A Methodology for Selective Localization of Capacitor Banks for Power Systems

by

Sivaramakrishnan Raman, Amit Jain, M Ramamoorty, Ashok Vaghamshi

in

Third International Conference on Power Systems
(*ICPS 2009*)

Report No: IIIT/TR/2009/208

Centre for Power Systems
International Institute of Information Technology
Hyderabad - 500 032, INDIA
December 2009

2009 Third International Conference on Power Systems, Kharagpur, INDIA December 27-29
318

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Sivaramakrishnan Raman, Amit Jain, M. Ramamoorty and Ashok Vaghamshi
Power Systems Research Center, IIIT Hyderabad
Hyderabad, INDIA
sivaramakrishnan.raman@research.iiit.ac.in, amit@iiit.ac.in, mrmoorty@gmail.com, ashokvaghamshi@gmail.com

***Abstract*— The issue of voltage instability has been a predominant one to deal with in what has developed into power systems loaded near its maximum capabilities in recent times. To address this concern, with the added responsibility of accomplishing it with the resources economically, is a challenge in itself. As stated, the problem thus naturally draws attention to the localization of the components able to contribute to the stepping up of overall voltage in the system. This paper discusses a methodology for the suitable selection of buses for the placement of capacitors wherein the injection of a fixed amount of reactive power into each bus is made to depict a picture of the overall improved voltage in the system for the respective injection at that bus. The reduced Jacobian is used to determine the impact of the reactive power injection in the form of system voltage improvement. The significance however lies in this analysis being done for different operating points of the power system using continuation power flow to choose the optimum location for capacitor to affect maximum voltage improvement in total over a range of operating points. The relevant results are enlisted for the IEEE 14 bus system.**

Keywords-brownout; continuation power flow; reduced Jacobian.

I. INTRODUCTION

Reactive power compensation with components like capacitors is a trend popular in power systems today so as to ensure the continuous system reliability, given the regular overloading and the resulting lack of reactive power supply and voltage collapse. The use of these components however, is not a subject of free choice. These components are expensive enough to ensure that they cannot be installed at every node. This paper discusses a suitable methodology for the selection localization of capacitor bank on a bus that is deemed better fit than the others for the purpose of overall system voltage improvement.

The idea of this paper is to point the locations or buses incapable of yielding a minimum voltage raise for the overall system even if it cannot answer the exact compensation amount required. Injecting a fixed amount of reactive power into each bus individually can be interpreted as the increase of the voltage at all the buses as a result of the particular analysis proposed in this paper. This would ensure that atleast a location better fit than the others can be found to provide a minimum overall improvement in voltage. The significance of the study done in the present paper is thus justified in the form of letting power system personnel concerned make a calculated decision of the constrained location for compensation device like capacitor because of the limited number possible to install or place, but at the same time cater to the requirement of a minimum voltage improvement overall in the system or in other terms, maintain or sustain a condition where the system does not collapse.

The next section discusses the background of the technique clearly. But they are noted in brief below.

- The conventional load flow analysis is done with the Newton Raphson technique.
- The Jacobian matrix is computed from the conventional load flow. The reduced Jacobian [1] is determined from this. The inverted reduced Jacobian is used to depict change in voltage in terms of reactive power injection.
- The inverted reduced Jacobian is useful in the analysis explained in a later section to determine the bus where placing a capacitor would yield maximum system voltage rise.
- The previous steps are repeated over a range of operating points to picture a trend followed by capacitor locations along the operating curve and most importantly at the proximity of the stability limit or, nose point of the P-V curve [2-5]. The continuation power flow [6-7] is used to attain different operating points and the procedure is applied to each of these points.

The contribution of the method proposed lies in two major aspects, namely, determining the capacitor location for the best overall improvement in system voltage, and, isolation of the locations which are sure to not yield significant improvement, even if not the exact amount of compensation required. In situations where a complete blackout can be avoided and a scenario like a brownout can be improved towards the normal condition, this may turn out a useful procedure. The paper uses the reduced Jacobian technique and the continuation power flow as part of proposed methodology.

II. BACKGROUND THEORY

A. *Computation of Reduced Jacobian*

The technique implements a simple computation on the elements of the reduced Jacobian to find the suitable bus for capacitor placement as seen in the later section. The reduced Jacobian [1] is formulated from the Jacobian of the load flow. A brief description of the formulation of the reduced Jacobian is given before proceeding further.

The load flow equations are given by

$$f(\theta, V) = 0, \tag{1}$$

$$g(\theta, V) = 0. \tag{2}$$

f represents the active power mismatch equation,

g represents the reactive power mismatch equation.

Equation 3 gives the known matrix model of the load flow.

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} \tag{3}$$

P and Q are the active and reactive power injections,

V and θ are the state variable vectors, namely voltage magnitude and bus angle, respectively,

ΔP is the difference in active power injection,

ΔQ is the difference in reactive power injection,

$\Delta\theta$ is the change in bus angle,

ΔV is the change in bus voltage magnitude,

J_1 represents $\partial f / \partial\theta$,

J_2 represents $\partial f / \partial V$,

J_3 represents $\partial g / \partial\theta$,

J_4 represents $\partial g / \partial V$.

The reduced Jacobian used in this technique assumes that change in active load i.e. $\Delta P = 0$. Substituting this in (3), we get

$$J_1 \Delta\theta + J_2 \Delta V = 0, \tag{4}$$

$$J_3 \Delta\theta + J_4 \Delta V = \Delta Q. \tag{5}$$

Putting $\Delta\theta$ from (4) in (5), we get

$$\Delta Q = (J_4 - J_3 J_1^{-1} J_2) \Delta V, \tag{6}$$

$$\Delta Q = J_R \Delta V, \tag{7}$$

$$\Delta V = J_R^{-1} \Delta Q. \tag{8}$$

where J_R is reduced Jacobian.

The reduced Jacobian would serve as the tool on which the proposed methodology, described in detail later in this paper, would yield the results regarding the capacitor location.

B. *Continuation Power Flow*

The main goal of the method is to observe the vagaries in the trend of the most suitable bus for the capacitor placement as the operating points of the power system differ. As the technique uses the elements of the reduced Jacobian as key, a briefing into the theory of reduced Jacobian was given in the previous section. The method of continuation power flow [6-7] is dealt with in brief here as the different operating points are obtained in this fashion to extend the mathematics of the previous section to all operating points.

The continuation power flow [1], as known, is a useful tool to plot the entire P-V curve [2-5] i.e. to show all the operating points therein like in Fig. 1. Although the aim here in the context of the paper is not to plot the entire operating region, the individual points can be subjected to the mathematical analysis required and thus the change in the trend of the solution whatever is possible to be observed over all the points.

The continuation power flow uses a predictor-corrector scheme [6-7] to solve the set of load flow equations which are reformulated to accommodate a load parameter λ which denotes the increase in load from the base point. The base point is where the continuation power flow starts from as an initial known solution. The conventional load flow equations shown in (1) and (2) are modified to

$$F(\theta, V, \lambda) = 0 \tag{9}$$

where, F represents the combination $[f, g]$.

The predictor estimates a subsequent solution point corresponding to a different load point and the corrector corrects this solution using the conventional Newton Raphson technique, only that the equations are slightly modified. Identifying each point is an integral part of the continuation power flow method.

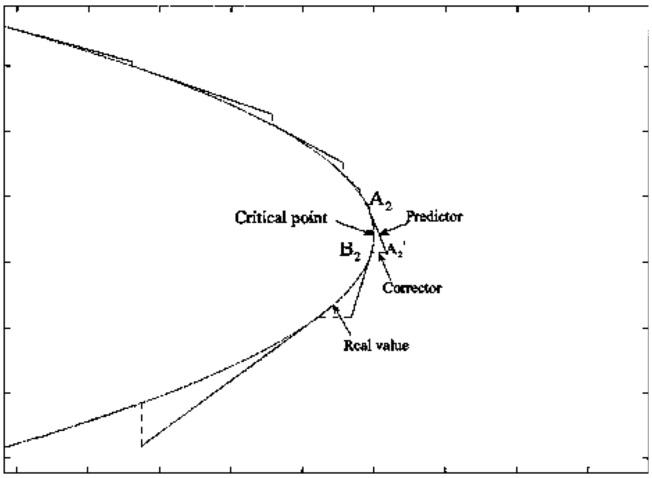

Figure 1. Depiction of Predictor and Corrector

III. IMPLEMENTATION OF METHODOLOGY

A. Reduced Jacobian Technique

The reduced Jacobian J_R gives a relationship describing ΔQ in terms of ΔV [1]. The inverse describes ΔV in terms of ΔQ. The elements in each column of the inverse matrix J_R^{-1} can be made to represent the change in voltage of every load bus for a given injection of reactive power into the bus corresponding to that column. The concept can be explained using a sample matrix like the one in (10) which shows J_R^{-1} as a (3 X 3) matrix.

$$\left[\Delta V\right] = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \left[\Delta Q\right]. \qquad (10)$$

A_{1i}, $A_{2\,i}$ *and* $A_{3\,i}$ represent partial derivatives of voltages of load buses 1, 2 and 3 of the system with respect to reactive power at load bus i,

ΔQ represents the vector of change in reactive power modelled by a fixed amount of reactive power injection,

ΔV represents the vector of change in voltage.

This implies that for studying the change in voltage ΔV as a result of the reactive power injection into load buses separately or individually, the corresponding element of ΔQ, say ΔQ_i alone must be made 1 p.u. and the others 0. Upon implementing this, the corresponding column i in J_R^{-1} directly gives ΔV. Thus one needs to only study the elements of the particular column i of the reduced Jacobian to get the change in voltage as an effect of 1 p.u. reactive power injection at that bus i.

$$A_{1\,i} = \Delta V_1, \qquad (11)$$

$$A_{2\,i} = \Delta V_2, \qquad (12)$$

$$A_{3\,i} = \Delta V_3. \qquad (13)$$

The sum of the elements of that column i of J_R^{-1} further gives the total improvement of system voltage $\Delta Vtotal_i$ as an effect of the injection at the bus i. This is shown in (14).

$$A_{1\,i} + A_{2\,i} + A_{3\,i} = \Delta Vtotal_i \qquad (14)$$

On comparison of the sums of all individual columns of J_R^{-1}, the bus corresponding to the column i which yields maximum $\Delta Vtotal_i$ is determined as the bus required.

$$bus_i \;:\; \Delta Vtotal_i = \max\{\Delta Vtotal_1, \Delta Vtotal_2, \Delta Vtotal_3\} \qquad (15)$$

corresponding to the matrix given in (10).

bus_i is not the i^{th} bus in the system but the i^{th} load bus in the system as the buses involved in the analysis are only load buses.

It should be noted that the term $\Delta V_{overall}$ depicts the total improvement in system voltage where as the individual change in the bus voltage information come with the individual elements of J_R^{-1}.

Some of the advantages of this method are:

- The method is simple mathematically as it deals with only the elements of the inverse of the reduced Jacobian directly.
- The method gives the overall voltage improvement in system and it ensures that the optimum bus can be found so that a condition of blackout can be avoided and in such circumstances, some amount of voltage can be sustained in the system with the selected capacitor(s) connected.

B. Application over range of operating points

The strategy discussed so far need not yield the same result at every operating point which is exactly why it is quite essential to study the same aspects discussed just before at different operating points over a continuous range. The continuation power flow aids the purpose of extending the idea discussed before over that continuous range of operating points.

Previously, the computations involving (10), (11), (12), (13) and (14) were focused on the reduced Jacobian J_R obtained from the conventional load flow. The extension to this would be to do the following:

- Obtain subsequent operating points with continuation power flow.
- Obtain the matrix J_R and its inverse from the Jacobian of this operating point.
- Perform the same computations as discussed in the previous section and obtain the bus location.
- Repeat the previous steps for points consequent enough to cover a continuous range of operating points like those in Fig. 2.

The bus numbers deemed best by the technique for capacitor placement at the operating points plotted by the continuation power flow can be enlisted to serve as a picture to let know the same bus location is fit enough over a particular range of operation within which any voltage recovery is possible. The range is not necessarily required to be very near to the critical point as system recovery need not wait till then.

The advantages with the continuation power flow in the context of the proposed methodology are:

- The step size can be adjusted accordingly to get the desired operating points over a desired continuous range.
- The continuum near and beyond the critical point is maintained by continuous power flow without disruption due to singularity problems. Thus the trend in the chosen bus locations over the different operating points near and away from the unstable region can be observed. Also, it becomes easier to find the steady bus location over a desired range.

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IV. SIMULATION AND RESULTS

The standard IEEE 14 bus system served as the test case for showcasing the results obtained. The continuous operating points of the system were simulated using MATLAB program for the continuation power flow study on the same system. The simulation results are as shown in Fig. 2. Table 1 highlights the results obtained from code in MATLAB which implements the methodology using the reduced Jacobian technique on all the operating points. The tabulation is useful to know as to when and where the bus location suitable for the capacitor placement remains the same over a considerable range of operating points. The location can be expected to change as the operating points seems to approach the unstable region or the critical point as the demand of reactive power from individual buses and on an overall basis is expected to vary.

The whole idea behind the analysis is to actually spot optimum bus location for the capacitor which would be same over a considerable range of operating points spanning over the steady and unsteady regions. The location need not be constant entirely over all points till the critical point. It may differ well even before but the location which seems steady enough over a range of operating points from where recovery of system is possible is the quintessential need.

In the 14 bus test system, the critical point was identified to be operating point no. 83 by the continuous power flow program. The simulation results of the 14 bus system based on the proposed methodology give the largest value for the bus no. 14 when the summation of the elements of each column values are compared for the first operating point. For each operating point this simulation is done and in case of the 14 bus system considered, bus no. 14 has been found to have the highest vale of the column element addition for each operating point till we reach the critical point which is the operating point no. 83 in our simulation study as show in Table no I. Thus, in this case the quest of that steady location required becomes simpler as it remains same till the critical point. As per this analysis, the bus 14 found to be the optimum bus location for the capacitor placement, at least to provide the best overall improvement in voltage to the system.

The aim is to use the tabulated results to know intuitively the range of operation for which the capacitor location can be maintained to support the system recovery or prevention of collapse, whichever possible.

V. CONCLUSION AND FUTURE WORK

This paper presents a simple methodology to determine the optimum bus location for capacitor placement which can contribute to the best overall improvement in system voltage or best improvement in total voltage. This is done keeping in mind the practical problems of incorporating large numbers of required capacitors for the voltage improvement cause. Zeroing down on one location suitable to contribute that total voltage improvement is useful in economic terms. It ensures that the emergencies like blackouts can be controlled well within our limits by maintaining an overall good voltage level and improving the overall voltage level of the system if it is the need of the hour.

The present methodology uses the simulation results to show the one optimum location for the capacitor placement. In fact, the proposed methodology is equally useful in giving the location of the capacitor placement in form of a ranking list in terms of the effectiveness of locations and can be very useful for the concerned personnel when they want to decide the capacitor placement on more than one location. The authors are presently working in this direction and will present the results on a bigger test system to show the methodology for giving more than one useful locations for capacitor placement according to their effectiveness ranking.

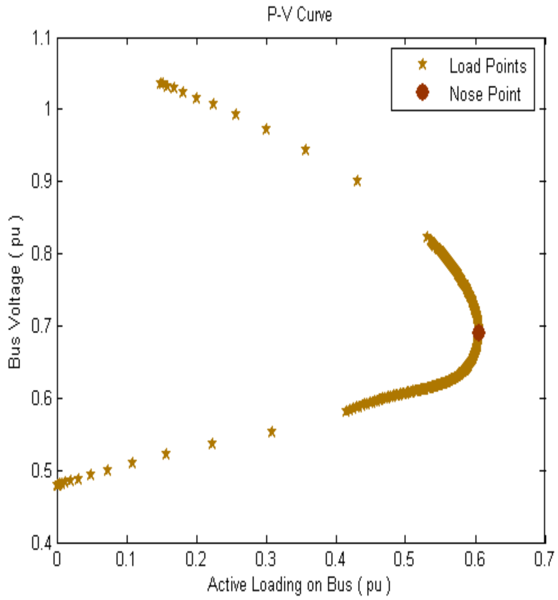

Figure 2. Load Points Traced for IEEE 14 Bus System

TABLE I. CAPACITOR LOCATIONS FOR IEEE 14 BUS SYSTEM

Operating Points	Capacitor Placement	Operating Points	Capacitor Placement
1	14	43	14
2	14	44	14
3	14	45	14
4	14	46	14
5	14	47	14
6	14	48	14
7	14	49	14
8	14	50	14
9	14	51	14
10	14	52	14
11	14	53	14
12	14	54	14

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13	14	55	14
14	14	56	14
15	14	57	14
16	14	58	14
17	14	59	14
18	14	60	14
19	14	61	14
20	14	62	14
21	14	63	14
22	14	64	14
23	14	65	14
24	14	66	14
25	14	67	14
26	14	68	14
27	14	69	14
28	14	70	14
29	14	71	14
30	14	72	14
31	14	73	14
32	14	74	14
33	14	75	14
34	14	76	14
35	14	77	14
36	14	78	14
37	14	79	14
38	14	80	14
39	14	81	14
40	14	82	14
41	14	83	9
42	14		

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