and connected to overhead distribution networks in rural areas. DG introduces some new challenges related to voltage quality, stability and fault handling in the distribution networks.

With an increased focus on power quality, fast and efficient fault handling becomes more important. Traditional manual sectioning of faults is very time-consuming. Today, with remote control of breakers becoming more common, fast remote controlled sectioning is possible provided that accurate fault localization is available.

In MV networks without DG, the challenge of fault localization is to minimize the impact of loads and fault resistance. Different methods [1] and lots of literature on this are available. Fault localization methods using fundamental frequency measurements in the substation, can utilize pre-fault measurements to minimize the impact from load on the distance estimate [2]-[4]. This approach seems to work well for feeders without DG. Fault localization in networks with DG using fundamental frequency measurements is treated in [5]. [6]-[8] deals with more advanced methods based on fault transients, adaptive protection schemes and relay agents.

This paper looks into possibilities for precise localization of three- and two-phase short-circuits, utilizing fundamental frequency currents and voltages. It is shown how load and DG introduce substantial errors in the distance estimate from traditional distance relays. Two methods to compensate for these errors are developed and tested with simulated data.

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II. MV-feeder model, simulated in PSCAD

A simple 30 km long, 22 kV MV feeder with up to 3 DG-units, shown in Fig. 1, is modeled in PSCAD. The DG-units are synchronous generators, operating at unity power-factor. High load (HL) for the feeder is 6 MVA, and low load (LL) is 1.5 MVA. The voltages and currents values during fault are sampled 40 ms (2 periods) after the fault inception.

U_S, I_S: substation voltage and current
U_{DG}, I_{DG}: voltage in DG connection point and DG current.
f-main/f-side: fault located on the main branch/side-branch.
2-ph./3-ph.: two-phase/three-phase short-circuit.

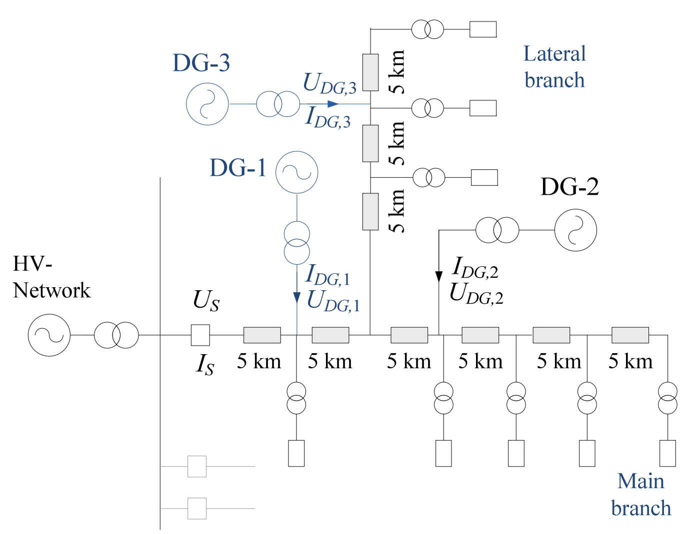

Fig. 1. Radial feeder with DG

III. Distance to Fault Estimation Based on Impedance from Substation Measurements

The distance from the substation to the fault location, d_S, can be estimated from the voltage and current measured in the substation. In order to minimize the influence from fault resistance, the imaginary part is used for distance estimation. Equation (1) give an estimate of the distance to a phase-to-phase short-circuit when phases B and C are involved [9].

$$d_S = \mathrm{Im}\left(\frac{U_S^B - U_S^C}{I_S^B - I_S^C}\right)\cdot\frac{1}{X_l} \tag{1}$$

Where X_l is line reactance per unit of length, and superscripts B and C denote phase voltages and currents.

The distance 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 cause errors in the distance estimate. This is shown in Fig. 2-4.

Δd_{Sf}, distance estimate error, is estimated minus real distance to the fault location. The error is positive when the estimated distance is to large, and negative when the estimated distance is too short.

One specific case is marked by a small circle in the plots. This is the case with one DG-unit connected 15 km from the substation, generating 3 MW at low load. The fault is a 2-phase short-circuit 30 km from the substation. This mark is meant to make it simpler to compare the different plot.

A. One DG-unit

Fig. 2 shows the distance estimate error when the faults are located at the end of the feeder (30 km from the substation, on the main branch) in all cases, and the DG-connection point is varied along the main branch. There is one DG-unit generating 3 MW (3M) or 6 MW (6M). All cases are at low load.

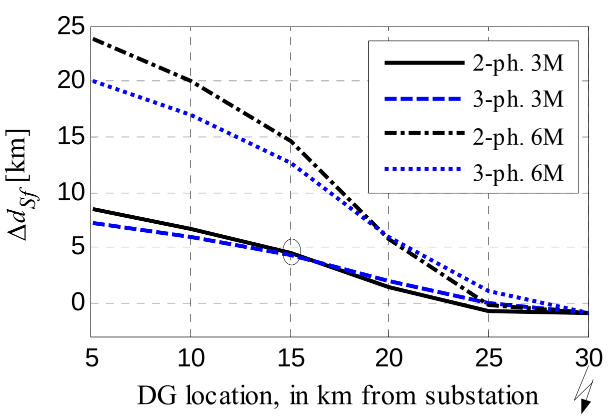

Fig. 2. Δd_{Sf} for faults at the end of the feeder, on the main branch. There is one DG-unit, and the connection point is varied. Low load.

The DG cause a positive error in the distance estimate, while the load cause a negative error. The distance estimate error is largest when the DG-unit is connected at the beginning of the feeder (5 km from the substation), and the fault is a two-phase short-circuit. The error increases substantially with the DG-size. While the maximum error is 8 km in the case with a 3 MW DG, it is 24 km with a 6 MW DG. Thus, a doubling of the DG-power results in a triplication of the distance estimate error in this case. If the DG is located 25-30 km from the substation, the error is very small.

Fig. 3 shows the distance estimate error when one 3 MW DG is connected 15 km from the substation on the main branch, and the fault location is varied. All faults are 2-phase short-circuits.

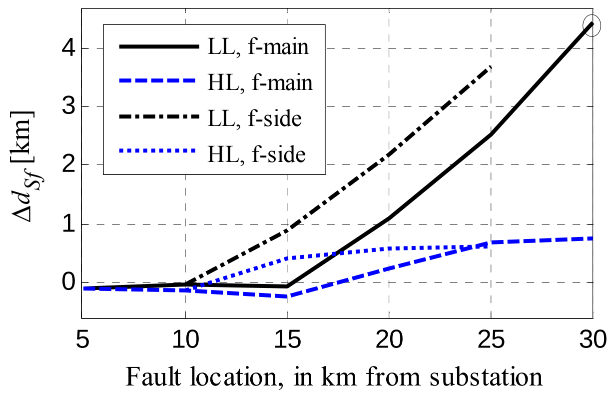

Fig. 3. Δd_{Sf} with the DG connected 15 km from the substation on the main branch, and the fault location is varied. All faults are 2-phase short-circuits.

The DG has negligible impact on the distance estimate for faults located on the main feeder branch, before the DG connection point. The errors seen in these cases are mainly due to load. These are negative errors and largest for the high load case. For faults on the side-branch the DG has the same impact as for a fault located after the DG-connection point, which is to increase the distance estimate error. A positive error means that the impact from the DG-unit dominates over the impact from the load. Similar curves for 3-phase short-circuits are shown in [10].

B. Three DG-units generating 1 MW each

Fig. 4 shows the distance estimate error with three DG-units connected to the feeder, as shown in Fig. 1, when the fault location is varied. Each DG is generating 1 MW, and all faults are 2-phase short-circuits.

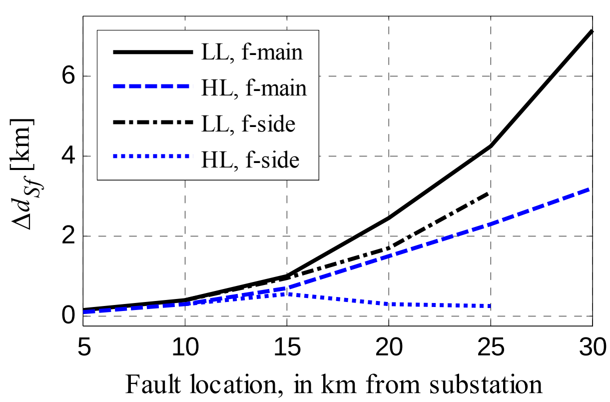

Fig. 4. Δd_{Sf} with 3 DG units, generating 1 MW each, and the fault location is varied. All faults are 2-phase short-circuits.

The distance estimate error is positive for all fault locations, thus the DG-infeed is always larger than the load consumption. The error is increasing as the short-circuit is moved farther away from the substation, confirming that a fault at the feeder-end is the worst-case.

IV. Load Estimation for Feeder with One DG, Utilizing Pre-Fault DG-Node Voltage Measurement

A simplified feeder model is used for analytical calculations. In this model, loads are included as shunts in a pi-equivalent, as shown in Fig. 5.

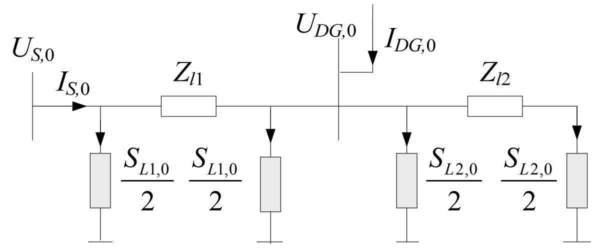

Fig. 5. Simplified representation of the feeder for analytical study. Loads are included as shunts in two pi-equivalents.

If the pre-fault value of the voltage magnitude in the DG connection point, $|U_{DG,0}|$, is known, the load between the substation and the DG, $|S_{L1,0}|$, can be estimated from a second order equation [10]. To be able to solve this equation, the phase-angle of the loads, $\varphi_{L,0}$, must be known. The utility companies are assumed to have knowledge about this angle. Since the DG-load is known, the total load can be estimated, and the remaining load can be assigned to the load after the DG connection point, $S_{L2,0}$. The estimated load also includes the loads on side-branches.

Knowing $S_{L1,0}$, the DG-voltage phasor can be estimated:

$$U_{DG,0} = U_{S,0} - Z_{l1}\left(I_{S,0} - 0.5\cdot\left(S_{L1,0}/U_{S,0}\right)^*\right) \tag{2}$$

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

The load current during fault, I_L, is estimated using a static load model [11]:

$$I_L = \left(\frac{S_L}{U}\right)^* = \frac{1}{U^*}\left(P_{L,0}\cdot\left(\frac{|U|}{|U_0|}\right)^{NP} - jQ_{L,0}\cdot\left(\frac{|U|}{|U_0|}\right)^{NQ}\right) \tag{3}$$

U_0, U: voltage across the load, pre-fault and during fault
P_0, Q_0: pre-fault active and reactive power of load
NP, NQ: voltage dependency factor for P and Q.

The impact from DG and load on the distance estimate can be compensated for when the load and DG currents are known or estimated. The new distance estimate is obtained from:

$$Z_{comp} = \frac{U_S^B - U_S^C}{\left(I_S^B - I_L^B + I_{DG}^B\right) - \left(I_S^C - I_L^C + I_{DG}^C\right)} \tag{4}$$

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

V. Utilizing Pre-Fault Measurements from DG for Fault Localization (Compensation A)

The DG-current during fault needed in (4) has to be measured or estimated. In this chapter, pre-fault measurements from the DG-unit are utilized for estimating this current. Only magnitude values of voltage and current and the phase-angle are measured ($|U_{DG,0}|$, $|I_{DG,0}|$, $\varphi_{DG,0}$). The advantage of not requiring phasors, is that the time-synchronization between measurements from the DG and the substation do not need to be as accurate as for instantaneous measurements.

A. Assuming constant transient internal emf

In the transient state, the generator can be represented by constant d- and q-axis transient emfs E_q' and E_d' 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 [12]:

$$E_d' = E_{d0}' \quad \wedge \quad E_q' = E_{q0}' \tag{5}$$

This property, (5), is utilized for calculating the DG-current during fault.

The DG voltage during fault can be estimated the same way as in (2), with the load calculated using (3).

To calculate the pre-fault transient internal emfs, the angle between a reference axis and the q-axis, $\angle E_{q0}$, has to be found. The angle is shown in Fig. 6. Phase A is used as the reference-axis that gives the reference angle for all measurements on the feeder. The d-axis is leading the q-axis by 90º.

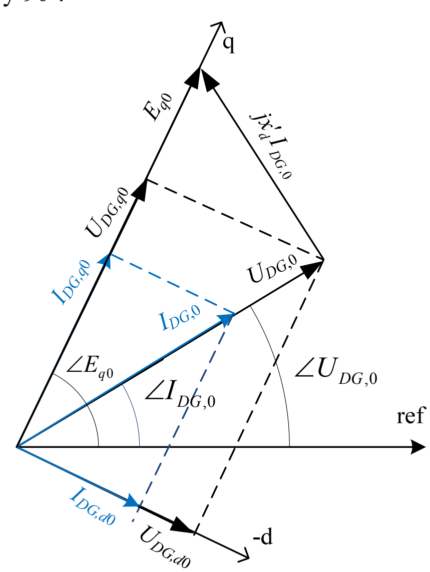

Fig. 6. Phasor-diagram for the DG-unit, in the pre-fault state

For a round-rotor machine the angle of the q-axis is found by calculating steady-state q-axis internal emf, E_{q0}:

$$E_{q0} = U_{DG,0} + j\cdot x_{DG,d} I_{DG,0} \tag{6}$$

By decomposing the DG-current and -voltage to the d- and q-axes, the transient internal emfs can be calculated (7).

$$E'_{d0} = U_{DG,d0} + \left(x'_{DG,q} \cdot I_{DG,q0}\right)$$
$$E'_{q0} = U_{DG,q0} - \left(x'_{DG,d} \cdot I_{DG,d0}\right) \quad (7)$$

$x'_{DG,d}, x'_{DG,q}$ include the transformer reactance in addition to the transient reactances of the generator.

B. Estimation of 3-phase short-circuit current for DG

Only positive sequence components are present during a three-phase short-circuit, and the amplitude values are equal in all three phases. The DG can be represented by a positive sequence equivalent, as shown in Fig. 7.

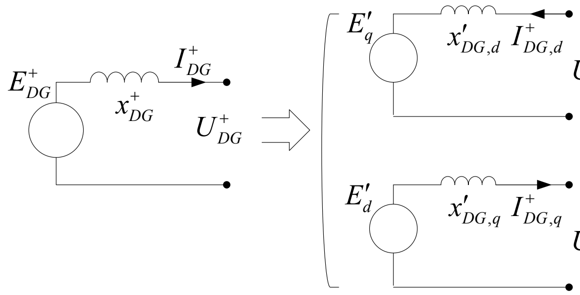

Fig. 7. Positive sequence equivalent circuit for the transient state

The d- and q-axis components of the currents are:

$$I_{DG,q} = \left(E'_d - U_{DG,d}\right) / x'_{DG,q}$$
$$I_{DG,d} = -\left(E'_q - U_{DG,q}\right) / x'_{DG,d} \quad (8)$$

And the resultant current magnitude is:

$$\left|I_{DG}\right| = \sqrt{\left(I_{DG,q}\right)^2 + \left(I_{DG,d}\right)^2} \quad (9)$$

Table 1 shows the calculated DG-current magnitudes for different DG-locations together with values from simulations, for comparison. The DG-locations are given in km from the substation, on the main feeder branch.

TABLE 1
ESTIMATED AND MEASURED DG-CURRENT MAGNITUDES FOR 3-PHASE SHORT-CIRCUITS AT THE FEEDER END

DG location [km]	$\lvert I_{DG} \rvert$ [pu] Low load (LL)		$\lvert I_{DG} \rvert$ [pu] High load (HL)	
	estimated	measured	estimated	measured
5	0.84	0.72	0.80	0.69
10	0.98	0.84	0.95	0.82
15	1.15	0.99	1.12	0.96
10	1.35	1.18	1.31	1.15
25	1.61	1.42	1.54	1.36

The estimated values are larger than the measured values. The reason for this is probably that transient reactance values that are used in the calculation, corresponds to a time in the short-circuit course earlier than 40 ms after fault inception, which is the time when the substation values are sampled.

C. Estimation of 2-phase short-circuit current for DG

For a two-phase short-circuit the generator has to be represented by a negative sequence equivalent in addition to the positive sequence equivalent shown in Fig. 7. The positive and negative sequence representations of the feeder are connected in parallel at the fault location. The negative sequence representation of the DG is shown in Fig. 8.

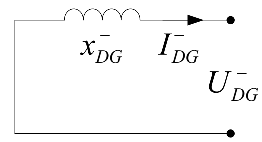

Fig. 8. Negative sequence equivalent circuit for the transient state

The phase voltages in the DG-node during fault are estimated in a similar way as in (2). The positive and negative sequence components are given by (10), where $h = e^{j2\pi/3}$.

$$U^+_{DG} = 1/3 \cdot \left(U^A_{DG} + hU^B_{DG} + h^2 U^C_{DG}\right)$$
$$U^-_{DG} = 1/3 \cdot \left(U^A_{DG} + h^2 U^B_{DG} + hU^C_{DG}\right) \quad (10)$$

Then the d- and q-axis components of the positive sequence DG-current are estimated from:

$$I^+_{DG,q} = \left(E'_d - U^+_{DG,d}\right) / x'_{DG,q}$$
$$I^+_{DG,d} = -\left(E'_q - U^+_{DG,q}\right) / x'_{DG,d} \quad (11)$$

The negative sequence DG-current is:

$$I^-_{DG} = -U^-_{DG} \big/ \left(j \cdot x^-_{DG}\right) = -U^-_{DG} \Big/ \left(j \cdot \sqrt{x''_{DG,d} x''_{DG,q}}\right) \quad (12)$$

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

$$I^B_{DG} = h^2 I^+_{DG} + hI^-_{DG} + I^0_{DG}$$
$$I^C_{DG} = hI^+_{DG} + h^2 I^-_{DG} + I^0_{DG} \quad (13)$$

The zero sequence component, I^0_{DG}, is equal to zero.

Table 2 shows calculated DG-current magnitudes together with the simulated values for different DG-locations.

TABLE 2
ESTIMATED AND MEASURED DG-CURRENT MAGNITUDES FOR 2-PHASE SHORT-CIRCUITS AT THE FEEDER END FOR LOW LOAD (LL) AND HIGH LOAD (HL)

DG location [km]	$\lvert I^B_{DG} \rvert$ [pu] estimated		$\lvert I^B_{DG} \rvert$ [pu] measured		$\lvert I^C_{DG} \rvert$ [pu] estimated		$\lvert I^C_{DG} \rvert$ [pu] measured	
	LL	HL	LL	HL	LL	HL	LL	HL
5	0.92	0.88	0.84	0.81	0.66	0.63	0.62	0.59
10	1.11	1.07	1.02	0.99	0.73	0.71	0.70	0.68
15	1.31	1.27	1.21	1.18	0.85	0.82	0.84	0.81
20	1.62	1.56	1.51	1.48	0.99	0.94	1.06	1.02
25	1.95	1.89	1.87	1.83	1.19	1.11	1.38	1.28

The estimated values are larger than the measured values, but the difference is less than it was for three-phase short-circuits. The negative sequence reactance of the generator, unlike the positive sequence reactance, is constant through the short-circuit course. Therefore, it is less critical that the DG-measurements are sampled at the exact same instant as the substation measurements for a two-phase short-circuit.

D. Results with compensation A

The distance estimate errors with compensation A for faults 30 km from the substation, on the main branch, are shown in

Fig. 9. There is one DG-unit, generating 6 MW or 3 MW, and the connection point is varied along the main branch. The results can be compared to Fig. 2.

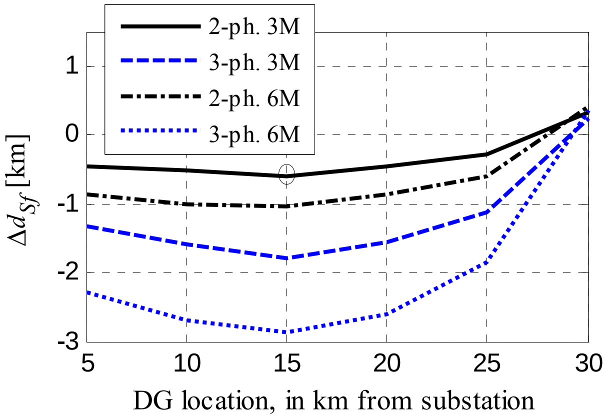

Fig. 9. Δd_{Sf} with compensation A. All faults are at the end of the feeder, while the connection point of the DG is varied. Low load.

The compensation is best for two-phase faults. For three-phase faults, all estimated DG-currents are higher than the real values. Thus there is an overcompensation of the impact from the DG. The result is a negative distance estimate error when the compensation is applied. Still, the result is much better than in Fig. 2, without any compensation.

Fig. 10 shows distance estimate errors with compensation A when the DG is located 15 km from the substation, on the main feeder branch. The results can be compared to Fig. 3.

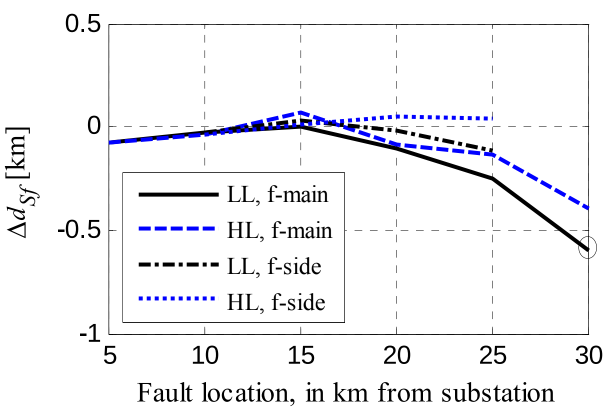

Fig. 10. Δd_{Sf} with compensation A. The DG is connected 15 km from the substation. The faults are 2-phase short-circuits at varying locations.

The distance estimate error is significantly reduced when the compensation is applied, compared to Fig. 3. The errors were positive without compensation, but are generally negative with compensation. The difference between the estimated DG-currents in phase B and C is larger than the simulated values, and the negative error is due to over-compensation of the DG fault-currents.

VI. Utilizing Measurements from the DG-node during Fault (Compensation B)

For compensation method B the DG-current and DG-node voltage magnitudes during fault ($|I_{DG}|$, $|U_{DG}|$) are measured, together with the phase angle (φ_{DG}). The DG-voltage phasor angle is estimated in a similar way as in (2). Since the DG-current magnitude is measured instead of estimated as for compensation A, the result is expected to be better.

A. One DG-unit

The distance estimate errors with compensation B for faults 30 km from the substation are shown in Fig. 11. The figure can be compared to Fig. 2 and Fig. 9.

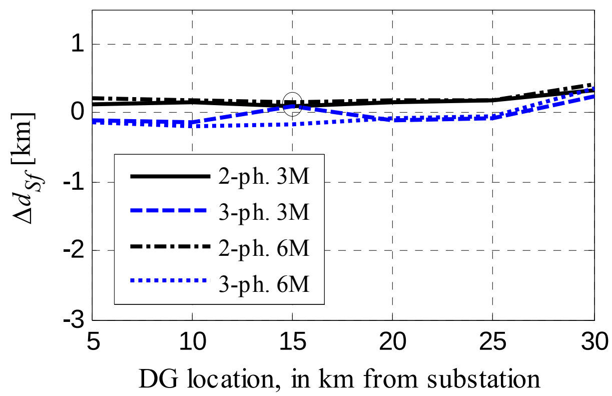

Fig. 11. Δd_{Sf} with compensation B. All faults are at the end of the feeder, while the connection point of the DG is varied. Low load.

As expected, the result is much better than with compensation A (Fig. 9), especially for 3-phase short-circuits.

Fig. 12 shows the distance estimate errors with compensation B when the DG is located 15 km from the substation, and can be compared to Fig. 3 and Fig. 10.

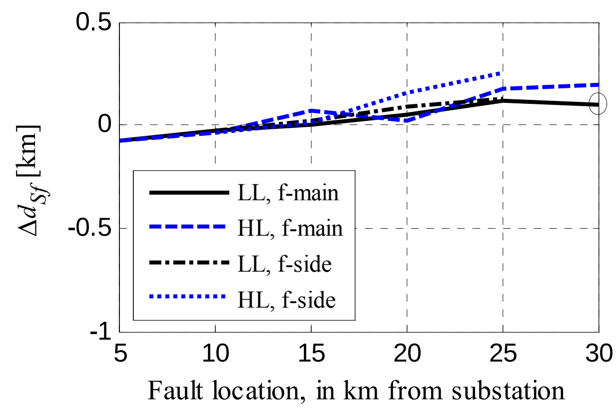

Fig. 12. Δd_{Sf} with compensation B. The DG is connected 15 km from the substation. The faults are 2-phase short-circuits at varying locations.

Compared to the result with compensation A, shown in Fig. 10, the errors are generally smaller. An exception is faults on the side-branch at high load, but the results are better than without compensation also in this case. The resulting errors are generally positive, so there is no overcompensation of the DG fault-currents. The overall errors are small, and the largest error for the cases shown is 0.25 km.

Without compensation, the estimate error for the specific case marked by a circle in the plots is 4.5 km. With compensation it is reduced to 0.6 km (A) and 0.1 km (B).

B. Three DG-units generating 1 MW each

Compensation method B can be used for networks with more than one DG-unit. Instead of estimating the pre-fault load flows to the sections before and after each DG-unit, they are assumed to be known. To be able to estimate the load distribution, at least the currents flowing to the main- and the side-branch need to be measured. The assumption that the utilities know the load in different sections of the feeder is not unrealistic. Automatic meter reading will provide data of the load consumption, which could be utilized in the fault localization. If accurate load data is not available, the rating of distribution transformers in combination with typical load profiles could give an estimate of the load in each section.

Fig. 13 shows the distance estimate error with compensation B for a feeder with three DG-units, located as shown in Fig. 1. Voltage and current magnitudes, and phase angle of all three DG-units are measured during fault.

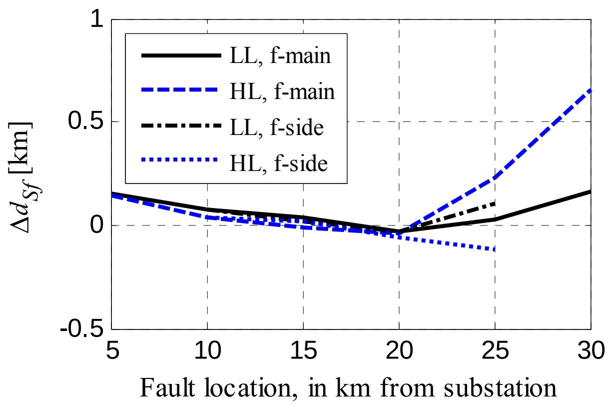

Fig. 13. Δd_{Sf} with compensation B for feeder with three DG-units. All faults are 2-phase short-circuits, and the fault location is varied.

There is a large reduction of the distance estimate error compared to the curves shown in Fig. 4, without compensation. As before, the error is smaller with compensation for low load than for high load, while it initially was opposite.

VII. Conclusion

The distance to the location of a phase-to-phase short-circuit can be estimated from the substation voltage and current. Loads and DG-units connected to the feeder cause errors in this distance estimate. The worst case for the example feeder is a two-phase short-circuit at the end of the main feeder branch, with the DG connected close (5 km away) to the substation. Low load is worse than high load, since there is less load to outweigh the impact of the DG infeed-current. In a real case, measurement errors and inaccurate line data may contribute to additional errors in the distance estimate.

This paper presents two methods for compensation of the errors due to load and DG. In compensation method A, the pre-fault power-flow from the DG is utilized to estimate the DG-current magnitude during fault. With this compensation, the distance estimate error is reduced in most cases compared to the situation with no compensation. The degree of improvement of the estimate, however, is dependent on the load level and the location of the DG-unit. The estimated DG-current tends to be too high, resulting in an over-compensation of the DG fault current.

In compensation method B, the DG-current magnitude during fault is measured. This results in more accurate distance estimates than with compensation A, especially for three-phase short-circuits, and the result is much less dependent on the location of the DG-unit. It is also shown that if the load in the different feeder sections is known, this method can be successfully used for fault localization with three DG-units.

Both presented compensation methods result in a reduction of the distance estimate error. The results are best for the low load case. For some of the high load cases only a very small improvement is obtained. The pi-equivalent representation of loads is a simplification, and the weakness of this model becomes more significant as the load is increased. Still, the simple pi-equivalent seems to be an acceptable load model.

Since phasor angles can be estimated from the simplified pi-equivalent model, only magnitude values of DG-current and -voltage are required. This means that the time-synchronization between DG- and substation measurements can be less accurate than with instantaneous values. Finally, since the compensation methods are meant for localization, and not protection, communication speed is not critical.

VIII. References

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