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Performance Enhancement of Primary Distribution Network Using Reactive Power Compensators

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ABSTRACT

This paper presents a method for optimal allocation of active and/or passive VAR compensation. The method is implemented using Static Var Compensator (SVC) and shunt capacitors to improve the overall performance of a radial primary distribution network. The impact of optimal allocation of shunt compensators on primary distribution networks performance with different load levels (20% increased or 20% decreased) is also studied. Modified IEEE 33-bus primary distribution network is used to verify the effectiveness of the proposed methodology with different load levels. Implementation of the suggested methodology is carried out by Power World Simulator (PWS). PWS is a software package that has strong analytical and visualization functions suitable for extensive power flow study of an electric power system.

Keywords: *Static Var Compensator (SVC), Fixed Capacitor-Thyristor Controlled Reactor (FC-TCR), Shunt Capacitor, Loss Sensitivity Factors, Power losses, Voltage profile*.

1. Introduction

Due to the rapid increase in electrical energy demand, power system, especially distribution level is heavily stressed in terms of high-power losses, low efficiency, overloading of feeders, poor voltage regulation and power factor [1-3]. So, distribution networks are undergoing a rapid rehabilitation process and are planning to expand their electrical networks to meet the increasing load demand through numerous technologies such as using distributed generation, reactive power compensation, feeder reconfiguration, optimal location of distribution transformers and locating substations near the load center etc. [4].

Reactive power compensation has a significant improvement in power transfer capabilities and a valuable enhancement in voltage stability as it has a virtuous role in decreasing power loss for transmission lines and reducing voltage deviation. Active and passive are two classes of reactive power compensation. Passive compensation is represented by shunt, series capacitors and shunt reactors which is switched or permanently connected to the transmission and distribution system [5, 6]. They control the voltage through modification of network characteristic. Active compensation includes synchronous condensers, Static Synchronous Compensators (STATCOM) and Static Var Compensators (SVC) which absorbed or generated reactive power automatically to maintain voltages of the buses to required values [7]. The benefits of these compensators depend on how and where to allocate these compensators on distribution system.

The objectives of this paper are to optimally allocate SVC (as one member of active compensator devices) and shunt capacitors (as passive compensator) for reducing distribution losses (active and reactive) and improving voltage profile of distribution network using suggested methodology and study the impact of optimal allocation on performance with 20% increase or decrease in load. The proposed methodology has been demonstrated on a modified radial distribution system IEEE 33 bus using PWS.

2. The suggested shunt reactive power compensators for improving voltage stability

In this paper, two types of shunt reactive power compensator are considered. These are SVC and shunt capacitors.

2.1 SVC (FC-TCR)

The SVC is one type of FACTS (Flexible AC Transmission Systems) devices controller that connects to a network shunt and operating as reactive power compensators [8]. The wide use of SVC in transmission and distribution networks is due to its advantages such as: fast operation and response, removal of additional voltage, good certainty, balancing phases, improving power factor and power quality, low maintenance cost, flexibility, simple control, increasing transient stability, prevention of voltage collapse [9].

In FC-TCR, a capacitor is placed in parallel with a thyristor-controlled reactor and its equivalent circuit in the PWS is shown in Fig. 1 [10-11]. The equivalent FC-TCR in PWS is comprised of transformer, switched capacitor, fixed reactor and switched reactor. Its switched capacitors provide leading VAR while lagging VAR is provided by rating TCR larger than the capacitor. Regulation of the voltage within its control limit is the main objective of FC-TCR [12-13]. So, FC-TCR provides continuous, rapid control of reactive power over the entire selected lagging to leading range [14-16].

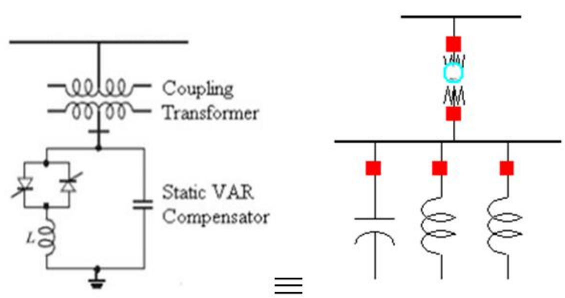

Fig.1. Schematic diagram of FC-TCR and its equivalent circuit in PWS

2.2 Shunt capacitors

Shunt capacitors which are either switched or permanently connected to transmission or distribution system provide passive compensation. Shunt capacitors are preferred to be installed in load areas especially at major substations to keep voltages at required values by producing reactive power [17]. Fig. 2 shows line diagram of distribution line with shunt capacitor and its equivalent circuit in PWS to control the voltage which is connected in parallel with the load. It is necessary to optimally allocate the shunt capacitors for reactive power support in the distribution system because improper allocation of capacitors would deteriorate the characteristics of the distribution system [18, 19].

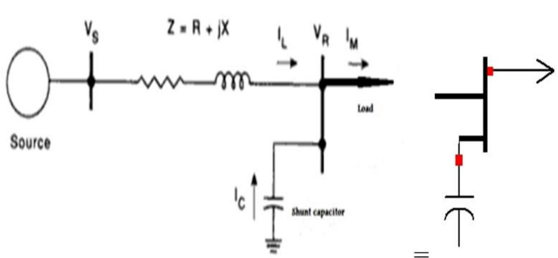

Fig.2 Line diagram of distribution line with shunt capacitor and its equivalent circuit in PWS

3. Optimal allocation of shunt compensators

In this section, the methodology to select the optimal allocation (size and site) of shunt reactive power compensators such as FC-TCR or shunt capacitors has been organized in two phases:

Phase I: Optimal size for shunt compensator

The steps to find the optimal size of each shunt compensator unit are:

1) Put shunt compensator with specified size on each bus sequentially. Then PWS is applied in each case to solve the power flow problem. Then, reactive power loss index from (1) is calculated:

Reactive power loss index = $\min Q_{loss} / Q_{insert}$ (1)

where,

$\min Q_{loss}$: Minimum reactive power losses when shut compensator has been put.

Q_{insert} : Reactive power inserted in the system.

2) Increase shunt compensator size by specified step and repeat step 1 until arriving 700 kVAr as shunt compensator.
3) The optimal size is chosen as the reactive power loss index becomes almost constant.

Phase II: Optimal location for shunt compensators

Two approaches have been used to identify the optimal location for shunt compensators:

A. The first approach is based on the loss sensitivity factor because of its ability to choose the buses whose loss reduction will be the biggest when shunt compensators are placed on them. Then, these buses are chosen to put shunt compensators on them. Consider a load of $P_{eff} + Q_{eff}$ connected between 'p' and 'q' buses and a distribution line with an impedance R +jX as shown in Fig. 3 below:

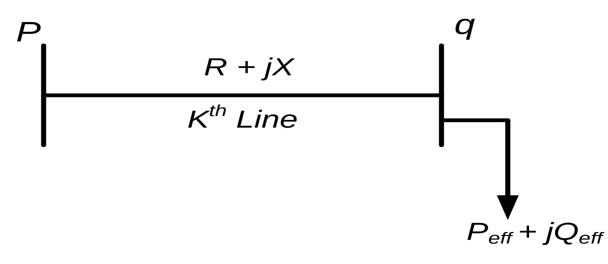

Fig. 3. Single line diagram of distribution line

The loss sensitivity factor can be obtained by [20]:

$$\frac{\partial P_{line\ loss}}{\partial Q_{eff}} = \frac{2Q_{eff}[q]*R[k]}{(V[q])^2} \qquad (2)$$

where,

P_{eff} = Total effective active power supplied beyond the node 'q'

Q_{eff} = Total effective reactive power supplied beyond the node 'q'.

The candidates' buses aren't all suitable for shunt compensators placement since shunt compensators can't be placed at bus with healthy voltage, so, additional method is required to select the weak buses in the radial distribution system. In this paper, normalized voltage magnitude method is used to find the weak buses in the radial distribution network. Normalized voltage magnitude, norm [i] which is voltage magnitude for bus i, can be obtained from (3):

$$\text{norm}[i] = \frac{|V_i|}{0.95} \tag{3}$$

The selection of candidate buses for shunt compensator placement is basically calculated as the following steps.

STEP 1: Calculate the loss sensitivity factor for all the buses of distribution system using (2).
STEP 2: Arrange the value of loss sensitivity factor in descending order. Also store the respective buses into bus position vector
STEP 3: Calculate the normalized voltage magnitude of the buses which are arranged as in the previous step using (3).
STEP 4: The buses whose normalized voltage is less than 1.01 are selected as candidate buses for shunt compensator placement.

B. The second approach for finding the optimal location is based on the buses which have minimum voltage magnitude. This approach is carried as follows:

1) On the first iteration, the load flow is carried out by PWS.
2) Identify the candidate location as bus with minimum voltage (weakest bus).
3) In the next iteration, place shunt compensator permanently at the weakest bus and repeat steps 1 and 2 to find the new bus with minimum voltage.
4) The procedure is terminated after four shunt reactive power compensators (FC-TCR or Capacitors) have been located at optimal locations.

4. Problem formulation

The optimal location and size of shunt compensators installation for maximum revenue of overall benefits of shunt compensators is considered as multi-objective function respecting system constrains (equality and inequality constraints).

4.1Objective Function

The main goals are to minimize the real power losses, reactive power losses in the distribution network and voltage regulation by optimally locating and sizing of shunt compensators. The three terms of multi-objective functions are formulated as follows:

a. Minimization of active power losses

The total active power losses are represented as [21]:

$$P_{loss}(p,q) = \sum_{p=1}^{N_r} g_p \left(V_p^2 + V_q^2 - 2V_pV_q \cos\theta_{p,q}\right) \tag{4}$$

where,

Nr = Total number of lines in the system.

g p = The conductance of the line 'p'

V_p , Vq =The magnitudes of the sending end and receiving end voltages of the line

$\theta_{p,q}$ =The angle between the sending and receiving end voltages.

b. Minimization of reactive power losses

The objective is to minimize the reactive power losses by using reactive power compensator, i.e., installation of FC-TCR or shunt capacitors. Thus, the objective can be expressed as (5):

$$Minimize\ Q_{Loss} = \sum_{p=1}^{N_r} I_{p,q}^2 * X_{p,q} \tag{5}$$

where,

Q_{Loss} = Total reactive power losses in system.

$X_{p,q}$ = Reactance of branch p-q.

c. Voltage regulation

$$\text{Percentage Voltage Regulation} = \frac{V_{\max} - V_{\min}}{V_{\min}} \times 100 \tag{6}$$

where,

Vmax: Maximum voltage magnitude in the distribution system.

Vmin: Minimum voltage magnitude in the distribution system.

4.2 Constraints

In this section equality and inequality constraints are formulated as follows:

1. Equality Constraints:

The total power generation from traditional generation (P_g & Q_g) and shunt compensators

($Q_{Shunt.compensators}$) must cover the load demand (P_d, Q_d) and the total power losses (P_{Loss}, Q_{Loss}) .

$$P_g - P_d = P_{Loss} \tag{7}$$

$$Q_g + \sum_{N=0}^{N_{Shunt.compensators}} Q_{Shunt.compensators} - Q_d = Q_{Loss} \tag{8}$$

2. Inequality Constraints:

For stable and secure operation, the values of reactive power added to the system mustn't exceed 70 % of reactive power demand [22].

$$\sum Q_{add} \leq 70\% Q_d \tag{9}$$

where,

Q_{add} :A reactive power added to the system.

Voltage limits constraints:

$$V_p^{\min} < V_p < V_p^{\max} \tag{10}$$

The value of the bus voltage (V_p) is restricted by lower and upper limits, ($V_p^{\min}$ & $V_p^{\max}$) [23].

Thermal limit of distribution lines for the network can be stated as follows [23]:

$$S_p \leq S_p^{\max} \tag{11}$$

where,

S_p : The power flow through distribution line.

$S_p^{\max}$: Thermal capacity of the line.

5. Case study

At a certain horizon year, the total loads are assumed to be increased by 50%. So, modified IEEE 33-bus is the original IEEE 33-bus (original case) with 50% load increased. The system consists of 33 buses, 32 branches and 32 loads with a total power of 6.1 MW and 3.582MVAr. The system has 12.66 kV as a base voltage and 100MVA as a base MVA. The first bus is considered as the substation bus and the loads are connected to all buses except the first bus. The line and bus data are obtained from [24-25]. The proposed methodology for FC-TCR or shunt capacitor allocation have been implemented using PWS and tested on modified IEEE 33-bus primary distribution network which is considered as base case.

1) The steps of optimal size of shunt compensator which is explained in section 3 (phase I) has been executed. The reactive power loss index is represented on Fig. 4 versus shunt compensator size range values from100 to700 kVAr. Focusing on Fig. 4 revels that the optimal size of shunt compensator is 500kVAr and when adding an additional reactive power above the 500 kVAr noted that the reduction in reactive power losses divided by Q_{Insert} is very small as shown in Fig. 4 which means that any further addition has a trivial effect and would not be economical.

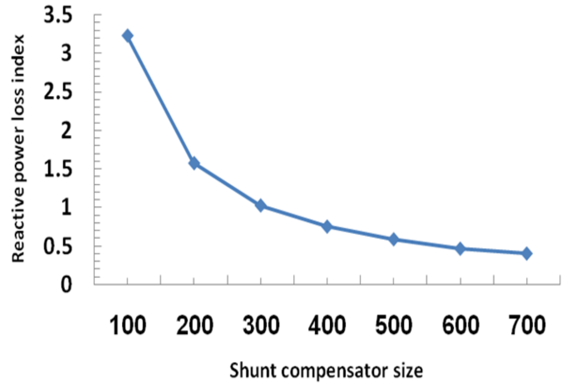

Fig.4. Reactive power loss index

2) The loss sensitivity values and normalized voltage magnitude which are used to find the optimal location of shunt compensators for the test system are tabulated in Table 1. From this table, buses with highest sensitivity values are selected for the location of the shunt compensators. It is clear that normalized voltage (less than 1.01) is considered as weak buses and they are arranged in decreasing order of their loss sensitivity factor values at buses 6-8-9-10-13-24-28-29-30 and so on. And the ranking is given by:
   Bus 6 > 28 > 8 > 29 > 30 >13…..
   The first four buses of the sequence are considered for shunt compensators placement.
3) The optimal location of shunt compensators according to the second approach (minimum voltage bus) gives priority to buses 18, 33, 16 and 32 which has been derived in section 3.

6. Simulation results and discussion

The PWS line diagram of the tested power system is shown in Fig. 5. From this Figure, modified IEEE 33-bus radial distribution system has low performance, which is represented by overloading on feeders (88%), the active losses is 531 kW, the minimum voltage is 0.85 p.u bad voltage regulation (17.6%) and low voltage stability margin. The most heavily loaded lines are 1-2, 2-3 and 3-4, 4-5, 5-6 (with orange circles which exceed 80% of load ability of line). By optimally locating four shunt compensators according to first and second approach, the results are shown in Figs (6-8) and Table 2. From these results:

- When FC-TCR (as active compensator) is located based on the first approach: active power losses are decreased to 352kW (decreased by 33.71%), voltage regulation is decreased to 13.77 % (decreased by 21.76%), minimum voltage is increased to 0.879 p.u and reactive power losses decreased to 239kVAr (decreased by 27.58%) ,the results are shown in row 2 of Table 2.
- While FC-TCR based on the second approach is effective in voltage regulation as it is decreased by 54.55%, minimum voltage increased to 0.920 p.u, active power losses decreased by28.25% and reactive power losses decreased by 19.1%, the results are shown in row 4 of Table 2.
- Using static capacitors based on the first approach enhance the performance in terms of reducing active losses by 31.83%., the results are shown in row 3 of Table 2. While based on the second approach reactive power losses and regulation are decreased by 23.64%and 43.18% respectively, the results are shown in row 5 of Table 2.
- The same remakes can be observed when studying the performance with 20% increase or decrease in load, after installing shunt reactive power compensators (FC-TCR or Capacitors) based on two approaches.
- It is important to clarify that the system with 20% increase in load resulting overload on the line to 108%. But it is reduced to 95% or 97% after installing FC-TCR or capacitors. The results are tabulated in Table 2.

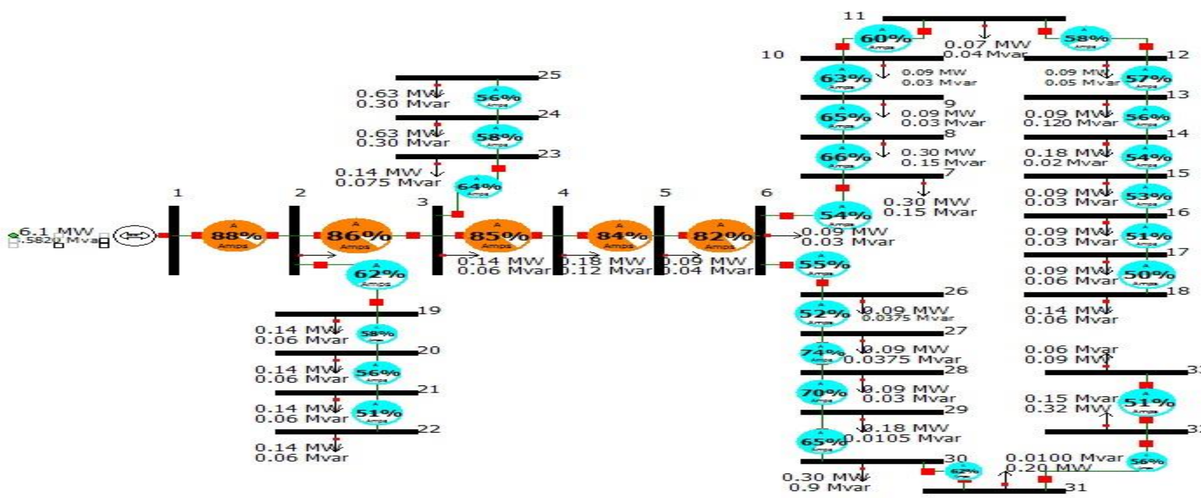

Fig. 5. Modified IEEE 33-bus system simulation using PWS (base case)

Table 1- The values of the loss sensitivity factor and normalized voltages for all lines and top four sensitive buses.

Line No.	Start Bus	dEn Bus	Loss Sensitivity Factor 10^{-3}	Normalized voltage (|V| in p.u/ 0.95)	Line No.	Start Bus	End Bus	Loss Sensitivity Factor 10^{-3}	Normalized voltage (|V| in p.u / 0.95)
1	1	2	3.767178	1.047832	17	17	18	0.758247	0.894905
2	2	3	18.91752	1.025053	18	2	19	0.496357	1.046979
3	3	4	10.75895	1.012937	19	19	20	3.453545	1.041147
4	4	5	10.84029	1.000958	20	20	21	0.628173	1.040011
5	5	6	24.25294	0.971411	21	21	22	0.544812	1.038968
6	6	7	2.096028	0.965579	22	3	23	4.052979	1.019284
7	7	8	16.10762	0.942842	23	23	24	7.323773	1.008579
8	8	9	7.455007	0.932274	24	24	25	3.692363	1.003242
9	9	10	7.209935	0.922453	25	6	26	3.700728	0.968379
10	10	11	1.266237	0.920989	26	26	27	5.063637	0.964347
11	11	12	2.178565	0.918453	27	27	28	18.96366	0.946779
12	12	13	7.507382	0.908074	28	28	29	14.4114	0.934189
13	13	14	2.335458	0.904211	29	29	30	9.119195	0.928484
14	14	15	1.356342	0.9018	30	30	31	3.492733	0.922284
15	15	16	1.530454	0.899453	31	31	32	1.063263	0.920758
16	16	17	1.998086	0.895958	32	32	33	0.334089	0.920284

Table 2- Simulation results of modified 33 bus radial distribution system

Cases		V_{min} (p.u)	Voltage Regulation (%)	Active Power Loss (kW)	Reactive Power Loss (kVAr)	Maximum Load ability (%)
Modified 33bus radial system (Base case)						
Without compensation		0.850	17.6	531	330	88
approach 1	**TCR-Four FC**	0.879	13.77	352	239	77
	Four Capacitors	0.875	14.29	362	246	78
approach 2	**TCR-Four FC**	0.920	8	381	267	77
	Four Capacitors	0.908	10	367	252	78
increase in load %20						
Without compensation		0.815	22.7	739	502	108
approach 1	**TCR-ur FCFo**	0.843	18.6	550	377	96
	Four Capacitors	0.839	19.2	570	388	97
approach 2	**TCR-Four FC**	0.890	12.3	560	389	95
	Four Capacitors	0.874	14.4	560	382	97
decrease in load %20						
Without compensation		0.883	13.12	299	203	69
approach 1	**TCR-Four FC**	0.912	9.6	209	142	60
	Four Capacitors	0.909	10	213	145	59
approach 2	**TCR-Four FC**	0.945	5.82	269	194	60

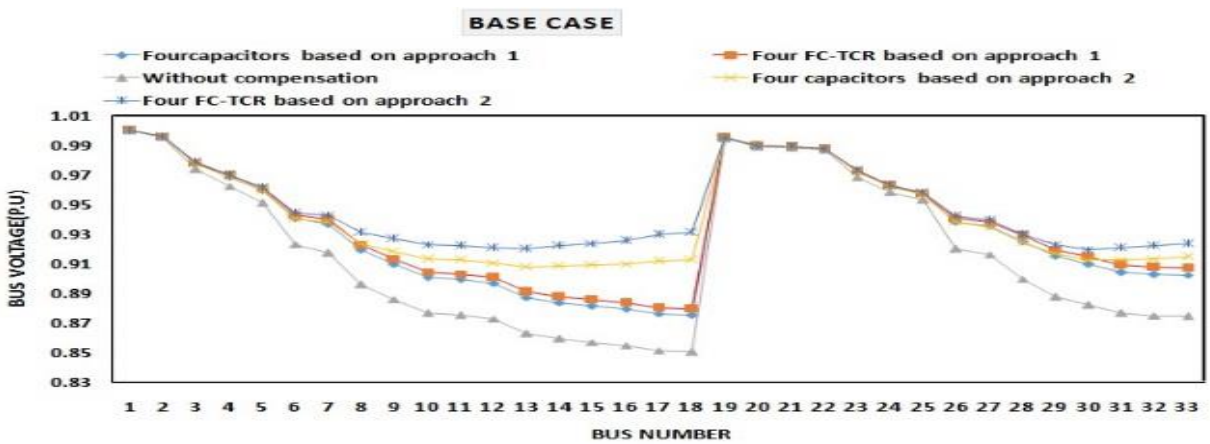

Fig. 6. Voltage profile for different cases

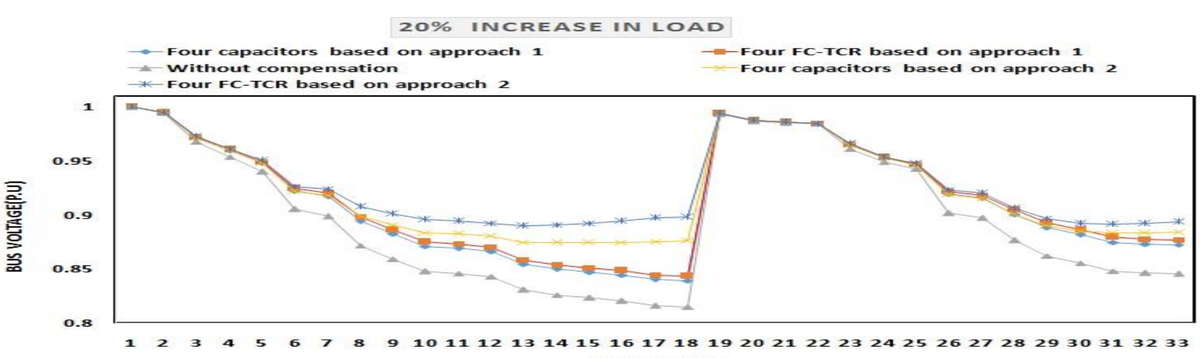

Fig. 7. Voltage profile for different cases of 20% increase in load

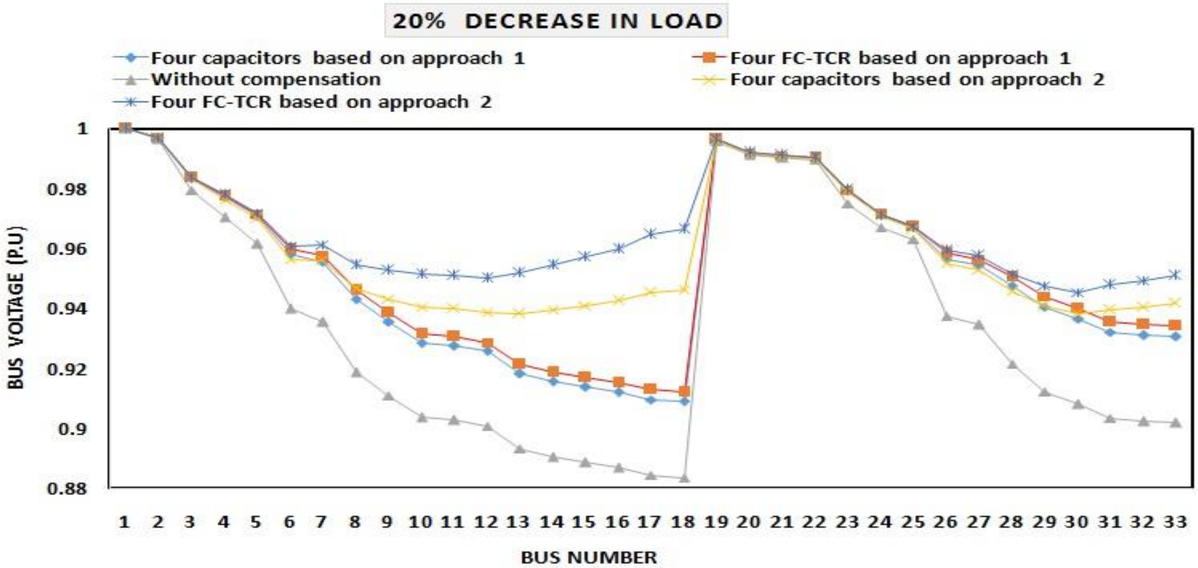

Fig. 8. Voltage profile for different cases of 20% decrease in load

7. Conclusions

In this paper, the application of the PWS for determining the optimal allocation of reactive power compensator devices in modified IEEE 33-bus distribution network has been presented to validate the effectiveness of the proposed methodology. The reactive power loss index is used to obtain the optimal size of shunt compensator. For shunt compensator location two approaches have been proposed to determine which buses are the optimal location of two suggested shunt compensators which are FC-TCR (as active compensator) and static capacitors (as passive compensator). The first approach is based on loss sensitivity factor and normalized voltage magnitude. The second approach is based on weakest buses (with minimum voltage magnitude). The impact of shunt compensators (FC-TCR or shunt capacitors) with optimal allocation is studied when the load is increased or decreased by 20%. The following remarks can be concluded from the simulation results:

- The optimal size of shunt compensator is specified (500 kVAr for each unit) using reactive power loss index.
- The optimal location of shunt reactive power compensators based on first approach reduced active power losses, reactive power losses and enhanced efficiency.
- While the optimal location of shunt reactive power compensators based on second approach improved voltage regulation and voltage profile.
- The effectiveness of installing FC-TCR than static capacitors within the same approach in terms of decreasing active and reactive power losses, load ability and voltage regulation is cleared in each approach.
- Anther an important advantage of FC-TCR is its fast response against load variations.
- The same remakes can be observed when studying the performance with 20% increase or decrease in load, after installing shunt reactive power compensators (FC-TCR or Capacitors) based on two approaches.
- It is important to clarify that the system with 20% increase in load resulting overload on the line to 108%. But it is reduced to 95% or 97% after installing FC-TCR or shunt capacitors.

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