Selection of generator fault impedances for enhancement of network-wide fault behaviour *

J D F McDonald and T K Saha
School of Information Technology and Electrical Engineering
The University of Queensland
Email: jdm@itee.uq.edu.au, saha@itee.uq.edu.au

SUMMARY: *This paper presents the development and application of a method for illustrating graphically the range of suitable generator designs for achieving a desired performance of a network under either balanced or single line-to-ground fault conditions. After derivation of its theoretical basis, the effectiveness of the method is verified by examination of the impact of generator design on either balanced or single line-to-ground fault currents produced in a small test system. The results demonstrate the ability of the technique to provide a clear representation of the range of generator designs that could enhance or degrade network-wide fault behaviour, aiding in the selection of generator parameters for suitable fault performance.*

1 INTRODUCTION

One of the most significant factors influencing the fault behaviour of a power system is the nature and design of the existing generation capacity. As stated in[1], synchronous generators represent one of the most significant contributors to fault current in a power system, with the magnitude of this contribution governed by both the generator fault impedance and the short-circuit impedance of any required step-up transformers. Changes to generator composition in a power system through generator augmentation or replacement may affect the fault behaviour of an appreciable portion of the network, requiring the reinforcement of switching equipment or the modification of the existing protective network.

The cost effectiveness of a generator replacement or augmentation scheme will then depend partly upon the cost of any network modifications required by a change in generator composition. Modifications to generator composition ideally should have a limited impact upon network fault performance, although this becomes less probable when considering more radical generator designs such as Powerformer™.

Powerformer™ is the innovative high voltage generator developed by ABB Corporate research in 1997.[2] As figure 1 illustrates, its configuration represents a major departure from conventional generator design. It would therefore be advantageous if a technique could be developed to ensure that even significant changes in generator design will result in only a limited impact upon network fault behaviour.

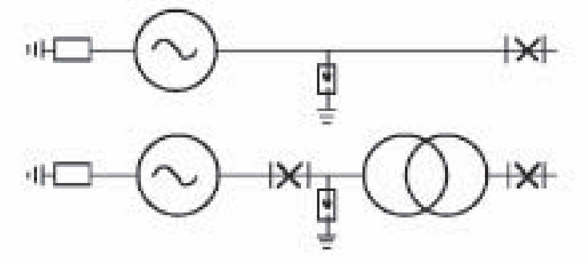

Figure 1: Comparison of Powerformer™ and conventional generator/transformer[2]

The aim of this paper is to present the development of a technique for determining the range of designs of a single generator used to replace an existing conventional generator in a transmission network that will produce suitable network behaviour under fault conditions. The procedure is derived for the fault current produced under both balanced and single line-to-ground (SLG) fault conditions and can be used to determine a range of generator impedances that will either improve fault behaviour or limit any degradation in fault performance produced by the replacement of the generator of interest.

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A graphical presentation is developed to provide a clear representation of these ranges of appropriate generator designs. Finally the technique is verified by application on a 17 bus test system based on the 14 bus network outlined in [3], with a more detailed description of this test system contained in [4].

2 NETWORK REPRESENTATION

In this investigation network fault behaviour was characterized using quasi-steady state fault analysis techniques.[5] This allows the entire network to be represented either by a single matrix under balanced fault conditions or by the positive and zero sequence matrices for unbalanced fault conditions. In both cases, when considering faults throughout the high voltage network but excluding faults directly on the terminals of the generator being replaced, a generator can be represented as a single radial connection to an existing network as in figure 2.

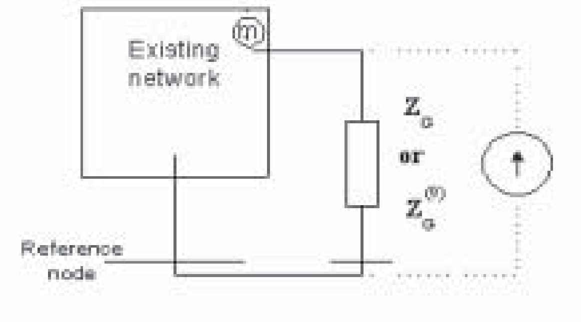

Figure 2: Connection of generator to existing power system

Under balanced fault conditions the single impedance Z_G represents either the total fault impedances of both a conventional generator and its associated generator step – up (GSU) transformer or the single fault impedance of a directly connected high voltage generator.

When considering unbalanced fault conditions, the identity of this radial connection is less obvious. The normally delta-wye connected GSU transformer ensures that the zero sequence impedance of a conventional generator, including its grounding impedance, does not affect the behaviour of faults occurring in the high voltage network. Instead, the single radial connection actually represents the zero sequence impedance and grounding connection of the high voltage winding of the GSU transformer.

For directly connected generators, such as Powerformer™, however, the removal of the GSU transformer means the behaviour of faults occurring in the high voltage network will be no longer influenced by neutral-ground impedance of the transformer but instead will be influenced by the directly connected generator's zero sequence impedance in combination with its neutral-ground impedance. Although this comparison is covered in greater depth in [6], it is particularly important that the value of the radial connection be altered to reflect this change.

3 NETWORK FAULT BEHAVIOUR

The key motivation for representing the generator of interest in the manner shown in Figure 2 is that it allows a clear illustration of the impact that changes in generator design will have upon the fault behaviour of the entire network. As stated previously in [7], this model can be used to contruct analytical expressions that illustrate the impact of generator impedance on fault behaviour at all points throughout the power system. For example, the fault current produced by a bolted three-phase fault at bus *k* in the high voltage network to which the generator of interest is connected at bus m can be given by eq (1).

$$I_f^{(k)} = \frac{V_k(0)}{Z_{kk}} \left(\frac{Z_G + Z_{mm}}{\left(Z_G + Z_{mm} \right) - \frac{Z_{km} Z_{mk}}{Z_{kk}}} \right) \qquad (1)$$

The parameters Z_{kk}, Z_{km}, Z_{mk} refer to the relevant driving point and transfer impedances from the impedance matrix describing the partial network to which the generator of interest is connected, while Z_G refers to the fault impedance of the generator.

The SLG fault current produced at bus *k* can also be expressed as a function of both the generator/transformer zero sequence impedance and the configuration of the network to which it is connected.

$$I_{slg}^{(k)} = \frac{3V_k(0)}{Z_{kk}^{(0)} + 2Z_{kk}^{(1)}} \left(\frac{Z_G^{(0)} + Z_{mm}^{(0)}}{\left(Z_G^{(0)} + Z_{mm}^{(0)} \right) - \frac{Z_{km}^{(0)} Z_{mk}^{(0)}}{Z_{kk}^{(0)}}} \right) \qquad (2)$$

In this expression the positive sequence Thévenin impedance at bus *k* includes a value of generator positive sequence impedance selected independently of the zero sequence impedance of this generator or transformer of interest. Initially this would appear to contradict the direct relationship between the positive and zero sequence generator impedances outlined in [3]. It should be remembered, however, that in this investigation the impedance actually consists of both the implicit zero sequence impedance of the transformer/generator and also the neutral-ground impedance of these components. In most cases the total zero sequence impedance will be dominated by this neutral – ground impedance that can be selected independently, supporting the previous assumption.

3.1 Circles of constant fault behaviour

The most important feature of eqs (1) and (2) is that their format allows one to determine clearly the potential impact that any changes in generator design will have upon fault performance of the transmission network. A direct correspondence can be drawn between these equations and the PZ-form of a transfer function as described in [8]. Considering eq (1) it can be seen that the expression has a zero in the complex impedance plane at $Z_G = -Z_{mm}$ and a complex pole at

$$Z_G = -\left(Z_{mm} - \left(\frac{Z_{km}Z_{mk}}{Z_{kk}}\right)\right).$$

In earlier work completed by the authors [9] it has been shown that these break points, calculated from the configuration of the network to which the generator of interest will be connected, defines the manner in which network fault behaviour will vary as design of the generator of interest is changed. It should be possible then to determine the range of generator designs that will produce specific fault behaviour from knowledge of only these break points.

From examination of eq(1), it can be seen that the magnitude of balanced fault current produced by a specific generator fault impedance is given by:

$$\left|I_f^{(k)}\right| = \left|\frac{V_k(0)}{Z_{kk}}\right| \frac{\left|Z_G + Z_{mm}\right|}{\left|Z_G + \left(Z_{mm} - \frac{Z_{km}Z_{mk}}{Z_{kk}}\right)\right|} \qquad (3)$$

The first term in this equation, $\frac{V_k(0)}{Z_{kk}}$, is independent of generator design, thus the variation in fault behaviour is governed by the second term alone. An equivalent magnitude of fault current will be produced at bus *k* for all generator fault impedance Z_G for which

$$G = \frac{\left|Z_G + Z_{mm}\right|}{\left|Z_G + \left(Z_{mm} - \frac{Z_{km}Z_{mk}}{Z_{kk}}\right)\right|} \qquad (4)$$

is also constant. By recognizing that eq (4) calculates the ratio of distances of the selected generator design from the relevant break points, it is possible to write:

$$G^2 = \frac{\left(R_G - R_Z\right)^2 + \left(X_G - X_Z\right)^2}{\left(R_G - R_P\right)^2 + \left(X_G - X_P\right)^2} \qquad (5)$$

where R_G, X_G, R_Z, X_Z and R_P, X_P represent the real and reactive components of the generator design of interest, the complex zero or the complex pole from eq (4) respectively. It can then be deduced that:

$$\left(R_G - \frac{G^2R_P - R_Z}{G^2 - 1}\right)^2 + \left(X_G - \frac{G^2X_P - X_Z}{G^2 - 1}\right)^2 = \left(\frac{G(R_P - R_Z)}{G^2 - 1}\right)^2 + \left(\frac{G(X_P - X_Z)}{G^2 - 1}\right)^2 \qquad (6)$$

Eq(6) defines a relationship for determining a range of generator designs corresponding to constant fault behaviour, or constant G. The range of generator fault impedances required to maintain constant fault behaviour will then consist of a circle in the complex impedance plane centred on:

$$\left(\frac{G^2R_P - R_Z}{G^2 - 1}, \quad \frac{G^2X_P - X_Z}{G^2 - 1}\right)$$

with a radius of

$$\sqrt{\left(\frac{G(R_P - R_Z)}{G^2 - 1}\right)^2 + \left(\frac{G(X_P - X_Z)}{G^2 - 1}\right)^2}$$

By defining the desired fault behaviour at a particular fault location in terms of the corresponding performance of a network from which the generator of interest has been removed, the location of the relevant pole and zero will then allow the calculation of the radius and origin of the locus of points of all generator designs producing the desired fault behaviour.

An example of this is shown in figure 3 illustrating circles corresponding to different levels of fault performance, measured as a gain in decibels with respect to the fault behaviour of system from which the generator of interest has been removed.

Figure 3 also illustrates how this technique can be used to determine a range of generator designs producing improved/degraded fault behaviour. As can be seen, for a circle of constant fault behaviour encircling a pole, the region inside this circle represents the range of generator designs where the fault parameter of interest will have a magnitude greater (positive gain) than the desired fault behaviour from which the curve was calculated.

Areas outside this circle represent generator designs producing fault behaviour with magnitude smaller than this figure of merit. Similar behaviour can be observed for circles enclosing a zero although the region enclosed by the circle defines generator designs for which the fault parameter considered will have a lower magnitude (more negative gain in decibels) than the behaviour desired.

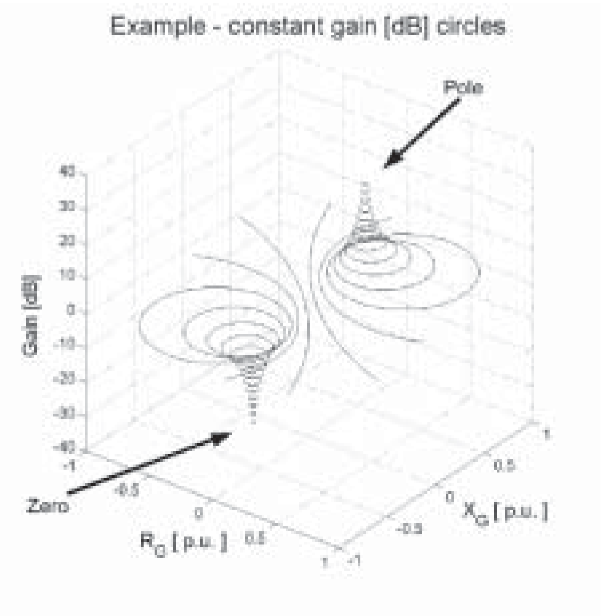

Figure 3: Circles of constant fault behaviour

4 RESULTS

In order to check the validity of this technique the fault behaviour of a simple 17 bus network was calculated. A diagram of this network is included in the appendix of this paper. In all cases it was assumed that the conventional generator connected to bus 15 and its corresponding GSU transformer connected between nodes 15 and 1 was to be replaced by new generator of variable fault impedance.

As highlighted previously, the poles and zeros describing the variation in fault behaviour must be calculated from an impedance matrix from which the influence of the generator under consideration has been removed. Thus to consider the replacement of the existing generator at bus 15 and the GSU transformer with HV terminal at bus 1, the total positive sequence impedance of these components of 0.0007 + j0.157 p.u and zero sequence impedance of GSU transformer of j0.157 p.u must first be removed from the matrices of the relevant sequence networks. Only then can the required break points be calculated.

4.1 Original fault behaviour

Initially the technique was used to determine the range of generator impedances for which the fault currents produced by either balanced or SLG faults at all points in the network would have the same magnitude as that developed by a fault at the corresponding location in the original network. These results are shown in figures 4 and 6.

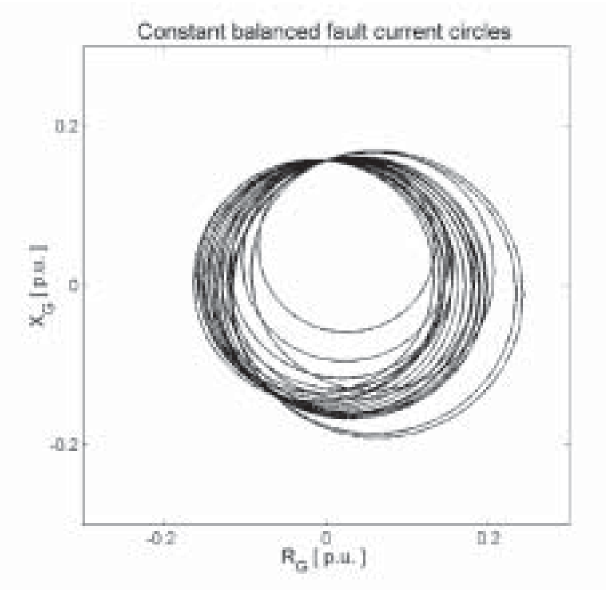

Figure 4: Balanced fault current – constant fault behaviour circles

As it is clearly illustrated in figure 4, a distinct circle of constant fault behaviour is produced for each fault location. These circles represent the set of generator positive sequence fault impedances that could produce fault currents with the same magnitude as that produced by the original network with generator and transformer fault impedances totalling 0.0007 + j 0.157 p.u. As expected, this original impedance of the components to be replaced is a common point of each circle.

By combining each of these curves on a common set of axes as shown it is possible to determine the range of generator designs for which the fault current will be either more/less than the corresponding fault levels in the original network at **all** fault locations concurrently. In all cases the constant fault behaviour circles enclosed the pole of each particular fault location. This implies that the regions inside these circles represent the generator designs producing increased fault current, or degraded fault performance at each fault location. Similarly the regions outside each curve represent the generator designs that will lead to improved fault behaviour, i.e. lower fault current. The region enclosed by all circles then represent generator designs for which fault performance will be degraded at all fault locations, while regions outside all the circles represent the generator designs leading to improved network-wide fault performance.

The distinct regions of operation are shown more clearly in figure 5. The heavily shaded region represents generator designs that produce increased fault current at all fault locations whereas the unshaded regions define the generator impedances for which all possible fault currents are either comparable to or less than that produced in the original system. The lightly shaded region represents generator designs for which fault performance would be considered marginal. These designs would result in increased fault currents at some fault locations, but at other locations, the fault performance may be improved.

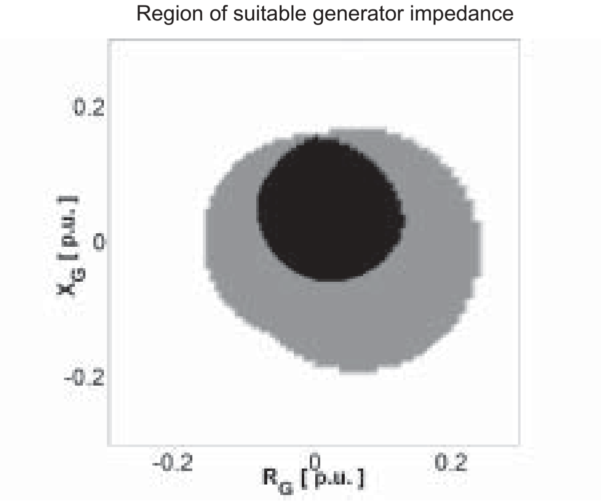

Figure 5: Balanced fault current – regions of suitable generator design

A similar set of diagrams can be obtained for SLG fault currents produced at all points throughout the network. These are shown in figures 6 and 7.

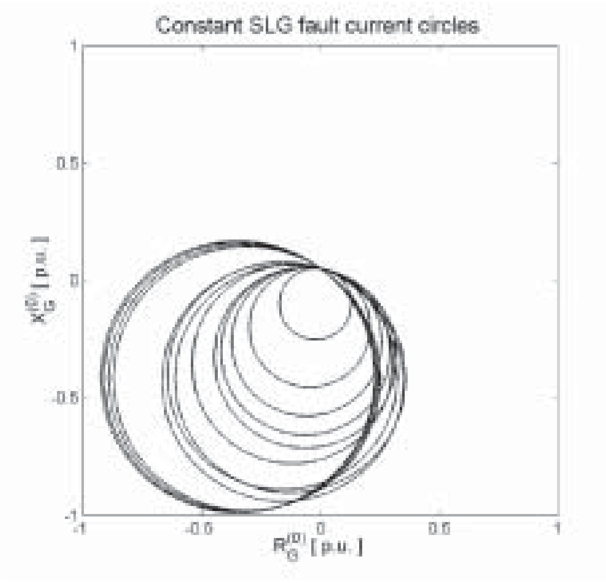

Figure 6: SLG fault current – constant current circles

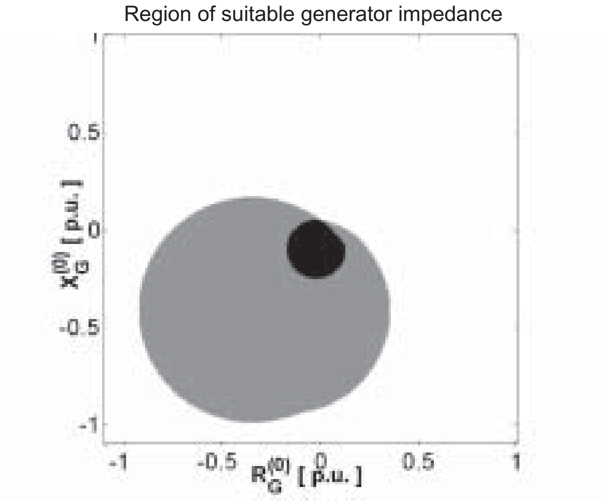

Figure 7: SLG fault current – regions of suitable operation

Using a shading pattern consistent with that in figure 5, figure 7 highlights the range of generator designs that will either improve or degrade the SLG current levels produced by faults throughout the HV network.

4.2 Modified fault behaviour

The technique outlined above can be used not only to determine the range of generator designs that will produce comparable fault behaviour to the original system, but also can be used to determine generator designs that will produce a required change in fault behaviour. An example of this is presented in figures 8 and 9. In this case it was assumed that a 10% increase in fault current at each fault location could be tolerated and the regions producing either acceptable or unacceptable fault currents were determined.

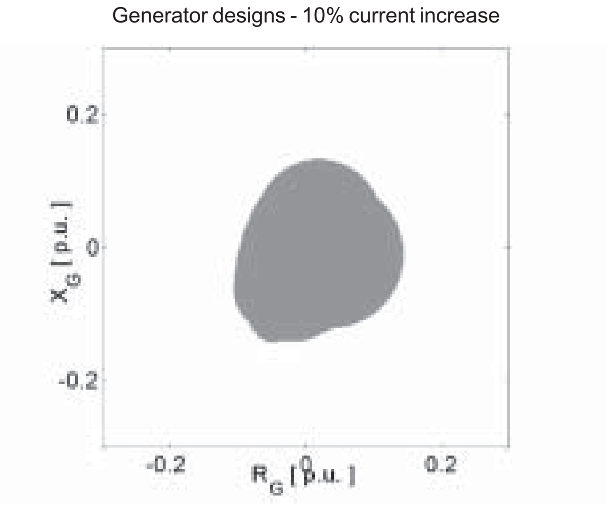

Figure 8: Generator designs - 10% balanced fault current increase

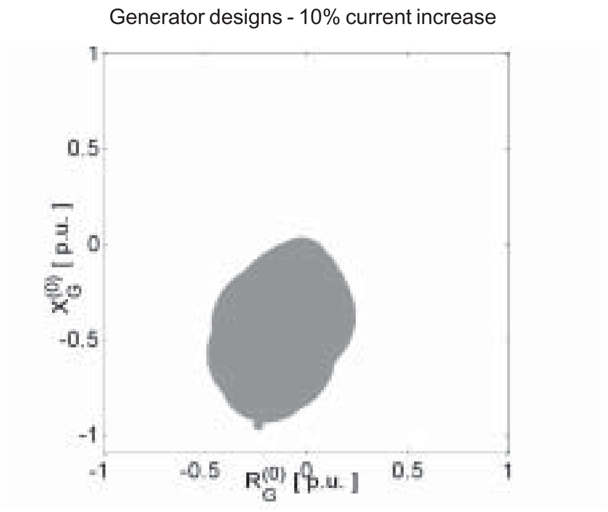

Figure 9: Generator designs - 10% SLG fault current increase

If similar shading is used in Figures 8 and 9 as was used in figures 5 and 7 it can be seen that there are now no generator designs that will produce a 10% increase in either balanced or SLG fault current at all fault locations. Similarly, the range of generator designs that would produce satisfactory fault behaviour is somewhat larger, as would be expected given that the fault constraint has been relaxed somewhat. Similar plots could also be produced for a desired improvement in fault behaviour. These would be possibly more informative as it is expected that the constraints on generator design would be more severe.

Although the results presented above illustrate the effectiveness of the developed technique, some limitations should be addressed. The algorithm used for constructing the constant gain regions is computationally intensive leading to slow execution when considering large networks or fault parameters such as fault voltages where there are as many as N^2 possible combinations to consider. Similarly, the shape of these regions is often predominantly governed by the behaviour of only a few fault locations, with the remaining locations reinforcing this behaviour. These problems can be addressed by selecting only critical buses at which fault behaviour is particular sensitive to changes in generator design, or fault locations at which original fault behaviour is close to the physical limits of network devices.

5 CONCLUSIONS

The technique described is this paper provides a clear and concise representation of the range of generator fault impedances that will ensure network behaviour remains suitable after replacement or augmentation of existing generation capacity. It also can be used to determine the most suitable range of generator designs for given location/application, aiding in the selection of generator types and design.

Alternatively the method can also be used to illustrate how different generator designs will affect network-wide fault behaviour and whether proposed changes will have beneficial impact on system performance. As highlighted previously, it is applicable to both changes in the positive sequence impedance of a generator, or alteration to any zero sequence radial connections in a network including both the ground connections of GSU transformers and the neutral connections of directly connected generators.

Future applications of this technique will involve its extension to consider other fault parameters such as network voltages under fault conditions, generator fault in-feeds and network voltage disturbances. It may be possible to combine a range of generator designs that provide acceptable levels of performance for each of these parameters to calculate an "optimal" range of generator fault impedances. This could then be used in selection of a generator to replace or augment existing network capacity while maintaining satisfactory system fault behaviour.

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APPENDIX

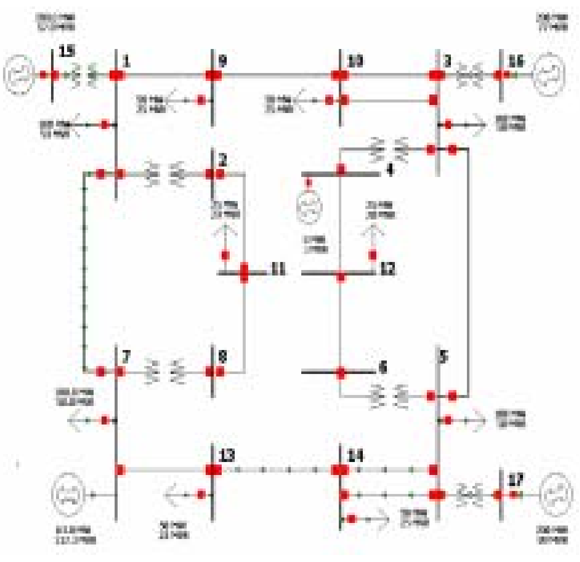

Figure10: 17 bus test system based on [3]

JOHN MCDONALD

John McDonald was born in Brisbane, Queensland. He obtained a BE (Hons – Elec)/BA (Chinese) from the University of Queensland in 1999 and at present he is completing for his PhD investigation at the University of Queensland entitled "Investigations into the design of Powerformer^{TM} for optimal generator and system performance under fault conditions." His fields of interest include power systems analysis, system fault performance and equipment condition monitoring.

TAPAN SAHA

Tapan Kumar Saha was born in Bangladesh and came to Australia in 1989. Dr Saha is a Senior Lecturer in the School of Information Technology and Electrical Engineering, University of Queensland, Australia. Before joining the University of Queensland in 1996 he taught at the Bangladesh University of Engineering and Technology, Dhaka, Bangladesh for three and a half years and at James Cook University, Townsville, Australia for two and a half years. He is a senior member of the IEEE and Fellow of the Institution of Engineers, Australia. His research interests include power systems, power quality and condition monitoring of electrical plants. He has published widely in these fields.