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Selection of Static VAR Compensator Location and Size for System Voltage Stability Improvement

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Abstract

This paper presents a methodology for selection of static VAR compensator location based on static voltage stability analysis of power systems. The analysis presented here uses the L-index of load buses, which includes voltage stability information of a normal load flow and is in the range of 0 (no load of system) to 1 (voltage collapse). An approach has been presented to select a suitable size and location of static VAR compensator in an EHV network for system voltage stability improvement. The proposed approach has been tested under simulated conditions on a few power systems and the results for a sample radial network and a 24-node equivalent EHV power network of a practical system are presented for illustration purposes.

Keywords: voltage stability, L-index, SVC selection.

1.0 Introduction

With the increased loading of existing power transmission systems, the problem of voltage stability and voltage collapse, has become a major concern in power system planning and operation. The trend of the de-regulated power system operation is also causing over loading of some of the transmission corridors. The application of FACTS devices to enhance the Power transmission also involves reactive power control/voltage stability problems. The voltage collapse phenomenon can be related to the action of OLTC transformers, current limiters of generators, inadequate reactive power supply (at least locally) and load characteristic in load voltage magnitude. Voltage collapse is characterized by a slow variation in the system operating point, due to increase in the loads, in such away that the voltage magnitude gradually decreases until a sharp accelerated change occurs.

It has been observed that voltage magnitudes do not give a good indicator of proximity to a voltage stability limit [2]. In a day-to-day operation of power system, preventing "loss of voltage control", instability requires siting additional capacitors or SVCs to maintain reactive reserves on generators, SVCs or synchronous condensers that otherwise exhaust reactive reserves and lose voltage control [5]. Since "loss of voltage control" instability and "clogging voltage instability" are both due to a shortage of reactive power supply to a bus or coherent bus group the structural stress test used must assess when and why a shortage of reactive power supply exists. Thus a Q-V curve is used in this voltage stability security assessment methodology since it directly assesses shortage of reactive supply [9]. In the literature many voltage stability and voltage collapse prediction methods have been presented. Some of these methods [7] are:

- Voltage collapse index based on closely located power flow solution pairs;
- Voltage collapse index based on P-V curves, Q-V curves;
- Voltage collapse index based on normal load flow solution (L-index) [1];
- Minimum Singular Value (MSV) of the power flow related Jacobian matrices;
- Voltage collapse index based on the optimal impedance solution at maximum power transfer.

While the different methods indicated above give a general picture of the proximity of the system to voltage collapse, the index proposed in Reference [1] gives a scalar number to each load bus, called L-index. This index values ranges from 0 (no load system) to 1 (voltage collapse). The bus with the highest L-index value will be the most vulnerable bus in the system and hence this method helps in identifying the weak areas in the system which need critical reactive power support. Among the different indices for voltage stability and voltage collapse prediction the L-index gives fairly consistent results [6,8]. The advantage of this method lies in the

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simplicity of the numerical calculations and expressiveness of the results. Different methods have been proposed in the literature to improve the voltage stability margin. Bansilal et. al [6], D. Thukaram et. al. [8] have shown the suitability of L-index as objective function for improvement of voltage stability and also they compared the results with other well-known voltage stability indices.

Static VAR Compensators are used by utilities in both transmission and distribution systems. The primary purpose is usually rapid control of voltage at weak points in a network. There are two major applications of installation of Static VAR Compensators in a power system. One, is for load compensation. The locations such as, steel plants arc furnace fluctuating loads, which cause voltage fluctuations. There are two main reasons for compensating fluctuating loads.

- The AC system is too weak to maintain the terminal voltage within the acceptable variations, and
- It is neither economical, nor practical to supply the reactive power demand from the AC system.

Installation of SVC at these load buses help in containing the voltage fluctuations, improve load power factor and also voltage profile. The size of these SVCs generally decided by the local load.

The other application of SVC is in the EHV network. The purpose of installation of Static VAR Compensator in EHV network is to provide dynamic reactive power (VAR injection) support to maintain the bus voltage close to the nominal (acceptable) value under varying load conditions and also improve voltage stability. It also provides fast response to control the bus voltages under disturbed conditions. The size and location of SVC is obtained based on detailed both steady state and dynamic analysis of the system.

In this paper we present the effect of Static VAR Compensator location in EHV network based on static voltage stability analysis. We also present an approach for selection of most suitable size and location of SVC. The proposed approach uses the voltage stability index [1], L, which is a scalar number corresponding to each load bus. The bus having maximum value of L (L_{max}) is considered to be the most critical bus and indicating the proximity to voltage collapse. Also ΣL^2 sum of the squares of L-indices of all load buses gives the indication of overall system voltage stability. The proposed approach has been tested with studies on a few systems. Results obtained for a radial EHV network and a 24-node EHV system are presented to illustrate the proposed approach.

2.0 Approach

The following blocks describe the major steps involved in the approach.

Perform steady state power flow for typical peak load conditions. Compute the L-indices for load buses. Make a list of load buses based on the descending order of L-indices.

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Select a set of critical buses based on higher value of the voltage stability L-indices.

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Perform the power flow analysis for both peak load and light conditions with a SVC considered to be connected at each of the selected load buses. Find the VAR requirements (capacitive/ inductive) to maintain a nominal voltage (or suitable acceptable voltage magnitude) at the SVC bus.

↓

Select the suitable size of SVC (inductive/ capacitive range) based on overall requirement of SVC reactive power output for various locations.

↓

Perform the voltage stability analysis, compute L-indices with selected SVC size, for each selected node.

↓

Prepare a list indicating SVC location, maximum value of L-index (L_{max}) and ΣL^2 of the system.

↓

From the above list we can identify the most suitable location for SVC, which gives least values for L_{max} and ΣL^2.

Fig. 1. Block diagrams showing the major steps in the approach.

3.0 Computation of voltage stability L-indices

Consider a system where:
n is the total number of buses with
1,2,…,g generator buses,
g+1,g+2,…,n, the load buses,

Using the load flow results the L-index [1,6,8] is computed as

$$L_j = \left| 1 - \sum_{i=1}^{i=g} F_{ji} (V_i / V_j) \right| \tag{1}$$

where j = g+1, …, n and all the terms within the sigma on the RHS of equation (1) are complex quantities. The values F_{ji} are obtained from the Y bus matrix as follows

$$\begin{bmatrix} I_G \\ I_L \end{bmatrix} = \begin{bmatrix} Y_{GG} Y_{GL} \\ Y_{LG} Y_{LL} \end{bmatrix} \begin{bmatrix} V_G \\ V_L \end{bmatrix} \tag{2}$$

where I_G, I_L, V_G, V_L represent the currents and voltages at the generator nodes and load nodes. Rearranging equation (2) we get

$$\begin{bmatrix} V_L \\ I_G \end{bmatrix} = \begin{bmatrix} Z_{LL} F_{LG} \\ K_{GL} Y_{GG} \end{bmatrix} \begin{bmatrix} I_L \\ V_G \end{bmatrix} \tag{3}$$

where $F_{LG} = -[Y_{LL}]^{-1}[Y_{LG}]$ are required values. The L-indices for a given load condition are computed for all load buses. A L-index value away from 1 and close to 0 indicates an improved voltage stability margin. The higher values for L-indices are indicative of most critical buses and thus maximum of L-indices (L_{max}) is an indicator of proximity the system to voltage collapse and also indicator of most critical bus. Also, summation of all L-indices or (ΣL^2) gives a relative indication of over-all voltage stability of the system for various operating conditions.

4.0 SVC model for Power Flow

Most power flow programs do not include a specific static var compensator model. SVCs are often modeled as a conventional PV (generator) bus with reactive power limits. This result in large errors if the SVC is on limit, operating as a capacitor or reactor. If low voltage is the main concern, the SVC can be modeled as a TCR-FC type of SVC (PV bus with shunt capacitor). For example, for low voltage problems, a ± 200 MVAR SVC can be represented as a 200 MVAR capacitor bank, and a PV bus with 400 MVAR inductive limit and zero capacitive limit; the capacitive limit is correctly represented but not the inductive limit. With a conventional power flow program, a SVC with susceptance regulator can be represented by a PQ (load) bus with voltage constraints [4]. SVCs are sited in critical locations in the network for regulation of transmission (high side) voltage bus. If the SVC coupling transformers are explicitly represented, the SVC model (steady state or dynamic) must be adjusted so the correct range of reactive power is delivered to the high voltage bus. Figure 2 shows the concepts of modeling SVC using an auxiliary bus.

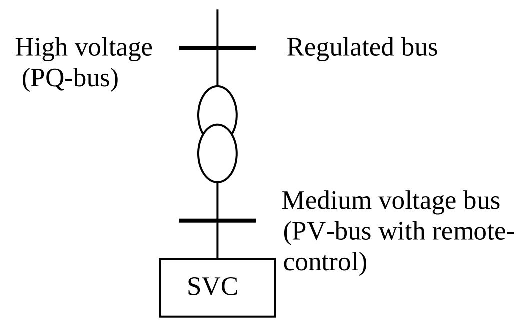


Fig. 2. SVC models with slope representation using conventional power flow PV buses.

5.0 SVC model for voltage stability analysis

Consider a system with a multiple generator buses. Run a load flow, compute the L-indices. From the load flow results observe the generate P, Q outputs. Repeat the load flow with only one generator bus as PV node, other generator buses as P, Q nodes with P, Q set at values obtained from the previous power flow. Compute L-index values for load buses (including the generator buses treated as P, Q nodes), we find that L-index values are higher at each node. So we can conclude that the number of buses (source nodes) makes a significant change in the L-indices results.

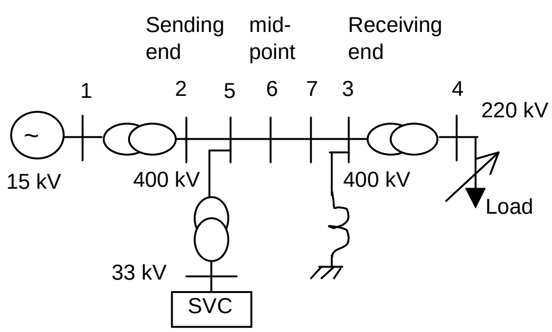
If we take SVC bus as generator bus and compute the L-indices, we get L values reduced significantly compared to the SVC bus treated as load bus. With same compensation as obtained for maintaining the same voltage as in previous output obtain the L indices. These L-indices are higher at each bus compared to previous case when SVC bus was assumed as PV bus. This gives indication that while computing L-indices, it is reasonable to treat SVC bus as load bus more appropriate than generator bus. The number of generator buses (PV-buses) in the system can significantly vary the value of L-indices values.

6.0 Systems studied and results

Analysis for two systems, a radial EHV network, and a 24-bus equivalent EHV network of a practical system for various cases are presented based on the proposed approach.

6.1 EHV radial network

A radial system (system-A) of 400 kV line, 400 km long as shown in Fig. 3 is considered for the analysis. Bus 6 is the midpoint, bus 5 is 100 km from the sending end, bus 7 is 100 km from the receiving end, bus 3. An SVC at 33 kV through a transformer is considered to be connected at various load buses to improve the system profile. Three case studies, case A-1, case A-2 and case A-3 are carried out, on the radial transmission system.



2-5, 5-6, 6-7, 7-3 each section distance is 100 km.

Fig. 3 System-A, A sample radial EHV system with reactor and SVC.

Case A-1:

The transmission system has a permanently connected shunt reactor of 50 MVAR at the 400 kV bus 3. Typically in EHV transmission network, shunt reactors are connected for system protection from transient over-voltages due to switching operations for line charging, lighting and load rejection, etc. The load is varied at bus 4 to obtain the critical loading on the transmission system. It is observed that for a load 400 MW at bus 4, L_{max} (L_4) is about 0.910 (close to 1, voltage stability limit), and any increase in the load will lead to voltage collapse condition. The minimum voltage at bus 4, V_4 is 0.793 p.u., the system total real power losses are 21.18 (5.17%). With load 400 MW fixed at bus 4, voltage stability analysis were repeated with Switchable VAR Compensator (SVC) connected at various 400 kV buses 5, 6, 7 and 3. The SVC, 33 kV bus is treated as variable compensation bus to maintain the high voltage 400 kV bus voltage at nominal 1.0 p.u.

The results are summarized in Table-1. It can be seen from the results that bus 3, receiving end bus, is the most suitable location for SVC compensation. The reactive compensation required to maintain the voltage at the high voltage bus to a nominal value is 72.4 MVAR, which is slightly more than the compensation required at bus 7. This is due to the fact that at bus 3, there is a permanently connected shunt reactor. The minimum voltage at bus 4 is 0.991 and the system total real power losses are lowest at 15.42 MW (3.71%). The maximum voltage stability index, L_{max} (L_4) is 0.581, the overall system index, ΣL^2 is 1.0851, indicating the significant improvement in the overall voltage stability of the system. In a radial network, it is obvious that suitable location for compensation is closed to the receiving end load bus.

Case A-2:

This case is a study with light load condition. A load of 180 MW with unity power factor is assumed at bus 4. It is observed that the voltages at buses 5 and 6 which are above the tolerable voltage (1.05 p.u) on EHV network. With load fixed at 180 MW unity power factor, the study is repeated considering a Switchable VAR compensator connected at various 400 kV buses 5, 6, 7 and 3. The SVC, 33 kV bus is treated as variable inductive compensation bus to limit the voltage at 400 kV bus to 1.0 p.u. The results are summarized in Table-2. It can be observed from the result that bus 3, receiving end bus, is the most suitable location for SVC compensation. The reactive (inductive) compensation required to contain the over-voltages below 1.05 p.u. during light load is -53 MVAR, which is lowest.

Case A-3:

In this case for the light load condition of 180 MW of the radial network a fixed inductive compensation of 50 MVAR is considered to be connected at the selected buses 5, 6, 7 and 3. Results of this case are summarized in Table-3. The results show that bus 3, receiving end bus is the most suitable bus for reactive compensation, as the maximum voltage observed is 1.034 at bus 6, which is lowest and also the reactive power absorption by generators (leading power factor) are lowest compared to the situations when compensation is at other buses. The voltage stability (L_{max}) index is also highest, L_4 = 0.266.

6.2 24-Bus EHV System

A 24-bus EHV equivalent network of a practical system (system-B) is also considered for analysis. The system single line diagram is shown in Fig.4. The network and load data for the system is given in Appendix. The system total peak load is about 2620 MW, 980 MVAR. There are shunt reactors connected at various 400 kV buses for transient over-voltage protection. Initial power flow analysis summarized in Table-4 indicates that the minimum voltage is 0.847 p.u. at bus 13, the overall total real power losses are 64.94 MW (2.42%). The voltage stability L-indices are also computed for the system. The maximum of voltage stability index, L_{max} (L_8) is about 0.542, and system overall voltage stability, ΣL^2 is about 2.5509.

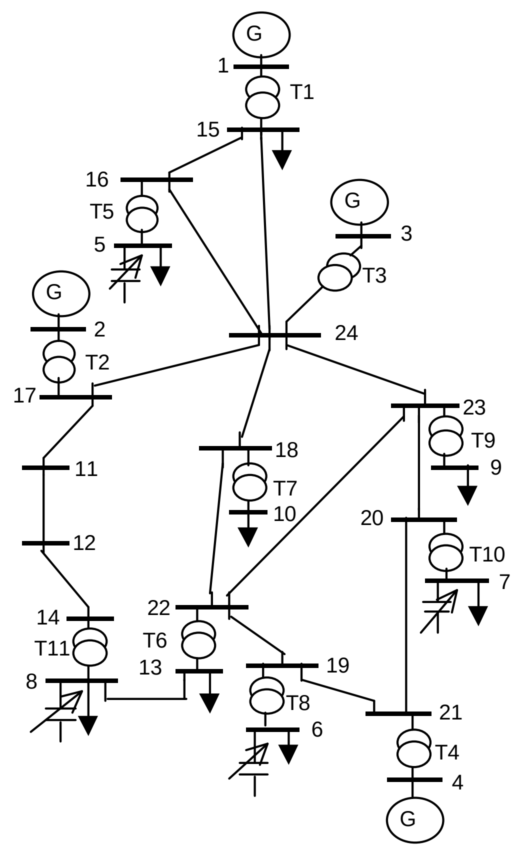


Fig.4 System-B, 24-Bus EHV system.

The system voltage profile and voltage stability indices of the load buses are shown in Fig.5. Also Table-4 gives the voltage profile and voltage stability indices in the descending order.

Based on the order of critical buses indicated by L-indices, the 220 kV buses 8, 13, 7, 6, 9, 5 and 10 are considered for reactive compensation for system improvement. Five case studies, case B-1, case B-2, case B-3, case B-4 and case B-5 are carried out as follows.

Case B-1: The system-B, peak load condition, with SVC variable compensation, at selected buses.

Case B-2: The system-B, peak load condition, with SVC fixed compensation of 210 MVAR at selected buses.

Case B-3: The system-B, peak load condition, with SVC fixed compensation of 150 MVAR at selected buses,

Case-B-4: The system-B in light load condition with SVC variable inductive compensation at selected buses,

Case B-5: The system-B in light load condition with SVC fixed compensation of 75 MVAR (inductive) at selected buses.

Case B-1:

In this case a variable capacitive compensation of SVC is considered to be connected at the selected 220 kV-buses to maintain the high voltage 220 kV bus voltage at 0.95 p.u. Results of this case are summarized in Table-5. The results show that bus 13 required SVC of 210 MVAR to achieve the voltage value of 0.95 p.u. with the minimum voltage of 0.885 p.u. at bus 5, lowest of L_{max} (L_8) about 0.426, ΣL^2 = 1.8919 and lowest system real power losses of about 59.36 MW lowest total 695.9 MVAR generation from the generators. It is also observed that bus 8 is the next best suitable location for SVC compensation. To maintain 0.95 p.u. voltage at high voltage bus, the reactive power support is low of 66 MVAR, while the compensator is connected at bus 9, and of 48 MVAR when compensator is connected at bus 10. However, the voltage stability index L_{max} and the overall voltage stability index ΣL^2 are higher. L_{max} is 0.519 and 0.522 and ΣL^2 = 2.3137 and 2.3437 respectively. Also it has higher total power losses 63.11 MW and 63.52 respectively. This follows that minimum compensation just for maintaining the voltage at local SVC bus alone should not be the criteria for the selection of SVC location.

The higher value of MVAR requirement at bus 13 for maintaining the 220 kV bus voltage is also an indication of the most critical bus for reactive support. The voltage profile and L-indices for the compensation at bus 5 (most un-suitable location for SVC) and bus 13 (most suitable location for SVC) are shown in Figs. 6 and 7 respectively.

Case B-2:

In this case a fixed capacitive compensation of 210 MVAR is considered to be connected at the selected buses. Results of this case are summarized in Table-6. The results show that bus 13 is the most suitable location for SVC compensation, as it gives the most improved voltage profile with minimum voltage about 0.885 p.u., lowest of L_{max} about 0.426, ΣL^2 about 1.892 and lowest system real power losses of about 59.36 MW, lowest total 695.9 MVAR generation from the generators.

It is also observed that bus 8 is the next best suitable location for SVC compensation. The results also show that bus 5, is the least preferable location for reactive compensation showing minimum voltage, V_{13} = 0.862 p.u., higher value of L_{max}, L_8 = 0.516 and ΣL^2 = 2.217 and higher real power losses of 61.58 MW, highest total 762.4 MVAR generation from the generators. The voltage profile and L-indices for the compensation at bus 5 and bus 13 are shown in Figs. 8 and 9 respectively.

Case B-3.

In this case a fixed capacitive compensation of 150 MVAR is considered to be connected at the selected buses. Results of this case are summarized in Table-7. The results show that bus 13 is the most suitable location for SVC compensation, as it gives the most improved voltage profile with minimum voltage about 0.881 p.u., lowest of L_{max} (L_8) is about 0.450, ΣL^2 about 2.0441 and lowest system real power losses of about 60.01 MW, lowest total 779.6 MVAR generation from the generators. It is also observed that bus 8 is the next best suitable location for SVC compensation.

The results also show that bus 5, is the least preferable location for reactive compensation, showing minimum voltage, V_{13} = 0.858 p.u., higher value of L_{max}, L_8 = 0.522 and ΣL^2 = 2.2830 and higher real power losses of 61.91 MW, highest total of 832.6 MVAR generation from the generators. The voltage profile and L-indices for the compensation at bus 5 and bus 13 are shown in Figs. 10 and 11 respectively.

Case B-4:

In this case the 24-bus EHV system (system-B) is considered in Light load condition, i.e., 60% of its peak load. The load flow results show that the system experiences over voltages, with maximum 400 kV bus voltage at bus 12, V_{12} about 1.107 p.u. A variable inductive compensation of SVC is considered to be connected at the selected buses to limit the over voltages at the 400 kV buses in the system and to maintain the 220 kV bus voltage of 0.97 p.u at selected SVC bus. Results of this case are summarized in Table-8.
The results show that bus 13 required SVC of -75 MVAR to achieve the voltage value of 0.97 p.u. with the maximum voltage of 1.050 p.u. at bus 5, and maximum L-index about 0.263, ΣL^2 = 0.672. It is to be noted that the generators total 29.7 MVAR absorption (leading power factor) is also lowest. It is also observed that bus 8 is next best location for SVC compensation. To maintain 0.97 p.u. voltage at 220 kV bus, reactive (inductive) support is low of -20 MVAR, while the compensator is connected at bus 7, and of -22 MVAR and -32 MVAR when connected at bus 5 and 6 respectively. However the total MVAR absorption (leading power factor) at generators is quite high of 126.9 MVAR, 135.3 MVAR and 110.6 MVAR when SVC connected at bus 7, bus 5 and bus 6 respectively.

Case B-5:

In this case the 24-bus EHV system (system-B) is considered in Light load condition, i.e., 60% of its peak load. A fixed inductive compensation of SVC of -75 MVAR is considered to be connected at the selected buses to limit the over voltages at 400 kV buses in the system. Results of this case are summarized in Table-9. The results show that bus 13 is the most suitable location for SVC compensation, as it gives the most improved voltage profile with maximum voltage at 400 kV buses limited to 1.050 p.u. and with minimum voltage about 0.966 p.u. at bus 5 and 7, maximum L-index about 0.263, ΣL^2 about 0.6720. The generators total 29.27 MVAR absorption (leading power factor) is also low. It is also observed that bus 8 is next best location for SVC compensation, which also results in V_{max} limited to V_{12} = 1.050 p.u and V_{min} (V_5, V_7) = 0.966 p.u, higher L_{max} (L_8) = 0.268 and the generators to lowest 26.8 MVAR absorption (leading power factor). It is also to be noted that when the same inductive compensator is connected at other buses, the over voltages at 400 kV buses are not contained. Also the reactive power absorption (leading power factor) of generators is high, which may cause angular stability problem.

From the analysis of the above cases, it can be concluded that, for the 24-Bus EHV system, bus 13 is the most suitable location (bus 8 is the next best) for SVC and the size of 210 MVAR/-75 MVAR is the most (150 MVAR/-75 MVAR next) appropriate rating for the SVC.

7.0 Conclusions

An approach for planning Shunt reactive compensation based on the criteria of improving static voltage stability is presented. Analysis of a test system and a practical EHV network are presented for illustration. The proposed approach selects the most suitable size and location for SVC compensator. The approach also leads to improved voltage and minimum loss condition.

8.0 References

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Table-1: Summary of the results (Case-A1) with fixed load of 400 MW.

SVC at bus no.	SVC Q (MVAR)	Voltage at load bus, (p.u)	Power Loss (MW)	(%)	(MVAR)	L-max	ΣL^2
No SVC	0.0	$V_4 = 0.793$	21.81	5.17	183.02	$L_4 = 0.910$	2.1125
5	75.0	$V_4 = 0.922$	16.75	4.02	41.73	$L_4 = 0.658$	1.1203
6	69.0	$V_4 = 0.944$	16.21	3.90	28.53	$L_4 = 0.629$	1.0831
7	68.3	$V_4 = 0.966$	15.80	3.80	18.11	$L_4 = 0.605$	1.0772
3	72.4	$V_4 = 0.991$	15.42	3.71	8.79	$L_4 = 0.581$	1.0851

Table 2: System A-Light load condition (Case-A2) with SVC variable compensation.

SVC at bus no.	SVC Q (MVAR)	Voltage at bus 4, (p.u)	V-max (p.u)	L-max	ΣL^2	Q-generator (MVAR)
No SVC	0.0	$V_4 = 1.066$	$V_7 = 1.078$	$L_4 = 0.227$	0.1690	-142.55
3	-53.0	$V_4 = 0.997$	$V_{5,6} = 1.031$	$L_4 = 0.270$	0.2498	-77.69
5	-106.0	$V_4 = 0.999$	$V_{6,7} = 1.011$	$L_4 = 0.275$	0.2414	-14.38
6	-89.0	$V_4 = 0.988$	$V_5 = 1.009$	$L_4 = 0.282$	0.2622	-32.68
7	-71.0	$V_4 = 0.988$	$V_5 = 1.020$	$L_4 = 0.279$	0.2623	-54.63

Table 3: System A-Light load condition (Case-A3) with SVC fixed compensation.

SVC at bus no.	SVC Q (MVAR)	Voltage at bus 4, (p.u)	V-max (p.u)	L-max	ΣL^2	Q-generator (MVAR)
No SVC	0.0	$V_4 = 1.066$	$V_7 = 1.078$	$L_4 = 0.227$	0.1690	-142.55
3	-50	$V_4 = 1.002$	$V_6 = 1.034$	$L_4 = 0.266$	0.2426	-81.80
5	-50	$V_4 = 1.037$	$V_7 = 1.049$	$L_4 = 0.245$	0.1729	-86.29
6	-50	$V_4 = 1.025$	$V_7 = 1.037$	$L_4 = 0.252$	0.1934	-84.61

7	-50	$V_4 = 1.013$	$V_6 = 1.035$	$L_4 = 0.259$	0.2166	-83.11

Table-4: System-B, Peak load initial conditions, Bus voltages and L-indices in descending order.

Bus No.	Nominal Voltage, kV	L-max	Voltage (p.u)	Bus No.	Nominal Voltage, kV	L-max	Voltage (p.u)
8	220	$L_8 = 0.542$	0.851	19	400	$L_{19} = 0.325$	0.895
13	220	$L_{13} = 0.540$	0.847	18	400	$L_{18} = 0.316$	0.915
14	400	$L_{14} = 0.464$	0.880	23	400	$L_{23} = 0.302$	0.923
7	220	$L_7 = 0.453$	0.854	12	400	$L_{12} = 0.267$	0.955
22	400	$L_{22} = 0.437$	0.875	16	400	$L_{16} = 0.226$	0.918
6	220	$L_6 = 0.412$	0.869	11	400	$L_{11} = 0.201$	0.969
9	220	$L_9 = 0.371$	0.901	21	400	$L_{21} = 0.198$	0.941
5	220	$L_5 = 0.360$	0.870	24	400	$L_{24} = 0.150$	0.961
10	220	$L_{10} = 0.350$	0.905	17	400	$L_{17} = 0.122$	0.985
20	400	$L_{20} = 0.348$	0.886	15	400	$L_{15} = 0.093$	0.966
Total losses : 64.94 MW, -968.14 MVAR; V-min (V_{13}) = 0.847 p.u.; L-max (L_8) = 0.542; $\Sigma L^2 = 2.7149$							

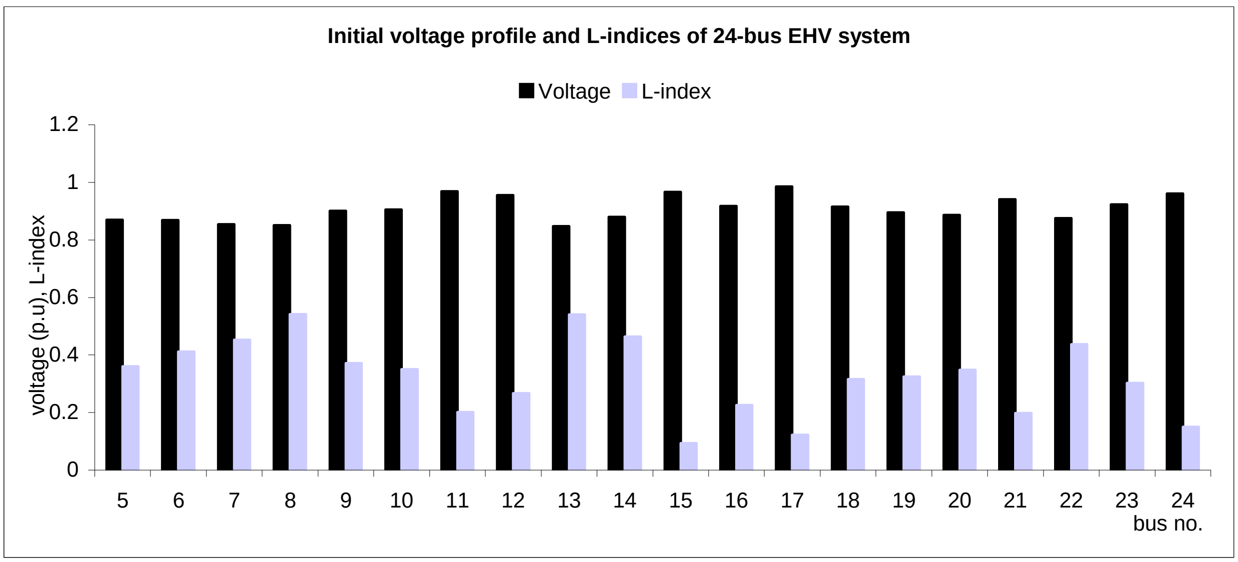

Fig. 5. 24-Bus EHV system, System-B, Initial voltage profile and L-indices for peak load conditions.

Table-5: System-B (Case-B1), Summary of the results with variable SVC compensation.

SVC at bus no.	SVC Q (MVAR)	V-min (p.u)	L-max	ΣL^2	P-loss (MW)	Sum of Gen. Q (MVAR)
No SVC	0.0	V_{13} = 0.847	L_8 = 0.542	2.5509	64.94	1046.30
5	172	V_{13}= 0.860	L_8= 0.520	2.2576	61.74	806.24
6	156	V_5 = 0.877	L_8= 0.491	2.1150	61.34	810.44
7	153	V_{13}= 0.875	L_8= 0.501	2.1362	61.17	809.25
8	166	V_5 = 0.882	L_{13}= 0.443	1.9921	60.57	759.47
9	66	V_{13}= 0.862	L_8= 0.519	2.3137	63.11	935.94
10	48	V_{13}= 0.860	L_8= 0.522	2.3437	63.52	964.70
13	210	V_5 =0.885	L_8= 0.426	1.8919	59.36	695.92

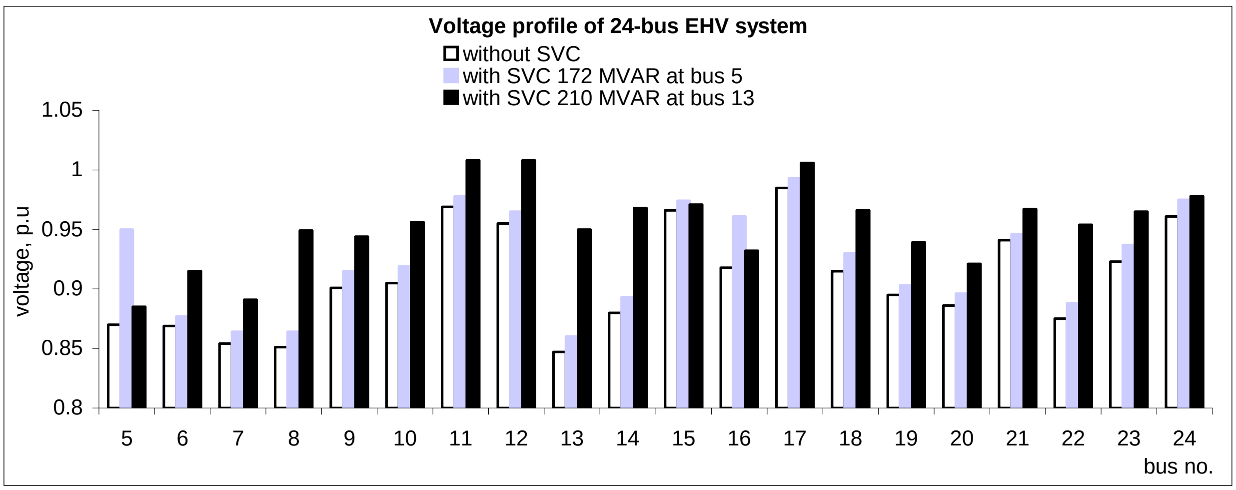

Fig. 6. System-B (Case-B1), Voltage profile without SVC and with SVC at Bus 5 and 13.

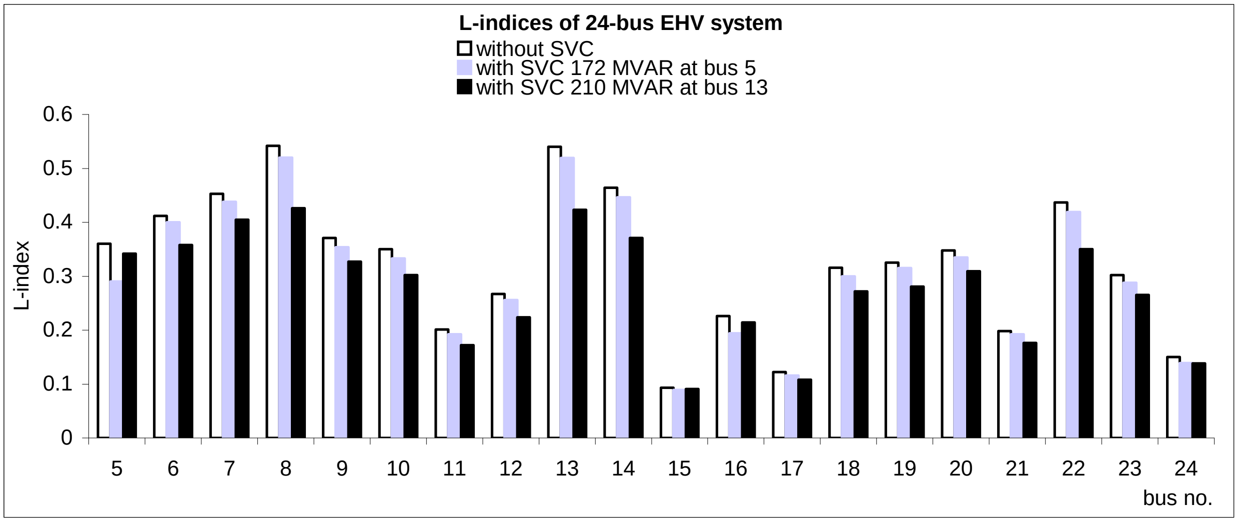

Fig. 7. System-B (Case-B1), Voltage stability L-index without SVC and with SVC at bus 5 and 13.

Table-6: System-B (Case-B2), Summary of the results with 210 MVAR fixed compensator.

SVC at bus no.	V-min (p.u)	L-max	ΣL^2	P-loss (MW)	Sum of Gen. Q (MVAR)
No SVC	V_{13} = 0.847	L_8 = 0.542	2.5509	64.94	1046.3
5	V_{13} = 0.862	L_8 = 0.516	2.217	61.58	762.4
6	V_5 = 0.879	L_8 = 0.479	2.016	61.00	745.2
7	V_5 = 0.881	L_8 = 0.489	2.033	60.84	740.4
8	V_5 = 0.884	L_8 = 0.427	1.888	60.45	700.3
9	V_5 = 0.885	L_8 = 0.484	2.002	61.97	748.0
10	V_7 = 0.879	L_8 = 0.476	1.979	62.49	755.5
13	V_5 = 0.885	L_8 = 0.426	1.892	59.36	695.9

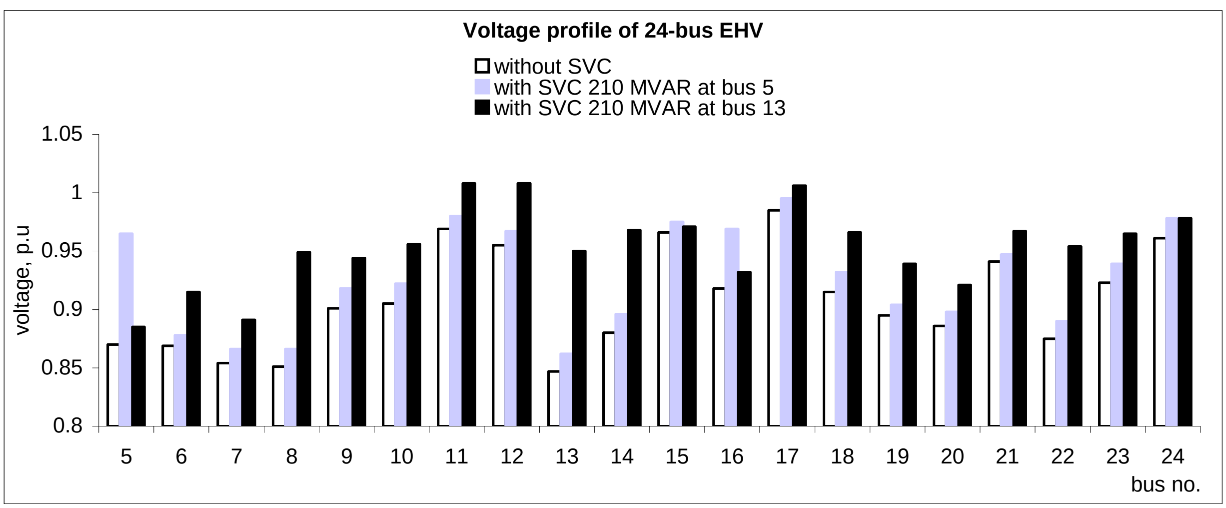

Fig.8. System B (Case-B2) Voltage profile with SVC of 210 MVAR at bus 5 and 13.

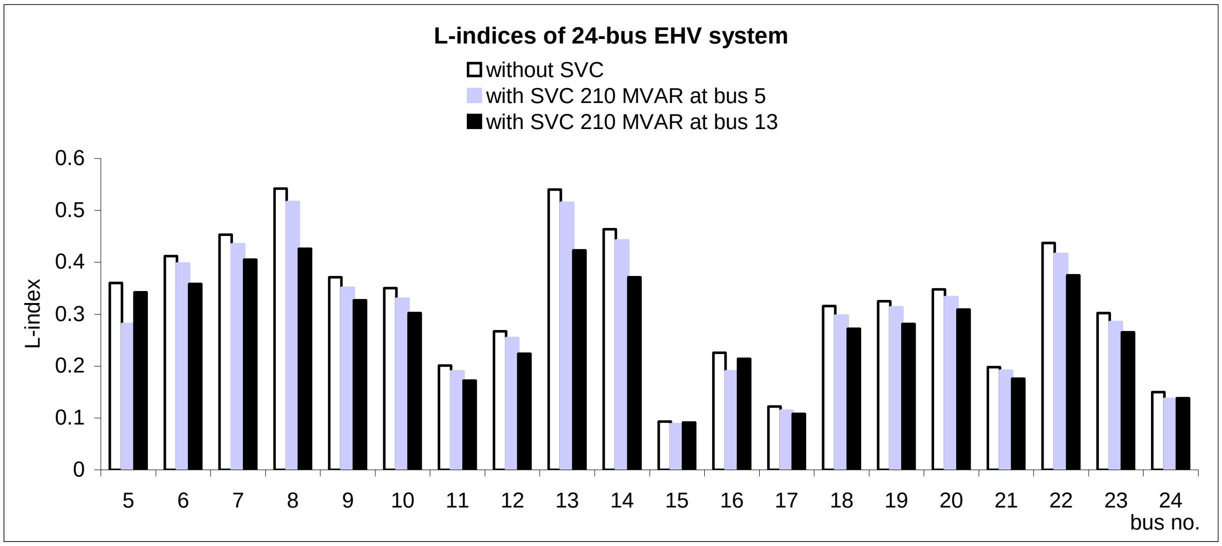

Fig. 9. System-B (Case-B2) Voltage stability L-index with SVC of 210 MVAR at bus 5 and bus 13.

Table-7: System-B (Case-B3), Summary of the results with 150 MVAR fixed compensator.

SVC at Bus no.	V-min (p.u)	L-max	ΣL^2	P-loss (MW)	Sum of Gen. Q (MVAR)
No SVC	V_{13} = 0.847	L_8 = 0.542	2.5509	64.94	1046.3
5	V_{13} = 0.858	L_8 =0.522	2.2830	61.91	832.6
6	V_5 = 0.887	L_8 =0.495	2.1274	61.40	818.1
7	V_{13} = 0.874	L_8 =0.501	2.1424	61.20	813.1
8	V_7 = 0.880	L_{13}=0.450	2.0356	60.69	782.1
9	V_{13} = 0.878	L_8= 0.497	2.1074	62.10	819.7
10	V_7 = 0.873	L_8 =0.490	2.0797	62.40	824.4
13	V_5 = 0.881	L_8 =0.450	2.0441	60.01	779.6

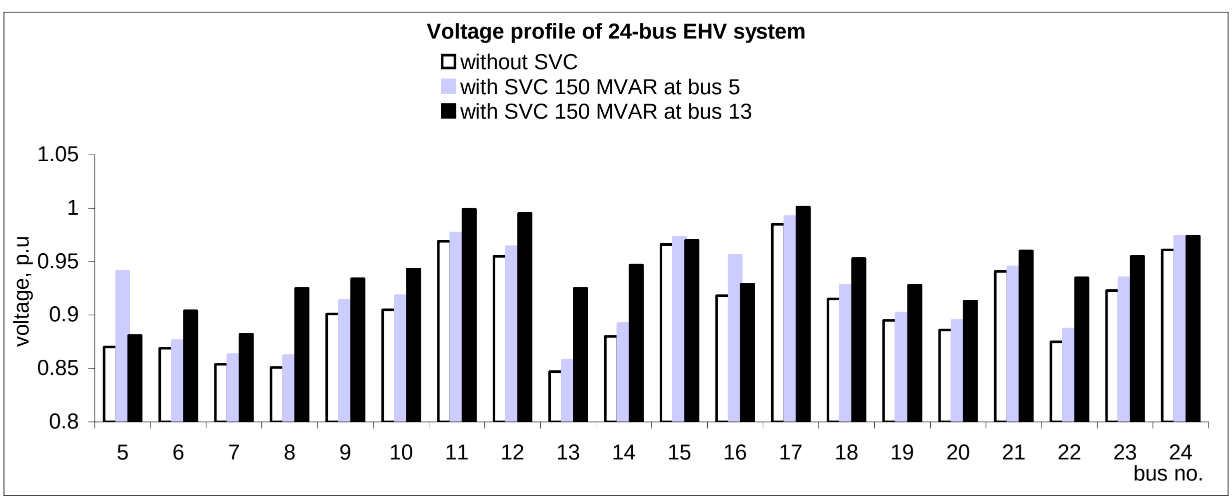

Fig. 10 System-B (Case-B3) Voltage profile with SVC of 150 MVAR at Bus 5 and 13.

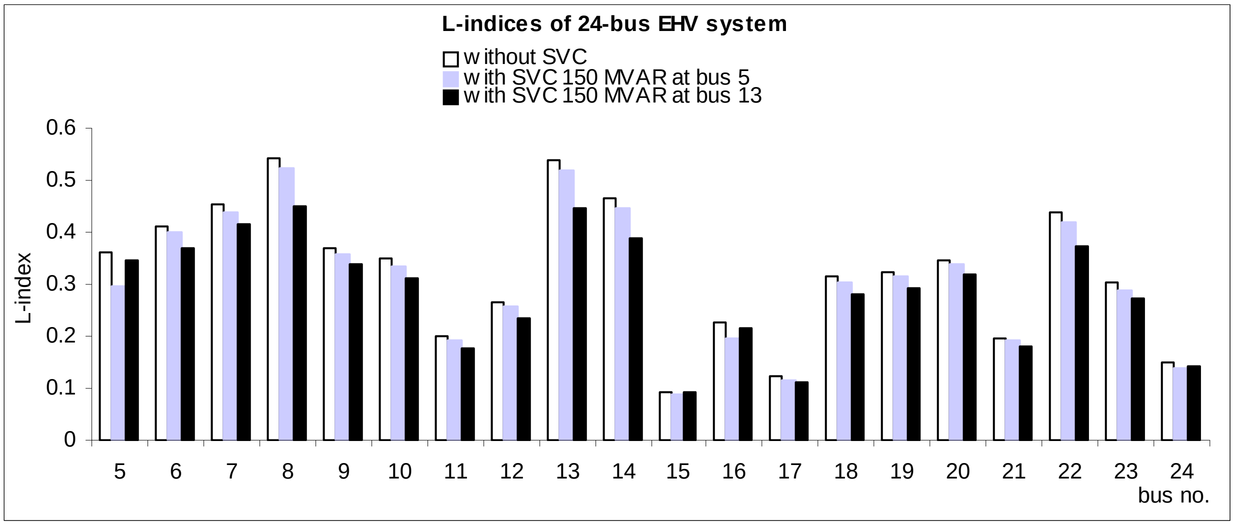

Fig. 11. System-B (Case-B3) Voltage stability L-index with SVC of 150 MVAR at bus 5 and 13.

Table 8: System-B (Case-B4), Light load condition with SVC variable inductive compensation

SVC at bus no.	V-max (p.u)	V-min (p.u)	L-max	ΣL^2	SVC Q (MVAR)	Q-generator (MVAR)
No SVC	V_{12} = 1.107	V_5 = 0.987	L_{13} = 0.222	0.4826	0.0	-187.8
5	V_{12} = 1.091	V_5 = 0.970	L_{13} =0.229	0.5222	-22.0	-135.3
6	V_{12} = 1.083	V_6 = 0.970	L_{13} =0.236	0.5583	-32.0	-110.6
7	V_{12} = 1.085	V_7 = 0.970	L_{13} =0.233	0.5534	-20.0	-126.9
8	V_{12} = 1.050	V_7 = 0.966	L_{13} =0.261	0.6807	-74.0	-28.8
9	V_{12} = 1.068	V_7 = 0.965	L_{13} =0.245	0.6196	-70.0	-43.4
10	V_{12} = 1.069	V_{10} = 0.957	L_{13} =0.250	0.6357	-59.5	-59.6
13	V_{12} = 1.050	V_7 = 0.966	L_{13} =0.263	0.6720	-75.0	-29.7

Table 9: System-B (Case-B5) Light load condition with SVC fixed inductive compensation

SVC at bus no.	V-max (p.u)	V-min (p.u)	L-max	ΣL^2	SVC Q (MVAR)	Q-generator (MVAR)
No SVC	V_{12} = 1.107	V_5 = 0.987	L_{13} = 0.222	0.4826	-75	-187.8
5	V_{12} = 1.073	V_5 = 0.934	L_{13}= 0.239	0.5939	-75	-38.6
6	V_{12} = 1.073	V_6 = 0.944	L_{13}= 0.245	0.6200	-75	-44.0
7	V_{12} = 1.073	V_7 = 0.930	L_7= 0.245	0.6412	-75	-38.8
8	V_{12} = 1.050	$V_{5,7}$ = 0.966	L_8= 0.268	0.6833	-75	-26.8
9	V_{12} = 1.067	V_7 = 0.963	L_{13}= 0.246	0.6300	-75	-34.3
10	V_{12} = 1.063	V_{10} = 0.951	L_{13}= 0.249	0.6490	-75	-30.6
13	V_{12} = 1.050	$V_{5,7}$ = 0.966	L_{13}= 0.263	0.6720	-75	-29.7

Appendix

Data of Radial system (System-A)

Transformer data (all taps = 1.0)

Bus From	Bus To	R	X	Rated MVA
2	1	0.00143	0.02850	500.0
3	4	0.00125	0.02500	500.0

Transmission lines data

Bus From	Bus To	R	X	B/2	Rated MVA
2	5	0.00164	0.02060	0.26920	500.0
5	6	0.00164	0.02060	0.26920	500.0
6	7	0.00164	0.02060	0.26920	500.0
7	3	0.00164	0.02060	0.26920	500.0

Data of 24-bus EHVsystem (System B)

Transmission lines data

Bus From	Bus To	R	X	B/2	Rated MVA
22	23	0.00430	0.04770	0.63700	500.0
22	18	0.00589	0.05995	0.78410	500.0
11	12	0.00198	0.02471	0.32304	500.0
11	17	0.00280	0.02998	0.42699	500.0
12	14	0.00546	0.06794	0.88836	500.0
17	24	0.00477	0.05103	0.72673	500.0
24	18	0.00569	0.06008	0.79414	500.0
24	23	0.00272	0.02872	1.51829	1000.0
23	20	0.00388	0.04834	0.65470	500.0
15	16	0.00372	0.03931	0.53139	500.0
24	16	0.00245	0.02587	0.34966	500.0
15	24	0.00261	0.02780	1.48500	1000.0
21	19	0.00145	0.01802	0.93968	500.0
22	19	0.00289	0.03603	0.46222	500.0
21	20	0.00297	0.03706	0.47543	500.0
13	8	0.00315	0.01569	0.05274	500.0

Generation data ($V_{specified}$ = 1.0)

Bus	P_{gen} (MW)	Q_{gen}^{max} (MVAR)	Q_{gen}^{min} (MVAR)
1	1820	950.0	-150.0
2	160	320.0	-50.0
3	350	400.0	-100.0
4	520	400.0	-90.0

Transformer data (all taps = 1.0)

Bus From	Bus To	R	X	Rated MVA
16	5	0.00099	0.01984	630.0
22	13	0.00063	0.01250	1000.0
18	10	0.00198	0.03968	315.0
19	6	0.00099	0.01984	630.0
23	9	0.00198	0.03968	315.0
20	7	0.00099	0.01984	630.0
14	8	0.00125	0.02500	500.0
15	1	0.00033	0.00670	2200.0
17	2	0.00198	0.03960	315.0
24	3	0.00099	0.01984	630.0
21	4	0.00099	0.01984	630.0

Shunt reactors data

Bus No.	MVAR rated at 420 kV	Bus No.	MVAR rated at 420 kV
22	113	24	313.0
11	63	23	100.0
12	50	16	50.0
14	50	18	113.0
17	50	20	150.0
15	100	19	200.0

Load data

Bus	P-load MW	Q-load MVAR	Bus	P-load MW	Q-load MVAR
5	430	170	9	120	40
6	280	90	10	60	20
7	320	110	13	450	180
8	180	70	15	780	300