IMPACT OF DIRECTLY-CONNECTED GENERATOR DESIGN ON BALANCED FAULT BEHAVIOUR

J.D.F. MCDONALD Member IEEE
School of Information Technology & Electrical Engineering
The University of Queensland
St Lucia, Brisbane, Australia, 4072

T. K. SAHA Senior Member IEEE

ABSTRACT
This paper considers the impact that the design of a directly connected generator will have upon the behaviour of an entire power system under the influence of a balanced three-phase fault (LLLG) fault. Initially a method for illustrating the effect of the connection of a single generator upon the entire network is demonstrated. This is utilized to derive algebraic comparisons between the fault currents, voltage disturbances and the generator fault in-feeds that are produced in a power system in which an existing generator and GSU (generator step-up) transformer is replaced by a directly connected generator. The qualitative relationships are verified with data obtained from simulation of a 17-bus test system and a 600-bus realistic power transmission network. The results highlight that the variation in design of a single generator may produce perceptible change to network fault behaviour in an appreciable portion of a power system.

KEY WORDS: Power system faults, Short circuit currents, Overvoltages, Powerformer™, Power systems planning.

1. INTRODUCTION
The selection of a new synchronous generator represents one of the most important decisions faced by generation companies. The choice of a new generator will be governed by regulatory, environmental, and, perhaps most importantly, financial considerations. Contingent to the selection of a new generator then is an accurate cost—benefit analysis of the performance of the new machine including costs incurred from any re-rating of switchgear or modification of the protective network enforced by the commissioning of the new generator.

1.1 POWERFORMER™
A study of such nature is further complicated by the increasing diversification of generator designs used in modern power systems, including innovative designs such as Powerformer™ [1], the novel high voltage generator developed by ABB corporate research in 1997. Powerformer™ has the ability to generate electricity at transmission voltages and thus inject power into a network directly without need for a GSU transformer.

Figure 1 Comparison of Powerformer™ and conventional generator/transformer [1]

Prior investigations [2, 3] indicate that in most cases the fault impedance of Powerformer™ will be either somewhat smaller or approximately equal to the total fault impedance of a corresponding generator-transformer combination. It would thus be worth examining how these differences in generator design would affect the performance of the entire network during fault conditions.

The aim of this investigation was to develop a method for assessing the impact of the design of a single generator upon the fault behaviour of an entire power system. This technique could then be used to make analytical comparisons between the fault behaviour of a conventional system and the corresponding network in which a single conventional generator/GSU transformer was replaced by a directly connected generator. Network behaviour was described by the fault currents, voltage disturbances and also the currents flowing in all network generators after the initiation of a three-phase (LLLG) fault at any point in network, excluding the terminals of the original conventional generator. The relationships developed were validated with numerical results from a 17-bus test system and a realistic 600-bus power system.

The results of preliminary comparisons between the fault behaviour of conventional networks and corresponding networks containing Powerformer™ are detailed in [2, 3]. These references present illustrative comparisons between
parameters such as fault currents, and the contributions to a fault from the network or the generator produced under either network configuration for a fault occurring on the generator terminals directly or at the connection to the high voltage network. The results obtained however are constrained by their reliance upon the specific numeric network parameters and the limited geographical spread of fault positions addressed that preclude characterisation of whole network behaviour.

2. NETWORK MODELLING

This investigation utilized quasi-steady state fault analysis techniques [4] in which the network was modelled in a linear manner, and described by either an admittance or impedance matrix. The main constraint of either form is the difficulty of illustrating the impact of a single element upon the behaviour of the entire network.

2.1 GENERATOR MODELLING

Under balanced fault conditions, generators may be represented as a single radial connection to the remainder of the network with impedance of either $Z_e + Z_f$ for a conventional generator and step-up transformer or by $Z_e$ for a directly connected generator, i.e. Powerformer™.

![Diagram of generator connection to existing power system](image)

Figure 2: Connection of generator to existing power system

As both configurations may be represented by a single radial connection to an existing network with unchanging configuration, the impedance matrix representation was used to determine the fault performance of the modified network. The required changes in the impedance matrix needed to represent the alteration in network configuration may be performed by either re-applying steps from an impedance matrix construction algorithm [5] or through re-factorisation or compensation as described in [6]. Given the limited change in network configuration required to represent the addition of single generator, the network modification was illustrated by re-application of the construction algorithm described in [5].

2.2 NETWORK MODELLING

An original system consisting of $N$ buses can be described by an impedance matrix of the general form:

$$Z_{BUS} = \begin{bmatrix} Z_{11} & \cdots & Z_{1N} \\ \vdots & \ddots & \vdots \\ Z_{N1} & \cdots & Z_{NN} \end{bmatrix}$$

(1)

This matrix could represent either a complete power system if the new generator is augmenting existing generator capacity, or a partial network from which a conventional generator/GSU-transformer has been removed, allowing consideration of the replacement of an existing generator. In either case, adding a generator to bus $m$ is modelled by connecting the impedance of the generator between the existing node $m$ and the reference node, as outlined in [3], to create the augmented matrix:

$$Z'_{BUS} = \begin{bmatrix} Z_{11} & \cdots & Z_{1m} & \cdots & Z_{1N} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ Z_{m1} & \cdots & Z_{mm} & \cdots & Z_{mn} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ Z_{N1} & \cdots & Z_{Nm} & \cdots & Z_{NN} \end{bmatrix}$$

(2)

After Kron reduction the general form of all elements of the modified impedance matrix is given by:

$$Z_{km} = Z_{km} - \frac{Z_{km} Z_{mn}}{(Z_e + Z_f) + Z_{mn}}$$

(3)

All elements of the new impedance matrix are now defined in terms of parameters describing the original high voltage network and the impedance of the new conventional or directly connected generator. It is then possible to determine the extent to which a generator design may influence network-side fault behaviour.

2.3 MODELLING CONSTRAINTS

A key assumption used in this analysis was that the new generator was added to a network dominated by reactive impedances to the extent that all elements of the original impedance matrix, $Z_{0k}$, can be approximated by $jX_{0k}$ where $X_{0k}$ represents the magnitude of the reactance of $Z_{0k}$. Thus the connection of a new radial branch of predominantly reactive impedance will reduce the magnitude of all elements of the original impedance matrix when representing the modified network.

Although this assumption can be readily applied in mature power systems in which the connections between the network buses and the reference node are dominated by the reactive impedances of network generators, in
networks in which there are few reactive connections between the network buses and the reference node, the addition of a new generator of predominantly reactive impedance may actually increase the driving point or transfer impedances at certain points in the network. The limit for which it can be assumed that the network is essentially reactive can be determined mathematically. Given that it is possible to write (3) in the form:

\[
Z_{i,\text{new}} = Z_0 \left( 1 - \frac{Z_{\text{in}} Z_{\text{out}}}{Z_0 (Z_x + Z_y) + Z_{\text{in}}} \right)
\]

where

\[
\left| \Delta \right| = \frac{Z_{\text{in}} Z_{\text{out}}}{Z_0 (Z_x + Z_y) + Z_{\text{in}}}
\]

\[
\phi = \arg \left( -\frac{Z_{\text{in}} Z_{\text{out}}}{Z_0 (Z_x + Z_y) + Z_{\text{in}}} \right)
\]

the impedance at all points in the modified network will then be smaller than in the original network provided

\[\cos \phi \leq \frac{1}{2}\]

This defines clearly the range of network impedances for which the connection of a new generator will reduce the magnitude of all elements in the modified impedance matrix in comparison to the corresponding elements in the original impedance matrix.

The other constraint applied to the analysis in this paper is that when comparing network configurations it is assumed that the pre-fault voltages should be the same irrespective of the type of generator being connected. This is consistent with classical fault analysis in which all pre-fault voltages are assumed to be 1 p.u. but could also apply to the comparison of an existing generator with a new generator design, in which case pre-fault voltages would have been determined already via load flow.

3. ANALYTICAL RELATIONSHIPS

The following section outlines the development of analytical relationships that relate the fault behaviour at all points in the network with generator fault impedance. These relationships however are derived assuming all parameters are expressed by per unit quantities and the relationships between real physical parameters may vary somewhat from the results presented.

3.1 FAULT CURRENT

The fault current produced by a balanced three-phase bolted fault is inversely proportional to the driving point impedance at the fault point. The addition of a new generator will decrease the driving point impedance at all points in the network with the degree of reduction also inversely proportional to the new generator’s impedance. This can be related to the specific design of the generator of interest by comparing the algebraic difference between the fault current produced by a fault at point \( k \) in the network containing the directly connected generator with the corresponding fault current produced in a conventional network. The difference was found to be:

\[
\left( X_x + X_{\text{in}} \right) \left( X_x + X_{\text{in}} \right) + X_{\text{out}} - \left( X_x + X_{\text{in}} \right) - A \left( X_x + X_{\text{in}} \right) = 0
\]

where

\[A = X_{\text{in}} X_{\text{out}}\]

This illustrates that the current produced in the directly connected network will be larger than that produced by the conventional network if the impedance of the directly connected generator is less than that of the conventional generator/TSU transformer combination it is replacing.

3.2 VOLTAGE DISTURBANCE

The voltage disturbance produced at any bus throughout the high voltage network by a balanced three-phase fault may also be expressed as a function of both network parameters and the impedance of the generator of interest. The voltage disturbance at bus \( i \) is given by:

\[
\Delta v_i^{(1)} = \frac{Y_{ii}(0) X_x}{X_{\text{in}}} \left( X_x + X_{\text{in}} - X_{\text{in}} + X_{\text{in}} X_{\text{out}} \right)
\]

Rather than assessing the voltage disturbance directly, the subsequent voltage produced at bus \( i \) under the influence of a fault at bus \( k \) was calculated. The difference between this voltage produced under fault conditions in the network containing the directly connected generator and that in the conventional network was proportional to

\[
\left( X_x + X_x \right) \left( X_x + X_x \right) - X_{\text{in}} X_{\text{out}} + X_{\text{in}} X_{\text{out}} Y_i X_{\text{in}}
\]

It can be shown that the network dependent term:

\[-X_{\text{in}} X_{\text{out}} + X_{\text{in}} X_{\text{out}} + X_{\text{in}} X_{\text{out}} Y_i X_{\text{in}}
\]

will always be negative provided the network impedances can be assumed to be predominantly reactive. If the impedance of the directly connected generator is smaller than the sum of the fault impedances of the conventional generator and its step-up transformer then equation (10) will be positive and the fault voltages will be higher in the network containing the directly connected generator.

3.3 GENERATOR CONTRIBUTION

The impedance of the generator under consideration will also affect the amount of current that all generators in the network must contribute under fault conditions. The
contribution of a specific pre-existing generator with fixed fault impedance to a fault at bus \( k \) is proportional to the voltage change that occurs at the terminals of that generator under fault conditions. The total current produced by the generator while a three-phase fault is incident is then given by:

\[
I_{p, k} = \frac{E'_{g} - (V_{g} + \Delta V_{g})}{Z'_{s}} = I_{s} - \frac{\Delta V_{g}}{Z_{s}}
\]

(12)

where \( V_{g} \) is the terminal voltage of the generator, \( E'_{g} \) is the generator’s subtransient internal voltage and \( Z_{s} \) is the subtransient fault impedance of the generator. The generator is supplying load current, \( I_{s} \), as well as contributing current to the fault, with the magnitude of this contribution proportional to the voltage disturbance produced by the fault at the generator terminals. Replacing a conventional generator with a directly connected generator with smaller fault impedance than that of the original generator/transformer will then reduce the fault contributions of all pre-existing generators.

Finally, the contribution of the new generator under consideration can also be established. The contribution to a balanced three-phase fault at bus \( k \) in the power system of the directly connected generator attached to the high voltage network at bus \( m \) is given by:

\[
X_{m} V_{m}
\]

\[
\left( X_{m} + X_{m} \right) \left( X_{m} + X_{m} \right) - X_{m} X_{m}
\]

(13)

It can then be concluded that lowering the impedance of the directly connected generator will increase its contribution to any fault throughout the network.

4. RESULTS

The analytical relationships developed were compared with results obtained from simulation of a small 17-bus test system and a realistic 600-bus network. The 17-bus test system is based on the 14-bus test system listed in [7], although the GSU transformers are modelled implicitly and the original generator impedances were replaced with more realistic values. Six in-line faults are also added creating up to 23 possible fault positions in the network.

In both networks, fault behaviour was verified by replacing a single conventional generator/transformer with a directly connected generator. The impedance of the new generator was varied by 2 decades centred on its rated fault impedance. The specific generator per-unit impedances used, adjusted for a base of 100 MVA, were \( Z_{g} = 0.000687 \) (0.01 \( \rightarrow \) 1.0) p.u. connected at bus \( AA135 \) in the 17 bus network and either \( Z_{g} = 0.00277 \) (0.05 \( \rightarrow \) 5.0) connected at bus 180 or \( Z_{g} = 0.00385 \) (0.0728 \( \rightarrow \) 7.28) at bus 551 in the realistic network.

The different points of connection in the realistic network include a single isolated unit (bus 180) or a single unit from a large station consisting of multiple units (bus 551).

4.1 FAULT CURRENTS

The variation in fault current increase with respect to the per-unit fault current measured in the original network is illustrated in figures 3-5.
Figures 3-5 support the developed analytical relationship (8), showing that if the conventional generator–transformer is replaced with a directly connected generator of lower fault impedance then the balanced fault current will increase, with varying degrees of significance, at most points in the network. As demonstrated in Figure 5, the fault current produced by a fault at the terminals of the original generator does not necessarily vary in this manner although this problem is addressed more thoroughly in studies [2. 3].

4.2 VOLTAGE DISTURBANCE

The relationships between generator design and fault voltage disturbance are shown in figures 6-8. The voltage illustrated is that at the point of connection of the new generator. The relationship between generator design and subsequent fault voltages is most pronounced at this point.

![Figure 6 LLLLG fault voltages](image)

The fault voltages are not illustrated for a fault at every point in the realistic network, as the relationships are too complex to show all fault locations. The behaviour at the fault positions shown however validates the expected relationship that voltage disturbance will be reduced in the network with a directly connected generator if its impedance is lower than that of the original configuration.

![Figure 7 LLLLG fault voltages—realistic system](image)

4.3 GENERATOR CONTRIBUTION

Finally figures 9-11 show the relationship between the fault in-feeds of existing generators and the design of the conventional or directly connected generator. In the realistic system the fault in-feed of a generator at bus 416, 500km from bus 180 but adjacent to bus 551, is assessed.

![Figure 8 LLLLG fault voltages—realistic system](image)

![Figure 9 Fault contribution of generator DDD138](image)

![Figure 10 Generator 416 fault contribution – Powerformer™ at bus 180](image)
Figure 11 Generator 416 fault contribution – Powerformer™ at bus 551

Again the relationships illustrated in figure 9-11 support the algebraic analysis and confirm that at all points in the network apart from the terminal of the conventional generator, the contribution of an existing generator can only decrease if a conventional generator is replaced by a directly connected generator of smaller impedance. These effects are not geographically localised with figure 10 illustrating that the variation of the contribution of a generator may be influenced by a machine 500 km away.

4.4 RESULTS SUMMARY

The overall fault behaviour of a network in which a conventional generator-GSU transformer is replaced by a directly connected generator with reduced fault impedance, as is consistent with the realistic design of Powerformer™ [2, 3], can be summarised as:

Table 1 Fault performance summary - \( Z_0 < Z_0 + Z_g \)

<table>
<thead>
<tr>
<th>FAULT PARAMETER</th>
<th>COMPARISON WITH ORIGINAL NETWORK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault Current</td>
<td>Higher</td>
</tr>
<tr>
<td>Voltage Disturbance</td>
<td>Lower</td>
</tr>
<tr>
<td>Original generator contributions</td>
<td>Lower</td>
</tr>
<tr>
<td>New generator’s contribution</td>
<td>Higher</td>
</tr>
</tbody>
</table>

These changes in fault behaviour will be produced at all points of a power system even when only a single conventional generator is replaced by Powerformer™.

5. CONCLUSIONS

This paper presents the development and application of a technique for comparing the network-wide fault behaviour of a power system in which an existing generator-transformer combination has been replaced by a directly connected generator of varying fault impedance. Analytical relationships have been derived that allow qualitative assessment of the relationships between network-wide fault behaviour and the design of this new directly connected generator. Of particular importance is the reliance of the fault in-feeds of existing generators upon the fault impedance of even geographically remote generators although considering the proportional variation in generator contribution only may over-state this impact.

Although the analytical relationships were derived utilizing the assumption that the network was predominantly reactive, a mathematical relationship between network change and the parameters of the existing network was outlined in (7) that allows one to determine accurately whether the analytical relationships can be applied to a particular realistic network design.

Finally, while these relationships have only been developed for balanced fault conditions, future work will concentrate upon extending the technique to unbalanced fault conditions, along with developing quantitative rather than purely qualitative relationships between generator parameters and network-wide fault behaviour.

6. ACKNOWLEDGEMENT

This work was supported by an Australian Research Council S.P.I.R.T. Grant along with the generous contributions of the affiliated industry partners.

7. REFERENCES


