Voltage Stability Enhancement of Low Voltage Radial Distribution Network Using Static VAR Compensator: A Case Study

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Abstract: - In this paper power flow analysis of 33/11 kV distribution substation and feeder is carried out to know the status of voltage and power flow at each bus. To maintain the rated voltage at load end, low rated static VAR compensators (SVC) are installed. For the case study typical heavily loaded distribution substation where the voltage variation on all the buses are maximum during peak load condition has been selected. Simulation of the distribution network with SVC has been developed in the Electrical Transient Analyzer Program (ETAP) environment. With the insertion of SVC, enhancement in voltage at various buses, reduction in system power loss, improvement in power factor and power flow are the objectives of the study. Description of the study network, simulation model and the results of simulation with comparison of recorded results are presented in the paper.

Key-Words: - Distribution network, Voltage stability, Power flow Analysis, Static VAR compensator, FACTS, ETAP

1. Introduction

The evolution of the power industry in recent years has imposed many challenges due to the radical changes in the energy market as power demand is more than the availability. The consequences of such scenario are high lodability of transmission and distribution lines, losing voltage stability and high power losses. This may affect the performance of operating loads and may results in blackouts. There are two ways to improve the performance of transmission/distribution system in terms of voltage and power. Installation of new power plant to meet the power demand is one of the options while addition of compensating devices is another. First option as suggested above is costly and time consuming. The second option is most economical and convenient.

Power flow analysis is the efficient tool to check the performance of electrical power system. The main objective of the power flow analysis is to find real and reactive powers flowing in each line along with the magnitude and phase angle of the voltage at each bus of the system for the specific loading condition. Many real time applications in the distribution automation system (DAS) and distribution management system (DMS), such as network optimization, var planning, switching, state estimation etc., need the support of a robust and efficient power flow method. Such a power flow solution must be able to model the special features of distribution systems in sufficient details. Some of the inherent features of electrical distribution systems are,

- A radial network structure
- An unbalanced distributed load
- An extremely large number of branches / nodes
- A wide range of resistance and reactance

For the analysis of power flow, the invention and widespread use of digital computers started in the beginning of 1950's and 1960's, and many methods for solving the power flow problem have been developed. In 1967, W.I. Tinny and C.E. Hart developed classical Newton based power flow solution method [1]. Scott and Alsac [2] have proposed fast de-coupled Newton method for power flow analysis. Shirmohammadi D. and Cheng C.S. [3,4] suggested power flow methods for weakly meshed and real time analysis of distribution network. Zimmerman et al [5] addressed fast decoupled power flow for unbalanced radial distribution systems and stated that the method is suitable for transmission but poor convergence due to high r/x ratio. Preedavichit et al [6] proposed application of FACTS devices in power flow analysis to improve the system performance. Jen et al [7] addressed network topology based three phase load flow for distribution systems with new ideas on compensation based technique. Antonino et al [8] focused on constant current and/or impedance load methodologies for load flow solution in radial distribution networks. The techniques currently available to solve such systems are based either on iterative methods or on the bus impedance matrix. As per many researchers Neural and Fuzzy set theories are the approaches to improve the performance of distribution network i.e feeder balancing, minimizing power losses, feeder current constraints and deviation of node voltages [9,10,11].

Due to heavy demand of power, distribution networks are always in stress which results in reduced voltage across the load and it affect on the performance. It is necessary to improve the performance of power system to received quality power at the consumer end. Reactive power compensation is the main measure to keep power network running with high voltage stability, high power quality and minimum system loss [12]. Flexible AC transmission system (FACTS) devices are found to be very effective controller to enhance the system performance. FACTS Technology invented in 1986 by N. G. Hingorani from the Electric Power Research Institute (EPRI) USA and it is based on thyristor operation techniques [13,14]. FACTS controllers are broadly classified as series and shunt, both used to modify the natural electrical characteristics of ac power system. Series compensation modifies the transmission or distribution system parameters, while shunt compensation changes the equivalent impedance of the load. In both the cases the reactive power that flows through the system can be effectively controlled by FACTS which improves the overall performance of ac power system. Series controllers enhance the power handling capacity where as shunt controllers improve the voltage at a particular location. Shunt – series combination improves both power handling capacity and voltage. Some of the FACTS controllers are,

Series Controllers

- Thyristor Switched Series Reactor – TSSR
- Thyristor Controlled Series Reactor – TCSR
- Thyristor Switched Series Capacitor – TSSC
- Thyristor Controlled Series Capacitor – TCSC
- Static Synchronous Series Capacitor – SSSC
- Interline Power Flow Controller – IPFC

Shunt Controllers

- Thyristor Controlled Reactor – TCR
- Thyristor Switched Reactor – TSR
- Thyristor Switched Capacitor – TSC
- Static Synchronous Compensator – STATCOM
- Static Synchronous Generator – SSG
- Static VAR Compensator – SVC
- Static VAR Generator or absorber - SVG
- Thyristor Controlled Breaking Resistor - TCBR
- Battery Energy Storage System – BESS
- Super conducting Magnetic Energy Storage – SMES

Series - Shunt Controllers

- Unified Power Flow Controller – UPFC
- Thyristor Controlled Phase Shifting Transformer – TCPST
- Inter Phase Power Controller – IPC [15,16,17]

This paper deals with power flow analysis of distribution feeders and substation. As a case study 33/11 kV distribution substation of Maharashtra State Distribution Company Limited (MSDCL-Nagpur zone), India, is considered. The main objective of the paper is to carry out the power flow analysis for peak load condition to know the

voltages at load end and its enhancement by installing low rated SVC. Voltage profile, power factor and power flows are noted for without and with SVC. Simulation has been made in the Electrical Transient Analyzer Program (ETAP) environment. Enhancement at the node voltages is the main objective and other objectives related to study are,
- Minimization of system power loss
- Enhancement in power transfer
- Minimization of branch current

Description of the study network, simulation model and the results of simulation with comparison of recorded results are presented in the paper.

2. Power Flow Analysis

Power flow analysis is a solution of the network under steady state condition subject to certain inequality constraints the system operates. These constraints can be in the form of load nodal voltages, reactive power generation, tap setting of transformers, etc.

A power flow analysis is used to determine the voltage, current, real power, reactive power, power factor, phase angle etc. at various points in an electrical network. It is useful for planning, control and operation of existing system as well as in future expansions. Power flow analysis helps to fix up the optimal capacity of the proposed generating stations, substations, new transmission lines, etc. It also helps to determine the best size and favourable location of the power capacitors to enhance the power factor, voltage level and to minimize the system power loss.

Four quantities are associated with power flow analysis. Quantities associated with power flow analysis of each bus are,
- Voltage magnitude V
- Phase angle δ
- Real power P and
- Reactive power Q

Three types of buses are represented in the power flow calculation and In solving a power flow problem, four quantities are associated with each bus. These are voltage magnitude V, phase angle δ, real power P, and reactive power Q. Three types of buses are represented in the power flow calculation and at every bus two out of four quantities are specified. For reference bus/slack bus/ swing bus the voltage magnitude V and phase angle δ are specified and real and reactive power at this bus is to be determined. At load bus real and reactive component of power are specified. It is desired to find out voltage magnitude and phase angle. At voltage-controlled bus, the real power and voltage magnitude are specified while phase angle δ and reactive power Q are to be determined. At this bus magnitude of voltage should be maintained constant by reactive power control method like shunt or series compensation.

2.1. Basic Requirements and Assumptions

For the execution of power flow specific steps and procedure are to be followed. This may help to obtain the accurate result with optimal conditions. Power flow consists of mainly two steps, formulation of power flow equation and selection of suitable mathematical technique. Requirements for carrying power flow analysis are as follows,
- Line diagram of the system
- Bus admittances
- Series impedances and shunt admittances of the lines
- Transformer Ratings
- Tap settings of transformers
- Load on each bus' etc.

Assumptions to carry the power flow analysis are as follows,
- Balanced system
- Variations in load and system parameters are neglected
- System mutual coupling is neglected
- Power flow equations are in nodal admittance form
- Single phase representation equivalent to positive sequence network

2.2. Approaches for Power Flow Analysis

The mathematical formulation of the power flow analysis results in a system of nonlinear equations. These equations can be established by using either the bus or loop frame of reference. The coefficient of the equations depends on the selection of independent variables that is voltages or currents. Thus, either the admittance or impedance network matrices can be used. These matrices can be solved by numerical methods like Gauss Seidel, Newton - Raphson, fast decoupled method. All these methods have their own advantages, disadvantages and limitations.

Matrix Formation

Early approaches to the digital solution of power flows employed the loop frame of reference Y loop in admittance form. This approach is not preferred because,
- Loop admittance matrix obtained by matrix inversion is time consuming and repetitive
- Voluminous data required to specifying the network loops

Bus frame of reference (Y_{Bus}) in the admittance form is comparatively better because,
- The simplicity of data preparation
- Voltage and current as the independent variables.
- Economy from the point of computer time and memory
- Power flow equations in nodal admittance form

2.3. Power Flow Equations

The real and reactive power at any bus *P* is given by

$$P_P - JQ_P = E^*{}_P I_P \qquad (1)$$

Current flowing in any bus *P* is given by,

$$I_P = \frac{P_P - JQ_P}{E_P *} \qquad (2)$$

Where P_P and Q_P are the net real and reactive powers available at bus *P* and I_P is current flowing in any bus *P*. The above equation is the total current of a bus if the shunt elements are grounded. If the shunt elements are not included, the total current at the bus P is

$$I_P = \frac{P_P - JQ_P}{E_P *} - Y_P E_P \qquad (3)$$

Where Y_P is the total shunt admittance at the bus and $Y_P E_P$ is the current flowing from bus P to ground. The performance equation in the admittance form is,

$I_{BUS} = [Y_{BUS}]\, E_{BUS}$

Expanded form of above equation is shown below,

$$\begin{bmatrix} I_1 \\ I_2 \\ \cdots\cdots \\ I_P \\ \cdots\cdots \\ I_n \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & \cdots\cdots Y_{1p} & \cdots\cdots Y_{1n} \\ Y_{21} & Y_{22} & \cdots\cdots Y_{2p} & \cdots\cdots Y_{2n} \\ \cdots\cdots & \cdots\cdots & \cdots\cdots\cdots\cdots & \cdots\cdots\cdots\cdots \\ Y_{p1} & Y_{p2} & \cdots\cdots Y_{pp} & \cdots\cdots Y_{pn} \\ \cdots\cdots & \cdots\cdots & \cdots\cdots\cdots\cdots & \cdots\cdots\cdots\cdots \\ Y_{n1} & Y_{n2} & \cdots\cdots Y_{np} & \cdots\cdots Y_{nn} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ \cdots\cdots \\ E_P \\ \cdots\cdots \\ E_n \end{bmatrix} \qquad (4)$$

At any bus P,

$$I_P = Y_{p1}E_1 + Y_{p2}E_2 + -- Y_{pp}E_p + -- Y_{pn}E_n \qquad (5)$$

$$I_p = \sum_{q=1}^{n} Y_{pq}E_q = Y_{pp}E_p + \sum_{q=1}^{n} Y_{pq}E_q$$

$$Y_{pp}E_p = I_p - \sum_{\substack{q=1 \\ q\neq p}}^{n} Y_{pq}E_q$$

$$E_p = \frac{1}{Y_{PP}}\left[I_P - \sum_{\substack{q=1 \\ q\neq p}}^{n} Y_{pq}E_q \right]$$

Substitute I_P from Equation (2) in above equation

$$E_P = \frac{1}{Y_{PP}}\left[\frac{P_P - JQ_P}{E_{P*}} - \sum_{\substack{q=1 \\ q\neq \mathrm{p}}}^{n} Y_{pq}E_q \right] \qquad (6)$$

These non-linear equations can be solved by one of the mathematical technique such as Gauss iterative method, Gauss Seidel iterative method, Newton-Raphson method, Fast decoupled method, etc.
Newton-Raphson Method is preferred for power flow analysis due to its following features,
- Superior convergence
- Suitable for large size systems
- Iteration ratio 1:8 as compared to Gauss-Seidel method
- Accurate and precise
- Less number of iteration and independent of system size
- Sensitive to slack bus selection, regulating transformers, etc
- Faster and more reliable [18,19,20]

3. Static VAR Compensators

Static VAR compensators (SVC) are the most popular first generation shunt devices belongs to FACTS. Mainly, SVC consists of a fast thyristor switch controlling a shunt capacitor or inductor which improves voltage and stability. The basic model for shunt FACT device is shown in figure 1.

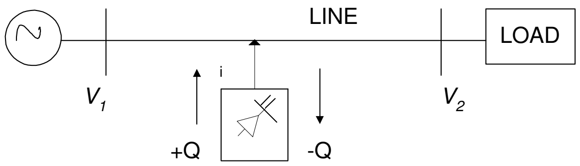

Fig.1: Basic model of shunt FACT device

Where, V_1 and V_2 are the voltages at sending and receiving end.
$+ Q$ and $-Q$ are the reactive power injected and absorbed by capacitor and inductor bank operated by thyristor [21,22].
Circuit shown in figure 2 is considered to explain basic principle and working of shunt FACTS device. Where, E and V are the voltages at sending and receiving end. R_S and R_L are system and load resistance. XS and XL are system and load reactance. I_S, I_L and I_C are system, load and capacitor current respectively. P and Q are active and reactive powers respectively. Shunt capacitor in the circuit inject the current at that location and helps to improving the voltage. Phasor diagram of shunt FACTS is shown in figure 3. In the case of without injecting I_C , I_L lags to V by an angle θ. When capacitor is connected in shunt , it is almost in phase with voltage, improving voltage at receiving end. Shunt reactors can be used to improve the voltage and power at the load end provided the load has capacitive in nature.

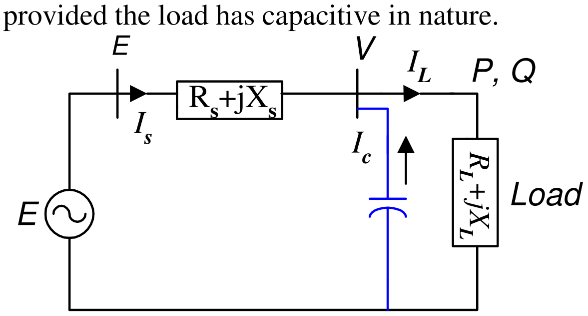

Fig. 2: Basic circuit of shunt FACTS

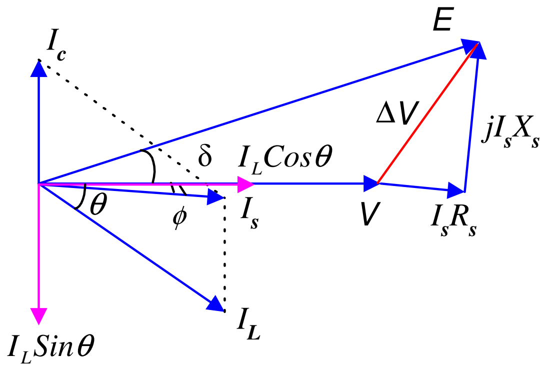

Fig. 3: Phasor diagram for basic SVC circuit

Equations related to flow active and reactive power are as follows,

$$P_{12} = \frac{V_1 V_2 \sin\delta}{X_L} \quad (7)$$

$$Q_{12} = \frac{V_1^{2} - V_1 V_2 \cos\delta}{X_L} \quad (8)$$

Where, P_{12} and Q_{12} are *the* real and reactive power flow from bus 1 to 2. V_1 and V_2 are the voltages at bus 1 and 2.
δ = Phase angle difference (δ_1 - δ_2), X_L is the impedance of the line, assumed to be purely inductive. The effective reactance impedance X_L of the line changes by injecting current due to change in reactances of inductor or capacitor and results in reactive power compensation, thus allowing control of real power flow between the two buses [23].

Shunt controllers can be of three types i.e., variable impedance, variable source and combination and can inject current to the system at the point of location. As long as injected current is in quadrature with the line voltage, the shunt controllers inject /absorb variable reactive power in case of inductive/capacitive components. Any other phase relationship involves handling of real power only. SVC based on Thyristor controlled reactor (TCR) and Thyristor switched capacitor (TSC) are shown in figure 4.

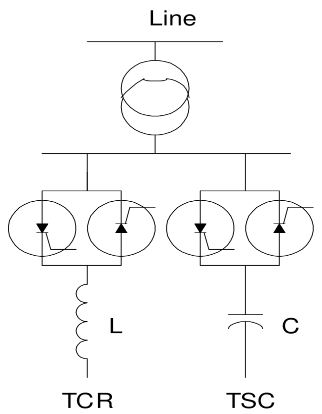

Fig. 4: Static VAR compensators – TCR and TSC

An elementary single phase TCR consists of a fixed reactor of inductance L and a bidirectional thyristor valve, it is a shunt connected inductor whose effective reactance is varied in a continuous manner by partial conduction of the thyristor valve. A thyristor valve can be brought into conduction by simultaneous application of a gate pulse. The current in the reactor can be controlled from maximum (thyristor valve closed) to zero (thyristor valve open) by the method of firing delay angle control.

A single phase TSC consists of a capacitor, a bidirectional thyristor valve, and a relatively small surge current limiting reactor. This reactor is needed to limit the surge current in the thyristor valve under abnormal operating conditions TSC is a shunt connected capacitor whose effective reactance is varied in a stepwise manner by full or zero conduction operation of the thyristor valve. Thyristor valve is delayed with respect to the peak of the applied voltage in each half cycle, and thus the duration of current conduction intervals is controlled [24,25].

4. Case Study

A 33/11 kV distribution substation of Maharashtra State Distribution Company Limited (MSEDCL) Nagpur zone, India, has been considered for analysis. The substation hosts two power transformers, each having capacity of 3 MVA. There are two outing feeders connected to each of power transformers. Incoming voltage level is 33 kV and the distribution voltage level is 11 kV. Load receives a voltage of 0.435 kV. Figure 5 shows the line diagram of substation under case study.

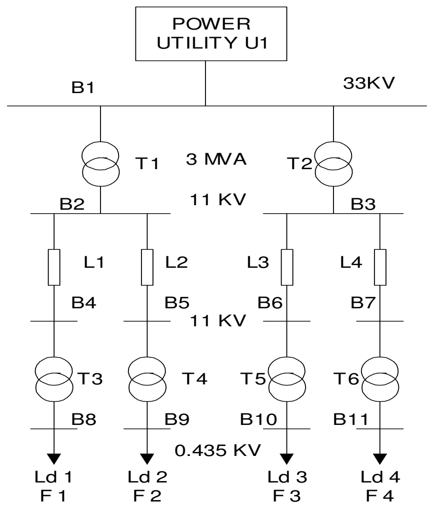

Fig.5: Single line diagram of the substation

Single line diagram has shown eleven buses (B1 to B11). T1 and T2 are the power transformers in substation. T3 to T6 are the distribution transformers on the field, each transformer represents the number of transformers on that feeder. L1 to L4 represents distribution lines. Ld1 to Ld4 are the loads on feeder F1 to F4 respectively.

For the simplicity and ease of analysis total transformers on each feeder are shown by its equivalent single distribution transformer with certain assumptions. For the analysis distribution feeders (F1 – F4) are considered with a resistance of 0.16 ohms per km and reactance of 0.32 ohms per km. Length of service line from distribution transformer to consumer end is neglected. Distribution line parameters and Number of transformers on each feeder are given in Table 1 and 2 respectively.
Recorded data collected from substation for voltage, power and current at various buses for peak load condition is reported in Table 3. Recorded system power losses are 20.21% and the power factor is 0.90.

Table 1: Distribution line parameters

Parameter	F1	F2	F3	F4
Resistance Per km in Ohm	0.16	0.16	0.16	0.16
Reactance Per km in Ohm	0.32	0.32	0.32	0.32
Length in km	43	30	27	28

Table 2: Transformers on each feeder

11kV feeder	200 KVA	100 KVA	63 KVA	25 KVA	Total
F1	4	36	18	2	60
F2	-	36	16	1	53
F3	1	12	16	-	29
F4	-	25	18	-	43

Table 3: Recorded Data at Substation for Peak Load

Parameter	F1	F2	F3	F4
Voltage at B2,B3 kV	9.80	9.80	9.80	9.80
Voltage at B4,B5,B6, B7 kV	8.50	8.91	9.14	8.87
Voltage at B8,B9,B10, B11 kV	0.334	0.350	0.359	0.349
Power sent MW	1.4	1.33	1.33	1.53
Power Received MW	1.11	1.11	0.97	1.27
Power Loss MW	0.29	0.22	0.36	0.26
Current A At feeders	84	80	68	92

5. System Analysis

System shown in figure 5 is used for with following assumptions,

- The incoming 33 kV bus is considered as reference bus
- Average temperature of transformer is 40 ^{0}
- Supply frequency is 50 Hz
- Power factor is assumed to be 90 %
- Length of 0.435 kV service line is neglected
- All loads are assumed to be static
- Analysis is made for steady state condition
- Marginal voltages limit 98 % to 102 % of nominal voltage
- Critical voltages limit 95 % to 105 % of nominal voltage

5.1. Simulation without Controller

System as discussed in figure 5 is simulated in ETAP environment and Power flow analysis is carried out by using Newton-Raphson method. This Simulation is carried out in steps as follows,

Step 1. Selection of Components
Power system components like transformers, transmission line, buses, loads, etc., is selected from the ETAP library.

Step 2. System Development
Line diagram is developed using various components in the ETAP library.

Step 3. Method for Analysis
Software provides three methods for analysis i.e., Gauss seidel, Newton Raphson and fast decoupled. Newton Raphson method have been used for the simulation due to superior convergence.

Step 4. Simulation Output
Power flow is carried out and results are obtained.

Simulation results show system power losses 10% and the power factor is 0.86. Simulation results for voltage, power sent and received and current for peak load conditions are reported in Table 4.

Table 4: Simulation results without controller for Peak Load

Parameter	F1	F2	F3	F4
Voltage at B2,B3 kV	10.56	10.56	10.82	10.82
Voltage at B4,B5,B6, B7 kV	8.82	9.32	9.85	9.56
Voltage at B8,B9,B10, B11 kV	0.343	0.363	0.381	0.366
Power sent MW	1.2	1.2	1.2	1.4
Power Received MW	1.1	1.1	1.0	1.3
Power Loss MW	0.1	0.1	0.2	0.1
Current A At feeders	77.2	77.7	69.2	90.3

5.2. Simulation with controller

Simulation with controller is carried out using steps explain in section 5.1. Low rated SVC are connected to all feeders at load end. This simulation results are compared with simulation results without SVC. It is observed that voltage at all buses is improved and is in the critical margin. Simulation results show system power losses 6.9% and the power factor is 0.96. Simulation results for voltage, power sent and received and current for peak load conditions are reported in Table 5.

Table 5: Simulation results with SVC for Peak Load

Parameter	F1	F2	F3	F4
Voltage at B2,B3 kV	10.82	10.82	11.08	11.00
Voltage at B4,B5,B6, B7 kV	10.00	10.10	10.46	10.22
Voltage at B8,B9,B10, B11 kV	0.392	0.400	0.410	0.401
Power sent MW	1.4	1.4	1.3	1.7
Power Received MW	1.3	1.3	1.2	1.6
Power Loss MW	0.1	0.1	0.1	0.1
Current A At feeders	77.1	76.6	67.3	89.1

6. Results and Discussion

Line diagram of substation shown in figure 5, with the data related to voltage, power, length of distribution feeder, transformer on each feeders, reactances and resistances of distribution line etc,. received from MSEDCL is considered for computer simulation. Power flow has been carried out by Electrical Transient Analyzer program - ETAP power station, during peak load condition. Comparison between recorded data and simulation results without SVC states the variation in voltage, power, current and power factor. Simulation results are found better than recorded. Recorded system power loss is 20.21%, whereas system power loss by simulation is 10% i.e almost half of recorded. Similarly recorded power factor is 0.90 and power factor by simulation is 0.86. Comparison between simulation results without SVC and with SVC has been made and it is observed that by the use of SVC all the parameters are enhanced. System power loss reduces from 10% to 6.9% and the power factor improves from 0.86 to 0.96, also power flow enhance from 5MW to 5.8 MW. In the comparison of all three cases, i.e, recorded data, simulation results without SVC and simulation results with SVC it is found that with the use of SVC at load end maximum improvement in the parameters are achieved. With insertion of SVC at load end during peak load condition voltages at various buses are found in critical margin i.e., rated voltage. Comparative analysis of voltage at various buses for recorded and simulation without SVC and with SVC are shown in Table 6.

Table 6: Voltage Profile at various Buses

Bus No	Voltage recorded (kV)	Simulation Result Voltage (kV)	
		Without SVC	With SVC
B 2	9.80	10.56	10.82
B 3	9.80	10.82	11.08
B 4	8.50	8.82	10.00
B 5	8.91	9.32	10.10
B 6	9.14	9.85	10.46
B 7	8.87	9.56	10.22
B 8	0.334	0.343	0.392
B 9	0.350	0.363	0.400
B 10	0.359	0.381	0.410
B 11	0.349	0.366	0.401

Results for recorded voltages and simulation voltages are also shown in figure 5 and 6. Figure 5 shows voltages at distribution buses and figure 6 shows voltages at load buses.

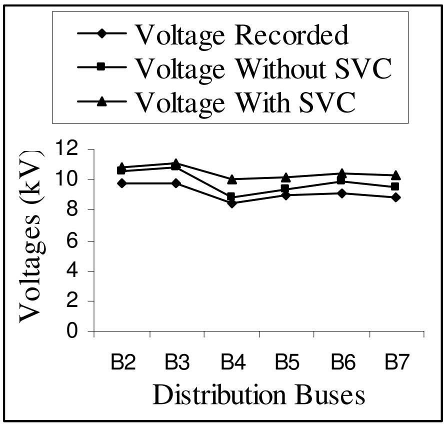

Fig. 5: Voltages at Distribution Buses

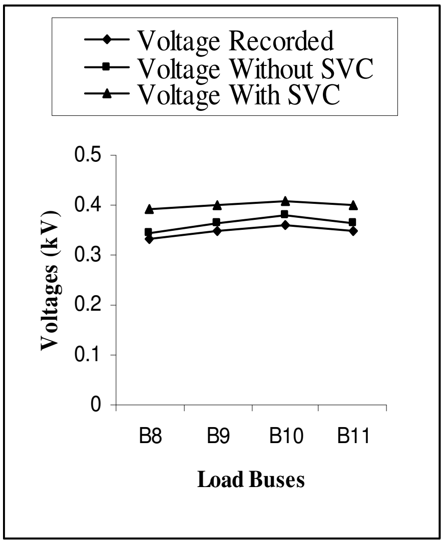

Fig. 6: Voltages at Load Buses

Graphical results also conclude that with the insertion of SVC voltages at various buses have been improved and found rated.

7. Conclusions

In this paper the performance of 33/11 kV MSEDCL distribution substation without and with SVC at load end has been examined in ETAP environment. In the comparison of recorded data and simulation results without SVC the deviations in the parameters are found. Improper length of distribution line, loose connections and number of joints and improper quality of transformers and accessories on the field may be the reasons for deviation in parameters. With the insertion of SVC at load end improvement in voltage, power factor, power loss and power flow is noted hence in this paper low rated SVC are suggested. To improve the system performance, use of quality transformers, proper length of distribution line, minimum joints and jumpers are suggested. In future it is possible to design low rated SVC and their installation at load end on the tower itself. It will avoid the installation of SVC substation separately which is bulky and costly.

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