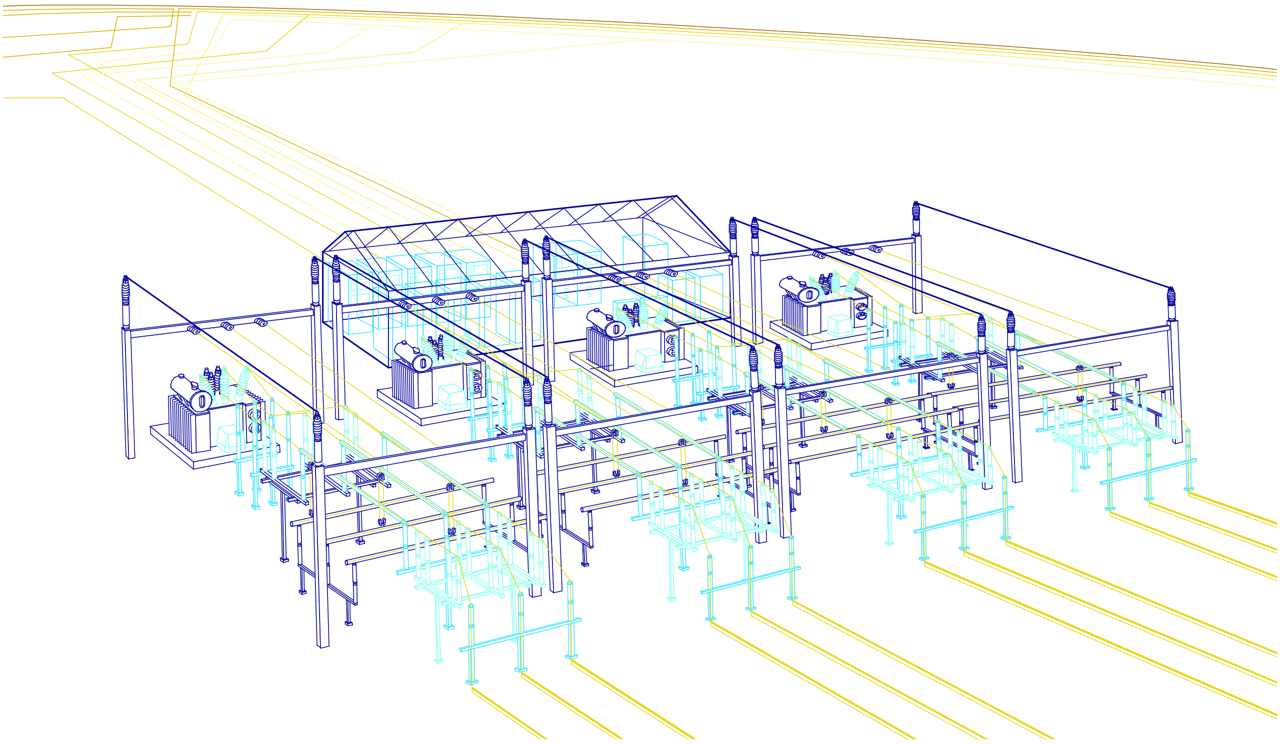
Distribution Automation Handbook

Section 8.15 Impedance-based Fault Location



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8.15 Impedance-based Fault Location

8.15.1 Introduction

As utilities today concentrate on continuity and reliability of their distribution networks, fault location has become an important supplementary function in modern IEDs. These fault location algorithms typically rely on the calculation of impedance from the fundamental frequency phasors measured in the substation. Therefore, it can be said that impedance-based methods have become an industry standard in this respect. The reason for their popularity is their easy implementation as they utilize the same signals as the other protection and measurement functions in the IEDs. Their performance has been proven quite satisfactory in locating short circuits, but improving further the performance in locating earth faults, especially in high-impedance earthed networks, is an on-going objective in the algorithm development.

Distribution networks have certain specific features which complicate and challenge fault location algorithms. These include, for example, non-homogeneity of lines, presence of laterals and load taps and the combined effect of load current and fault resistance. Typical fault location algorithms are based on the assumption that the total load is tapped to the end point of the feeder, that is, the fault is always located in front of the load point. In real distribution feeders, this assumption is rarely correct. In fact, due to voltage drop considerations, loads are typically located either in the beginning of the feeder or distributed more or less randomly over the entire feeder length. In such cases, fault location accuracy becomes easily deteriorated unless somehow taken into account in the algorithm design. The effect of the above factors on the accuracy becomes more substantial the lower the fault current magnitude in relation to the load current becomes.

In the following, basic principles of impedance-based methods are introduced, and the performance of different algorithm implementations is demonstrated using computer simulations.

8.15.2 Short Circuit Faults

8.15.2.1 Basic loop-modeling method

Like in distance protection, the impedance measurement is typically based on the concept of fault loops. The measured loop impedance used for the fault distance estimation is of the form:

$$\underline{Z}_{SC\_LOOP} = \frac{\underline{U}_{SC\_LOOP}}{\underline{I}_{SC\_LOOP}} \qquad \textbf{(8.15.1)}$$

Ideally Equation (8.15.1) produces the positive-sequence impedance $\underline{Z}_1$ to the fault point.

The voltage $\underline{U}_{SC\_LOOP}$ and current $\underline{I}_{SC\_LOOP}$ are selected in accordance with the fault type. Table 8.15.1 shows a summary of the fault loops and applied voltages and currents in the impedance calculation for typical short circuit faults.

Table 8.15.1: Voltages and currents used in the impedance calculation for short circuits

Fault type	Phases Involved	Voltage $\underline{U}_{SC\_LOOP}$ used in loop impedance calculation	Current $\underline{I}_{SC\_LOOP}$ used in loop impedance calculation
Phase-to-phase fault	A-B	$\underline{U}_{AB}$	$\underline{I}_{AB}$
	B-C	$\underline{U}_{BC}$	$\underline{I}_{BC}$
	C-A	$\underline{U}_{CA}$	$\underline{I}_{CA}$
Three-phase fault with or without earth	A-B-C(-E)	$\underline{U}_{AB}$ or $\underline{U}_{BC}$ or $\underline{U}_{CA}$ $\underline{U}_{A}$ or $\underline{U}_{B}$ or $\underline{U}_{C}$	$\underline{I}_{AB}$ or $\underline{I}_{BC}$ or $\underline{I}_{CA}$ $\underline{I}_{A}$ or $\underline{I}_{B}$ or $\underline{I}_{C}$

Because the possible fault resistance affects the measured fault loop impedance, the distance estimation is always based on the reactive part of the $\underline{Z}_{SC\_LOOP}$, that is, X_{SC_LOOP}. This fault loop reactance is then converted to physical distance by using the specified positive-sequence reactance value per kilometer of the conductor type of which the faulted feeder is composed.

However, especially in distribution networks the accuracy of the above loop model is also affected by the load current magnitude and its distribution along the feeder. These factors make the measured impedance from the IED location to appear typically too low. In case there is distributed generation along the feeder, this impedance can also be seen as too high. In the following, two basic scenarios are analyzed using simplified circuit models.

8.15.2.1.1 Short circuit behind load or generation tap

Figure 8.15.1 shows a situation where a three-phase fault occurs behind a single load or distributed generation tap.

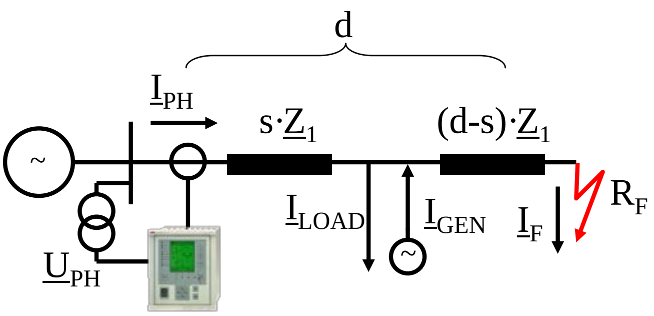

Figure 8.15.1: Three-phase fault occurs behind a single load or distributed generation tap

According to Figure 8.15.1, the equations for measured voltage and impedance from the IED location are:

$$\underline{U}_{SC\_LOOP} = s \cdot \underline{Z}_1 \cdot \underline{I}_{PH} + (d-s) \cdot \underline{Z}_1 \cdot (\underline{I}_{PH} + \underline{I}_{GEN} - \underline{I}_{LOAD}) + R_F \cdot (\underline{I}_{PH} + \underline{I}_{GEN} - \underline{I}_{LOAD})$$
$$\underline{Z}_{SC\_LOOP} = d \cdot \underline{Z}_1 + R_F + ((d-s) \cdot \underline{Z}_1 + R_F)(\underline{I}_{GEN} - \underline{I}_{LOAD}) / \underline{I}_{PH} \qquad \textbf{(8.15.2)}$$

Equation (8.15.2) clearly shows the effect of the ratios $\underline{I}_{LOAD}/\underline{I}_{PH}$ and $\underline{I}_{GEN}/\underline{I}_{PH}$ together with a possible fault resistance R_F on the estimated impedance to the fault point when Equation (8.15.1) is used for estimation. In these cases, the correct impedance value would be $d\underline{Z}_1 + R_F$.

8.15.2.1.2 Short circuit in front of load or generation tap

Figure 8.15.2 shows a situation where a three-phase fault occurs in front of a single load or distributed generation tap.

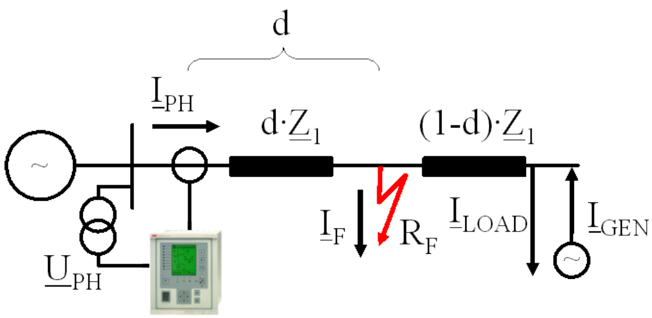

Figure 8.15.2: Three-phase fault occurs in front of a single load or distributed generation tap

According to Figure 8.15.2 the equations for measured voltage and impedance from the IED location are:

$$\underline{U}_{SC\_LOOP} = d \cdot \underline{Z}_1 \cdot \underline{I}_{PH} + R_F \cdot (\underline{I}_{PH} + \underline{I}_{GEN} - \underline{I}_{LOAD})$$
$$\underline{Z}_{SC\_LOOP} = d \cdot \underline{Z}_1 + R_F \cdot (1 + (\underline{I}_{GEN} - \underline{I}_{LOAD}) / \underline{I}_{PH}) \quad \textbf{(8.15.3)}$$

Due to the fault and the resulting severe voltage collapse in front of the load tap, the load current component in Equation (8.15.3) can typically be neglected. With this assumption, the effect of possible fault resistance on the estimated fault loop impedance depends on the ratio I_{GEN}/I_{PH}. As this ratio becomes lower, the estimated impedance to the fault point approaches its correct value $d\underline{Z}_1 + R_F$.

The above schemes represent the problem as simplified, because in a real distribution feeder the load is distributed along the feeder and multiple generation locations are possible. As a result, more complicated schemes must be analyzed using computer simulations. The following example illustrates this.

Example 1: The performance of the *basic loop-modeling method* is simulated in a feeder with the following data:

Main transformer:

- 110/20 kV
- S =20 MVA
- x_K =0.09 p.u

Protected feeder:

- Positive-sequence impedance, $\underline{Z}_1$, of the main line per unit length: 0.288+j0.284 Ω/km
- Total load: 4 MVA (evenly distributed)

Distributed generation (synchronous generator):

- Capacity: 1 MVA
- x'_D =0.155 p.u
- Operation mode: fixed $\cos(\varphi)$

A three-phase fault was simulated at steps of 0.1 p.u line length. The location of the distributed generation was fixed to 0.5 p.u. The applied fault resistance represents the estimated maximum value of 2.5 Ω.

Figure 8.15.3 shows the results.

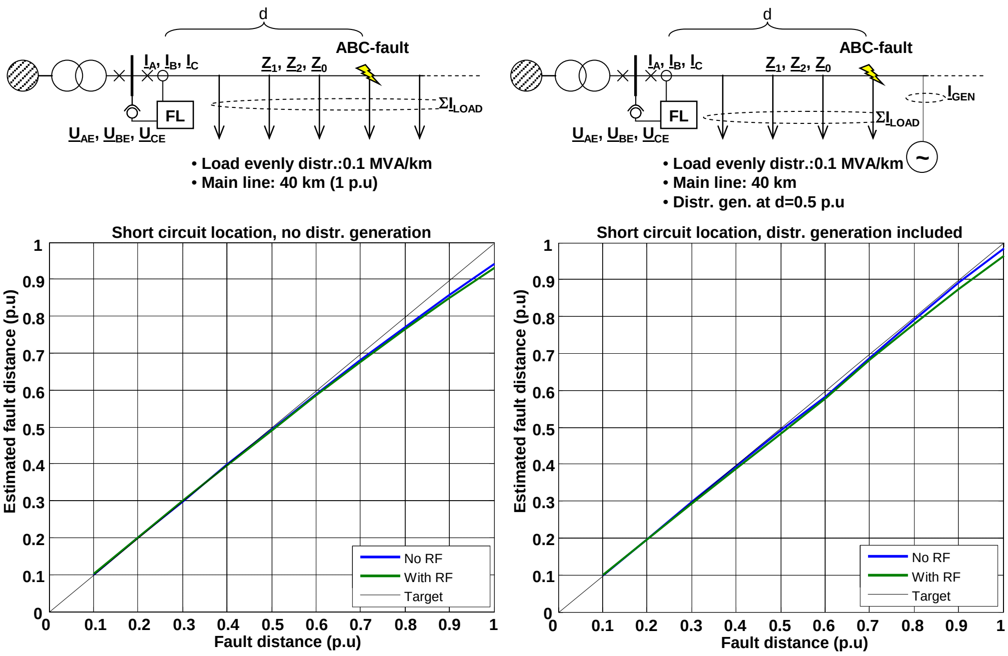

Figure 8.15.3: Simulated fault location estimates using the basic loop modeling method. Left: no distributed generation, right: distributed generation included.

Considering the case without a distributed generation, it can be seen that the lower the ratio $I_{PH}/\Sigma I_{LOAD}$ during the fault becomes, the higher is the error in the impedance estimation. This ratio decreases as the fault spot moves towards the end of the feeder. The current term ΣI_{LOAD} is the total load current during the fault. When the distributed generation is included, the error at fault points behind the generation point is affected additionally by the ratio I_{PH}/I_{GEN}. Typically, there will be an increase in the measured impedance as can also be seen in this case. To mitigate the errors, *load compensation* together with the *advanced loop-modeling method* can be incorporated.

8.15.2.2 Advanced loop-modeling method

The calculation model of the basic loop-modeling method assumes that the same current flows through each impedance element of the loop. As seen above, this assumption generates errors in the impedance estimation. One way of improving the model is to use a different current quantity depending on the loop impedance element in question. For example, estimate of the actual fault current is modeled to flow only through the fault resistance, while the measured phase current is assumed to flow through the positive-sequence impedance of the feeder. This kind of modeling in fact introduces the *load compensation* feature. Figure 8.15.4 demonstrates this principle.

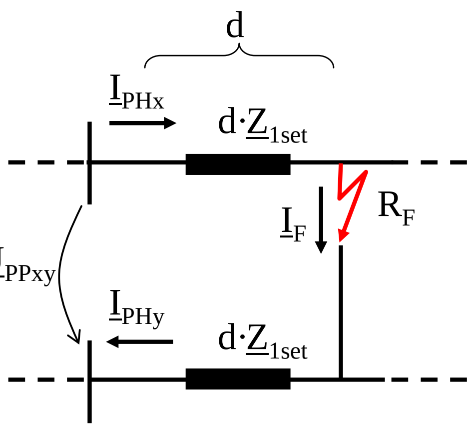

Figure 8.15.4: Loop model for a phase-to-phase fault

According to Figure 8.15.4, the following equations can be written with d and R_F as unknown parameters.

$$\begin{aligned}
\underline{U}_{PPxy} &= d \cdot \underline{Z}_{1set} \cdot \underline{I}_{PHxy} + R_F \cdot \underline{I}_F \\
\underline{I}_{PHxy} &= (\underline{I}_{PHx}(fault) - \underline{I}_{PHy}(fault)) - k \cdot (\underline{I}_{PHx}(pre) - \underline{I}_{PHy}(pre)) \\
\underline{I}_F &= (\underline{I}_{PHx}(fault) - \underline{I}_{PHy}(fault)) - (\underline{I}_{PHx}(pre) - \underline{I}_{PHy}(pre))
\end{aligned} \qquad \textbf{(8.15.4)}$$

where

$(fault)$ refers to the time instant during the fault

(pre) refers to the time instant before the fault

The parameter k is known as the *load reduction factor*. With this parameter, it is tried to compensate the effects of load distribution and voltage dependability of the load on the fault location estimate. However, a typical assumption for the parameter k would equal 0. This assumes that during the fault, the total fault current together with the load current flows through the positive-sequence impedance of the feeder to the fault point. It is also assumed that the estimate for the fault current at the fault point is obtained by subtracting the total pre-fault load current from the current measured from the feeder during the fault. In Figure 8.15.4, the term $\underline{Z}_{1set}$ is the positive-sequence impedance of the protected feeder. In case of a distribution feeder with branch lines, this impedance is typically selected according to the total impedance of the main line. Therefore, $\underline{Z}_{1set}$ is a known parameter and a setting value for this calculation method. The variables d and R_F can be solved from Equation (8.15.4) by dividing it into real and imaginary parts:

$$\begin{cases}
\mathrm{Re}(\underline{U}_{PPxy}) = d \cdot \mathrm{Re}(\underline{Z}_{1set} \cdot \underline{I}_{PHxy}) + R_F \cdot \mathrm{Re}(\underline{I}_F) \\
\mathrm{Im}(\underline{U}_{PPxy}) = d \cdot \mathrm{Im}(\underline{Z}_{1set} \cdot \underline{I}_{PHxy}) + R_F \cdot \mathrm{Im}(\underline{I}_F)
\end{cases} \qquad \textbf{(8.15.5)}$$

Equation (8.15.5) consists of two equations with two unknown variables d and R_F which can therefore be solved by further calculus as the values of voltage $\underline{U}_{PPxy}$ and currents $\underline{I}_{PHxy}$ and $\underline{I}_F$ are obtained from the measurements.

The effect of using the advanced loop model is studied by repeating the previous simulations with this impedance estimation method implemented.

Example 2: The performance of the *advanced loop-modeling method* is simulated in a feeder with the data from Example 1:

The load reduction factor has been estimated based on the network data typically available in the DMS-system of the utility. Here a load reduction factor of 0.22 has been used.

Figure 8.15.5 shows the results.

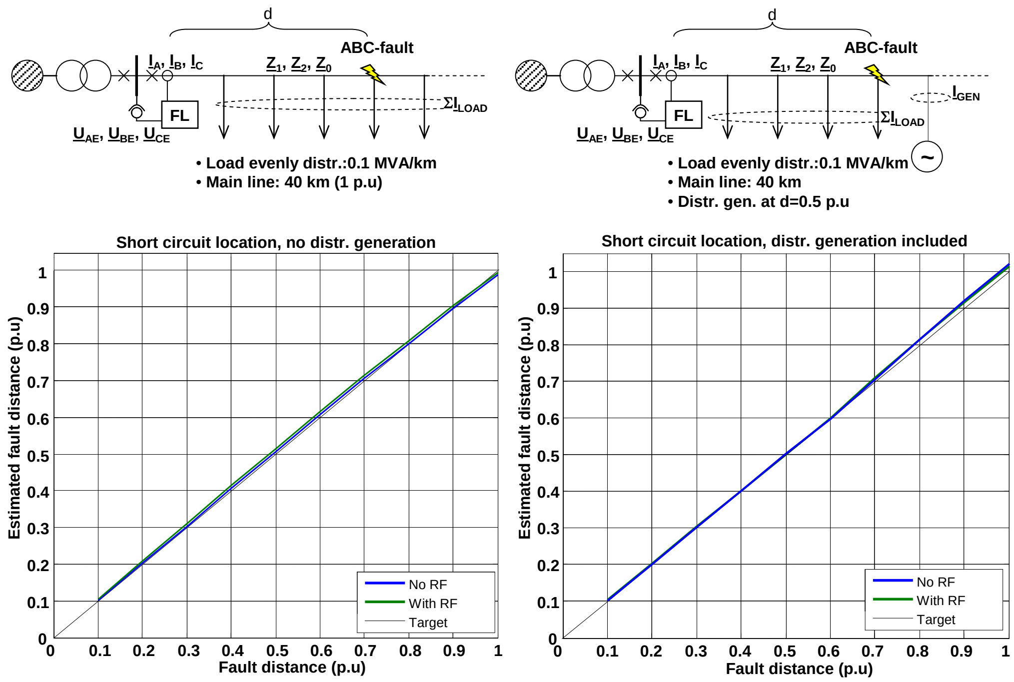

Figure 8.15.5: Simulated fault location estimates using the loop-modeling method. Left: no distributed generation, right: distributed generation included.

In conclusion, more accurate modeling decreases the errors as can be seen in the results of Figure 8.15.5.

8.15.3 Earth Faults

8.15.3.1 Basic loop-modeling method

In case of earth faults, the measured loop impedance consists of the positive-sequence impedance $\underline{Z}_1$ as the ”go” path impedance and $\underline{Z}_N$ as the ”earth return” path impedance. The impedance to the fault point is estimated from the equation:

$$\underline{Z}_{EF\_LOOP} = \frac{\underline{U}_{EF\_LOOP}}{\underline{I}_{EF\_LOOP}} \quad \textbf{(8.15.6)}$$

Ideally, Equation (8.15.6) produces the sum of positive-sequence impedance $\underline{Z}_1$ and the earth return path impedance $\underline{Z}_N$ to the fault point.

The voltage $\underline{U}_{EF\_LOOP}$ and current $\underline{I}_{EF\_LOOP}$ are selected in accordance with the fault type. Table 8.15.2 shows a summary of the fault loops and applied voltages and currents in the impedance calculation for earth faults:

Table 8.15.2: Voltages and currents used in the impedance calculation for earth faults

Fault type	Phases involved	Voltage $\underline{U}_{EF\_LOOP}$ used in loop impedance calculation	Current $\underline{I}_{EF\_LOOP}$ used in loop impedance calculation
Phase-to-phase fault	A-E	$\underline{U}_A$	$\underline{I}_A$
	B-E	$\underline{U}_B$	$\underline{I}_B$
	C-E	$\underline{U}_C$	$\underline{I}_C$
Two-phase-to-earth fault	A-B-E B-C-E C-A-E	$\underline{U}_A$ or $\underline{U}_B$ $\underline{U}_B$ or $\underline{U}_C$ $\underline{U}_C$ or $\underline{U}_A$	$\underline{I}_A$ or $\underline{I}_B$ $\underline{I}_B$ or $\underline{I}_C$ $\underline{I}_C$ or $\underline{I}_A$

As in short circuit faults, the possible fault resistance affects the measured fault loop impedance, the distance estimation is always based on the reactive part of $\underline{Z}_{EF\_LOOP}$, that is, X_{EF_LOOP}. This effect is now more substantial as higher fault resistances can be expected in case of earth faults. The fault loop reactance is then converted to physical distance by using the specified positive-sequence and earth return path reactance values per kilometer of the conductor type of which the faulted feeder is composed.

The accuracy of the above loop model is also affected by the load current magnitude and its distribution along the feeder. These factors make the measured impedance from the IED location to appear typically too low. In case there is distributed generation along the feeder, this impedance can also be seen as too high. Also the magnitude of the earth-fault current without any fault resistance is typically much lower than the corresponding three-phase short circuit current. Due to these facts, the lower the earth fault current is and the higher the fault resistance becomes, more stringent requirements must be set on the accuracy of the applied loop model. In the following, the basic scenarios are again analyzed using simplified circuit models.

8.15.3.1.1 Earth fault behind load or generation tap

Figure 8.15.6 shows a situation where an earth fault occurs behind a single load or distributed generation tap.

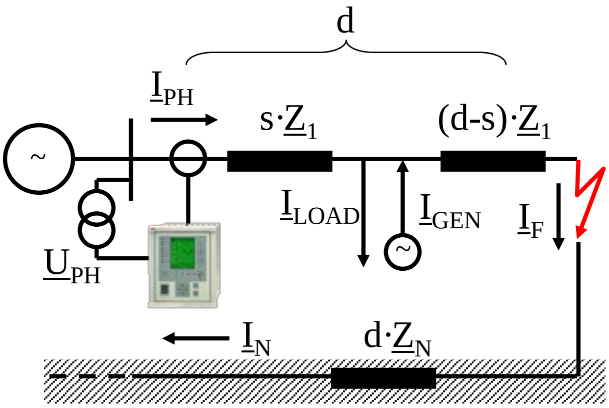

Figure 8.15.6: Single phase-to-earth fault occurs behind a single load or distributed generation tap

According to Figure 8.15.6, the equations for measured voltage and impedance from the IED location are:

$$\begin{aligned}
&\underline{U}_{EF_LOOP} = s \cdot \underline{Z}_1 \cdot \underline{I}_{PH} + (d-s) \cdot \underline{Z}_1 \cdot \underline{I}_F + R_F \cdot \underline{I}_F + d \cdot \underline{Z}_N \cdot \underline{I}_N \\
&\underline{I}_{PH} = \underline{I}_{LOAD} + \underline{I}_F - \underline{I}_{GEN} \\
&\underline{I}_N = \underline{I}_F \\
&\underline{Z}_{EF_LOOP} = d \cdot (\underline{Z}_1 + \underline{Z}_N) + R_F - ((d-s) \cdot \underline{Z}_1 + R_F + d \cdot Z_N) \cdot (\underline{I}_{LOAD} - \underline{I}_{GEN}) / \underline{I}_{PH}
\end{aligned} \tag{8.15.7}$$

Equation (8.15.7) shows the effect of the ratio $\underline{I}_{LOAD}/\underline{I}_{PH}$ and $\underline{I}_{GEN}/\underline{I}_{PH}$ together with a possible fault resistance R_F on the estimated impedance to the fault point when Equation (8.15.6) is used for the estimation. In these cases, the correct impedance value would be $d\left(\underline{Z}_1 + \underline{Z}_N\right) + R_F$.

8.15.3.1.2 Earth fault in front of load or generation tap

Figure 8.15.7 shows a situation where an earth fault occurs in front of a single load/distributed generation tap.

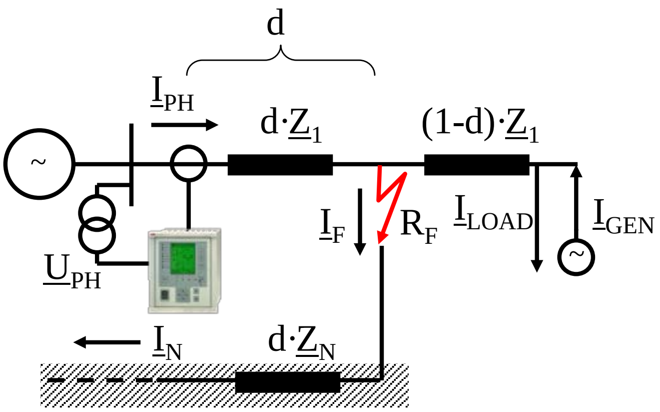

Figure 8.15.7: Single phase-to-earth fault occurs in front of a single load or distributed generation tap

According to Figure 8.15.7, the equations for the measured voltage and impedance from the IED location are:

$$\begin{aligned}
&\underline{U}_{EF_LOOP} = d \cdot \underline{Z}_1 \cdot \underline{I}_{PH} + R_F \cdot \underline{I}_F + d \cdot \underline{Z}_N \cdot \underline{I}_N \\
&\underline{I}_{PH} = \underline{I}_{LOAD} + \underline{I}_F - \underline{I}_{GEN} \\
&\underline{I}_N = \underline{I}_F \\
&\underline{Z}_{EF_LOOP} = d \cdot (\underline{Z}_1 + \underline{Z}_N) + R_F - (d \cdot \underline{Z}_N + R_F) \cdot (\underline{I}_{LOAD} - \underline{I}_{GEN}) / \underline{I}_{PH}
\end{aligned} \qquad \textbf{(8.15.8)}$$

It can be seen that even in case the load or generation is located in the end of the feeder, the simple model of Equation (8.15.8) does not produce the correct result unless the phase current equals the fault current.

The above schemes represent the problem again as simplified, because in a real distribution feeder the load and the possible generation is distributed along the feeder, and therefore more complicated schemes must be analyzed using computer simulations. The following example illustrates this.

Example 3: The performance of the *basic loop-modeling method* is simulated in a feeder with the following data:

<u>Main transformer:</u>

- 110/20 kV
- S =20 MVA
- x_K =0.09 p.u
- $I_{EF\max}$ =1000 A (low-resistance earthing in the neutral point)

Protected feeder:

- Positive-sequence impedance, $\underline{Z}_1$, of the main line per unit length: 0.288+j0.284 Ω/km
- Zero-sequence impedance, $\underline{Z}_0$, of the main line per unit length: 0.438+j2.006 Ω/km
- Earth return path impedance, $\underline{Z}_N$, of the main line per unit length: 0.05+j0.574 Ω/km
- Total load: 4 MVA (evenly distributed)

Distributed generation (synchronous generator):

- Capacity: 1 MVA
- x'_D=0.155 p.u
- Operation mode: fixed $\cos(\varphi)$

Single-phase earth fault was simulated at steps of 0.1 p.u line length. The location of the distributed generation was fixed to 0.5 p.u. The applied fault resistance equals to $1*\mathrm{Re}(\underline{Z}_1+\underline{Z}_N)$ of the whole line, that is, 14 Ω.

Figure 8.15.8 shows the results.

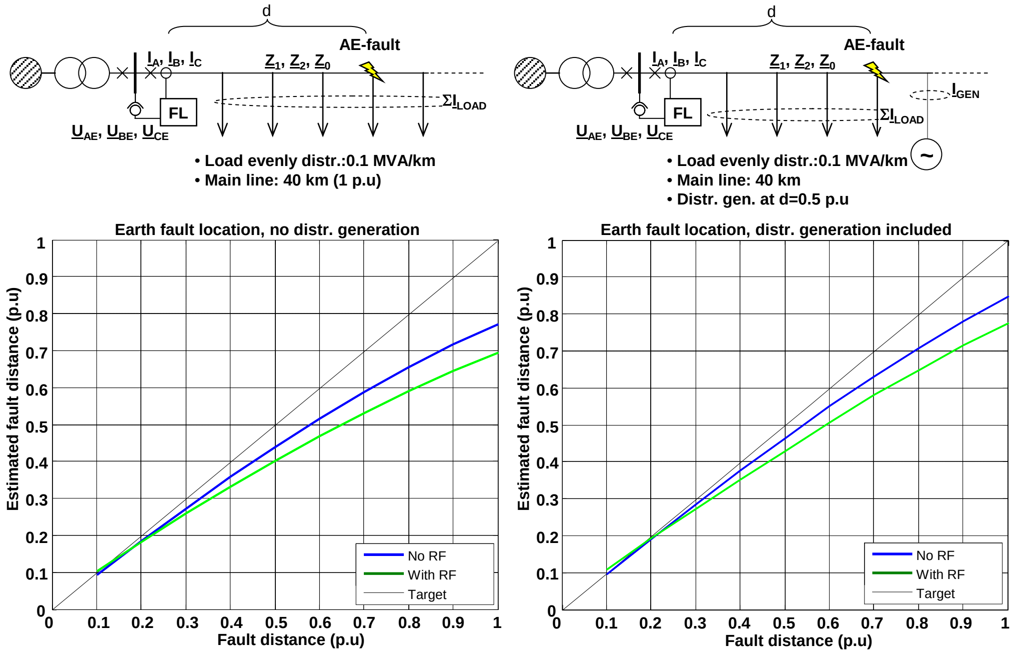

Figure 8.15.8: Simulated fault location estimates in low-resistance earthed network using the basic loop-modeling method. Left: no distributed generation, right: distributed generation included.

The conclusion from the above simulation results is that basically the lower the ratio $\underline{I}_{PH}/(\Sigma\underline{I}_{LOAD}-\underline{I}_{GEN})$ becomes during the fault, the higher is the error in the impedance estimation. This ratio also equals $1/(1-\underline{I}_F/\underline{I}_{PH})$, which clearly shows that if the measured phase current contains only the fault current, the error is reduced to zero. Also increasing of the fault resistance increases this error. To mitigate the errors, a more *advanced loop model* with *load compensation* must be incorporated.

8.15.3.2 Advanced loop-modeling methods

8.15.3.2.1 Advanced loop model with load compensation

Improving of the model can be done using again different current quantities flowing through each impedance element. For example, estimate of the actual fault current is modeled to flow only through the fault resistance. Figure 8.15.9 demonstrates this.

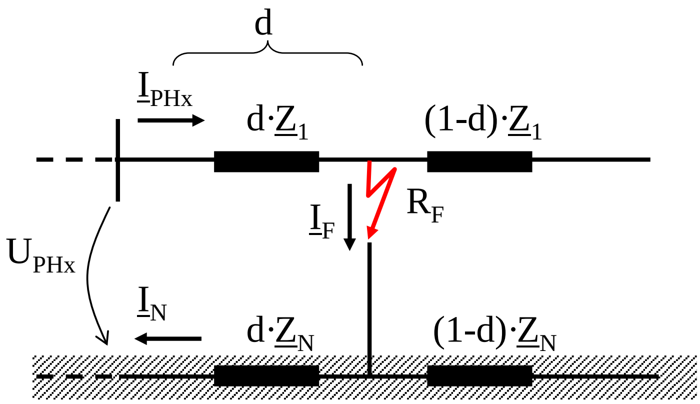

Figure 8.15.9: Loop model for phase-to-earth fault

According to Figure 8.15.9, the following equation can be written with d and R_F as unknown parameters.

$$\underline{U}_{PEx} = d\cdot\underline{Z}_{1set}\cdot\underline{I}_{PHx} + R_F\cdot\underline{I}_F + d\cdot\underline{Z}_{Nset}\cdot\underline{I}_N \qquad \textbf{(8.15.9)}$$

In Equation (8.15.9), $\underline{I}_N$ and $\underline{I}_F$ are estimations of the earth return path and fault currents respectively. Depending on the earthing method of the network, these currents can be estimated in different ways, but the most straightforward way is to assume that both $\underline{I}_N$ and $\underline{I}_F$ equal to the sum of the phase currents. Further in Equation (8.15.9), Z_{lset} is the positive-sequence impedance of the protected feeder and $\underline{Z}_{Nset}$ the impedance of the earth return path. The latter impedance is calculated simply by $(\underline{Z}_{0set}-\underline{Z}_{lset})/3$, where Z_{0set} is the zero-sequence impedance of the protected feeder. In case of a distribution feeder with branch lines, these impedances are typically selected according to the total impedance of the main line. Therefore, $\underline{Z}_{lset}$ and $\underline{Z}_{Nset}$ are known parameters and setting values for this calculation method. The variables d and R_F can be solved from Equation (8.15.9) by dividing it into real and imaginary parts:

$$\begin{cases} \mathrm{Re}(\underline{U}_{PHx}) = d \cdot \mathrm{Re}(\underline{Z}_{1set} \cdot \underline{I}_{PHx}) + R_F \cdot \mathrm{Re}(\underline{I}_F) + d \cdot \mathrm{Re}(\underline{Z}_{Nset} \cdot \underline{I}_N) \\ \mathrm{Im}(\underline{U}_{PHx}) = d \cdot \mathrm{Im}(\underline{Z}_{1set} \cdot \underline{I}_{PHx}) + R_F \cdot \mathrm{Im}(\underline{I}_F) + d \cdot \mathrm{Im}(\underline{Z}_{Nset} \cdot \underline{I}_N) \end{cases} \qquad \textbf{(8.15.10)}$$

Equation (8.15.10) consists of two equations with two unknown variables, d and R_F, which can be solved by further calculus as the values of voltage $\underline{U}_{PHx}$ and currents $\underline{I}_{PHx}$, $\underline{I}_F$ and $\underline{I}_N$ are obtained via measurements.

Example 4: The performance of the *advanced loop model with load compensation* method is simulated with the data from Example 3.

Figure 8.15.10 shows the results.

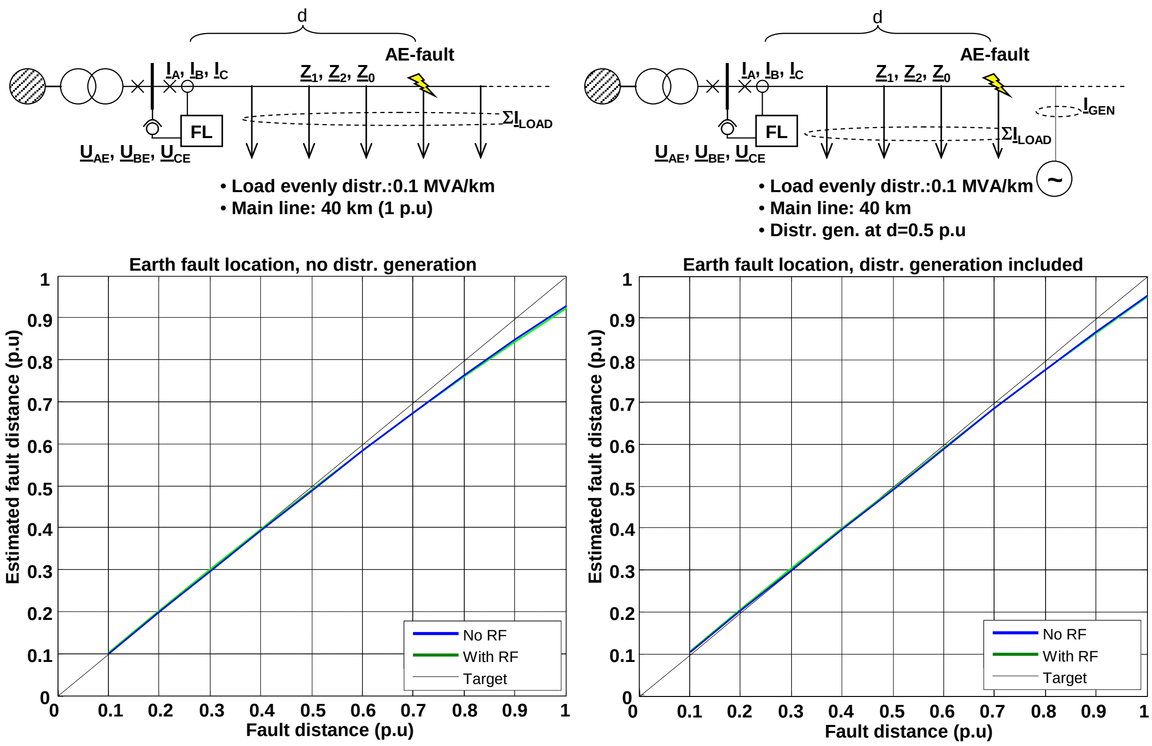

Figure 8.15.10: Simulated fault location estimates in low-resistance earthed network using the advanced loop model with load compensation method. Left: no distributed generation, right: distributed generation included.

In conclusion, more accurate modeling clearly decreases the errors, as can be seen in the results of Figure 8.15.10.

8.15.3.2.2 Advanced load compensation method

In no-load conditions, the models defined by Equations (8.15.6) and (8.15.9) produce accurate results for fault location estimates. As the load current equals zero, ideally all the current quantities in the above loop models become equal, that is, $\underline{I}_{PH} = \underline{I}_N = \underline{I}_F$, and therefore whichever of these current quantities can basically be used to calculate the impedance to the fault point simply by dividing the measured phase-to-earth voltage of the faulted phase by this current. The *advanced load compensation method* makes use of this fact by trying to compensate the effect of load from all related voltage and current sequence components measured from the faulted feeder, and in this way the fault situation during normal load becomes reduced back to the corresponding no-load situation. The detailed description of this method is given in reference [8.15.1].

For the currents, the load compensation is done only for zero- and negative-sequence components according to Equation (8.15.11), because they can then be used directly for the distance estimation. The compensation thus removes the effect of load from the amplitudes and phase angles of these current phasors.

$$\begin{aligned} \underline{I}_{0Lcomp} &= \Delta\underline{I}_0 + \underline{I}_{0Lcomp\_factor} \\ \underline{I}_{2Lcomp} &= \Delta\underline{I}_2 + \underline{I}_{2Lcomp\_factor} \end{aligned} \qquad \textbf{(8.15.11)}$$

where

$\Delta\underline{I}_0$	is the measured change in the feeder zero-sequence current due to fault
$\Delta\underline{I}_2$	is the measured change in the feeder negative-sequence current due to fault
$\underline{I}_{0Lcomp\_factor}$	is the calculated compensation factor for the feeder zero-sequence current
$\underline{I}_{2Lcomp\_factor}$	is the calculated compensation factor for the feeder negative-sequence current

Similarly for the sequence voltages it can be written:

$$\begin{aligned} \underline{U}_{0Lcomp} &= \Delta\underline{U}_0 + \underline{U}_{0Lcomp\_factor} \\ \underline{U}_{1Lcomp} &= \underline{U}_1 + \underline{U}_{1Lcomp\_factor} \\ \underline{U}_{2Lcomp} &= \Delta\underline{U}_2 + \underline{U}_{2Lcomp\_factor} \end{aligned} \qquad \textbf{(8.15.12)}$$

where

$\Delta\underline{U}_0$	is the measured change in the zero-sequence voltage due to fault
$\Delta\underline{U}_2$	is the measured change in the negative-sequence voltage due to fault
$\underline{U}_1$	is the measured positive-sequence voltage during the fault
$\underline{U}_{0Lcomp\_factor}$	is the calculated compensation factor for the zero-sequence voltage
$\underline{U}_{2Lcomp\_factor}$	is the calculated compensation factor for the negative-sequence voltage
$\underline{U}_{1Lcomp\_factor}$	is the calculated compensation factor for the positive-sequence voltage

In the above equations the compensation factors for currents and voltages are estimated based on the measured positive-sequence current and changes in zero- and negative-sequence currents. In addition, also network data-based parameters such as phase-to-earth admittance values of the protected feeder and the background network and the source impedance are utilized in the calculation. All these parameters can be estimated based on measurements during earth faults inside and outside the protected feeder.

After the compensation, the fault location can be done according to the equation:

$$\underline{Z}_{EF\_LOOP} = \frac{\underline{U}_{Lcomp}}{\underline{I}_{2Lcomp}} \qquad \textbf{(8.15.13)}$$

In the above equation, $\underline{U}_{Lcomp}$ is the compensated phase-to-earth voltage of the faulted phase, for example, $\underline{U}_{Lcomp} = \underline{U}_{0Lcomp} + \underline{U}_{1Lcomp} + \underline{U}_{2Lcomp}$ is valid for the phase A.

The fault location is then based on the reactive part of $\underline{Z}_{EF\_LOOP}$, that is, X_{EF_LOOP}.

Example 5: The performance of the *advanced load compensation method* is simulated in a feeder with the following data:

Main transformer:

- 110/20 kV
- S =20 MVA
- x_K =0.09 p.u

Network:

- $I_{EF\max}$ =150 A (neutral point unearthed)

Protected feeder:

- Positive-sequence impedance, $\underline{Z}_1$, of the main line per unit length: 0.288+j0.284 Ω/km
- Zero-sequence impedance, $\underline{Z}_0$, of the main line per unit length: 0.438+j2.006 Ω/km
- Earth return path impedance, $\underline{Z}_N$, of the main line per unit length: 0.05+j0.574 Ω/km
- Total load: 4 MVA (evenly distributed)
- No distributed generation included

Single-phase earth fault was simulated at steps of 0.1 p.u line length. The applied fault resistance equals to $5 * \mathrm{Im}(\underline{Z}_1 + \underline{Z}_N)$ of the whole line, that is, 170 Ω.

Figure 8.15.11 shows the results with a reference to the corresponding results given by the method applying the *advanced loop model with load compensation***.**

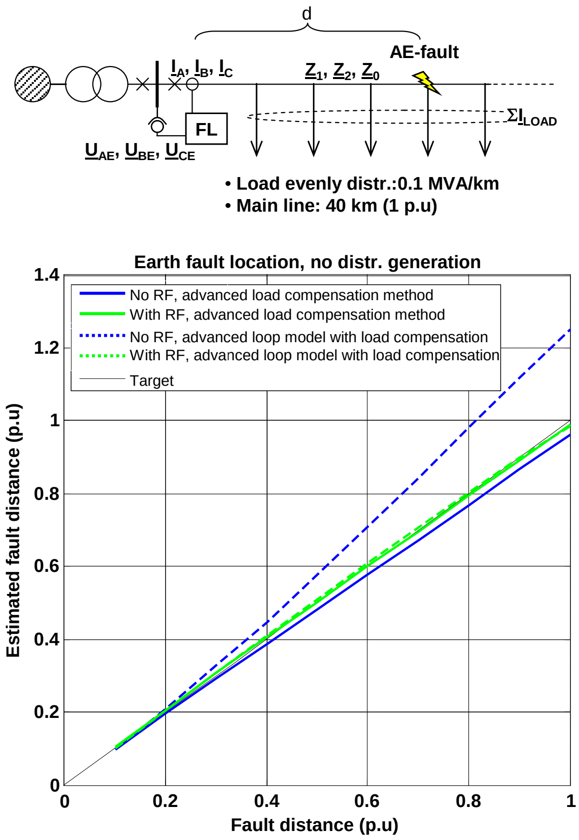

Figure 8.15.11: Simulated fault location estimates in unearthed network using the advanced load compensation method

8.15.3.2.3 Load-modeling method

In order to further increase the accuracy of the various loop-modeling methods, one way is to take the load into account by modeling it. In this *load-modeling method*, [8.15.2] and [8.15.3], two network or loop models are introduced.

1. A model where the earth fault is located in front of the equivalent load tap.

2. A model where the earth fault is located behind the equivalent load tap.

These loop models are illustrated in Figure 8.15.12, where the distance of the equivalent load tap is denoted as s.

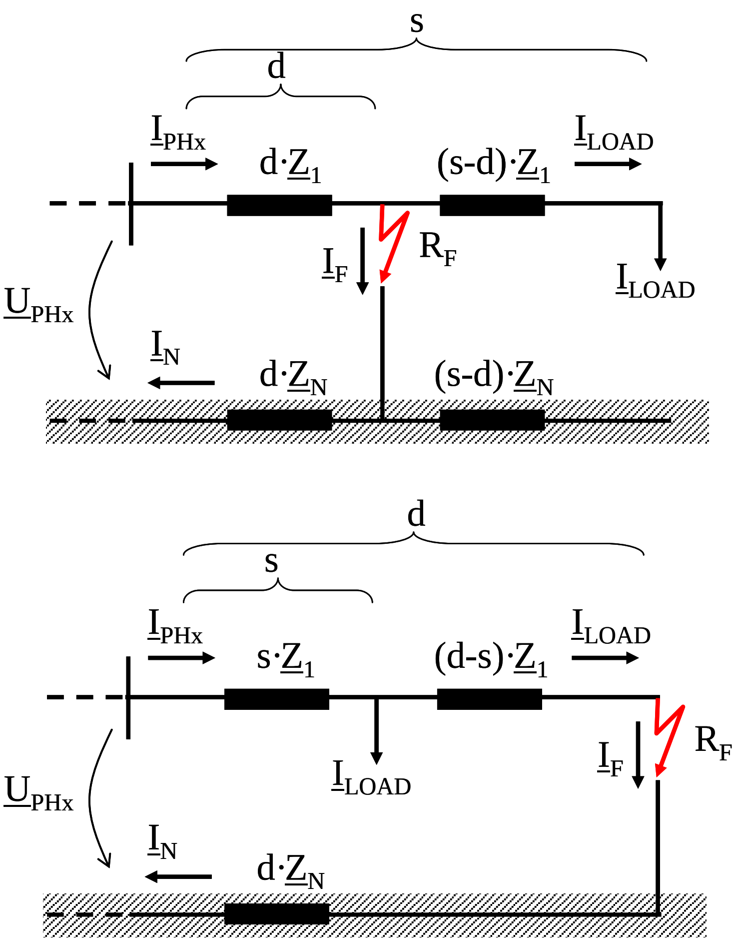

Figure 8.15.12: Loop models for the load modeling method. Top: a single phase-to-earth fault is located in front of the equivalent load tap (d<s), bottom: a single phase-to-earth fault is located behind the equivalent load tap (d>s).

The equivalent load tap and its distance introduced in Figure 8.15.12 represents a fictional load tap at a per-unit distance s from the substation. The derivation and meaning of this parameter is illustrated in Figure 8.15.13, where the load is assumed to be evenly distributed along the feeder. The maximum value of the voltage drop, denoted $U_{drop(real)}$, appears in the end of the line. Parameter s is the distance at which a single load tap corresponding to the total load of the feeder would result in a voltage drop equal to $U_{drop(real)}$. The dashed curve in Figure 8.15.13 shows the voltage drop profile in this case.

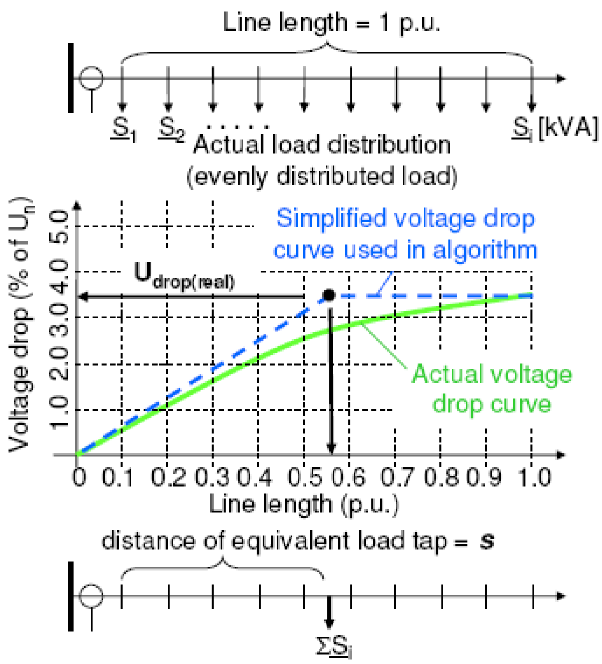

Figure 8.15.13: Description of the equivalent load distance.

The value of s can be estimated based on load flow and voltage drop calculations using Equation (8.15.14):

$$s = \frac{U_{drop(real)}}{U_{drop(s=1)}} \tag{8.15.14}$$

where

$U_{drop(real)}$ is the actual maximum voltage drop of the feeder

$U_{drop(s=1)}$ is the fictional voltage drop if the entire load were tapped at the end of the feeder

Alternatively, parameter s can be calculated based on the voltages and currents measured by conducting a single-phase earth-fault test (R_F =0 Ω) at that point of the feeder where the maximum actual voltage drop takes place.

According to Figure 8.15.12 the following equation can be written with d and R_F as unknown parameters.

Earth fault is located in front of the equivalent load tap ($d < s$):

$$\underline{U}_{PEx} = d_1 \cdot \underline{Z}_{1set} \cdot \underline{I}_{PHx} + R_{F2} \cdot \underline{I}_F + d_1 \cdot \underline{Z}_{Nset} \cdot \underline{I}_N \tag{8.15.15}$$

Earth fault is located behind the equivalent load tap ($d > s$):

$$\underline{U}_{PEx} = s \cdot \underline{Z}_{1set} \cdot \underline{I}_{PHx} + (d_2 - s) \cdot \underline{Z}_{1set} \cdot \underline{I}_F + R_{F1} \cdot \underline{I}_F + d_2 \cdot \underline{Z}_{Nset} \cdot \underline{I}_N \tag{8.15.16}$$

In Equations (8.15.15) and (8.15.16), $\underline{I}_N$ and $\underline{I}_F$ are estimations of the earth return path and fault currents respectively. These currents can be modeled in different ways, but the most straightforward way is to assume that $\underline{I}_N$ equals the sum of the phase currents, and that $\underline{I}_F$ equals $\underline{K} \cdot \underline{I}_N$. The parameter $\underline{K}$ is the *current distribution factor* that takes into account the capacitive earth fault current contribution of the protected feeder itself. Furthermore in Equations (8.15.15) and (8.15.16), $\underline{Z}_{lset}$ is the positive-sequence impedance of the protected feeder and $\underline{Z}_{Nset}$ the impedance of the earth return path. The latter impedance is calculated simply by $(\underline{Z}_{0set} - Z_{lset})/3$ as before, where $\underline{Z}_{0set}$ is the zero-sequence impedance of the protected feeder. In case of a distribution feeder with branch lines, these impedances are typically selected according to the total impedance of the main line. Therefore, $\underline{Z}_{lset}$ and $\underline{Z}_{Nset}$ are known parameters and setting values for this calculation method. The variables d_1, R_{F1} and d_2, R_{F2} can be solved from Equations (8.15.15) and (8.15.16) by dividing them into real and imaginary parts similarly as described already in Section 8.15.3.2.1. As Equations (8.15.15) and (8.15.16) both need to be solved in parallel for each fault case, two solutions, d_l and d_2, for the distance estimate are always obtained. The logic for selecting between these results is based on the calculated fault distance estimates: if d_1 of Equation (8.15.15) is less than s, then this is the valid fault distance estimate, otherwise the distance estimate d_2 is taken from Equation (8.15.16).

Example 6: The performance of the *load-modeling method* is simulated with the data from Example 5. The equivalent load distance has been estimated based on the network data typically available in the DMS-system of the utility. Here, an equivalent load distance of 0.47 has been used.

Figure 8.15.14 shows the results with a reference to the corresponding results given by the method applying the *advanced load compensation* method.

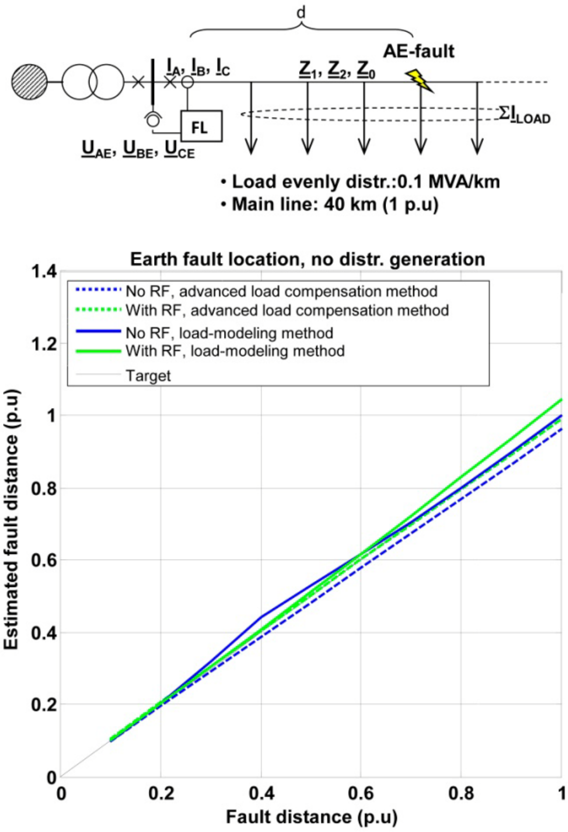

Figure 8.15.14: Simulated fault location estimates in unearthed network using the load-modeling method

References

[8.15.1] Wahlroos, A. & Altonen, J.: "System and method for determining location of phase-to-earth fault," 20055232 F.3606FI 2041841FI.

[8.15.2] Wahlroos, A. & Altonen, J.: "System and method for determining location of phase-to-earth fault," EP 06 127 343.9.

[8.15.3] Altonen, J. & Wahlroos, A.: "Advancements in Fundamental Frequency Impedance Based Earth-Fault Location in Unearthed Distribution Networks," CIRED 19th International Conference on Electricity Distribution, Vienna 2007.

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