PRELIMINARY INVESTIGATIONS INTO THE INFLUENCE OF GENERATOR AND TRANSFORMER IMPEDANCE ON POWER SYSTEM FAULT BEHAVIOUR

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Abstract

This investigation considers the influence of generator and unit transformer impedance upon fault behaviour of a power system containing either conventional or directly connected generators. The impact is quantified by considering the fault behaviour of a single machine infinite bus (SMIB) system as transformer and generator impedance is varied. Changes in these parameters will affect the fault performance of the entire network. The major effect is a large reduction in the severity of generator terminal faults and in the generator contribution to network fault currents. The impact of parameter variation upon fault performance was also considered using analytical techniques with the results obtained used for design optimisation or sensitivity analysis.

Keywords: fault analysis, machine parameters, parameter optimisation

1. INTRODUCTION

The increasing utilization of co-generation or directly connected high voltage generators, i.e. Powerformers™ – the high voltage generator developed by ABB Corporate Research in 1998, will have a significant impact upon the structure and operation of both new and existing power systems in steady state and fault conditions.

An accurate knowledge of the fault performance of a power system is necessary for determining component ratings, co-ordinating protective settings, limiting component damage and plant down-time and even fulfilling regulatory obligations. It is essential that accurate fault studies be completed whenever network configuration is modified.

1.1 Investigative Objectives

The dependence of network fault performance upon generator characteristics was highlighted in [11]. It was emphasised that a generator would provide the majority of fault current into a network, via its unit transformer. The level of this contribution is dependent upon the:
- system voltage,
- tap position of the generator transformer,
- impedance of the both the generator and the generator transformer.

It is expected that the replacement of a conventional generator and unit transformer with a single generator directly connected to the high voltage bus will have a major impact upon network fault behaviour.

The aim of this investigation was to quantify the relationship between system fault behaviour and generator and transformer impedances by completing a comprehensive assessment of the fault performance of single machine infinite bus system containing either a traditional generator and unit transformer or a directly connected generator.

A numerical comparison of fault behaviour was obtained by completing quasi-steady-state fault analysis at several points in the networks. Faults considered included: balanced three phase faults and unbalanced fault such as single line to ground, line to line, double line to ground, single open conductor and finally double open conductor faults. Analytical expressions describing the impact of generator impedance upon fault performance were also derived, and the behaviour of each network configuration was compared so that the appropriateness of the selected generator sub-transient reactance could be assessed.

The contributions of the respective sources of fault current were also measured as the position of the fault and the network impedances were varied. These sources included either the single generator or the network slack bus with the slack bus representing either a second generator or corresponding to the equivalent impedance of a much larger system. These results complement those obtained [2, 3]. Similar studies that focused on generator and transformer terminal faults particularly, rather than considering the impact of the fault throughout the network.
2. POWER SYSTEM MODELLING

2.1 Test System

The test system used in this study was based on a network taken from [4] with power flows and machine impedance modified to make the study more realistic.

2.2 Generator Representation

The generator was represented by a simple voltage source behind a reactance. Sub-transient reactance was used to allow maximum available fault current. The reactances of the both the conventional generator and the directly connected generator were obtained from [3] using a system MVA base of 73 MVA.

<table>
<thead>
<tr>
<th>Generator Sub-transient Reactance</th>
<th>$Z_e = j0.184$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformer Impedance</td>
<td>$Z_T = j0.15$</td>
</tr>
<tr>
<td>Directly connected generator</td>
<td></td>
</tr>
<tr>
<td>Sub-transient Reactance</td>
<td>$Z_p = j0.2707$</td>
</tr>
<tr>
<td>Equivalent Slack Bus Impedance</td>
<td>$Z_r = j0.184$</td>
</tr>
<tr>
<td>Line Impedance - branch 1</td>
<td>$Z_{11} = j0.5$</td>
</tr>
<tr>
<td>Line Impedance - branch 2</td>
<td>$Z_{12} = j0.93$</td>
</tr>
</tbody>
</table>

Table 1 System Parameters

2.3 Sequence Components

Unbalanced fault analysis was performed using symmetrical components. It was assumed that the positive and negative sequence networks were identical, but zero sequence impedances must still be defined explicitly.

2.3.1 Generator

The zero sequence impedance of a synchronous machine may vary from 0.1-0.7 times its positive sequence reactance depending upon rotor position.

The minimum value was used producing more conservative fault levels.

2.3.2 Transformers

The method in which the transformer windings are connected and grounded will affect significantly the zero sequence impedance of the network. The transformer was assumed to be connected Δ-Y with the high voltage Y-connected winding solidly grounded, consistent with results detailed in [5].

2.3.3 Transmission Line

It was assumed that the connection between bus 2 and 3 consisted of a double circuit transmission line for which it is generally assumed that the zero sequence impedance in approximately 5.5 times the positive sequence impedance [6].

3. FAULT CURRENTS

This investigation concentrated on worst-case fault scenarios and thus some choices of system operating parameters may not be entirely realistic. These

![Figure 1 Test System Diagram](image1.png)

![Figure 2 Zero Sequence Network](image2.png)

Figure 1 Test System [4]

Figure 2 Zero Sequence Network
include considering only bolted faults and in most cases assuming that the generator was solidly grounded.

3.1 Balanced Faults

Results were obtained for the fault current, \( I_f \), produced by balanced three-phases faults along with the contribution to this current from the generator connected at bus 1, \( I_g \), and the slack bus at bus 3, \( I_L \).

Network configuration was adjusted by first reducing the transformer impedance from its initial value of 0.15 p.u. to 1E-6 p.u. At this point the transformer is virtually a short circuit although it is still acting as an interface between the low voltage/ high current generator and the high voltage/low current transmission system. In the final case considered the transformer was completely removed and the conventional generator with its sub-transient reactance of \(0.184\) p.u. was replaced by a generator connected directly into the high voltage network, with a sub-transient reactance of \(0.2707\) p.u.

Network voltages as obtained from a load flow study were used as pre-fault voltages rather than assuming the network was unloaded. Voltage ratings for the network include were 20 kV on the generator terminals and 150 kV on both the high voltage side of the unit transformer and across the entire directly connected generator network.

<table>
<thead>
<tr>
<th>Transformer</th>
<th>Fault Current [kA]</th>
<th>Fault Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>( j0.15 )</td>
<td>( I_g ) ( 20.1 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( I_L ) ( 17.2 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( I_L ) ( 0.407 )</td>
<td></td>
</tr>
<tr>
<td>( j1x10^4 )</td>
<td>( I_g ) ( 21.4 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( I_L ) ( 17.2 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( I_L ) ( 0.536 )</td>
<td></td>
</tr>
<tr>
<td>Directly Connected Generator</td>
<td>( I_g ) ( 1.63 )</td>
<td></td>
</tr>
<tr>
<td>( (XI = 0) )</td>
<td>( I_L ) ( 1.46 )</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3 Balanced three-phase fault currents

3.1.1 Influence of Transformer Impedance

A reduction in the transformer impedance leads to an increase in fault current for a fault at any bus, with the largest comparative increases in fault current appearing at bus 2.

The contribution to fault current from the generator is largely unaffected by the reduction in transformer impedance for faults at bus 1. For faults at bus 2 or 3 the removal of transformer reactance produces a significant increase in generator contribution to fault current, especially at bus 2. The contribution from the slack bus, corresponding to the equivalent impedance of the remainder of the network, is not as strongly influenced by transformer impedance, although reducing this impedance results in increased slack bus contribution to faults at the generator terminals.

3.1.2 Influence of Generator Impedance

Replacing the conventional generator with a directly connected high voltage generator produced a dramatic reduction in both fault current for faults at bus 1 and the magnitude of generator contribution to faults at other points in the network. This was due to the lower base current of the directly connected generator.

The reduction in fault current at bus 1 is also due to the higher sub-transient reactance of the directly connected generator. Fault performance on all buses could be made comparable to or even better than the original network if the sub-transient reactance of the directly connected generator were set equal to or greater than the sum of the sub-transient reactance of the original generator and the short circuit impedance of the transformer. As the given generator did not quite reach this figure of merit, fault performance for faults at either bus 2 or 3 was degraded with both fault current and particularly contribution from the external system higher than that in the original system.

3.2 Unbalanced Faults

Although extensive studies were performed for unbalanced fault conditions only the results for single line-to-ground faults are presented. For near-to-generator faults on solidly grounded generators, earth fault current may exceed three-phase bus fault current so these fault measurements will also be used for determining adequate rating of circuit breakers. The behaviour of single line-to-ground faults was also shown to be representative of the behaviour of other shunt fault although fault current magnitudes differed.

The actual fault currents determined for single line to ground faults occurring at any of the network buses or at the midpoint between either line connecting bus 2 and 3 are shown in figures 4-6.
Figure 4 Variation in single line-to-ground fault current

Figure 5 Variation in contribution from generator to single-line-to-ground fault current

Figure 6 Variation in contribution from system equivalent to single line-to-ground fault current
Similar behaviour to balanced faults was observed, with the biggest variation in fault current resulting from the change in base current at bus 1 when the directly connected generator replaces the conventional generator.

3.2.1 In-line faults
In-line fault, rather than bus fault constitute the majority of faults incidenes in real systems. These faults were found to be less severe than faults at network buses. Reducing the transformer impedance increased the generator contribution to these faults although once the conventional generator is replaced this contribution is considerably reduced. The equivalent system contribution however was almost independent of generator impedance but increases slightly as transformer impedance is decreased.

3.2.2 Grounding
The contrasting zero sequence networks of the different generator configurations ensure the selection of generator neutral-ground connection. Z_n. has perhaps a greater influence upon network behaviour during ear faults than the generator's zero sequence reactance. Initially both configurations were examined with solidly grounded generators and as stated previously the subsequent fault behaviour was similar to balanced faults. In the directly connected network generator zero sequence impedance will effect fault current at all points in the network but only at bus 1 in the conventional network.

Different behaviour is observed when both generators are assumed to be ungrounded. The results obtained for that situation are detailed in the following table.

<table>
<thead>
<tr>
<th>Transformer Impedance (Xb)</th>
<th>Fault Current [kA]</th>
<th>Fault Position</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I_0</td>
<td>1</td>
</tr>
<tr>
<td>j0.15</td>
<td>I_0 = 0</td>
<td>1.54</td>
</tr>
<tr>
<td></td>
<td>I_2 = 2.18</td>
<td>5.71</td>
</tr>
<tr>
<td></td>
<td>I_3 = 0.291</td>
<td>0.48</td>
</tr>
<tr>
<td>Directly Connected Generator (Xb = 0)</td>
<td>I_0 = 0.731</td>
<td>0.731</td>
</tr>
<tr>
<td></td>
<td>I_2 = 0.521</td>
<td>0.521</td>
</tr>
<tr>
<td></td>
<td>I_3 = 0.383</td>
<td>0.383</td>
</tr>
</tbody>
</table>

Table 2 Single Phase Earth Fault – \( Z_n = \ldots \)

In the absence of zero sequence capacitance the single phase earth fault current in the conventional network was zero, while a similar fault in the directly connected network produced appreciable fault current, and also drew slightly more current from the system equivalent although in both cases this current was fairly small. For faults at bus 3, both networks had comparable performance, with the generator contribution reduced in the directly connected network, while fault performance at bus 2 was improved by replacing the conventional generator.

4. PARAMETER OPTIMISATION
Although it has been possible to determine the fault behaviour of a system with a directly connected generator, it would be useful if generator parameters could be selected to ensure network fault behaviour was comparable or better than the original network. Determining network fault behaviour as a function of generator impedance would facilitate both parameter selection and possible optimisation of overall network performance.

The fault current at any bus \( k \) and the voltage disturbance caused at buses \( m \) is given as follows.

\[
I_f = \frac{V_f}{Z_{km}} \quad \Delta V_k = -I_f Z_{km}
\]

In algebraic form the Thévenin impedances at each of the buses in the network is given by:

\[
Z_{11} = \left( Z_0^* + Z^* + Z^*_f \right)
\]

\[
Z_{21} = \left( Z_0^* + Z^* + Z_f + Z^*_f \right)
\]

\[
Z_{22} = \left( Z_0^* + Z_f + Z_f + Z^*_f \right)
\]

\[
Z_{33} = \left( Z_0^* + Z_f + Z_f + Z^*_f \right)
\]

Similar formulae can be constructed for the transfer impedances, thus allowing the derivation of expressions describing the dependency of network fault performance on \( Z_n^* \), e.g. for a fault at bus 2.

\[
I_f = \frac{V_f(0)}{Z_{22}} - V_f(0) \left( \frac{Z_0^* + j0.65917}{Z_0^* + j0.50917} \right)
\]

\[
dV_f = -I_f Z_{21} = -V_f(0) \left( \frac{Z_0^* + j0.15}{Z_0^* + j0.15} \right)
\]

\[
dV_f = -V_f(0) - I_f Z_{22} = -V_f(0) \left( \frac{Z_0^*}{Z_0^* + j0.50917} \right)
\]

The variation in fault behaviour with respect to generator impedance is shown in figures 7 and 8. Fault current and voltage disturbance are measured as a ratio to the rated line current of 1.00917 p.u. or the rated voltages of 1.0 p.u. and 0.9068 p.u. at bus 1 and bus 3 respectively.
Figure 7 Fault behaviour - conventional network

Although the variation in sub-transient reactance of a generator is usually limited to 0.1-0.5 per unit [6], the selection of generators with different impedances within this range would change fault current magnitude at bus 2 appreciably. Similarly, it would seem that the voltage change at bus 1 can be limited if the generator impedance is minimized, whereas at bus 3 this change is independent of machine parameters.

Figure 8 Fault behaviour - modified network

The effect of the directly connected generator can be determined from figures 7 and 8. For realistic values of sub-transient reactance both fault current and voltage change will be higher in the modified network than in the conventional network with identical generator impedance but these relationships are only valid for the fault configuration considered.

5. CONCLUSIONS

The most obvious impact of replacing a conventional generator with a directly connected generator is that it will reduce considerably both the fault current at the generator terminals and the contribution from the generator to faults throughout the entire network. The impact of replacing the conventional generator upon fault behaviour however will not be confined to the immediate vicinity of the generator, but will have an appreciable influence upon fault behaviour throughout a significant proportion of the network. This includes the current drawn from the system equivalent; suggesting that the current drawn from un-faulted generators in a realistic system would also increase.

Although the choice of generator parameters will have an effect for balanced fault conditions, the selection of parameters, especially the manner in which the network is grounded, will be more critical under unbalanced fault conditions given the significant change that occurs in zero sequence impedance when a conventional generator is replaced by a directly connected generator. Future work will concentrate upon assessing this impact in a more realistic system.

Finally the variation in network fault performance over an extensive range of generator impedances was assessed and the results obtained providing either a means to select appropriate generator parameters, or else determine the sensitivity of network performance to variations in design or measured machines values.

6. ACKNOWLEDGMENTS

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7. REFERENCES


