THE IMPACT OF GENERATION MIX ON PLACEMENT OF STATIC VAR COMPENSATORS

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Abstract: This paper looks at the problem of placing Static Var Compensators to provide the maximum transfer capability for all possible generation mixes. The margin to low voltage limit is one of the quantities used to determine power system transfer capability. Fast methods for finding the location of SVC systems that will have the greatest impact on low voltage margin will be shown. The IEEE 24 bus system will be used to demonstrate this method over a wide range of generation patterns.

Keywords: power system control, power system reliability, power system security, power transmission reliability, power semiconductor devices.

I. INTRODUCTION

Electrical power systems are going through their first major change in over a hundred years. This change is brought about by the combined forces of new technologies and the restructuring of electrical utilities. These technologies (power electronics and information systems) can provide the means for the transmission system to be both flexible and competitive. Due to the marketplace forces the generation mix could change day to day. The transmission planner (and operator) will be faced with highly unpredictable generation mixes requiring new technologies to insure maximum availability and reliability. One important group of technologies is FACT devices. This paper will focus on the placement of Static Var Compensators (SVC)[1] to increase power transfer capability.

SVC uses power electronic to control its reactive power output to regulate bus voltage. Compared to mechanically switched capacitor banks, SVC reacts very fast and has high reliability. The basic applications are power oscillation damping, load compensation, bus voltage support, reduction of the total system cost, and increasing power transfer capability. There are many different factors to consider when locating an SVC. The list includes: total cost, impact on the system, and harmonic generation.

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Most work in voltage support and transfer capability has been done in reactive power planning [4,5]. Current work on SVC placement [6-10] either focuses on load margin to point of collapse (PoC) boundary or oscillation damping as a measure of effectiveness. This work proposes a fast estimation method to judge SVC location base on the generation margin to low voltage boundary (LVB) [3]. The main feature of this method is that it only needs a solution close to LVB to estimate the results. Without further power flow calculation and system Jacobian inversion, the method is very fast in computation, making it effective to consider many different generation mixes as well as SVC location.

II. FORMULATION OF THE POWER FLOW EQUATIONS

To consider all possible SVC locations in a power system is a formidable task. Traditionally a SVC location is chosen and the power flow equations are solved. The load is increased until a limit boundary is reached. Then, another bus is chosen for the SVC and the process is repeated. The SVC location that enables the maximum power transfer is usually selected. The inclusion of different generation and load mixes makes the problem more formidable.

To achieve this objective, the power flow equations need a particular structure. In this structure each load bus includes a shunt capacitance as a controllable parameter. The generation and load mix are defined by a unit direction vector. This allows for changes in generation and load without changing the mix. Power balance is achieved through a load scaling factor.

The generation mix is defined by a unit direction vector, P_{gen}:

$$P_{gen} = \frac{1}{\sum_{i=1}^{i=n} P_{G_i}} \begin{bmatrix} P_{G_1} \\ \vdots \\ P_{G_n} \end{bmatrix} \quad (1)$$

Total generation is defined as gP_{gen} where g is a scalar. The load is also defined by a unit direction vector.

$$S_{load} = \frac{1}{\sum_{i=1}^{i=n} \mathrm{Real}(S_{L_i})} \begin{bmatrix} S_{L_1} \\ \vdots \\ S_{L_n} \end{bmatrix} \quad (2)$$

The total load is defined as lS_{load}, where l is a scalar and the "slack" parameter.

The general power flow equation for a n bus system can be described in complex vector forms as:

$$S(\lambda,\mu) = VI^* = V(YV)^* \quad (3)$$

$$S(\lambda,\mu) - gP_{gen} + lS_{load} = 0 \quad (4)$$

where:

λ system state variables containing bus voltage magnitudes |V| and angles θ

μ controllable system parameter vector. (In this case μ is a controllable shunt capacitance or SVC. The equivalent capacitance ωC, is included in Y matrix)

P_{gen} unit generation direction vector

g generation parameter

S_{load} unit load direction vector

l slack variable needed for power balance.

III. SENSITIVITY RELATIONSHIPS

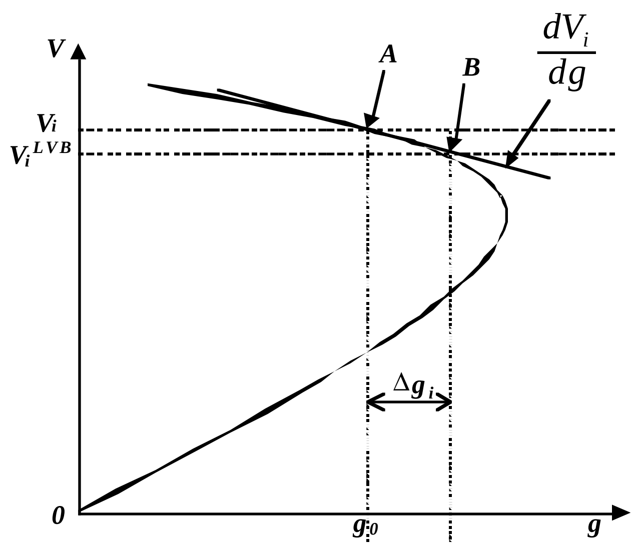

Fig. 1.Voltage on bus i as a function of total generation g.

Basic sensitivity concepts can be illustrated in Fig. 1. This figure plots voltage on bus i against the power transfer of the system. In this example it is assumed that a solution is known for voltage at g_0, as indicated by the point A. Using this solution, linear techniques provide an estimate of the additional power transfer Δg_i. This is defined as the point where the bus voltage equals low voltage boundary (LVB) at B. In this case Δg_i is:

$$\Delta g_i \cong \frac{V_i^{LVB} - V_i}{dV_i/dg} \quad (5)$$

A more systematic approach starts with representing the power flow equations (3) and (4) as a set of algebraic equations.

$$f(x,\mu,g) = 0 \quad (6)$$

The vector x denotes the states or dependent variables of the system. It contains the slack variable l and bus voltage magnitudes and angles. The vector μ denotes the controllable parameters, in this case a shunt capacitance at each PQ load bus. The scalar g denotes the total generation.

If it is assumed that x_0, μ_0, g_0 are solutions to the power load flow without SVCs then:

$$f(x_0,\mu_0,g_0) = 0 \quad (7)$$

where $\mu_0 \equiv 0$. It is now possible to determine changes in the systems states, x, due to small changes in μ and g. Expanding about the base solution using Taylor-series it follows from (7):

$$f_x \Delta x + f_\mu \Delta\mu + f_g \Delta g = 0$$

or

$$\Delta x = -f_x^{-1} f_u \Delta\mu - f_x^{-1} f_g \Delta g \quad (8)$$

where the Jacobian matrices f_x , f_μ, and f_g are evaluated at x_0, μ_0, g_0. The inverse of f_x is the same Jacobian inverse used in the Newton's method and needs to be calculated once for each generation direction. For convenience of notation, equation (8) can be rewritten in terms of sensitivity matrices M and G as:

$$\Delta x = \mathrm{M}\Delta\mu + G\Delta g \quad (9)$$

with

$$\mathrm{M} = -f_x^{-1} f_u \quad (10)$$

$$G = -f_x^{-1} f_g \quad (11)$$

IV. ESTIMATING GENERATION MARGIN TO THE LOW VOLTAGE BOUNDARY (LVB) AFTER A SVC IS INSTALLED

Starting from the initial load flow solution at x_0, μ_0, g_0, sensitivity relationships discussed above can be used to estimate the increase in generation margin when a single SVC is added to the system. To approximate the new margin to LVB, Δg, estimates of the change in bus voltage V_i and the tangent [11,12] dV_i/dg need to be calculated, (see Fig.1.).

Using (9) the change in the voltage at the i-th. and k-th. buses due to controlling voltage at the k-th. bus using the parameter μ_k are:

$$\Delta V_i = M_{ik} \Delta\mu_k \quad (12)$$

$$\Delta V_k = M_{kk}\Delta\mu_k \quad (13)$$

where generation is fixed at g_0. The components M_{ik} and M_{kk} of the sensitivity matrix M are the terms that couple the voltages on bus i and k to the control parameter μ_k. From these relationships the sensitivity of the i-th. bus voltage to change in the k-th. bus voltage can be expressed as:

$$\Delta V_i = M_{ik}(M_{kk})^{-1}\Delta V_k \quad (14)$$

An estimate of the voltage at the i-th. bus, when the voltage at the k-th. bus is held at 1.0 pu, using a SVC can be expressed as:

$$V_{i,new} \cong V_i + M_{ik}(M_{kk})^{-1}(1.0 - V_k) \quad (15)$$

The sensitivities of the voltage on the i-th. and k-th. buses to small changes in generation and control are necessary to find the change in the tangent, dV_i / dg, when there is a SVC on the k-th. bus. From (9) the voltages sensitivities are:

$$\Delta V_i = M_{ik}\Delta\mu_k + G_i\Delta g \quad (16)$$

$$\Delta V_k = M_{kk}\Delta\mu_k + G_k\Delta g \equiv 0 \quad (17)$$

In (17) the change in voltage on the k-th. bus is held to zero by the SVC on the k-th. bus. Equations (16-17) allow the change in the tangent, dV_i / dg, to be expressed as:

$$\frac{dV_i}{dg} = G_i - M_{ik}(M_{kk})^{-1}G_k \quad (18)$$

The change in margin Δg, to the low voltage boundary for the i-th. bus, due to an SVC at the k-th. bus can be approximated using (5), (15) and (18):

$$\Delta g_{i,k} \cong \frac{V_i^{LVB} - \left(V_i + M_{ik}\left(M_{kk}\right)^{-1}\left(1.0 - V_k\right)\right)}{G_i - M_{ik}\left(M_{kk}\right)^{-1}G_k} \quad (19)$$

where all elements of M and G are evaluated at x_0, μ_0, g_0.

The change in total generation for the complete system with a SVC at the k-th. bus is the minimum change in margin. This is defined by the first bus to reach its LVB.

$$\Delta g_k = \min(\Delta g_i) \text{ for } i = 1, \ldots, n \ (i \neq k) \quad (20)$$

The best placement could be defined as the k location that achieves the maximum Δg_k.

For two SVCs it can be shown that (19) becomes:

$$\Delta g_{i,jk} = \frac{V_i^{LVB} - \left(V_i + \begin{bmatrix} M_{ij} & M_{ik} \end{bmatrix}\left(\begin{bmatrix} M_{jj} & M_{jk} \\ M_{kj} & M_{kk} \end{bmatrix}^{-1} \times \begin{bmatrix} 1 - V_j \\ 1 - V_k \end{bmatrix}\right)\right)}{G_i - \begin{bmatrix} M_{ij} & M_{ik} \end{bmatrix}\left(\begin{bmatrix} M_{jj} & M_{jk} \\ M_{kj} & M_{kk} \end{bmatrix}^{-1} \times \begin{bmatrix} G_j \\ G_k \end{bmatrix}\right)} \quad (21)$$

where the SVCs are placed on the j-th. and k-the bus.

The boundary increase for the system with SVCs placed at buses *j* and *k* is:

$$\Delta g_{jk} = \min_i\left(\Delta g_{i,jk}\right) \qquad i = 1, \ldots, n \ (i \neq j, k) \quad (22)$$

Maximum increase in margin is given by

$$\Delta g_{\max} = \max(\Delta g_{jk}) \quad \begin{matrix} j = 1, \ldots, n. \\ k = 1, \ldots, n. \end{matrix} (j \neq k) \quad (23)$$

Equation (23) identifies the two SVC locations for maximum increase in power transfer.

V. SVC RATINGS

In the last section methods were presented to estimate the increase in power transfer using SVC(s). In these approximations it was assumed that the SVC(s) could hold the bus voltage to 1 pu at the maximum transfer level. This assumption implies a minimum SVC rating. In some case this value will be too large to be a practical alternative.

Sensitivity methods can again can be used to approximate the size of the SVC(s). From (9) the sensitivity of the k-th. bus voltage to changes in *g* and *m* can be expressed as:

$$\Delta V_k = M_{kk}\Delta\mu_k + G_k\Delta g \quad (24)$$

The rated pu reactive power required to hold bus k at 1.0 pu voltage can be approximated from (24):

$$\Delta\mu_k \cong M_{kk}^{-1}[\Delta V_k - G_k\Delta g] \quad (25)$$

where the change in voltage is:

$$\Delta V_k = 1.0 - V_k \quad (26)$$

and $\Delta g = \Delta g_k$ as evaluated in (20). Similar relationships can be derived for two or more SVCs.

VI. TEST RESULTS

A modified IEEE 24 bus system [13] as shown in Fig. 2 is used to test the estimation method against traditional results. The modified 24 bus system has 10 generators with the synchronous var generator (bus 14) removed. The 24 bus system uses 100MVA base. The normal loading totals 28.5 per unit. As load increases, buses 3, 4, 5, 6, 8, 9, 10 and 24 will have large voltage drops due to some generators reaching their MVAR limits.

Fixed generation and load directions are selected, as shown in (1) and (2). The output ratio between generators is fixed as generation increases. Every bus load ratio is also fixed as total load increases. Starting from zero generation and loading, continuation power flow method [2] is used to increase generation until low voltage boundary (LVB) is reached. Here 0.9 per unit is chosen as low voltage limit for all buses. At LVB, the lowest bus voltage is 0.9 pu. Along a selected direction, at LVB, the power outputs for generators are 398MW(bus 1), 398(2), 531(7), 608(13), 183(15), 109(16), 497(18), 497(21), 331(22) and 426(23) respectively, totaling

3977MW, with generators 15 and 16 at MVAR limit. Key low voltage buses are shown in Table 1. Bus 3 reached low voltage limit first.

At this calculated LVB, the estimation method is performed first for single SVC placement, using (19), (20) and (25). To compare, traditional method is also used to obtain exact solution, using continuation power flow and holding the SVC bus at 1 per unit. Results are shown in Table 2. Column 2 and 3 show the LVB percentage increases over the original LVB of 3977MW, after a load bus is hold at 1.0 per unit by SVC. Column 4 and 5 show the rating of SVC that is required. Result show that a SVC at bus 9 can increase LVB by as much as 20%(796MW), with SVC rating of 351MVAR. Note that the bus that reaches its low voltage limit (bus 3) may not be the best place to install a SVC (bus 9).

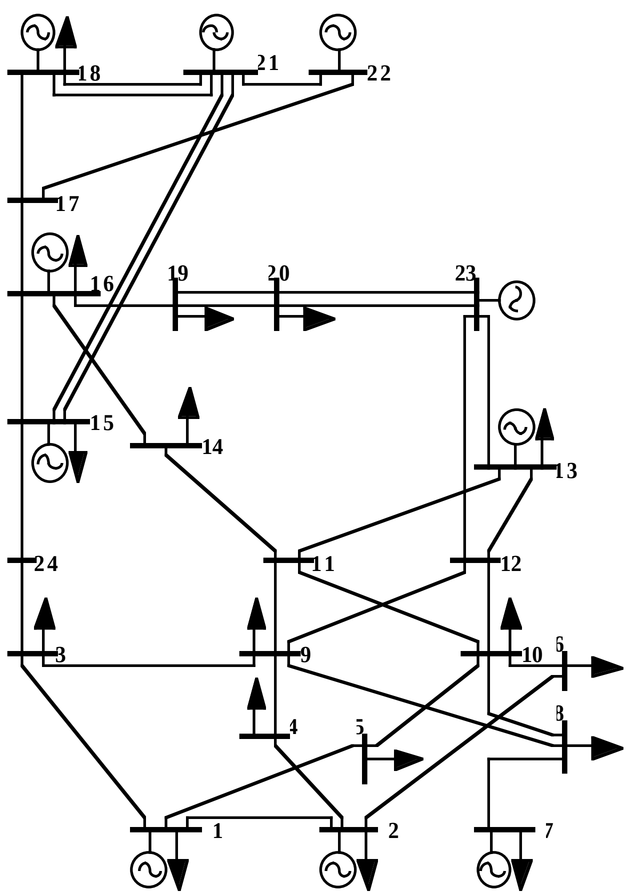

Fig. 2 IEEE 24 bus system with synchronous condensor on bus 14 removed.

At the same original LVB as in Table 1, two SVC placement was also estimated as in (21-23). All possible pairs of load buses are estimated with SVCs holding two load bus voltages at 1.0 per unit. Three best pairs are shown in Table 3. Of all the combinations, the optimal is bus 6 and bus 9. They together will increase LVB by over 37% (1471MW), with total SVC rating of 5.37 pu (537MVAR).

TABLE 1
KEY LOW VOLTAGE LOAD BUSES AT LVB

V(3) (pu)	V(4) (pu)	V(5) (pu)	V(6) (pu)	V(8) (pu)	V(9) (pu)	V(10) (pu)	V(24) (pu)	Generator at MVAR limit	Total generation
0.900	0.922	0.947	0.918	0.913	0.918	0.944	0.938	15,16	3977MW

TABLE 2
ESTIMATION RESULTS AND TRADITIONAL RESULTS
FOR SINGLE SVC INSTALLATION
(BASE GENERATION AT 3977MW)

SVC bus	LVB increase(%)		SVC rating (100MVAR)		Generators at MVAR limit on new LVB
	estimate	exact	estimate	exact	exact
3	12.79	12.40	2.20	1.97	16,15
4	6.75	6.74	1.36	1.25	16,15
5	1.18	1.21	1.08	1.03	16,15
6	2.10	2.15	1.32	1.22	16,15
8	6.09	6.13	2.52	2.12	7,16,15
9	20.01	19.17	3.51	3.20	16,15
10	3.78	3.80	1.86	1.76	16,15
11	7.13	7.08	2.52	2.40	15,16
12	4.42	4.40	1.80	1.74	16,15
14	5.25	5.23	2.08	1.96	15,16
17	0.80	0.80	1.02	1.01	16,15
19	2.15	2.16	1.65	1.61	15,16
20	0.68	0.69	1.46	1.44	16,15
24	11.09	10.71	1.63	1.52	16,15

TABLE 3
ESTIMATION RESULTS AND TRADITIONAL RESULTS FOR TWO SVC INSTALLATION
LVB IS AT 3977MW TOTAL GENERATION
TABLE SHOWS THREE PAIRS OF SVC WITH GREATEST INCREASE

bus (A)	bus (B)	LVB increase(%)		SVC(A) rating (100MVAR)		SVC(B) rating (100MVAR)		Generators at MVAR limit on new LVB
		estimate	exact	estimate	exact	estimate	exact	exact
9	10	37.36	34.87	3.69	3.35	2.64	2.45	16,15,18
6	9	37.24	34.81	1.99	1.79	3.93	3.58	16,15,18
3	10	33.85	31.16	2.66	2.34	2.97	2.73	16,15,18

So far, only one direction of generation is considered. Due to the fast speed of the estimation method, full generation space can be estimated as well. To visualize the results, generators are divided into three groups. Each generator inside the group has fixed ratio of output to each other. The outputs between groups, however, are selected at all possible combinations. Therefore the direction of three groups will scan a 3-D space. The LVB points of all directions will form a surface in 3-D space, as shown in Fig. 3 and 4. The three groups are buses (1,2,7), (13,15,16,23) and (18,21,22). Group (13,15,16,23) reaches MW generation limit in some directions. The generation direction are chosen as

$$
\begin{aligned}
P_{gen} &= a \times (0.3_{bus1} + 0.3_2 + 0.4_7) \\
&+ b \times (0.46_{13} + 0.14_{15} + 0.08_{16} + 0.32_{23}) \\
&+ c \times (0.38_{18} + 0.38_{21} + 0.25_{22})
\end{aligned}
\tag{27}
$$

where *a*, *b* and *c* are parameters that scan the whole 3-D space. When $a = b = c = 1/3$, the generation direction is the same as the first example in Table 1. Table 4 shows 10 LVB points of different directions, from evenly chosen *a,b,c*'s. Direction 6 is the same as the example in Table 1, totaling 3977MW generation. Table 4 shows that different directions yield different total generation at LVB. Also the buses that reach low voltage limit (0.9 pu) are different, as circled by black boxes.

TABLE 4
FOR 10 EVENLY SELECTED GENERATION COMBINATION DIRECTIONS,
THE LIST OF SOME LOW VOLTAGE BUSES AND THEIR VOLTAGES AT LVB

	Load bus voltages (per unit)								Total genera-tion (100 MW)	Generators at MVAR limit
	V(3)	V(4)	V(5)	V(6)	V(8)	V(9)	V(10)	V(24)		
1	0.960	0.960	0.983	0.980	0.959	0.958	0.988	0.978	21.15	16*
2	0.916	0.941	0.967	0.950	0.938	0.936	0.967	0.964	31.72	16,15*
3	0.900	0.926	0.953	0.939	0.905	0.915	0.946	0.963	20.52	16,15
4	0.903	0.924	0.951	0.939	0.900	0.908	0.937	0.964	13.10	none
5	0.916	0.923	0.948	0.932	0.900	0.914	0.940	0.969	20.98	16,15
6	0.900	0.922	0.947	0.918	0.913	0.918	0.944	0.937	39.77	16,15
7	0.900	0.903	0.928	0.919	0.915	0.905	0.933	0.927	26.20	16,15,1,2,13,7
8	0.900	0.935	0.964	0.958	0.941	0.928	0.968	0.902	24.18	16,15,1,2
9	0.900	0.934	0.961	0.944	0.936	0.925	0.960	0.900	30.75	16,15,18,21,13
10	0.916	0.959	0.990	0.991	0.965	0.949	0.996	0.900	18.95	16,15,21,18

*Generators reached power limit before LVB is reached.

To show SVC performance over full generation space, the estimation method was performed at many different LVB points for SVC at bus 3 and bus 9, as shown in Fig. 3-4. In Fig. 3, the increment due to SVC at bus 3 is shown by the line pointing out of the surface. Only the increments larger than 10% are plotted. Comparing Fig. 3 for SVC at bus 3, to Fig. 4 for SVC at bus 9, it shows that generation direction affects the SVC performance as well. While SVC at bus 9 can increase LVB over wider directions, SVC at bus 3 has larger than bus 9 for some generation directions. Generation direction is also a very important factor for choosing SVC locations.

To determine the best place for single SVC placement over all directions of the three groups of generators, average of the results is listed in Table 5 for evenly chosen 10 directions. Results show that bus 9 is the best place to place a SVC to increase LVB, followed by bus 3 and 24.

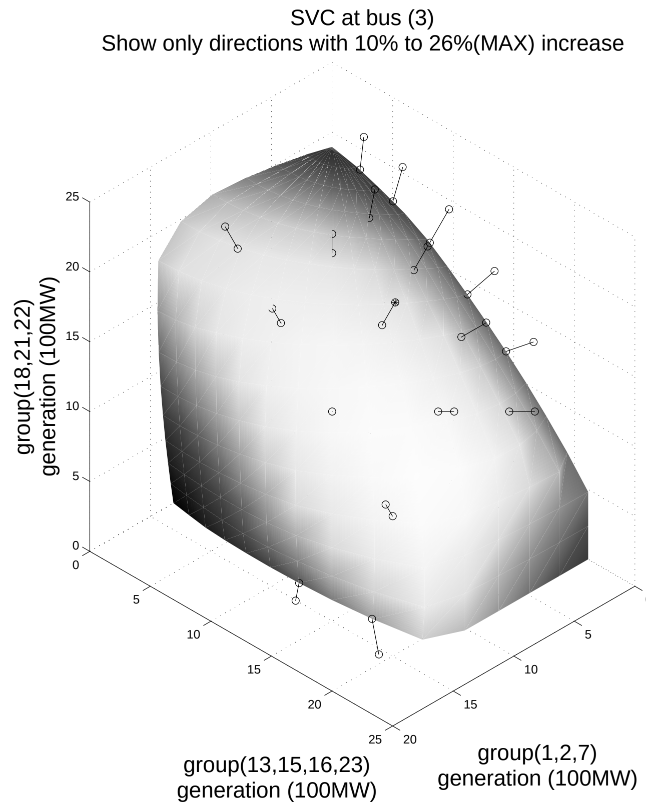

Fig. 3. The LVB Surface and Changes by SVC at Bus 3.

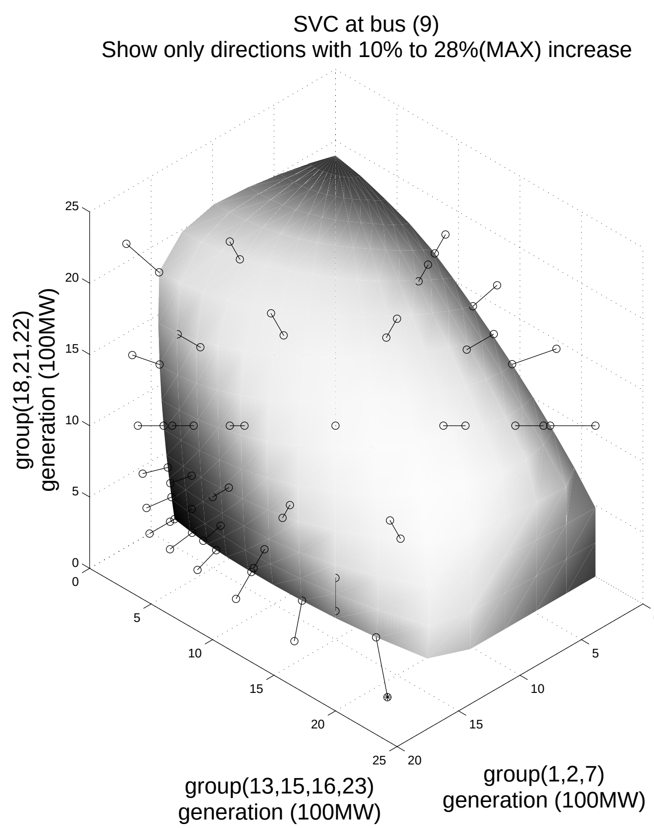

Fig. 4. The LVB Surface and Changes by SVC at Bus 9.

TABLE 5
AVERAGE OF RESULTS OF SINGLE SVC TO INCREASE LVB OVER MANY GENERATION DIRECTIONS

	Average on 10 directions of 10 generators in 3 groups		Average on 220 directions of 10 generators in 10 groups	
SVC bus	Average LVB increase (100MW)	Average SVC rating (100MVAR)	Average LVB increase(pu) (100MW)	Average SVC rating (100MVAR)
3	2.33	2.09	1.81	1.59
4	1.09	1.15	1.45	1.14
5	0.53	0.86	1.21	1.87
6	0.67	0.91	1.02	0.82
8	1.52	2.13	3.44	2.85
9	3.43	3.19	2.44	2.60
10	1.26	1.59	1.38	1.34
11	1.59	2.41	1.11	1.81
12	1.00	1.61	0.77	1.30
14	1.40	2.13	0.81	1.49
17	0.56	1.04	0.36	0.76
19	0.66	1.62	0.34	1.09
20	0.19	1.28	0.10	0.90
24	2.16	1.85	1.21	1.34

When the fixed relations among generators in each group are relaxed, the full generator space is 10-dimensional. In the 10-D space, averages of results are calculated over 220 evenly selected directions as listed in Table 5. It shows the best location is bus 8 followed by bus 9 and 3.

Since the selection of direction set will affect the results very much, system planer should determine the set of future generation directions before selection a best place for SVC placement.

VII. CONCLUSION

The fast estimation methods is able to predict the results obtained from traditional method. The fast estimation makes it easy to consider SVC locations for a wide range of generation mixes.

Also rating is an issue. An optimization method could be used with this estimation to reduce the cost. The cost function could include rating, SVC bus voltage, required margin and generation and load directions.

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IX. BIOGRAPHIES

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