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Fault Location in Distribution Feeders with Distributed Generation using Positive Sequence Apparent Impedance

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Abstract: The existing methods of fault location for distribution systems consider that the system has a radial power flow, in other words, they don't consider the presence of another generator in the distribution line. Thus, in systems with the presence of distributed generation, these methods show to be inefficient. In this paper, it is presented a new fault location method based on positive sequence apparent impedance. Computational simulations were made and the method was tested and compared with other existing fault location techniques in order to validate the method. The basic characteristics of the method, the new algorithm and a variety of case studies are presented in the paper in order to illustrate its efficiency.

Key–Words: Distribution Systems, Distributed Generation, Protection Systems, Fault Location, Apparent Impedance

1 Introduction

The correct fault location in power distribution systems (PDS) is a basic theme in the protection systems. With a good estimative of the location of a fault the problems in the network are solved faster, and bigger problems that might occur in consequence of these faults can be avoided. This reduces the interruption time and increases the system reliability.

Since the early days of electric power engineering the fault location problem has been studied and several techniques were developed. But the power systems have been changing since those days and new problems arrive each day. The new challenge for the power protection engineers nowadays is to combine the new trend on PDS, known as distributed generation (DG), with the protection schemes, in which the fault location is included.

Distributed generation is defined as the generation of power inside the PDS [1], and because of that, it changes the characteristics of the distribution systems, occasioning an impact in the protection schemes. That includes the fault location, since the current methods do not consider the power generation inside the PDS, which is shown in this paper. This way, to maintain the system security, efficiency, quality and reliability it is necessary to develop new fault location techniques.

Since the major part of fault location methods for transmission systems in use nowadays are based in positive sequence apparent impedance with one-terminal data [2], it is developed and presented in this paper a new method based in this measurement. In this way, the compatibility with the current protection systems is maintained.

The present article starts showing a classic fault location technique for PDS that don't consider DG in the system. The impacts of DG in PDS are discussed in the third section and the complete proposed method is shown in the fourth section. In the fifth and sixth sections, the results and the conclusions are presented, respectively.

2 Fault Location Using Positive Sequence Apparent Impedance

Consider the circuit shown in Figure 1, which represents a faulted distribution system without DG. All the load after the location of the fault are represented as one equivalent load Z_r and the total current dispatched to it is I_{L_a} [3].

The voltage measured at the local terminal is

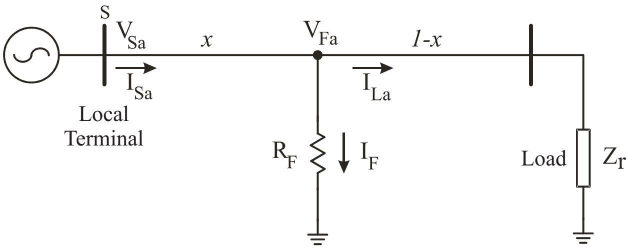

Figure 1: Faulted distribution system.

given by the Equation 1:

$$V_{S_a} = x \cdot (Z_{l_{aa}} \cdot I_{S_a}) + R_f \cdot I_f \qquad (1)$$

where:

V_{S_a}	Phase a Voltage (measured)
I_{S_a}	Phase a Current (measured)
Z_l	Line Impedance Matrix [per km]
x	Fault Distance
V_{f_a}	Phase a Fault Point Voltage
I_f	Fault Current
R_f	Fault Resistance
I_{L_a}	Phase a Load Current
Z_r	Equivalent Load Matrix

Multiplying both sides of Equation 1 by I_f^* (fault current complex conjugate) and observing that $I_f \cdot I_f^* \cdot R_f$ is a real number, Equation 2 is obtained:

$$x = \frac{\Im\left(V_{S_a} \cdot I_f^*\right)}{\Im\left(Z_{L_a} \cdot I_{S_a} \cdot I_f^*\right)} \qquad (2)$$

where:

$$I_f = I_{S_a} - I_{L_a} \qquad (3)$$

The Equations 2 and 3 are valid for phase-to-ground faults and the following algorithm can be used to locate the fault:

1. It is assumed I_{L_a} as the total load current before the fault occurrence ($I_{S_{a_{pre-fault}}}$).
2. Using Equation 3 an estimative of the fault current is calculated.
3. Using Equation 2 a fault point is estimated.
4. Using Equation 4 the voltage at the estimated fault point is calculated.

$$\begin{bmatrix} V_{f_a} \\ V_{f_b} \\ V_{f_c} \end{bmatrix} = \begin{bmatrix} V_{S_a} \\ V_{S_b} \\ V_{S_c} \end{bmatrix} - x \cdot \begin{bmatrix} Z_{L_a} \cdot I_{S_a} \\ Z_{L_b} \cdot I_{S_b} \\ Z_{L_c} \cdot I_{S_c} \end{bmatrix} \qquad (4)$$

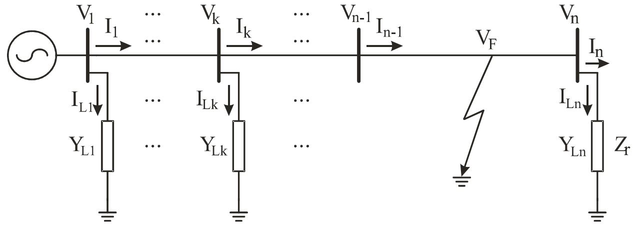

Figure 2: Voltage and Current update at the local terminal.

5. Using the voltage at the fault point calculated in the above step, a new load current (I_{L_a}) is calculated.
6. With an updated load current, the algorithm restarts at step 2.

On step 5 of the described algorithm, it is necessary to calculate the system load current. This current is obtained with the direct circuit analysis. As shown in Figure 1, the load current is the current beyond the fault point. Knowing the voltage at the fault point, which is estimated, and the equivalent load, obtained using a constant impedance model of the loads and considering the line impedances, it is easy to obtain the load current I_{L_a}.

After the convergence of this algorithm the fault will be estimated in any section of the PDS. If the fault is localized in any section after the first one, an update of V_{S_a} and I_{S_a} for the values of voltage and current at the next bus is done. This update is done to diminish the errors referring to the line losses and the unique topology of PDS, which is the distributed loads along the lines.

As shown in Figure 2 the voltage and current update is done by the Equations 5 to 7:

$$V_{k+1} = V_k - Z_k \cdot I_k \qquad (5)$$
$$I_{L_k} = V_k \cdot Y_{L_k} \qquad (6)$$
$$I_k = I_{k-1} - I_{L_k} \qquad (7)$$

With the voltage and current at the local terminal updated, the algorithm starts again and a new fault point is determined. This process rests until the fault is estimated at the same section of the updated voltage and current, V_{S_a} and I_{S_a}, or the feeder ends.

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3 Distributed Generation Impacts

The problems related to the connection of power generators inside the PDS appears in different areas of power engineering: stability, voltage regulation, protection systems and others. Many different consequences enclose at the same time more than one area, as the occurrence of voltage sag when using overcurrent protection in systems with DG, as described in [4].

The main impact is the change of the power flow of the system. Distribution systems were naturally radial, because they had only one source of power. Now with DG, the distribution systems can have more than one source of power. In this way, the system is no longer radial.

In fault analysis, the insertion of a distributed generation in a distribution system makes the fault current to vary, since it contributes with power in the fault state. Thus, parameters like the fault current magnitude are changed, since there is a dynamic influence of the new machine on the system.

Besides the fault current magnitude, the fault current direction (angle of the current phasor) in the different sections of the system is also a parameter that changes. The DG contribution to the system in the fault state can change the current direction in some of the feeder sections. The magnitude and the direction of the fault current are parameters that vary with the injected power by the DG and the siting of it in the system [5].

Another important impact of the DG in PDS inhabits directly on the protection systems. The protection schemes of PDS commonly use non-directional overcurrent relays, sectionalizers, automatic reclosers, fuses and circuit breakers [6]. The presence of the DG in PDS modifies, as explained, the fault current magnitude and direction. Thus, the coordination and adjustment of these equipment must be done again [7], this time considering the DG. Still, since DG affects the radial characteristic of the system, new protection equipment with directional characteristic must be incorporated to the system in order to detect faults correctly, in order to promote an efficient protection of the system.

4 Modified Fault Location Method Considering Distributed Generation

Consider the PDS with DG shown in Figure 3. The system can be splitted in two separate parts: the part before the generator and the part after the generator. As shown in Figure 3, the part before the DG corresponds to the buses 1 to $j-1$ and the part after the DG corresponds to the buses $j+1$ to $n+2$.

The proposed fault location algorithm considering DG starts with steps 1 to 6 described on section 2. However, a electric modeling of the generator is done in these steps, in order to consider the DG in the fault location process.

The algorithm starts considering a fault in the beginning of the feeder, thus, before the DG:

1. I_{L_a} is assumed as the load current before the fault state ($I_{S_{a_{pre-fault}}}$).
2. Equation 3 is used to calculate the fault current.
3. Using Equation 2 the fault point is estimated.
4. The voltage at the fault point is calculated. For that, all system topology is considered, including DG, using the modeling described on section 4.1. Voltages and currents out of the buses for buses before the faulted bus are calculated. As shown in Figure 2, the fault point voltage is calculated using Equation 8:

$$V_f = V_{n-1} - I_{n-1} \cdot Z_{line} \cdot x \qquad (8)$$

where Z_{line} is the line impedance per km in the faulted section and x is the distance from bus $n-1$ until the fault point (in km).

5. Using the voltage at the fault point calculated at the previous step, a Thévenin equivalent circuit of all system beyond the fault

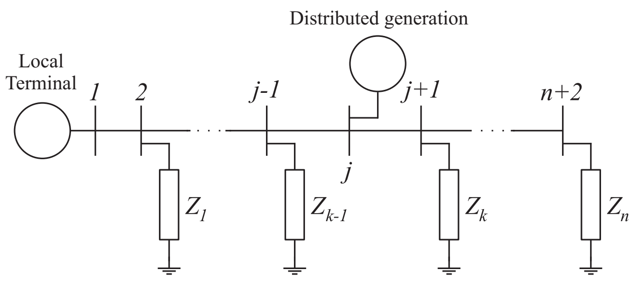

Figure 3: Distribution system with distributed generation.

point is done. If the estimated fault location in step 3 is after DG, the equivalent circuit is simply the parallel of all loads mixed with the line impedance after the estimated fault point, for there are no generating devices after the fault. After that, the load current is updated again, with equation 4, but this time with the voltage and current values, V_{S_a} and I_{S_a}, updated to data of the first bus before the fault point. If the fault is estimated before the DG, the Thévenin equivalent circuit will have a source of power. In this case the new load current is obtained using Equation 9:

$$I_{L_a} = \frac{(V_f - V_{th})}{Z_{th}} \quad (9)$$

6. Back to step 2, with the updated data of the load current.

4.1 Distributed Generation Modeling

The distributed generation electric model used in the algorithm is the model of a synchronous generator in the subtransient time period (very first cycles after the occurrence of a fault), as described in [8]. The model, shown in Figure 4, is composed by the machine subtransient reactance X_s'', its armature resistance R_a and its internal voltage E_g''. The generator internal voltage can be obtained by a power flow algorithm for PDS including DG, as described in [9], where the voltage at the generator bus and the current injected by it is obtained using the pre-fault state measured characteristics of the system. As the study period is the subtransient one, it is assumed that the internal voltage of the generator is kept constant during the fault, and an electrical model for the DG is obtained.

4.2 Voltages and Currents Calculation

With the faulted system and assuming that loads, line impedances and local terminal voltage and current data are available, the voltage and current of the bus very before the distributed generation

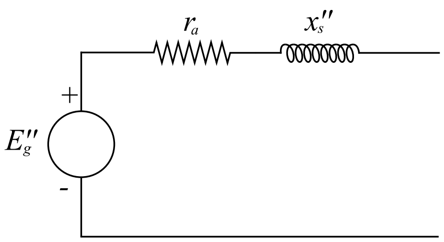

Figure 4: Distributed generation model.

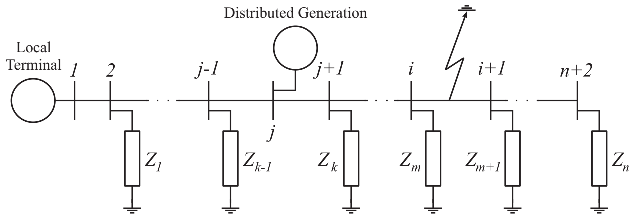

Figure 5: Faulted distribution system with distributed generation.

is obtained through successive voltage and current calculations in the buses before the fault, as shown in Equations 10 to 12, only to load buses:

$$V_{k+1} = V_k - Z_{line} \cdot I_k \quad (10)$$

$$I_{L_k} = V_k / Z_k \quad (11)$$

$$I_k = I_{k-1} - I_{L_k} \quad (12)$$

where V_k and I_k are related to the already calculated bus, V_{k+1} and I_{k+1} are related to the interested values of voltage and current of the bus to be calculated and Z_k is the load impedance of the bus k.

With the voltage and current at the local terminal during the fault period known, the voltages and currents at the posterior buses are calculated successively, until the estimated fault section. If the DG is in the way between the local terminal and the fault, the influence of the DG must be calculated, using the Expressions 13 to 15 (using the notation of Figure 5):

$$V_j = V_{j-1} - Z_{line} \cdot I_j \quad (13)$$

$$I_{GD} = \frac{V_j - E_g''}{(X_s'' - R_a)} \quad (14)$$

$$I_{j+1} = I_j - I_{GD} \quad (15)$$

where in Equation 14 the machine parameters developed on Section 4.1 appear.

5 Simulations and Results

Towards the method validation a total of 67 three-phase solid faults in a distribution feeder were simulated. The distribution system was taken from the literature [10] and a distributed generation facility was added. The system was modeled in the ATP/EMTP software [11], and also where the faults were simulated. The fault location algorithm was implemented in the MATLAB® software [12].

The study system, shown in Figure 6, has a total three-phase power of 14,5 MVA and works

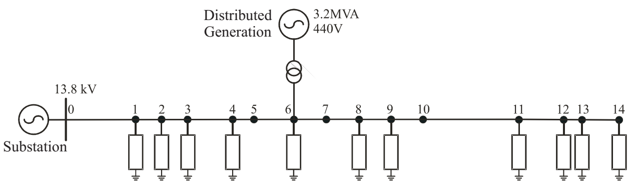

Figure 6: Distribution system with distributed generation for study.

in 13,8 kV. The DG contributes with 3,2 MVA of this power and works with 440 V. It is connected to the system by a transformer. The total line length is 27,6 km, and the DG is in the km 11,86.

First the classic fault location technique described in [3] was implemented and the 67 faults simulated tested its efficiency. The results are shown in Figure 7. The distributed generation influences the results of this method, specially for faults located after the DG point, where the error increases, getting to high levels of error, around 20%.

The same 67 fault cases were tested with the proposed technique in this work. As the results shown in Figure 8, the method revealed efficient in the location of the simulated faults. The error introduced by the DG in [3] is diminished with the new methodology. The error is practically zero for all simulated fault (0,2% = 55 meters), including for faults after the DG, without the influence of the fault point.

As the fault distance increases in relation to the local terminal, the error is held in a constant level, even after the point where the DG is inserted (11,86 km). Thus, the method shows its robustness in relation to the possible different DG locations in the system, estimating the fault points with precision independently from where the DG is inserted.

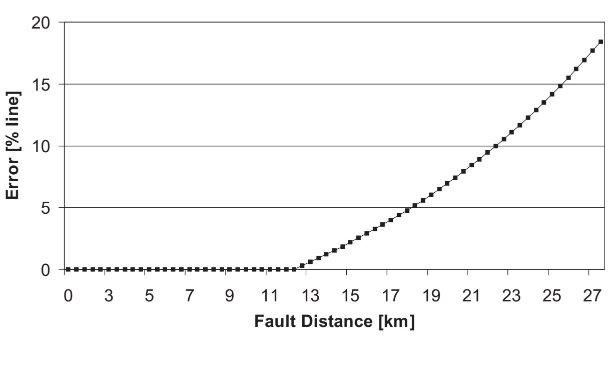

Figure 7: Classic method results in DG systems.

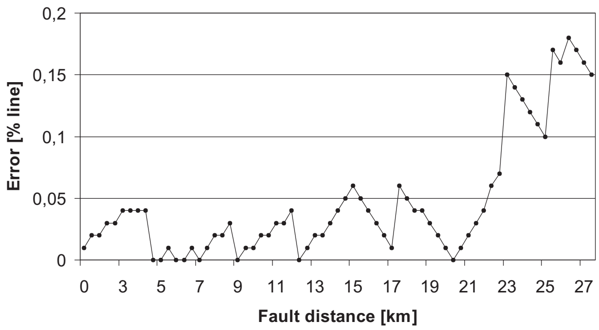

Figure 8: Proposed technique results is DG systems.

6 Conclusions

In this article a new fault location method considering the DG is proposed, described and analyzed. The results obtained show the high precision of the method when compared to methods that are currently in use, showing that the methodology is worthy of continued research aiming the improvement of the fault point estimative in the present distribution systems.

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