THE EFFECTS OF DIFFERENT DG GENERATORS ON DISTRIBUTION NETWORK’S PROTECTION AND EXTERNAL FAULT DETECTION

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ABSTRACT
In recent years, there has been a fast development in the implementation of Distributed Generation (DG) due to several reasons such as remarkable growth in energy consumption, the increase in fossil fuel prices and environmental concerns. Despite its economic and technological benefits, large amounts of DG penetration into distribution grids have affected the grid's normal operation on various aspects, including voltage control, power quality, protection system's reliability and safety, etc. These effects should be studied in order to make accurate prediction and appropriate grid design. In this paper, after a brief introduction, first, the effects of DG on distribution grid will be analyzed, then, to evaluate the accuracy of this analysis, a three phase short circuit fault will be simulated using DigSILENT Power Factory software package and the effects of DG will be studied on aspects of fault current level and protection coordination. Besides, the key parameters of DG which have the most significant effects on either grid protection or DG protection will be derived. Finally, the behavior of different DG sources like synchronous and induction generators will be compared.

KEY WORDS
Distributed Generation, Protection System, External Fault, Blinding

1. Introduction

Distributed generation units are composed of relatively small units installed and operated much closer to the load centers, compared to large conventional power plants. Variable power output, power quality, operation and maintenance costs, long term energy production reliability, short circuit capacity, re-closer problems, unwanted islanding and issues concerning operational instructions are the most important challenges related to DG connection to the power grid [1]. The protection of the power grid is another limitation on widespread DG connection. To summarize, the following are of the most frequent problems happening in the grid protection in presence of DG unit [2]:
False operation,
Blinding of protection functions,
Protection miss-coordination,
External fault detection

The connection of a DG unit to distribution network affects the network's fault current. This fault current depends on the level of the DG unit's contribution to the fault current. This contribution, in turn, depends on many parameters such as the technology of the generators, generator size and its relative distance from the network feeder [3].

Moreover, different behavior of different DG generators in case of a fault is another problem related to the DG connection to the grid.

DG units employing asynchronous (induction) generators cannot contribute to the fault current for a long time. This is also valid for converter-based DG units like micro turbines, fuel cells and photovoltaic systems. In these cases, the generator's fault current is negligible [4]. However, it has been demonstrated in [4] that in weak networks, inverter-based DG units can contribute to the fault current for high impedance faults. Synchronous generators, on the other hand, contribute to the fault current continuously and affect the network's contribution to that current. These generators, often, can be found in Combined Heat and Power (CHP) plants [5].

On the other hand, and unlike synchronous generators, induction generators are not equipped with field current independent from the network. Subsequently, the fault current drops out quickly and the induction machine's contribution diminishes after a rise during the first few cycles. In many cases, this current dip is quicker than the protective relay's accuracy [1].

2. Effects of DG on protection system

2.1. Analysis of fault currents on feeders with DG

Figure 1 is used for studying and analysis of the fault currents.
Figure 1: A typical network with DG

The distance of the DG unit from the network feeder is “d” and the fault is located at the end of the feeder. For simplification, the relative distance (l) is defined as follow:

\[
l = \frac{d}{d_{\text{total}}} \tag{1}
\]

Where, \(d_{\text{total}}\) is the total length of the feeder. The equivalent electric circuit is depicted in Figure 2. In this figure, \(Z_t\) is the total line impedance, \(Z_g\) is the generator impedance and \(Z_s\) is the source impedance or the network impedance. \(U_s\) and \(U_g\) are network and generator voltages, respectively.

Figure 2: The equivalent electric circuit of Figure 1

According to Kirchhoff voltage and current laws:

\[
\begin{bmatrix}
U_s \\
U_g
\end{bmatrix} = \begin{bmatrix}
Z_s + Z_t & (1-l)Z_t \\
(1-l)Z_t & Z_g + (1-l)Z_t
\end{bmatrix}\begin{bmatrix}
I_1 \\
I_2
\end{bmatrix} \tag{2}
\]

In Figure 2 and (2), \(I_1=I_{\text{grid}}\) is the grid fault current and \(I_2=I_g\) is the generator fault current. So, the total fault current is \(I_1+I_2=I_{k,3\text{ph}}\).

In this paper, Thevenin theory has been used to calculate fault currents. This theory is very similar to IEC 60909 standard procedure for fault analysis [6]-[10].

Figure 3 shows the Thevenin equivalent circuit of Figure 1.

According to Kirchhoff voltage and current laws:

\[
\begin{bmatrix}
U_{th} \\
U_g
\end{bmatrix} = \begin{bmatrix}
Z_s + Z_t & (1-l)Z_t \\
(1-l)Z_t & Z_g + (1-l)Z_t
\end{bmatrix}\begin{bmatrix}
I_{k,\text{grid}} \\
I_{k,3\text{ph}}
\end{bmatrix} \tag{2}
\]

According to Figure 3, the network current also can be derived as follow:

\[
I_{k,\text{grid}} = \frac{Z_g}{Z_s + l(Z_t + Z_g)} \cdot I_{k,3\text{ph}} \tag{6}
\]

2.2. Analysis of the fault

2.2.1. The relationship between Thevenin impedance and DG parameters

According to (4), the fault short circuit current depends on \(Z_{th}\). Based on (3), \(Z_{th}\) depends on the technology, size and location of generators as shown in Figures 4 and 5. \(Z_{th}\) has been depicted vs. location of generator (l) for different sizes in these figures. Curves in different colors in figures 4 to 9 represent different generator sizes (\(S_{sc,g}\)). It also depends on the short circuit capacity of the grid (\(S_{sc,grid}\)). Unlike weak networks (networks with limited short circuit capacity), a network with high short circuit capacity (\(S_{sc,grid} \rightarrow \infty\)), or so-called an ideal network, has negligible source impedance (\(Z_s \rightarrow 0\)) that affect \(Z_{th}\) as demonstrated in (3).
The Thevenin impedance increases when the relative location of DG unit decreases, so the fault current decreases accordingly.

The other parameter that affects $Z_{th}$ is the short circuit capacity of the generator ($S_{sc,g}$). According to Figures 4 and 5, the highest impedance is achieved when $S_{sc,g} \rightarrow 0$ or when the DG unit is disconnected from the grid. On the other hand, as the $S_{sc,g}$ increases (different curves in Figures 4 and 5), $Z_{th}$ decreases accordingly. Hence, there is an inverse relationship between $Z_{th}$ and $S_{sc,g}$ in these figures.

The short circuit capacity of the local network is also effective on $Z_{th}$. The higher the short circuit capacity of the network, the lower the impedance of the network is. In ideal networks, the short circuit capacity is remarkable ($S_{sc,k} \rightarrow \infty$) and the impedance is negligible ($Z_{th} \rightarrow 0$).

So, $I_{sc,3ph}$ can be derived from (5) which is a nonlinear equation (Figures 6 and 7). Consequently, this grid current will be nonlinear too. Equation (5) can be simplified for an ideal network as follow:

$$I_{k,grid} = \lim_{S_{sc,k} \rightarrow \infty} \frac{z_g}{z_s + \frac{1}{z_g} + \frac{1}{z_g}} \cdot I_{k,o}$$

$$= \frac{z_g}{z_g + \frac{z_g}{z_s} \cdot I_{k,o}}$$

$$= \frac{1}{\frac{z_g}{z_s} + 1} \cdot I_{k,o}$$

(7)

A grid current change is depicted in Figures 8 and 9. It has been demonstrated that, in ideal networks, for a generator located very close to the grid ($l \rightarrow 0$), the grid fault contribution is negligible. However, as $l$ increases, the grid contribution also increases and reaches a peak at the middle of the feeder line (section 2.2.2). But, in weak networks, the closer location of generator (smaller $l$) leads to greater grid current fault contribution. This is discussed in more detail in the next section.
2.2.2. The most effective location of the DG unit

The most effective location of the DG unit along the feeder is where the contribution of the grid causes the minimum fault current. This current is calculated from (7) and (5) as follows:

\[ I_{k,\text{grid}} = \frac{u_{k}z_{g}}{\sqrt{3}\left(z_{l}z_{g} + z_{l}z_{l} + z_{l}z_{l}\right)} + \frac{l_{l}\left(z_{l} - z_{l}ight) - l^{2}z_{l}^{2}}{2} \]  

(8)

\[ \frac{d}{dl} I_{k,\text{grid}} = \frac{0 - [0 + z_{l}(z_{l} - z_{l}) - 2lz_{l}^{2}]u_{k}z_{g}}{3\left(z_{l}z_{g} + z_{l}z_{l} + z_{l}z_{l}\right)} \]  

(9)

\[ \frac{dl_{k,\text{grid}}}{dl} = 0 \rightarrow z_{l}(z_{l} - z_{l}) - 2lz_{l}^{2} = 0 \rightarrow \]

Equation (9) specifies the worst location of the DG unit in general. But, for an ideal network, the worst location of the DG unit is the center of the feeder:

\[ \lim_{l_{s} \to 0} = \lim_{z_{s} \to 0} \frac{1}{2}\left(1 - \frac{Z_{g}}{Z_{l}}\right) = \frac{1}{2} \]  

(10)

3. The case study

3.1. The case study network

Figure 10 shows the selected circuit, using DIgSILENT Power Factory software package, to study the effects of DG units on distribution network. WT1 bus bar is dedicated to DG generators. The simulation process is shown as a flowchart in Figure 11.
Generation technology: In this paper, doubly fed induction generators (DFIG) and synchronous generators are compared. Only one of the generators is connected to the grid at any time.

The generator’s size: The size of each generator is 0.4MVA. However, the number of generators is varying to simulate 50, 100 and 150 percent of the full load of the Tr2 transformer.

Relative distance of the generator (l (km)): Relative location of the generator from the grid (so-called the distance of the generator) changed by varying the length of line “D” and “1-D”. But, the total length of the feeder is kept fixed. In this research, the total length of the feeder is 5 km, but the distance is varied by steps of 20%, from 0 to 100%, of the total length.

Type of fault: A 3-phase balanced short circuit was simulated at the local bus bar using the IEC standard [6][10].

3.2. Setting calculations

The setting of the parameters of the relay must ensure the reliability and the security of the protection system [15] and [16]. In [3] the range of the setting is limited between:

\[2I_r < I_{setting} < 3I_r\]  \hspace{1cm} (11)

In this paper, the protection relay has been installed on the primary side (HV side) of Tr2 transformer. So, relay setting calculation should be done using HV side parameters:

\[I_r = \frac{S_n}{\sqrt{3} \cdot U_n} = \frac{10 \cdot 2.5 \cdot 10^6}{\sqrt{3} \cdot 20 \cdot 10^3} = 0.72\] \hspace{1cm} (12)

\[1.44 < I_{setting} < 2.16\] \hspace{1cm} (13)

3.3. The results

3.3.1. Effect of size and technology on grid protection

The simulation is carried out for 3 different sizes of synchronous generator and DFIG at 4 different locations.

3.3.1.1. DFIG

Figure 12 confirms what the calculations have demonstrated before in Figure 9. The effects of DFIG on network current depend on the size, distance and the technology of the generator. The smaller the distance of generator, the more effective the generator on grid current is. The minimum and maximum settings of the relay calculated in (12) are shown in this Figure 12. Although the relay setting is selected from the above range, the coordination with downstream relays should be considered.

According to Figure 12, with DFIG connected to the grid, the maximum setting of the relay must be less than 1.56 kA in the worst case. It means that the setting area must be revised within the following limits:

\[1.44 < I_{setting} < 1.56\] \hspace{1cm} (14)

Within this range, if the relay setting is edited, the protection coordination with downstream relays must be verified.
3.3.1.2. Synchronous generator

The effect of synchronous generator on the grid current contribution is noticeably more than DFIG. In this case, for the generators located very close to the network \((l \to 0)\) the grid contribution is much less than the minimum pickup current. As illustrated in Figure 12, while according to (13) the minimum pickup current of relay must be 1.44 kA, the fault current is less than 1.4 kA for synchronous generators larger than 25 MVA in rated capacity. Hence, the relay settings are invalid and must be revised in such cases.

3.3.2. External fault detection

Due to some technical and safety reasons, the protection system of DG must be able to detect faults happening on the main grid. These faults are known as external faults[1].

The behavior of different technologies of generators related to this issue is very different. Figure 13 shows DFIG’s contribution to external faults. Unlike synchronous generators, DFIG is not equipped with independent field source. Subsequently, in case of a fault, the rotor’s electromagnetic field drops immediately after a rise in the first cycle. Therefore, the stator current becomes negligible and the protection function becomes blind. However, in the first cycle, the amplitude of the stator current is considerable as shown in Figure 13. The behavior of these generators is very similar in the first one or two cycles. However, in the steady state situation the current of DFIG drops significantly. Besides, the stator current of DFIG decays very quickly while the stator current of synchronous generator decreases slowly. The amplitude of the current in DFIG peaks in the first cycle after the fault but drops after less than 10ms. On the other hand, the minimum response time of utilized relays are almost between 20ms and 60ms, hence, the practical relays cannot detect the fault.

4. Conclusion

High penetration of electric energy from DG sources affects the reliability and security of grid protection. These effects, which depend on numerous parameters such as the location, the size and the technology of generators, were studied in this paper. It has been demonstrated that in an actual network, generators installed very close to the feeder are much more effective on the grid protection system. There is also a direct relationship between the protection blinding and the size of the generator.

Besides, it has been concluded that different types of generators have different effects on the protection systems. The synchronous generator affects the grid current much more than DFIG. Because, unlike DFIG, this type of generator is equipped with an electrical source, usually independent from the network, that supports the electromagnetic field of the rotor. Moreover, due to very fast drop out of DFIG stator currents during external faults, its protection system is unable to detect external faults.

References


