Determination of Power System Coherent Bus Groups by Novel Sensitivity Based Method for Voltage Stability Assessment

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***Abstract*--This paper presents a method that is used to determine the coherent bus groups of a system who have similar reactive reserve basins. The differences between this proposed method and another widely accepted voltage stability analysis method will be highlighted in this paper and results obtained from the proposed method will be discussed. This method will be shown to be more efficient and requiring less VQ curve computations. Results obtained from the test systems support the method's validity. By determining the reactive reserve margin it is possible to determine which generators will have an impact on the maximum permissible loading of a bus and which will not. This information is particularly useful for performing voltage stability analysis.**

***Index Terms*—Coherent Bus Groups, Voltage Stability, Sensitivity analysis.**

I. INTRODUCTION

In many modern power systems voltage instability is becoming an increasingly important issue. Voltage instability in a power system is generally considered to be a reactive power supply problem. Some of the more infamous examples of voltage collapse include voltage instability incidents in France 1978, Sweden 1983 and Japan 1987 where either increasing loads or the loss of supply lines and/or generation sources led to critical deterioration in system voltages[1]. As generators normally provide the bulk of controlled reactive power supply in a system it is extremely vital to determine which generators have an impact on the maximum possible loading at a bus, and which generators do not have any impact at all. This paper presents a method that allows easier determination of the generator(s), which have the most impact on the maximum permissible loading at a particular bus. The differences between this proposed method and another widely accepted voltage stability analysis method[2] will be highlighted in this paper and results obtained from the proposed method will be discussed.

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II. BACKGROUND THEORY

Many techniques have been used in the past to look at the voltage instability problem. Two of the most widely used techniques are the PV and VQ curve analyses. It has been argued that VQ curve analysis technique is preferable to PV curve analysis when determining reactive supply problems because the VQ curve allows direct assessment of reactive supply shortages including their location and impact[3]. PV curve analysis, while providing a much better indication of loading and transfer limits than the VQ curve, does not automatically allow easy location of reactive shortage or its causes. When VQ curve analysis is performed at a bus the set of generators that exhaust at the curve minima can be found. A generator is considered exhausted when its reactive limit has been reached. These generators have been referred to in the literature as the reactive reserve basin (RRB) for this bus[2, 3]. An important feature of these reactive reserve generators is that they have the most impact on the permissible reactive loading of a bus. In fact, depending on the type of instability the load bus under consideration suffers from the reactive reserve generators may be the only generators where an improvement in reactive capability has any impact on the permissible loading of the bus.

Schlueter[2] suggests that there are two main types of instability in a power flow model, loss of voltage control and clogging.

- Loss of voltage control instability is a form of voltage instability that arises from an exhaustion of reactive supply and subsequent loss of voltage control by a set of reactive sources on a system including generators, synchronous condensers and SVCs.
- Clogging voltage instability is a form of voltage instability that occurs when I^2X losses, tap changer limitation and reduction in shunt capacitor reactive supply due to reducing voltages results in an inability to supply reactive supply to a region requiring reactive support. Clogging voltage instability can occur even if reactive reserves are not depleted.

When a bus suffers from a loss of voltage control instability at the point of collapse this bus's loading limit can only be improved by an increase in the reactive limits of one of the reactive reserve basin generators. If any or all of the other non-

RRB generators in the system are given infinite limits the VQ curve minima, and therefore the loading limit, does not increase. These generators therefore have no impact on the loading limit of the bus. The loading of the bus can be increased via the increase in RRB generator limits until the transfer of reactive power and clogging instability becomes the overriding issue.

Schlueter has indicated that if a bus is not suffering from loss of voltage control instability than it must be suffering from clogging. The actual situation is not quite so cut and dry. While there are many cases where a bus's loading limit does not increase no matter how much all generator limits in the system are increased. There are also many situations where the loss of control of a generator can cause reactive flow to the load to follow paths that exacerbate and speed up the clogging instability that the bus suffers from. This can be highlighted by the fact that certain buses can have an improvement in loading limits if the reactive limits on one or more of its reactive reserve generators are increased. Despite the fact that loss of voltage control in these generators does not directly lead to voltage collapse. Examples of this situation will be highlighted in the results section.

III. Assessment Methods

In the introduction a voltage stability assessment method called VQ curve analysis was highlighted. VQ curve analysis involves the placement of a synchronous condenser with infinite limits at a bus and observing the reactive generation required for different set point voltages. Figure 1 shows an example VQ curve obtained for a bus at a test system. The most important information to be obtained from this curve is the reactive margin from the base case operating point to the curve minima. This reactive reserve margin indicates how much further the loading on the bus can be increased before its loading limit is exceeded and voltage collapse occurs.

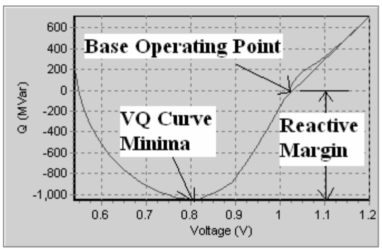

Figure 1 Example VQ curve

VQ curve analysis can be time consuming if VQ curves have to be found for every bus in the system. A method has been proposed by Schlueter[2], which reduces the number of VQ curves that need to be found for a system's reactive reserve basins to be determined. In this method Schlueter finds coherent bus groups of a system that have similar VQ curve minima and share a similar set of exhausted generators at this VQ minima. He calls these groups of coherent buses voltage control areas. The following algorithm has been provided by Schlueter to find the coherent bus groups:

1. Search for the largest diagonal element (d) of the reactive power voltage Jacobian Jqv that includes both load and generator buses: d=max{Jqv}ii;
2. For each row i of Jqv, rank the absolute value of the off-diagonal Jacobian elements from smallest to largest. The Jacobian elements with the smallest absolute values are eliminated from each row and until the sum of the elements removed is less than or equal to αd. Where alpha (α) is a coherency parameter chosen for the system.
3. The groups of buses, which are still interconnected after the weakest branches connected to each bus are eliminated, are the coherent bus groups for that value of α.

The main problem with Schlueter's method is that in order to obtain the coherent bus groups a correct value of α must be used to determine which branches will be removed. Schleuter has pointed out the difficulty in determining the correct value of α[2]. In order to determine if the correct value of α has been used he suggests that VQ curve analyses be performed on buses in the system above a certain reasonable high voltage threshold to determine if these buses have been correctly grouped and that these buses have similar VQ curve minima and reactive reserve basins. His argument for this particular procedure is that as loss of voltage control instability problems do not generally occur at sub transmission and distribution networks below 100 kV, and his method aims to determine the different subregions with loss of voltage control instability problems, focusing on the higher voltage buses would be adequate. This method therefore involves a fairly high degree of trial and error and involves the computation of VQ curves at a number of additional buses before the VQ curves for each individual bus group can be found.

This paper proposes a method that will determine the voltage control area coherent bus groups of a system without the need for VQ curves to be computed beforehand. The proposed sensitivity based method ensures that buses grouped together have the same reactive reserve basin generators, provided they suffer from loss of voltage control instability. When the buses in a group do not suffer from a loss of voltage control problem directly, and therefore suffer from some level of clogging, some of the buses in the system may not have as many reactive reserve generators as other buses in the group. This occurs because the actual clogging point may vary for the buses in this group and while a similar generator exhaustion pattern occurs for all the buses in this group the loss of generator control may lead to earlier exacerbation of the clogging problem at some buses compared to others. What this means is that at the max loading point for some buses in these groups the generators that do exhaust for some other buses in the group may not have reached their point of exhaustion and will not be reactive reserve generators for this bus. If necessary it is a simple matter of performing VQ curve analysis at the bus(s) of interest individually to determine their particular reactive reserve. This process may not always be needed as the buses that do not suffer from loss of voltage control instability are generally not as effected by the limits of their reactive reserve generators and therefore it is not as crucial to accurately determine their reactive reserve basin. Furthermore, as already mentioned the differences in reactive reserve basin for the buses in this group will often be minimal because they will share the same generators just for some buses it may be less of the large group that others. Examples highlighting this situation will be discussed later in the results.

Central to the proposed method is a technique provided by Alvarado[4], which can be used to determine the sensitivity of the reactive flows on a line in the system to an injection of reactive power at a bus. This sensitivity forms the basis of the proposed method. In order to understand how this sensitivity is utilised in the proposed method it is crucial to realise that the power produced by a generator is equivalent to the flow through the transformer branch, or generator branch, as it shall be called, connecting this generator to the system. In this way the sensitivity of a generator branch, and therefore generator, to an injection of reactive power, or alternatively a change in load, can be determined. If two adjacent buses have similar generator branch sensitivity values within a reasonable limit, say five percent, it indicates that the system's generators will be effected in a similar manner as load is increased at either of these buses. It has earlier been pointed out that generators are usually the main sources of controlled reactive supply in a system, which would seem to indicate that because the generators will exhaust their reactive supply at roughly the same rate and therefore in a similar pattern that the reactive reserve basin generators will be the same for both buses. By determining which buses have similar generator branch sensitivities it is possible to determine coherent groups of buses that will have the same reactive reserve basin.

The algorithm used in this method is as follows:

1. Obtain line flow Jacobian (Jf) which relates the flows at either end of a line to changes in voltage magnitudes and angles
   *(The subscripts p and q denote real and reactive power flows)
   $$Jf = \begin{vmatrix} \frac{\partial f_p}{\partial \delta} & \frac{\partial f_p}{\partial V} \\ \frac{\partial f_q}{\partial \delta} & \frac{\partial f_q}{\partial V} \end{vmatrix}$$
2. Obtain power flow Jacobian (J) which relates injected powers to voltage magnitudes and angles
   $$J = \begin{vmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} \end{vmatrix}$$
3. Determine the sensitivities of reactive power flows to an injection of reactive power at a bus (dfq/dQ) using the equation:
   $$\partial f_q / \partial Q = Jf * (J \setminus ER)$$
   *Where " \ " denotes the left matrix divide function (If Ax = B then x = A\B), and
   ER is an error matrix set up to simulate the injected power △Q. The ER matrix is set up similar to the power flow Jacobian, J in that the top rows of ER correspond the non-slack buses in the system and to △P real power injections and the bottom rows correspond the PQ buses in the system and to △Q imaginary power injections. The columns of ER correspond to all system buses. The value of 1 is placed at the relative positions of the system's PQ buses in the bottom section of the matrix to represent △Q injections at these buses.
   $$ER = \begin{array}{c|ccccc|} & (1) & (2) & (3) & (4) & (5) \\ \hline (1) & 0 & 0 & 0 & 0 & 0 \\ (2) & 0 & 0 & 0 & 0 & 0 \\ (3) & 0 & 0 & 0 & 0 & 0 \\ (5) & 0 & 0 & 0 & 0 & 0 \\ \hdashline (1) & 1 & 0 & 0 & 0 & 0 \\ (2) & 0 & 1 & 0 & 0 & 0 \\ (3) & 0 & 0 & 1 & 0 & 0 \end{array}$$
   E.g. For the 5 bus system shown in Figure 2↑
   (Slack = 4)
4. Create a matrix X identical to Y bus matrix with all non-zero elements replaced with the value 1.
5. Remove lower triangular section of the X matrix by setting all elements to zero. The X matrix is symmetrical and this lower section is a mirror image of the upper triangular section and will not be needed.
6. Go through the X matrix element by element and determine if the buses that the element corresponds to have similar sensitivity values within a limit of 5%. Remove those elements that do not satisfy this condition.
7. The groups of buses, which are still interconnected after the elements are eliminated, are the coherent bus groups.

In this method only the generator branch sensitivities to reactive injections at PQ buses and not generator buses (slack and PV) are obtainable. This is considered to be acceptable as we are more interested in changes in load, not generation and it is therefore not as necessary to observe the sensitivity of generator flow to injections by other generators.

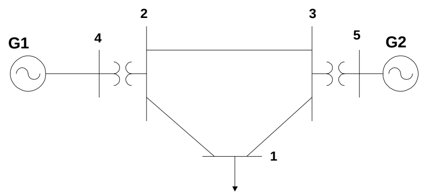

Figure 2 Simple 5 bus system

IV. Results

The proposed method has been tested on a number of systems, including the 10-bus BPA test system and a modified Nordic test system[5].

A. BPA test system

The 10-bus BPA test system[5] is shown in Figure 3. Table 2 shows the sensitivity values found for this system. It is possible to see from this table that the BPA test system's coherent bus groups are:

Table 1 BPA Coherent Bus Groups

Group	1	2	3	4
Bus(s)	10,9,8,6	7	5	4

*(Note. Buses 1,2 and 3 are the generator buses for this system.)

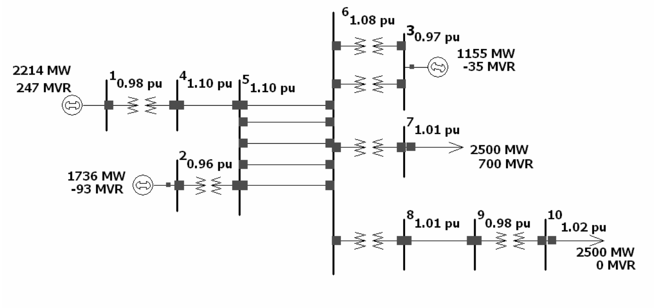

Figure 3 10 Bus BPA test System

Table 2 Generator branch sensitivity values for 10-bus BPA system

	Generator Branch			
	From bus 1	2	3	3
Bus	To bus 4	5	6	6
4	-0.8045	-0.1727	-0.0348	-0.0348
5	-0.3973	-0.5182	-0.1044	-0.1044
6	-0.2742	-0.3568	-0.3242	-0.3242
7	-0.2891	-0.3762	-0.3418	-0.3418
8	-0.2858	-0.3713	-0.3370	-0.3370
9	-0.2926	-0.3796	-0.3443	-0.3443
10	-0.2929	-0.3801	-0.3447	-0.3447

The VQ curve analysis data shown in Table 3 support the results found by the proposed method by showing that the groups found contain the same reactive reserve generators and similar VQ curve minima.

Table 3 VQ curve analysis data for 10-bus BPA system

Bus no.	V(pu)	Q(MVAR)	Reactive reserve generators		
4	0.9527	-7320.48	1	2	3
5	0.9653	-2475.08	1	2	3
6	0.9339	-1110.3	2	3	
7	0.818	-1604.93	2	3	
8	0.8453	-1050.78	2	3	
9	0.7882	-1076.73	2	3	
10	0.8096	-1056.26	2	3	

Table 4 provides data on the VQ minima found when different sets of generators have their limits removed. The generator limits were effectively removed by setting them to 99999MVAR. Generator limits were removed from the reactive reserve basin generators (RRB), the non-RRB generators and from all generators. As can be seen from Table 4 the PQ load buses (buses 4-10) have the same VQ curve minima when all non-RRB generators are unlimited as in the base case and that the VQ curve minima is the same when the RRB are unlimited as when all generators are unlimited. This indicates that all of these buses suffer from loss of voltage control instability. Only the RRB generators can have any impact in the maximum loading of these buses.

Table 4 VQ curve data for different sets of unlimited generators

	Basecase		Non RRB unlimited		RRB unlimited		All unlimited	
Bus	V(pu)	Q(MVAr)	V(pu)	Q(MVAr)	V(pu)	Q(MVAr)	V(pu)	Q(MVAr)
4	0.95	-7320.48	0.95	-7320.48	0.56	-18599.41	0.56	-18599.41
5	0.97	-2475.08	0.97	-2475.08	0.72	-10426.09	0.72	-10426.09
6	0.93	-1110.30	0.93	-1110.30	0.74	-3864.34	0.74	-3864.34
7	0.82	-1604.93	0.82	-1604.93	0.59	-3225.02	0.59	-3225.02
8	0.85	-1050.78	0.85	-1050.78	0.66	-2469.66	0.66	-2469.66
9	0.79	-1076.73	0.79	-1076.73	0.60	-1811.40	0.60	-1811.40
10	0.81	-1056.26	0.81	-1056.26	0.61	-1713.69	0.61	-1713.69

B. Modified Nordic Test System

Using the same method as for the BPA test system the coherent groups for the modified Nordic test system, shown in Figure 4 were found. This test system is based on the CIGRE Nordic test system[5] and differs from this standard test system in one area only. The step-up transformers in this modified system have been modelled externally and the reactive limits of the generators increased to allow for the additional losses in the transformers. This has been done to ensure an accurate indication of the loading limit of the buses in the system is obtained. It has been found in previous investigations that accurate loading limit results cannot be obtained if the transformers are modelled internally[6]. The coherent groups found for this system are:

Table 5 Modified Nordic System Coherent Bus Groups

Group	1	2	3	4	5	6	7
Bus(s)	4062 62	4061 61	4051 51	4047 47	4043 43	4042 42	4041 41

*(All other buses are either generator buses or belong to their own individual one bus group)

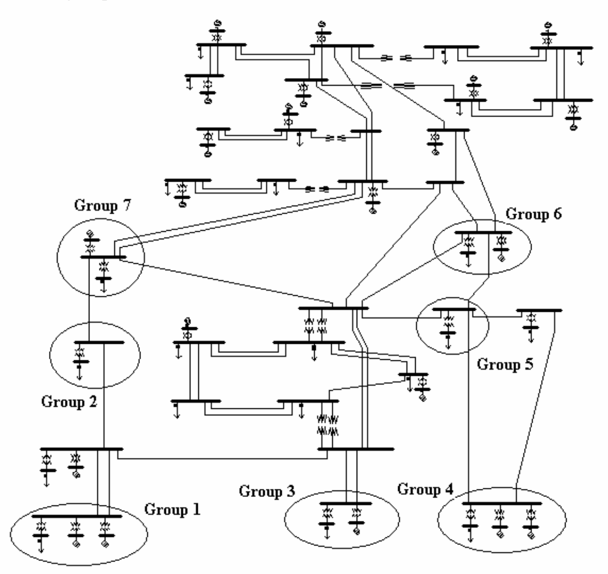

Figure 4 Modified Nordic test system

Reactive reserve basins for these select groups have been found via VQ curve analysis for the modified Nordic test system. The data from these can be seen in Table 6. The most important information found from the sensitivity and reactive reserve data obtained is that while groups 1,3 and 5 do have buses with the same reactive reserve basin, groups 2,4,6 and 7 do not have buses with the same reactive reserve basins. This can be easily explained by the fact that groups 2,4,6 and 7 contain buses that do not suffer directly from loss of voltage control instability. This situation was determined by performing a VQ curve analysis on all of the bus groups with all generators except for the reactive reserve unlimited to determine if the minima remains the same. The fact that buses in groups 2,4,6 and 7 did not have the same minima indicates that a loss of voltage control instability was not the cause of collapse for these buses. Because these buses have a different VQ curve minima they do not suffer from loss of voltage control and they must obviously suffer for some degree of clogging. As the instability is not directly caused by loss of generator control, even though the generators for these buses exhaust in a similar pattern, the generators that are exhausted at the minima point for this bus can be different, as they do not directly affect this point.

Table 6 VQ curve data for select Nordic Coherent groups

Bus	V(pu)	Q(MVAR)	Reactive reserve generators
4062	0.8821	-724.172	122, 431, 442, 462, 4631, 4632
62	0.6779	-630.742	122, 431, 442, 462, 4631, 4632
4061	0.8008	-542.372	122, 143, 431, 442
61	0.7059	-548.085	122, 431,442
4051	0.891	-176.357	122, 431, 442, 451
51	0.8727	-491.812	122, 431, 442, 451
4047	0.9827	-355.376	122, 143, 442, 4471, 4472
47	0.822	-334.142	122, 442, 4471, 4472
4043	0.926	-152.673	122, 431, 442, 4471, 4472
43	0.8788	-538.463	122, 431, 442, 4471, 4472
4042	0.9132	-303.176	122, 431, 442
42	0.8503	-400.529	122, 143, 431, 442
4041	0.9034	-236.038	122, 143, 431, 442
41	0.8469	-490.319	122, 431, 442, 451

Table 7 provides the results of VQ curve minima obtained for three example buses when individual generator limits are removed. As can be seen from Table 8 Bus 62 has been found by VQ curve analysis to be a candidate for loss of voltage control instability whereas buses 2031 and 2032 do not suffer directly from loss of voltage control instability. This is clear because the VQ curve minima for Bus 62 is the same even if all non RRB generator limits are removed and the VQ curve minima for the RRB generators unlimited is the same for all generators unlimited. Bus 62's RRB generators are 122, 143, 431, 442, 462, 4631 and 4632. Bus 2031's RRB generators are 122, 143, 431, 442 and 451. Bus 2032's RRB generators are 122, 143, 232, 431 and 442. Note how regardless of whether a bus suffers from loss of voltage control instability, or not, the VQ curve minima is only increased if the generator with an increased limit is one of the RRB generators.

Table 7 VQ curve minima for different individually unlimited generators

	BUS62		BUS2031		BUS2032	
Gen	V(pu)	Q (MVAR)	V(pu)	Q (MVAR)	V(pu)	Q (MVAR)
112	0.70	-629.35	0.94	-384.02	0.93	-455.25
113	0.70	-629.35	0.94	-384.02	0.93	-455.25
114	0.70	-629.35	0.94	-384.02	0.93	-455.25
121	0.70	-629.35	0.94	-384.02	0.93	-455.25
122	**0.69**	**-630.66**	**0.92**	**-441.05**	**0.92**	**-470.57**
142	0.70	-629.35	0.94	-384.02	0.93	-455.25
143	**0.70**	**-628.66**	**0.93**	**-395.00**	**0.96**	**-457.03**
232	0.70	-629.35	0.94	-384.02	**0.90**	**-1178.26**
411	0.70	-629.35	0.94	-384.02	0.93	-455.25
412	0.70	-629.35	0.94	-384.02	0.93	-455.25
421	0.70	-629.35	0.94	-384.02	0.93	-455.25
431	**0.69**	**-635.98**	**0.90**	**-569.55**	**0.86**	**-508.11**
441	0.70	-629.35	0.94	-384.02	0.93	-455.25
442	**0.69**	**-639.22**	**0.88**	**-554.01**	**0.86**	**-483.64**
4471	0.70	-629.35	0.94	-384.02	0.93	-455.25
4472	0.70	-629.35	0.94	-384.02	0.93	-455.25
451	0.70	-629.35	**0.93**	**-393.39**	0.93	-455.25
462	**0.65**	**-706.13**	0.94	-384.02	0.93	-455.25
4631	**0.69**	**-632.95**	0.94	-384.02	0.93	-455.25
4632	**0.69**	**-632.95**	0.94	-384.02	0.93	-455.25
471	0.70	-629.35	0.94	-384.02	0.93	-455.25
472	0.70	-629.35	0.94	-384.02	0.93	-455.25

Table 8 VQ curve data for selected buses

	Basecase		Non RRB unlimited		RRB unlimited		all unlimited	
Bus	V(pu)	Q(MVAr)	V(pu)	Q(MVAr)	V(pu)	Q(MVAr)	V(pu)	Q(MVAr)
62	0.70	-629.35	0.70	-629.35	0.52	-782.93	0.52	-782.93
2031	0.92	-394.27	0.91	-398.53	0.82	-768.14	0.74	-935.14
2032	0.93	-455.25	0.86	-483.64	0.78	-1644.15	0.62	-1904.11

V. CONCLUSIONS

This paper has presented a method that is used to determine the coherent bus groups of a system who have similar reactive reserve basins. The differences between this method and the method proposed by Schleuter have been highlighted and this method has been shown to be more efficient and requiring less VQ curve computations. Results obtained from the test systems support the method's validity. By determining the reactive reserve margin it is possible to determine which generators will have an impact on the maximum permissible loading of a bus and which will not. This information is particularly useful for performing voltage stability analysis, as Schlueter has already shown[2]. This proposed method is currently being utilised in a study of the 700+ bus Queensland transmission system and results of this study will be published at a later date.

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VII. BIOGRAPHIES

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