A Research Project to Investigate the Impact of Electricity System Requirements On the Design and Optimal Application of the Powerformer™

M Darveniza, T K Saha, B Berggren, M A Leijon, P O Wright

Abstract: This paper describes the aims and the methodology of a major collaborative research project between the University of Queensland and Australian and Swedish industry partners, including ABB Corporate Research (Sweden), Alstom Power (Sweden and Australia), PowerLink Queensland, Stanwell Corporation, C S Energy and Tarong Energy. The project is investigating the likely benefits of significance to the Queensland system, which will arise from the optimisation of the new Powerformer technology for the generation of electricity at transmission or sub-transmission voltages, i.e. without step-up transformers.

Index Terms—Powerformer, voltage stability, fault levels, earthing, power systems dynamics

1. INTRODUCTION

For over 50 years, electricity has been produced by generators that conventionally operate at medium voltages, typically up to 25,000 volts (25kV). However, modern long-distance transmission systems use much higher voltages, typically in Australia 132, 275, 330 and 500kV. So generators must be connected to the transmission networks by step-up transformers. In the past, the reason given for the relatively low generator voltage was that it was not possible to provide insulation structures in the generator windings, which were capable of withstanding higher voltages. This meant that large capacity generators (typically 100 to 500 MVA) were associated with relatively large winding currents. These not only caused large ohmic losses (which reduced their efficiency), but also placed significant constraints on the design and operating characteristics of the generators. These constrained characteristics of conventional generators meant that there was little flexibility in matching them to best suit the technical requirements of the electricity system to which they were connected.

In 1998, ASEA – Brown Boveri (ABB), the largest electro-technology group of companies in the world, announced the development of a new type of generator capable of producing electricity directly at transmission voltages as high as 400kV [1]; later details are in [2]. Thus, there is no need for a step-up generator transformer, as illustrated in Fig 1.

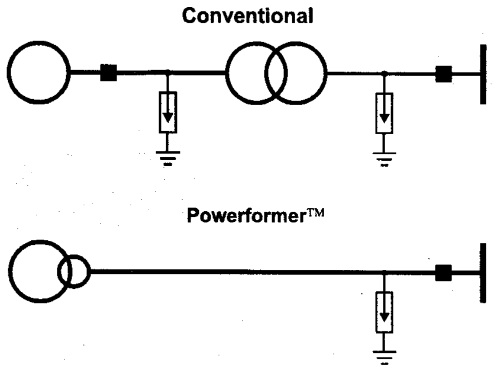

Figure 1: Comparison between conventional and Powerformer system

ABB has named the new high voltage generator Powerformer™. The major technological innovation is the replacement of conventional mica-insulated rectangular conductors in the stator windings by high voltage polymer insulated cables, so taking advantage of the simple and well proven technology used for cables at operating voltages as high as 500kV. The cable conductors are round and are insulated with cross-linked polyethylene (XLPE); there are inner and outer semi-conducting layers on the XLPE, thus producing an even electric field distribution. The new generator has a number of obvious advantages when compared to conventional generators, including i) there is no generator transformer, thus producing savings in cost, space and reducing losses, ii) the current in the high voltage generator windings is relatively low and so ohmic losses are greatly reduced, iii) both of the previous points contribute to substantial gains in the overall efficiency of generation, and iv) the simplicity and the proven reliability of the high-voltage cable insulation results in a marked improvement in the expected reliability of Powerformer and in its assessed life-cycle environmental performance. Many of the advantages of

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Powerformer can be achieved by using a HV machine in an underground hydro power plant and an autotransformer above ground that connects to an EHV transmission system. It has turned out that the Powerformer has other less obvious advantages, which become apparent when consideration is taken of their interaction with the electricity system to which they are connected directly. These are considered next.

The fact that Powerformer is connected directly to transmission voltage systems (without a step-up transformer) introduces new dimensions in the interaction between generators and electricity systems. These include such matters as the effects on the system as – load transfer capability, the benefits of increased reactive power availability on steady-state voltage stability and transient system stability during disturbed conditions, the influence of earthing on the control of harmonics and on short-circuit currents, and overall generation and system reliability. The increased reactive power and overload capability of Powerformer result from the facts that it has a lower stator current density and a larger thermal mass and so does not have the same limitations on stator current as conventional generator technology [1, 3]. Preliminary studies of these effects on the transmission system in Sweden have revealed that Powerformer's enhanced capability to supply reactive power in a short-term overload mode can be of significance to the system per se [4]. As can be seen in Figs 2 and 3, both the Swedish and Queensland systems extend over large distances (~ 1600km) and this poses stability challenges for both. However, the technical challenges are far more demanding for the Queensland system because of its far smaller number of north-south transmission lines (two 275kV lines overlaid on some 132kV lines compared to eight 400kV lines overlaid on 220 kV lines in Sweden with some parallel lines in Norway and Finland).

The high-tension grid in the Nordic countries

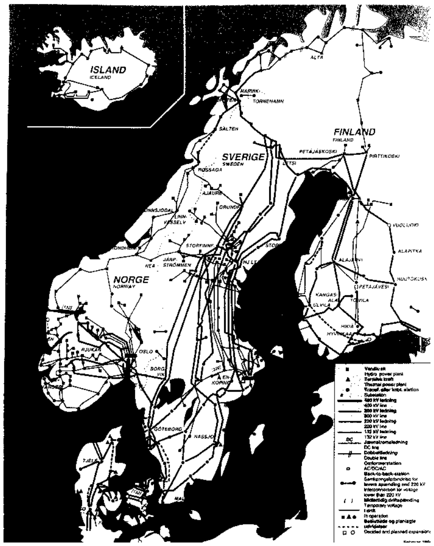

Figure 2: Nordic Power Systems

In addition to its long north-south geographic layout, the Queensland system is of particular interest because of the underlying growth of about 3% pa in electricity consumption (about 6 % pa when there are new large spot loads) and the continuing expansion of its generation and transmission. Currently, there is 8100 MW of installed generation with set sizes up to 350MW. The maximum demand is about 6500MW and the main transmission line voltage is 275kV supported by sub-transmission lines at 110 and 132kV. Apart from the replacement of about 72MW of old hydroelectric generation, the new generation will be either coal-fired turbo-generators (located near coal fields) or gas-fired turbo-generators (located near major gas pipelines) with expected ratings mostly in the range 100 to 400MW and bagasse-fired steam turbo-generators with ratings of about 40MW (located at large sugar mills). The smaller machines will be near existing 33 or 66kV lines, intermediate size machines near 132kV lines and the large machines near 275kV lines. So if the guideline is followed that the voltage rating of Powerformer in kV should have a numerical value near its rating in MVA, then there are prospects for considering the use of Powerformer technology as follows –

Hydro-generators, 80MVA, 132kV
Small turbo-generators, 40MVA, 33 or 66kV
Intermediate turbo-generators, 100 to 150MVA, 132kV
Large turbo-generators, 300 to 400MVA, 275kV.

This guideline is really a requirement that the winding current is greater than 500A. The likely locations for the smaller generators would be in central and northern regions of Queensland, and for large generators in the southern region where there is an extensive network of 275kV lines. Because of its long and largely radial north-south transmission lines, there is every expectation that Powerformer would have strong impacts on the Queensland electricity system, both when it is isolated from and when connected to the national transmission network.

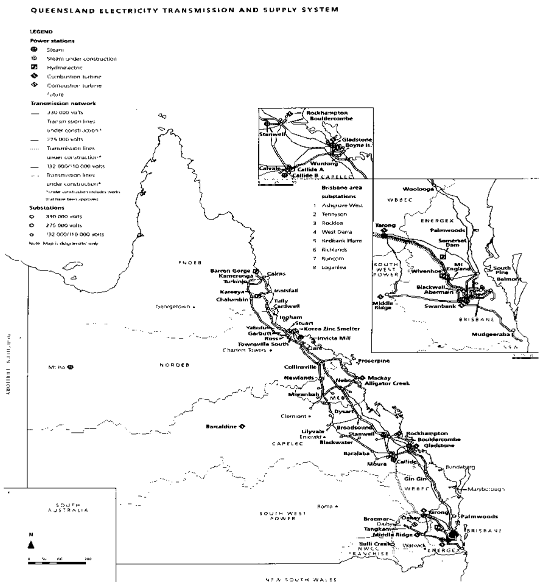

Figure 3: Queensland power systems

2. PROJECT AIMS

The aims of the project [5] follow from the technical challenges referred to above –

(1) – To carry out technical studies of the interaction between Powerformer and electricity systems, with particular reference to the Queensland and the Australian national systems;

(2) – To investigate how to make optimal selection of the desirable design characteristics of Powerformer for the benefit of the Queensland electricity system, both when isolated from and when connected to the national system; and

(3) – To carry out reliability and cost/benefit analyses for Powerformer in Queensland.

Investigations of the impacts and identification of how the design of Powerformer can be adjusted to give maximum benefit to the Queensland system are the reasons for the proposed research project. The importance and the significance of the project are highlighted by the number of industry partners from Queensland and Sweden who are participating in it. Because Powerformer is based on a new concept in high voltage generation and which is of particular importance to the Queensland electricity system, the proposed project is novel and will lead to innovative developments. It is expected that optimal design of Powerformer for use in the Queensland system will contribute to the effectiveness of electricity generation and transmission in Australia's national electricity market.

3. RESEARCH PLAN AND PROJECT WORK

3.1 Plan - The broad plan is that most of the investigations and studies are being carried out at University of Queensland (UQ) by the Chief Investigator and two PhD candidates with technical support from Powerlink Queensland and from ABB Corporate Research and Alstom Power in Sweden. An important feature of the project is that funds are available to enable the UQ workers to travel to and work for short periods at ABB Corporate Research in Vasteras Sweden and that they can make field trips to and work with the industry partners in Queensland and New South Wales. The various aspects of the project work and its funding are coordinated by the Team Leader. The funds for the project [5] are provided in roughly equal parts by the Australian Research Council and by the six industry partners. In addition, the partners provide considerable in-kind support.

3.2 Project Methodology and Work - The overall methodology for the project is to make system impact comparisons between conventional generators with step-up transformers and directly connected Powerformer. The comparisons are first being made with a number of standard test systems, including the 10-bus BPA system and the 32-bus Swedish system [6] and other small test systems available from the WWW. With experience gained from the test system studies, the comparisons are then made on the 700-bus Queensland system initially alone and finally when connected to the national electricity system (which interconnects the State systems of Queensland, New South Wales, Victoria, South Australia and the Snowy Mountains system). The software in use for the studies includes PSS/E Power System Analysis from Power Technologies Inc, MatPower in the Matlab environment and Powerworld Simulator System Analysis. The studies fall into two broad groups. The first group is concerned with static and quasi-static analyses of system voltage collapse and loadability, and with dynamic stability analyses. The second group is concerned with the fault calculations and consideration of earthing arrangements. Both groups of studies will begin by using nominally-standard sets of parameters for Powerformer and will then examine the further benefits that may be obtainable by optimising Powerformer parameters to best suit the system. More details of the work being carried out in the two groups of studies are given below, and this is followed by some preliminary results on loadability.

The ability of an electricity system to transfer power from generation plants to load busses is always studied using static analyses of voltage collapse and dynamic analyses of transient stability. The impact of Powerformer technology on the loadability of the Queensland system is the subject of the first group of studies. The static analyses use several methods to determine indices for the 'distance' to voltage collapse and the range of system loadability. These include the voltage stability (VSM) indices, voltage stability assessment (VSA), minimum singular value (sigma) of the Jacobian matrix, and real power-voltage (PV) and reactive power-voltage (QV) curves. The initial static studies were made on the BPA and Swedish test systems [7] by examining the effects of removal of step-up transformers at selected generator busses, i.e. direct connection to the high voltage bus. As will be seen in the preliminary results below, this approach has also been applied to the Queensland system. This will be followed by simulating the placement of Powerformer (with standard parameters) at selected busses on the Queensland system, first alone and then interconnected to the national system. The next static and quasi-static studies examine the impact and potential benefits to the system of the overload capability of Powerformer, in particular its ability to provide increased reactive power for significant periods of time. With reinforced rotor cooling calculations have shown cases where 100 % overload for up to 30 minutes is feasible. Further static studies will use Schlueter's VSA method [8] based on QV curve analyses to identify regions in the system which may experience either voltage collapse due to loss of voltage control caused by exhaustion of reactive supply or clogging voltage instability resulting from an inability to supply sufficient reactive power even if reserves are not exhausted. Quasi-static analyses using the Powerworld System Analysis software allows PV and QV curves to be determined for various system arrangements. This software can simulate generator operation with automatic generator control (AGC) and with automatic voltage control (AVC) accounting for individual reactive overload capability curves. These affect the maximum MVAR output for a given MW output and therefore simulate armature, rotor and under-excitation limiters. These quasi-static analyses will enable the full potential of Powerformer's reactive power overload capability to be explored for the Queensland system. The static analyses will of course be supplemented by dynamic transient stability studies using the PSS/E software. Because of its long distances and the small number of north-south transmission lines, the Queensland system had always required careful study of potential transient instability problems that may be encountered during fault conditions. Solutions to such problems have included the optimal sizing and location of static var compensators (SVC). The dynamic analyses will examine both the contributions that Powerformer can make during disturbed conditions, both in terms of its reactive power overload capability and because of its inherent capacity in voltage support to control the high voltage level directly. The latter is secondary or high-side voltage control, as it provides a means of mitigating voltage collapse by direct excitation control of the system high voltage (rather than low-side voltage control at the generator terminals of a conventional generator/step-up transformer arrangement). These studies will enable a technical assessment to be made of the advantages of Powerformer's secondary high-side voltage control when compared to the voltage control available from excitation of conventional generators and from SVCs. If time and resources permit, the project will also make economic and reliability assessments of this aspect of Powerformer technology.

The second group of studies involves investigations into the impact of Powerformer technology on system performance under fault conditions [4], including consideration of earthing arrangements and optimisation of parameters to best suit the system. The studies use PSS/E software for static and dynamic analyses of fault currents and voltage disturbances on un-faulted phases and on impedance grounded neutrals. After gaining experience with fault calculations on a 14-bus system taken from [9], the studies will concentrate on the Queensland transmission system. The initial studies using static analysis involve making comparisons of system fault currents and voltage disturbances between conventional generators with step-up transformers and directly connected Powerformer. The fault events simulated will mainly be un-balanced faults both near the generator and on the system. The critical influence of the method used to ground the generator's neutral will be studied in detail, in respect of the effects of the fault(s) on the generator itself and on the whole system. This will include a careful assessment of the methods available for grounding the neutral of Powerformer and the selection of the most appropriate method. The next studies will use dynamic fault analyses to determine the actual current and voltage waveforms resulting from various fault conditions. Analytical models will be developed to determine the processes involved, including sensitivity analyses of roles of system and Powerformer parameters and, if necessary, determine what corrective actions are required. As is well known, faults on power systems generally occur at random, particularly when initiated by natural events such as lightning strikes to line. As is usually the case with such stochastic events, deterministic analyses are often of limited value and so probabilistic modelling is likely to be more useful [10]. Monte Carlo techniques will be used to simulate the interaction of the many system variables that are relevant to various types of fault. In this approach, the variables are described by probabilistic distributions, and simulations are carried out for a sufficient number of events (each with randomly selected variables) to provide sets of profile curves of fault currents and voltage disturbances. These will enable more meaningful comparisons to be made between conventional generator/step-transformer technology and Powerformer technology. The final part of this group of studies will involve the use of the obtained fault data to determine if further benefits can be obtained through selection of the most appropriate range of Powerformer parameters in respect of system performance during fault conditions. In effect, this will aim to optimise the design of Powerformer to best suit the system to which it is connected, which for the purposes of this project is the Queensland system. As well as using the simulation approach, it is intended to develop an analytical approach to the optimisation goal using generalised expressions for the impedance matrix of the system to which Powerformer is connected. Early work with this approach indicates that is very promising.

4. SOME PRELIMINARY RESULTS

Powerformer generates at a sufficiently high voltage for it to be connected directly to the high voltage bus without the need for a step-up transformer, see Fig 1. To date, static load flow analyses have been made to determine the impact on voltage stability and loadability of a conventional system arising from the simple removal of the step-up transformer between (a) selected generator(s) and the associated high voltage bus. PV curve analyses may be performed on the different system arrangements. Three power systems were used in the initial studies, including the 10-bus BPA test system, the 32-bus Swedish test system [1] and the 700-bus Queensland power system. The results on the first two are reported in [6] and are summarised here together with the preliminary results for the Queensland system.

The results obtained for the BPA system, see table 1, indicate that the location of the directly connected generator has a noticeable impact on the loadability, and therefore distance to voltage collapse, of the system. These results are not completely surprising when it is realised that direct connection to the high voltage bus is an ideal form of secondary voltage control. As discussed above, secondary, or "high-side" voltage control, is a concept which involves the control of bus voltage levels beyond the generator terminals. This provides a means of mitigating voltage collapse by excitation control of the high side voltage on the system side of the step-up transformer rather than at the generator terminals.

Table 1 - Maximum and minimum critical power for the BPA test system

Case No.	Case Descript-ion	Pcritical (min) (MW)	Pcritical (max) (MW)	Range (MW)
1	Base case	3950	6300	2350
2	G2 to HV	3900	6350	2450
3	G3 to HV	3600	6250	2650
4	G3 and G2 to HV	3550	6250	2700

(Note. Reactive power at bus 7 increased to keep P/Q ratio constant)

Table 2 provides the results of preliminary loadability studies performed on the Queensland System, see Fig 3. Three cases have been considered; the base case where no generators are connected to HV, case 2 where a generator has been connected to HV at the Barron Gorge hydroelectric station and case 3 where a generator has been connected to HV at the Wivenhoe hydroelectric station. For each case considered, a number of different generator buses have been chosen as the slack bus for the purposes of the load flow analysis. As can be seen from table 2, the location of the slack bus as well as the location of the HV connection can have an impact on the value of maximum loadability. An important issue has been highlighted in the preliminary study; when the loads in a system are increased, the system can continue to solve numerically despite the fact that the limits of the generator connected to the slack bus have been violated. The maximum loadability point should therefore be taken as the 'practical' point at which the slack bus generator limits have been violated. (Note that Gladstone 3 is the slack bus chosen by Powerlink, the Queensland Transmission System Operator)

Table 3 illustrates how the set point voltage level of the HV bus can also impact on the maximum numerical loadability. (Note that the original control voltages of the generators at Barron Gorge and Wivenhoe were both 1.05 pu and the HV bus voltages were 1.0128 and 1.0651 pu respectively.) As can be seen with the case where Wivenhoe is the generator without a step-up transformer, there is a voltage level range at which the loadability is a maximum (1.065 to 1.08 pu in this case). However, as can be seen from table 3, the voltage has little impact on the maximum practical limits (Gladstone generator 3 being the slack bus in this case).

Table 2: Practical and numerical loadability limits for Queensland power system.

	Practical limit (MW)	Numerical limit (MW)
Case1: Basecase		
Gladstone 3	6600	6720
Gladstone 4	6600	6740
Stanwell 1	6580	6740
Callide B 1	6660	6720
Tarong 1	6780	6800
Wivenhoe 1	6820	6820
Swanbank B 1	6420	6740
Case2: Barron Gorge 1		
Gladstone 3	6620	6740
Tarong 1	6780	6780
Case3: Wivenhoe 2		
Gladstone 3	6620	7000
Tarong 1	6800	6940
Wivenhoe 1	6860	6940

5. FINAL COMMENTS

As its title suggests, this paper describes a research project which is in progress. Its aims and methodology have been outlined and a detailed description has been given of the work that is being carried out. The authors believe that it is an important project because it is examining the potential benefits of the applying the new Powerformer technology to a relatively weak and geographically extended system, the Queensland system. It is believed that the project's prospects for success are good and the preliminary results provide support for this view. The authors hope that it will be of interest to all the partners in the project and to others, and would welcome discussion and suggestions that would assist in its execution.

Table 3 Impact of terminal set point voltage on loadability limits of Queensland system.

Voltage (pu)	Pmax (MW) Numerical	P max (MW) Practical
Barron Gorge		
1.0	6740	6620
1.0128	6720	6620
1.05	6740	6620
1.065	6740	6620
Wivenhoe 2		
1.035	6520	6620
1.05	6720	6620
1.0651	6980	6620
1.08	7000	6620
1.09	6940	6620

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7. BIOGRAPHIES

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