Load Capability and Collapse Margin Analysis of the Large Scale Queensland Power System

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***Abstract*—This paper provides an overview of load capability and collapse margin analyses carried out on a modified CIGRE 'Nordic' test system and on the large-scale Queensland Transmission system. The importance of certain key generators in the loading capability of a transmission system is highlighted. Emphasis is also placed on the impact of potential installations of Powerformer™ on the loading capability of these two real and representative systems. Powerformer™ is a unique form of generator that can be directly connected to transmission, without the need for a step-up transformer. Select system sensitivity parameters are determined for the two systems and used to aid explanation of the relative importance of the key generators and the impact of Powerformer observed.**

***Index Terms*— Power System Planning, Load capability, Collapse Margin, Voltage Stability, Voltage Collapse.**

I. INTRODUCTION

SYSTEM load capability is an important issue in most, if not all, modern power systems. It is therefore vitally important to know not only what levels and patterns of dispatch and consumption of load are achievable but if these levels and patterns of dispatch and consumption of load can be improved upon. A novel sensitivity based voltage stability assessment method has been proposed [1]. This method facilitates both determination of key generator sets that cause voltage instability and collapse when they limit and determination of the associated buses that provide the mechanisms for the collapse. The heart of the assessment method in [1] is the calculation of the sensitivity of system generator reactive power outputs to changes in loading at load buses in the system. These sensitivities indicate how much a generator will increase its reactive output in response to a change in load. When a select group of one or more generators limits in the course of increased loading the sensitivities calculated may change sign and/or increase dramatically in value. Such a qualitative change in system behaviour is indicative of bifurcation [2]. When the load reaches the collapse point, and the sensitivities change sign, any increase in loading will actually have a corresponding decrease, rather than increase, in reactive outputs from the generators. This is obviously not a satisfactory condition for voltage stability.

In reference [1] two power systems, the modified CIGRE Nordic test system and the large scale Queensland Transmission system were analysed and assessed. This paper continues the work of [1] and will further highlight, via the production and analysis of PV curves and select system sensitivity values, the relative importance of certain key generators and generator sets in these two real and representative power systems. The concept of, and presence of, key generators not only in these two systems, but also in all power systems in general, and the role these key generators play in system security and load capability will be discussed.

As we are interested in system loading capability this paper will also investigate the impact of potential installations of Powerformer™ on the loading capability of the two systems considered. The Powerformer™ [3, 4] connects directly to the high voltage bus and therefore controls this high side bus's voltage directly. A single line comparison between this Powerformer and a conventional generator is illustrated in Figure 1 [5]. Two major benefits of the Powerformer are immediately clear. Firstly there is the potentially higher reactive power capacity, compared to a similarly sized conventional generator, resulting from the fact that the transformer reactive losses are non-existent and secondly there is the beneficial condition that it controls the high voltage bus. The potential benefits of high side voltage control in maintaining voltage stability and load capability are now generally well accepted [6, 7].

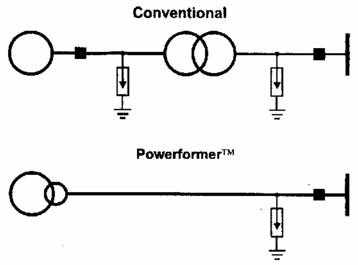

Figure 1 Comparison of Conventional and Powerformer

It will be highlighted in this paper that the limiting problems of the aforementioned key system generators can be directly improved by their replacement with Powerformer, but

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even if the limiting problem of these key generators can not be improved directly by replacement with a Powerformer, Powerformer installation at other generator buses in the system can have both directly and indirectly beneficial impacts on the subsequent limiting of these key generators.

II. LOAD CAPABILITY AND COLLAPSE MARGIN ANALYSES

A. *Modified Nordic Test System*

Bus 62 of the modified Nordic test system has been found via VQ curve analysis to be a candidate for reactive reserve limiting [8]. The implications of this condition is that when a certain select grouping of generators, the so called reactive reserve basin (RRB) of the bus, reach their reactive output limits the bus loading cannot be increased without system collapse. The RRB generators for bus 62 were generators located at buses 122, 431, 442, 462, 4631 and 4632. Sensitivity analysis has further confirmed the occurrence of bifurcation when these RRB generators are limited [1].

PV curve analysis was performed on this bus to determine the permissible loading level at this bus. When the load at Bus 62 was incremented with constant power factor the collapse point occurred at 420MW (120MW greater than the base case loading of 300MW). The first item to note from this PV curve analysis was that as the loading pattern in this case included an increase in real power as well as reactive power the generators that were limited at the collapse point differed from the RRB group. These RRB generators were limited by the reactive only loading pattern simulated in the production of the VQ curve. The generators limited at the collapse point of the PV curve were generators 122, 143, 431, 442, 451, 4471 and 4472. Table 1 provides a list of the maximum MVAR capabilities of the generators in the system. Figure 2 illustrates how the aforementioned generators reach these limits in the production of the PV curve at Bus 62.

Table 1 Modified CIGRE Nordic system maximum generator MVAR limits

Gen Number	Max Mvar	Gen Number	Max Mvar
112	520	431	227.5
113	390	441	330
114	455	442	455
121	390	4471	390
122	162.5	4472	390
142	260	451	455
143	130	462	390
232	552.5	4631	390
411	650	4632	390
412	520	471	325
421	195	472	1675

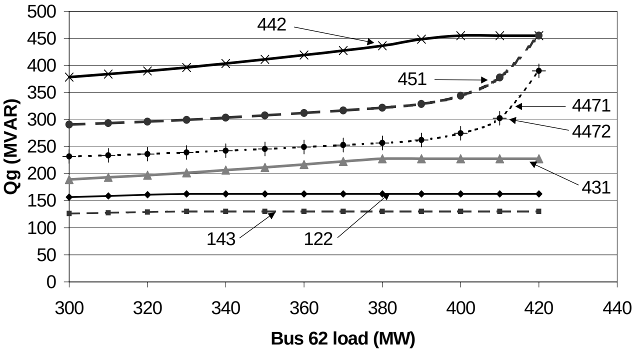

Figure 2 Bus 62 PV curve -generator MVAR outputs

Sensitivity analysis was again used to confirm if the limiting of this different group of generators would, and did in fact in this case, bring about the observed collapse and bifurcation. Sensitivity calculations were firstly carried out using the current base load flow data for this system, setting bus types to PQ rather than PV so as to simulate the generators of interest as being limited. A new set of sensitivity values was subsequently obtained. When these values were obtained it was noticed that the sign of the generator sensitivities to load changes had changed sign for a number of buses in the system compared with the base case. Such a change in sign would indicate that the system undergoes bifurcation in this condition [1]. Sensitivity calculations were also carried out at every step in the production of the PV curve to observe the impact of the limiting of each individual generator on the sensitivities of the system and the impact on the sensitivities when the collapse point is reached. Figure 3 illustrates how the combined sum of the sensitivity values for Bus 62, and therefore total changes in generator reactive output for a change in Bus 62 reactive power load, changes as the loading at bus 62 is increased. The sum has a negative sign because the individual sensitivities we have calculated are negative. The sensitivities are negative because they are related to an injection of reactive power at Bus 62, or in other words, a decrease in loading at the bus rather than an increase. It can be noted that the sensitivity values decrease noticeably (an increase in overall magnitude) when the key generators of interest reach their respective limits. When the generators reach their limit the other generators in the system ramp up their reactive output rates in response to having to share more of the increase in load.

The minimum singular value (MSV) of the power flow Jacobian, being a useful indicator of the presence collapse [9, 10], even if not a good proximity indicator when not close to the collapse point [11, 12] is also provided in Figure 3 to further highlight the existence of a bifurcation and collapse. The MSV also noticeably decreases in value when the key generators of interest reach their respective limits and is close to zero at the maximum loading point, indicating the collapse point has been reached.

Both the MSV and the bulk of the sensitivities calculated for Bus 62 change sign at the collapse point, which further indicates that bifurcation point has been reached.

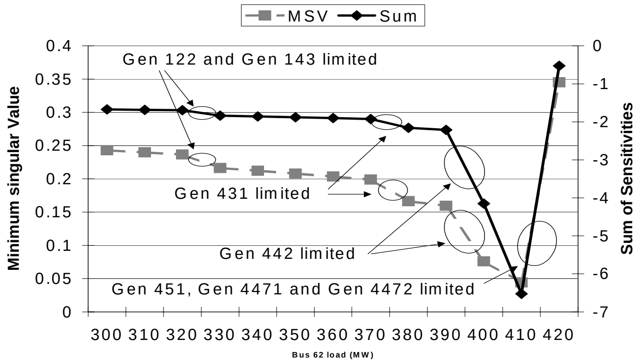

Figure 3 Minimum singular value and Sum of bus 62 Sensitivity values, found in the production of PV curve at Bus 62.

B. Impact of Powerformer on Modified Nordic Test System

In the introduction we indicated that we were interested in determining if the load capability of a system could be improved by the replacement of existing system generators with an equivalent sized Powerformer. This aforementioned replacement was achieved in the system analysis model in a simple manner. The generator step up transformer impedance was reduced by a factor of 100 and the control voltage set to the high voltage per unit value in the initial loading case. This ensures that the initial load flow solution for both the base case and the different Powerformer location cases will essentially be the same. All twenty-two generators in the Nordic system were replaced with Powerformer to see if any improvement on the base "No Powerformer" case was possible. The results of the PV curve loading capability analyses are illustrated in Figure 4.

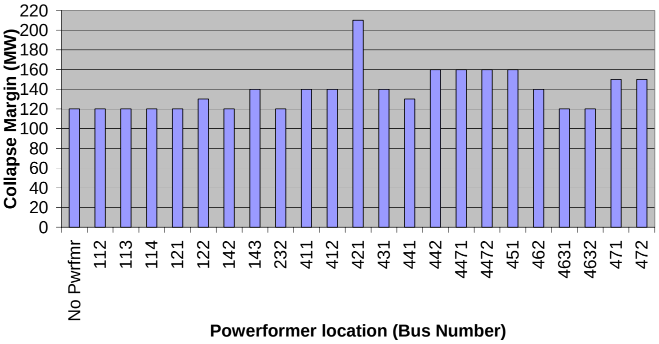

Figure 4 PV-Curve analysis of different Powerformer locations

From Figure 4 it is clear to see that if Powerformer replaces one of the key generators, 122, 143, 431, 442, 451, 4471 and 4472 then the collapse margin improves. PV curve analysis of Bus 62 has however highlighted an interesting situation. As can be seen in Figure 4 the best improvement in collapse margins occurs when the generator at bus 421 is modelled as being replaced with an equivalent sized Powerformer. This is surprising given that generator 421 is located in the Northern region of the system and therefore is relatively distant from Bus 62 in the South Western region of the system. Figure 5 illustrates how installing Powerformer at this bus can have a suitably beneficial impact on the collapse margin even though this generator is not located in the same region and is not even a reactive reserve basin generator or key generator. Figure 5 shows in comparison to Figure 2 that when the generator at bus 421 is replaced with a Powerformer, the reactive outputs of the key generators for Bus 62 change their reactive outputs less rapidly for a change in loading at bus 62. This is further highlighted in Figure 6 by the fact that the sum of sensitivity values is noticeably lower in this case. This means that it will take longer for the key generators to exhaust. By making the generators less sensitive to changes in loading at bus 62 the loading at bus 62 can be increased further without exhausting these reserves and bringing about the system collapse point. It is also important to note that in this case the collapse point occurs when generator 421 limits and not when generators 451, 4471 and 4472 limit. The key group of generators has been changed by the replacement of a conventional generator with Powerformer at bus 421, which has now become a key generator. The improvement in the collapse margin can either be a result of an improvement of the reactive reserve directly or as a result of reducing the rate at which the key generators exhaust.

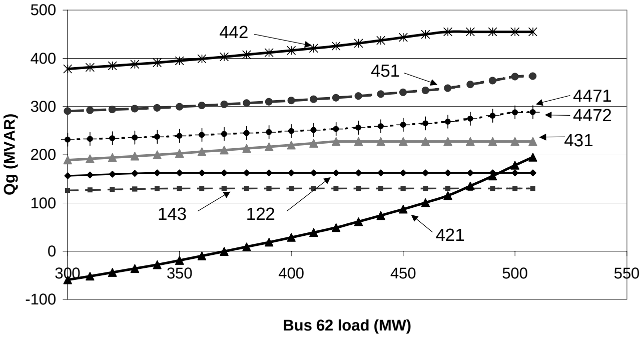

Figure 5 Bus 62 PV curve, 421 Powerformer - generator MVAR outputs

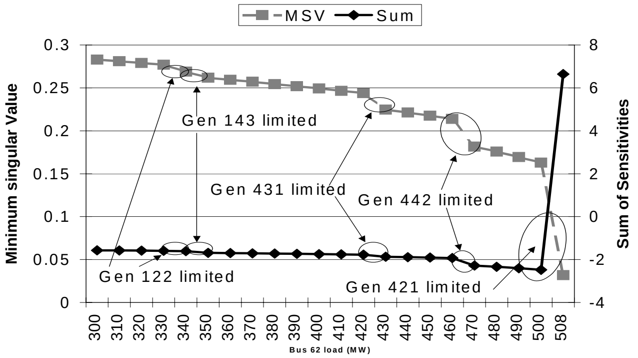

Figure 6 Minimum singular value and Sum of bus 62 Sensitivity values, found in the production of PV curve at Bus 62, 421 Powerformer.

Figure 7 has been included to illustrate that even though a generator may be located in the same region as a load bus of interest, replacing it with Powerformer may not necessarily have noticeable improvement on the collapse margin. Despite the fact that it means that the addition reactive capability is closer at hand. The generator at Bus 4631 is located in the South Western region of the system and is therefore relatively close geographically and electrically to Bus 62 but as can be seen in Figure 4 replacing it with Powerformer has little noticeable impact on the collapse margin. Sensitivity analysis confirms that the sensitivity values are only slightly changed in this case and as can be seen in Figure 7 the key generators exhaust in a similar pattern to the case where there are no Powerformer units, as illustrated in Figure 2.

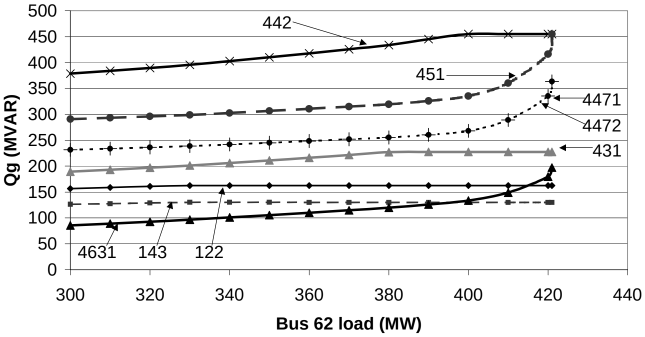

Figure 7 Bus 62 PV curve, 4631 Powerformer - generator MVAR outputs

C. Impact of Powerformer on Queensland Power System

In reference [1] the Blackwall SVC located in the southern region of Queensland was of particular interest and for the purposes of this study, as well as that of the study in [1], it has been modelled as synchronous condenser to allow sensitivity values to be ascertained. When Blackwall had its limit set to its current reactive output it was found that loads in the northern region could be increased without causing the system solution to fail but loads in the southern and central regions could not be increased without the system load flow solution failing. The southern region and central region sensitivity values, but not northern region sensitivity values, were noticeably larger than the base case when the Blackwall unit bus was set to PQ type, indicating that if Blackwall limits the system will encounter bifurcation if southern and central loads are increased. This was of great interest as the bulk of the system loads are located in the southern and central regions.

Particular emphasis was made in this study on the replacement of generator-transformer combinations with Powerformer(s) connected directly to the high voltage bus at two select power station locations. The two main locales chosen for the replacement of existing generators with the Powerformer were the Swanbank B and Wivenhoe power stations. These stations were chosen because they were relatively old and therefore possible candidates for replacement, because they were located in the southern region along with the Blackwall SVC and because they were reactive reserve basin generators for many of the southern region buses.

In our PV curve, load capability, analyses we looked at three key regions in the Queensland system, the Northern, Central and Southern regions. The maximum loading capability, or collapse margin, before system bifurcation can be seen in Table 2 for the three regions with Powerformer units replacing conventional units in the two aforementioned power stations Wivenhoe and Swanbank.

Table 2 PV Curve Collapse margin Analyses of Queensland System

Collapse Margin (MW)	No Powerfomer	Swanbank B4	Wivenhoe 1
Northern	181	181	181
Central	1080	1136	1156
Southern	95	134	164

The reason why Wivenhoe 1 provides the best improvement in loading capability in the southern region, compared to Swanbank B4, is that it becomes the critical generator. The critical generator is considered to be the generator whose limiting coincides with a significant change in the system sensitivity values. When Wivenhoe 1 is connected directly to high voltage the system sensitivities do not change drastically after Blackwall limits and the system can continue with loading increase until the Wivenhoe 1 generator limits at which the sensitivity value are observed to increase dramatically.

Figure 8 shows how the maximum permissible increase in loading at Southern region buses (95 MW), in the base case where no generators are modelled as Powerformer, coincides with the Blackwall SVC reaching its reactive output limits (250 MVAR). The Blackwall SVC is the only unit in the system at its limits when maximum loading is reached.

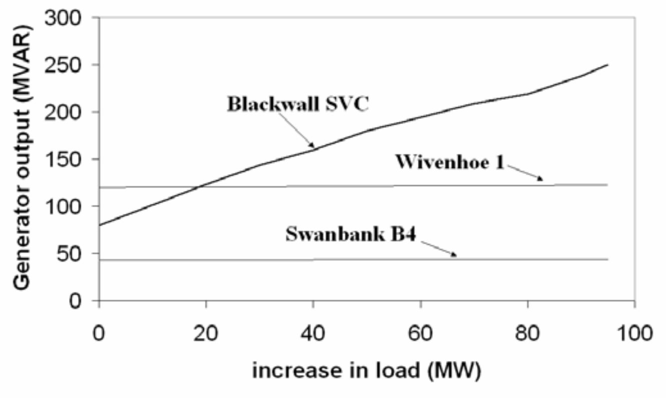

Figure 8 Southern Queensland Loads, PV curve - generator MVAR outputs

When the Wivenhoe 1 unit is modelled as a Powerformer the change in generator reactive outputs can be observed for southern load increase in Figure 9. Figure 9 shows that even though the reactive outputs from the three generators shown increase at roughly the same rate with an increase in Southern region load as the base case, the system does not reach its maximum point when Blackwall reaches its limit. Unlike the base case, shown in Figure 8, the maximum loading is reached at a point coinciding with Wivenhoe 1 reaching its reactive limit.

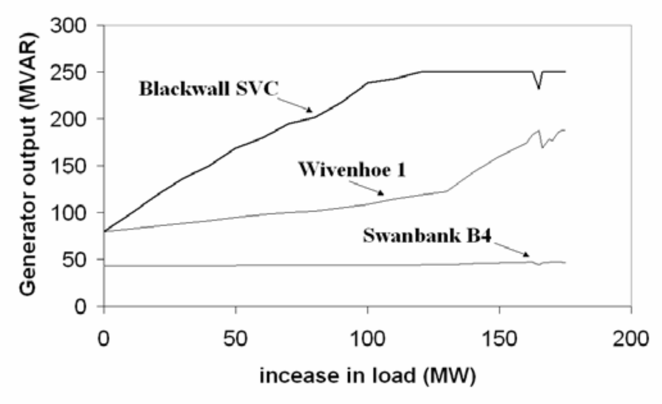

Figure 9 Southern Queensland Loads, PV curve - generator MVAR outputs, Wivenhoe 1 Powerformer.

The Swanbank B4 Powerformer option, unlike the Wivenhoe 1 option, improves the sensitivity of the Blackwall SVC to southern loads. This means that it will take longer to limit. When the Swanbank B4 unit is modelled as a Powerformer the Blackwall SVC is, however, still the critical generator. The sensitivities are observed to increase dramatically when it limits. After the Swanbank B4 generator, which is the first to limit, reaches its limits the sensitivities return to values similar to that found in the base, no Powerformer case. Figure 10 illustrates how the rate of change in reactive output from the Blackwall SVC is lower, but that the maximum loading still coincides with it reaching its limit.

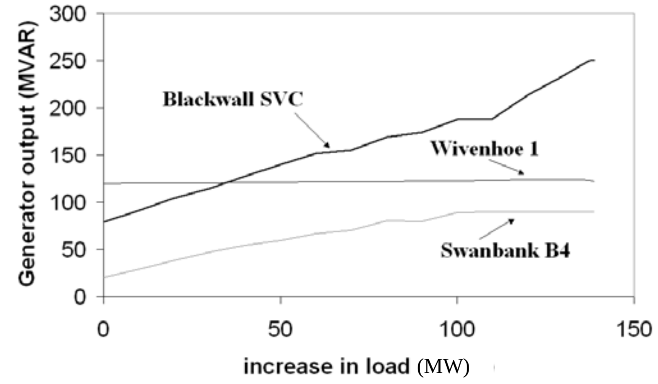

Figure 10 Southern Queensland Loads, PV curve - generator MVAR outputs, Swanbank B4 Powerformer

As already highlighted in this section of the paper not only the Southern region, but also the central region sensitivities were found to change sign when Blackwall limits. Because the Blackwall SVC is the critical generator for the central region loads, despite the fact that it is located in a different region of the system, replacement of the conventional units with Powerformer at Wivenhoe and Swanbank B in the Southern region can still have an improvement on the loading because they reduce the rate of exhaustion of Blackwall. This means that they can have a beneficial improvement of the loading capability of the central region loads as well as the Southern region loads.

III. CONCLUSIONS

It can be noted from the results of this paper that the determination of key generator groups at the base loading case allows us to know which groups we cannot allow to limit if we wish to maintain stability when we heavily load the system. We can also know which buses cannot have their load increased without collapse. Suitable alarm indications may be implemented to inform operators if any key groups are close to limiting. We have also highlighted in this paper that the placement of Powerformer in a system can have both direct and indirect impacts on the permissible loading of a system. Either by directly reducing the rate of exhaustion of key generator(s) by the replacement of the key generator(s) or by indirect reduction in the rate of exhaustion by key and critical generator(s) we can improve the collapse margin. We can also improve the collapse margin by changing which generators are in the key group and having the Powerformer as the critical generator in this group, as we saw with the case of the Powerformer replacement at bus 421 in the Nordic system and the replacement of the generator at Wivenhoe 1 in the Queensland system.

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V. BIOGRAPHIES

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