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An Empirical Relationship for Capacitor Bank Requirement for Distribution Utilities

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Abstract

Load growth and seasonal variations in loading pattern are two key factors for the poor voltage profile in power distribution utilities (DISCOM). Shunt capacitor banks are the most economical compensating devices widely preferred for local reactive power management & voltage control in these utilities. In most of the large sized power systems, the network data is not readily available for modelling DISCOM and this is a great hurdle for identifying reactive power compensation requirement for DISCOM. Regional Power Committees are engaged in coordination with transmission utilities for management of reactive power exchange for better voltage control during their operations. Regional Power Committee are not in a position to validate/guide the DISCOM for Capacitor Bank requirement due to non-availability of DISCOM Network. In this article, an empirical relationship for capacitor bank requirement for DISCOM has been developed based on the variation in loading profile and nature of loading for a defined DISCOM network. This identified capacitor bank requirement is validated against the amount of compensation needed at upstream transmission substation level. In this research work, it has been observed that proposed empirical relationship for capacitor bank requirement is quite a handily tool for estimating capacitor requirement without modelling the DISCOM network.

Keywords: Capacitor Banks, Distribution Networks, Load Flow, Peak Loading, Voltage Control

1. Introduction

In any power network the reactive power oscillates between the ac source and the reactive power devices such as capacitors or reactors. The transfer of the reactive power from generating stations to long distance load centres generally causes overloading of conductors and other power equipments. This results in huge active power loss and voltage drop in transmission & distribution levels. Hence, efficient reactive power management plays a huge role in determining the quality of electric power supplied in a large power system[1]. According to Indian Electricity Grid Code (IEGC) Regulations, 2010 it is advised to manage the reactive power demand of any DISCOM network locally by placing the compensating devices nearer to the load centres[2].

Various techniques have been used for reactive power management at different levels of power systems. It includes automatic voltage control at the plant level[3], FACTS devices at transmission level and switched as well as fixed shunt compensation at the distribution levels respectively[4]. However, synchronous condensers are widely preferred for the reactive power management and voltage control from the very early period. It is considered as one of the flexibale method to maintain voltage within desired limits under various loading conditions and contingencies[5]. For large interconnected power systems, Q-V sensitivity and index vector based analysis are the most commonly adopted approaches for reactive power management as discussed[6,7]. A hybrid technique of short circuit study and Q-V analysis to identify the reactive power compensation up to transmission level of Indian grid is presented[8]. Some of the other detailed analysis of reactive power compensation principles for radial distribution networks are discussed[9–12]. Even though different algorithms are developed for the optimal placement of capacitor banks in distribution networks,

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the number of buses in the network under study[13–18] is quite low.

In this article the highly interconnected DISCOM network in northern region of Indian power grid is considered for studying the performance of proposed methodology for the reactive power compensation with synchronous condenser and Fixed Capacitor (FC) method. Most of the northern states of India has vast power distribution network with diversified loads. The Presented Formula is empirical and may yield satisfactory results if the nature of load remains same for seasonal varying nature of load. Other factors which may affect the reactive requirement identified in phase-1 are feeder lengths, no of distribution transformers, layout of distribution feeders etc. In order to meet this huge reactive power demand, the northern state utilities of Indian grid draw more power from the national grid during that period. They receive power at different voltage levels which is then delivered to the consumers with the help of different transmission companies (TRANSCOM) and DISCOMs. But this long distance transmission and distribution results in poor voltage profile at the load end. So it is necessary to keep the performance of power system networks in the northern states within standard limits irrespective of the seasonal changes. Thus the modelling of power networks with suitable compensation nearer to load centres are a prerequisite. But the modelling of the huge DISCOM networks and meeting their reactive power demand locally is a tedious task.

Hence, this research paper discusses an empirical relationship for capacitor bank requirement for varying load profiles and power factors at distribution level. It mainly focuses on identifying the locations and the amount of required fixed capacitor banks for each utilities of northern region at transmission level and distribution level under peak loading conditions. The selection of candidate locations for capacitor placement and amount of compensation required are determined using a two-stage algorithm. Phase-I of the algorithm explains about amount of compensation required at transmission level. Then an empirical relationship is formulated in phase-II in order to allocate the compensation identified at transmission level to the DISCOM networks without modelling the distribution systems.

Section 2 of the article discusses the proposed two-stage algorithm followed by results & discussions in Section 3 and the conclusions drawn in Section 4.

2. Proposed Algorithm

The proposed algorithm recommends the amount of capacitor bank required for the year 2019-‘20 at the load centres of northern state utilities of Indian grid. It improves the bus voltage profile and minimizes the exchange of the reactive power between other areas. This in turn will ease the heavy exchange of reactive power flow in the inter-regional transmission lines during extreme loading conditions in the northern grid.

Phase-I of proposed algorithm explains the identification of candidate locations for fixed shunt capacitor placement and compensation required for TRANSCOM networks using synchronous condenser method. In this stage, a synchronous machine with zero active power & non-zero reactive power limits is integrated at every load bus. After performing the load flow, machines delivering reactive power are sorted out and they indicate the necessity of reactive power support at that particular bus. And those buses are treated as candidate locations for capacitor bank placement. Phase-II discusses a heuristic method to identify the required amount of compensation at downstream 11 kV buses determined using Phase-I. Modelling of DISCOM networks and allocation of lumped loads represented at higher voltage levels to actual load centres are performed in this step. Then switched shunt capacitors are placed at these final load buses and load flow analysis is carried out again. As a result, for a per unit change in bus voltage the amount of compensation required is evaluated and a generalised pattern is formulated.

The relationship between the change in voltage (ΔV) and change in reactive power (ΔQ) at ith bus is given by the equation (1)[7].

$$\boldsymbol{\Delta} Q_i = \frac{\boldsymbol{\Delta} V_i}{\partial V_i / \partial Q_i} \tag{1}$$

Where ∂Vi/∂Qi term represents the slope of the curve between the change in voltage and the reactive power injected by the compensating device integrated at the ith load bus. Using (1) and from phase-II of the proposed algorithm, the relationship between voltage at any 11 kV bus and reactive power injected in MVAr is found to be more or less linear. An empirical equation can be then formulated using curve fitting method as shown in (2).

$$\boldsymbol{\Delta} Q = m * \boldsymbol{\Delta} V + Q_{ini} \tag{2}$$

where, "m" represents the slope of the curve, which is Δ Vi/ Δ Qi term mentioned in (1) and Qini is the initial reactive power support at that particular bus. Empirical relationship formulation is explained in subsection 3.2.

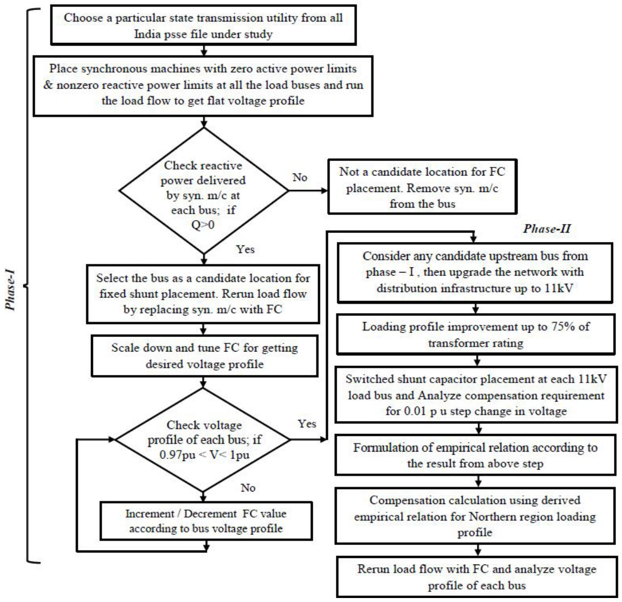

Figure 1. Proposed two-stage algorithm.

For each state utility of Northern Regional Power Committee (NRPC), the methodology as shown in Figure 1 is followed and thus total compensation required is obtained. All these steps are carried out by considering that the already existing compensating devices are in operation. Thus, the final amount of compensation recommended can considered to be supplemental at each location.

3. Results and Discussions

The modelling of various power system components and loads are performed using PSS/E. Network data file up to the transmission level of 132/66/33kV for peak loading scenario on July 2018 as provided by NRPC have been used for conducting the pilot study.

3.1 Reactive Power Compensation for TRANSCOM Networks

As per the information provided by NRPC, approximate demand of the northern region is 62140.6 MW against a power generation of 47951 MW in July 2018. The load and generation balance details are given in Table 1. There are several elements in power system which manages the generation and absorption of the reactive power. The generating stations, line/cable charging and shunt capacitor bank are the sources for reactive power while transformer, shunt reactors, lines reactance and loads are the main sinks. The total reactive power demand in the northern region is 69511.6 MVAr which consists of 17595.8 MVAr load demand, line shunt absorption of 25844 MVAr and network reactive loss of 26071.8MVAr. This large amount of reactive power requirement is met from generating stations (3270 MVAr), line charging (70548.5 MVAr), bus shunt capacitor/ inductor (-4820.9 MVAr) and total is 68997.6 MVAr. The deficit of 514 MVAr is imported from other regions of the national grid. This regional exchange of reactive power is the main cause of artificial loading conditions in transmission and distribution lines and bus voltage reduction.

Table 1. Generation and load balance

Generation		Load		Shunt Capacitor (-cap/ +ind)	Line Absorption (Inductive)	Line Charging (capacitive)	Losses		Tie-Line Flow (-import/+export)	
P	Q	P	Q	Q	Q	Q	P	Q	P	Q
MW	MVAr	MW	MVAr	MVAr	MVAr	MVAr	MW	MVAr	MW	MVAr
47951	3270	62140.6	17595.8	4820.9	25844	70548.5	1900.7	26071.8	-16091	-513.8

Table 2. Base case Central and State transmission utility power exchange in Northern region

FROM	TO	P(MW)	Q(MVAr)
PUNJAB	OTHER AREA	-6157	-1318
HARYANA		-7979	-2199
RAJASTAN		-3325	-967
DELHI		-4910	-1312
UTTAR PRADESH		-10121	-299
UTTARKHAND		-757	-453
HIMACHAL PRADESH		-161	614
JAMMU & KASHMIR		-514	-884

The exchange of active and reactive power among different power transmission and generation utilities in northern grid are mentioned in Table 2. Haryana (2199 MVAr) and Punjab (1318 MVAr) are the main states with high import of the reactive power. Similarly, the reactive power import for other states is listed in Table 2. The commutative import of reactive power from the other region is 514 MVAr and is shown in Table 3.

Table 3. Base case Inter regional power exchange

FROM AREA	TO AREA	Base case	
		P (MW)	Q (MVAr)
UP	ER_ISTS_BIH	-37	20
	JHARKHAND	63	-28
	WR_ISTS_MP	-3373	225
RAJASTHAN	MP	24	-6
	WR_ISTS_MP	-1314	197
	WR_ISTS_GUJ	-264	-262
NR_ISTS_UP	WR_ISTS_MP	-2729	261
	NER-ISTS	-902	-366
	ER_ISTS_WB	-541	-134
	ER_ISTS_BIH	-2609	1630
NR_ISTS_HAR	WR_ISTS_CHAT	-2500	-1128
AURAIYA	MP	16	1
NR_ISTS	GUJARAT	-2006	-991
NR_ISTS_RAJ	GUJARAT	162	-33
RAPS-C	WR_ISTS_MP	-108	110
TANAKPUR	FAR-WEST NEP	28	-10
TOTAL		-16090	-514

Methodology mentioned in Phase-I of the proposed algorithm is utilized in this part for recommending compensation at the transmission level. The consolidated view of reactive power compensation recommended state wise can be found in Table 4. Total compensation recommended for NRPC is 5401.41 MVAr. Some capacitor banks 8226.95 MVAr (switched shunt) and 423.47 MVAr (fixed shunt) capacitors are already existing in northern grid as per the PSSE data. Hence, the total compensation (14051.88 MVAr) in Northern region is the summation of existing capacitor banks and recommended capacitor banks.

Table 4. Recommended Capacitor banks for NRPC

State	Existing Capacitor Bank as per base case file dated on 11.07.2018 (operational)		Recom-mended Capacitor Banks (MVAr)	Total Com-pensation (MVAr)
	Switched Shunt (MVAr)	Fixed Shunt (MVAr)		
Punjab	1465.49	301.27	629.25	2396.01
Haryana	227.1	0	1304.83	1531.93
Rajastan	45.3	0	1659.4	1704.75
Delhi	0	0	1254.3	1254.3
Uttarpradesh	6020.46	0	37	6057.46
Uttarakhand	155	0	163	318
Himachal Pradesh	853.12 (293.6)*	122.2	0	415.8
Jammu & Kashmir	20	0	353.63	373.63
Total	8226.95	423.47	5401.41	14051.88

* Only 293.6 MVAr of switched shunt among 853.12 MVAr is enabled in HP during the study.

Then the load flow results show that the excessive reactive power drawn from other states and inter regional tie lines is limited by installing fixed shunt capacitor banks at the identified locations. This in turn results in the improvement in bus voltage profile of all buses in northern region and are in line with limits specified in IEGC. The reduction in reactive power flow between states and inter regional tie lines are given in Tables 5 and 6 respectively.

Table 5. Central and State transmission utility power exchange in Northern region with recommended compensation

FROM	TO	P(MW)	Q(MVAr)
PUNJAB	OTHER AREA	-6148	-1021
HARYANA		-7965	-1763
RAJASTAN		-3289	-105
DELHI		-4905	-554
UTTAR PRADESH		-10113	-285
UTTARKHAND		-755	-362
HIMACHAL PRADESH		-156	141
JAMMU & KASHMIR		-511	-731

Table 6. CTU/STU power exchange in Northern region with recommended compensation

FROM AREA	TO AREA	Year 2019-2020	
		P (MW)	Q (MVAr)
UP	ER_ISTS_BIH	-36	23
	JHARKHAND	63	-28
	WR_ISTS_MP	-3356	299
RAJASTHAN	MP	30	-5
	WR_ISTS_MP	-1314	278
	WR_ISTS_GUJ	-256	-199
NR_ISTS_UP	WR_ISTS_MP	-2716	375
	NER-ISTS	-902	-366
	ER_ISTS_WB	-541	-134
	ER_ISTS_BIH	-2580	1764
NR_ISTS_HAR	WR_ISTS_CHAT	-2500	-1129
AURAIYA	MP	20	9
NR_ISTS	GUJARAT	-2006	-988
NR_ISTS_RAJ	GUJARAT	172	47
RAPS-C	WR_ISTS_MP	-103	136
TANAKPUR	FAR-WEST NEP	28	-11
TOTAL		-15997	71

3.2 Capacitor Bank Placement at DISCOM Networks

Compensation identified at 132 kV substation is distributed to 11 kV substation based on variations in loading conditions, voltage profile and amount of compensation required. Then Phase–II of proposed algorithm is implemented to derive an empirical relationship for capacitor bank requirement against voltage profile in the DISCOM networks. The proposed empirical relation might not guarantee the amount of exact compensation needed at the downstream substation due to broad assumptions taken while modelling the distribution systems. But it may definitely work as a thumb rule for DISCOMs for capacitor bank planning. The major assumptions are;

i. Typically, 4 to 6 no. of 11 kV substations are considered for each 132 kV.
ii. One or two no. of transformers are considered at 132/33/11 kV substation.
iii. Length of line feeder for 33 kV is considered as 5 km Dog Conductor.
iv. 132/33/11 substation are loaded up to 75% of their transformer rating. Whereas, they are only loaded around 50 % as per PSSE file.
v. All the downstream 33/11kV station are uniformly loaded.

The performance of the proposed index is studied for few candidate locations at which the capacitor bank requirement is identified using Phase I. Distribution system data of few NRPC states are reviewed and it is observed that there exist some general DISCOM network configurations Viz 132/33/11kV (Config 1) and 132/11kV (Config 2) in northern region. Then DISCOM network data of Haryana state has been reviewed in detail and five 132 kV substations are considered for further study. Dhamtaan_132 is one among them. And its downstream structure is modelled with configurations 1 and 2 as shown in Fig. 2. At Dhamtaan_132, four 11 kV substations are considered. Then loads and switched shunt capacitor banks are integrated to these 11 kV buses. In Figure 2 highlighted red portion is 11kV DISCOM network and highlighted green portion is 132 and 33 kV TRANSCOM network. The study has been performed for 50 to 75 % loading capacity of 132 kV power transformers. The loading at all 11 kV buses are varied to generate a low voltage profile which is generally observed in the northern region. Then switched shunts are allowed to operate for preset voltage with step size 0.01 p. u. Reactive power support provided by switched shunt capacitors placed at the low voltage load bus under Config. 1 and 2 is then recorded. Figures 3, 4 represents the graphical relation between per unit voltage and reactive power injected in MVAr at particular bus.

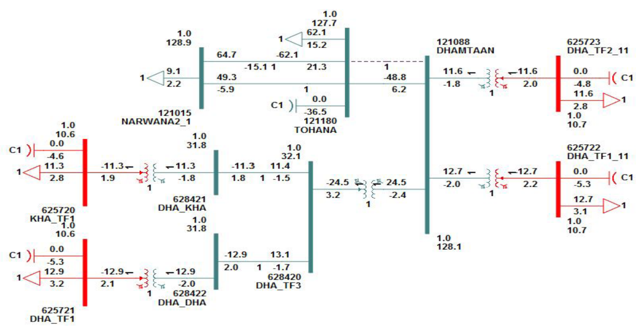

Figure 2. General distribution network configuration for Dhamtaan.

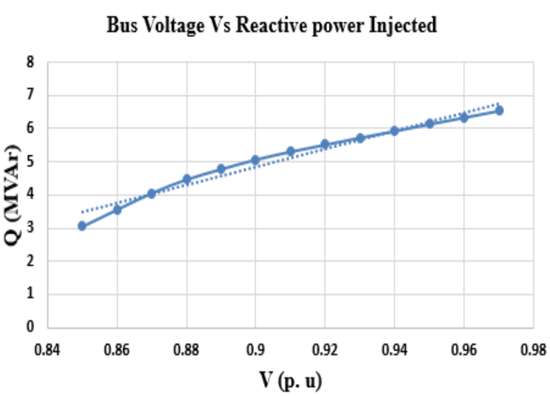

Figure 3. Variation in reactive power compensation for Config 1.

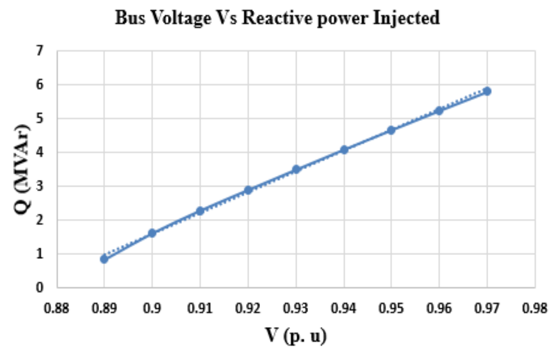

Figure 4. Variation in reactive power compensation for Config 2.

The compensation required for 0.01 p. u boost in the voltage of downstream bus is then obtained using the empirical relation and is tabulated in Table 7. It is observed that, the additional compensation required for different configurations are different for same per unit change in bus voltage. These variations arise due to the different network connectivity, number of feeders and number of distribution transformers associated with each configuration.

Table 7. Empirical Relationship For Identifying Capacitor Bank Requirement at DISCOM Networks

Voltage at 11 kV bus (pu)		Incremental capacitor requirement Qem (MVAr)	
Vi(initial) (pu)	Vd(Desire) (pu)	Config1 (132/33/11kV)	Config2 (132/11kV)
0.8	0.81	0.66	-
0.81	0.82	0.6	-
0.82	0.83	0.55	-
0.83	0.84	0.53	-
0.84	0.85	0.52	-
0.85	0.86	0.51	-
0.86	0.87	0.5	-
0.87	0.88	0.41	-
0.88	0.89	0.31	0.84
0.89	0.9	0.29	0.78
0.9	0.91	0.24	0.67
0.91	0.92	0.21	0.61
0.92	0.93	0.21	0.6
0.93	0.94	0.2	0.59
0.94	0.95	0.2	0.58
0.95	0.96	0.2	0.57
0.96	0.97	0.2	0.56

Table 8 shows the comparison of voltage and compensation found at the substation Dhamtaan. The amount of compensation obtained at transmission level is denoted by Qt and summation of compensation identified at 11kV buses using empirical relation is Qem. It is observed that, the summation of compensation found at all 11kV buses for the 132kV station are in close proximity with compensation found at transmission level as per the initial study. And the bus voltages are also within the IEGC limits.

Table 8. Bus voltage profile comparison in Dhamtaan

Bus Name	Initial Voltage Vi (pu)	Qt (MVAr)	Bus Voltage with Qt, Vd (pu)	Qem (MVAr)	Bus Voltage with Qem, Vd' (pu)
DHAMTAAN	0.921	15	0.9729	15.59	0.97

Voltage profile of 11kV load buses without and with required capacitor banks are listed in Table 9.

3.3 Validation of Empirical Relationship

The empirical relationship is evaluated in this section in another 132kV substation named Rai_1. The downstream structure of this station is modelled in a similar way with configurations 1 and 2 as shown in Figure 5. The no. of 11kV substations considered is 6 at this station. Then load flow analysis is performed and voltage profile of all load buses.

Table 9. Voltage profile of 11kV buses at Dhamtaan

Bus Name	Base kV	Initial Bus Voltage, Vi (pu)	Qem (MVAR)	Bus Voltage with Qem, Vd' (pu)
DHAMTAAN	132	0.9181	15.59	0.97
KHA_TF1	11	0.863	2.97	0.95
DHA_TF1	11	0.8571	3.48	0.947
DHA_TF1_11	11	0.8982	4.96	0.9761
DHA_TF2_11	11	0.9	4.18	0.9738

Table 10. Bus voltage profile comparison in Rai_1

Bus Name	Initial Voltage Vi (pu)	Qt (MVAr)	Bus Voltage with Qt, Vd (pu)	Qem (MVAr)	Bus Voltage with Qem, Vd' (pu)
RAI _1	0.8608	41	0.9745	41	0.9554

are observed. Subsequently required compensation is calculated using Table 7 based on the initial voltage at each load bus. And load flow studies are performed again by placing fixed capacitor banks with calculated amount of compensation at these load buses and improvement in voltage profile at each bus is analyzed. Table 10 shows the comparison of voltage and compensation found at the substation Rai_1 and it is observed that, the summation of compensation found at all 11kV buses as per the empirical relation is also in close proximity with compensation found up to TRANSCOM network level. And the bus voltage profiles are also within the IEGC limits.

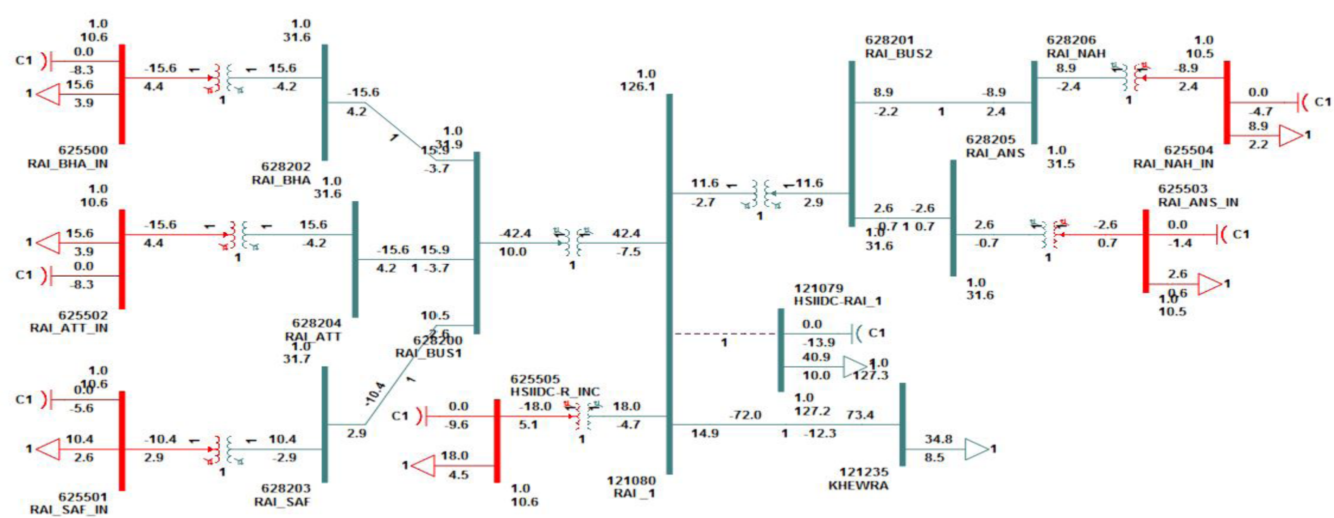

Figure 5. General distribution network configuration for Rai_1.

Table 11. Voltage profile of 11kV buses at Rai_1

Bus Name	Base kV	Initial Bus Voltage, Vi (pu)	Qem (MVAR)	Bus Voltage with Qem, Vd' (pu)
RAI _1	132	0.8437	41	0.9554
RAI_BHA_IN	11	0.791	7.06	0.9508
RAI_SAF_IN	11	0.8019	6.34	0.9584
RAI_ATT_IN	11	0.791	7.06	0.9508
RAI_ANS_IN	11	0.8338	4.53	0.969
RAI_NAH_IN	11	0.8212	5.08	0.9594
HSIIDC-R_ INC2	11	0.8381	10.93	0.961

Table 11 gives the voltage profile of 11kV load buses without and with required capacitor banks identified. So the improvement in bus voltage of the station Rai_1 shows the effectiveness of empirical relation formulated. And it is observed that the amount of compensation obtained for DISCOM networks are enough to keep the bus voltages within the IEGC limits.

4. Conclusion

Reactive power management is an essential operational requirement for smooth voltage control in power utilities. The requirement of reactive power in power networks can be estimated at planning stage by modelling the power networks. The load growth and installation of reactive power consuming devices necessitates the requirement of reactive power compensation devices.

In a large distributed power network, with large no. of generators, long transmission lines and giga watt sized load centres it is a very time consuming and complicated affair to model the network and estimate the reactive power requirement based on system studies. In India power flow network models for TRANSCOM networks are mostly modelled for power systems studies. But the downstream DISCOM network information is not easily available and without this information it is very difficult to estimate the requirement of reactive power compensation.

In this article, an empirical relation based on the variation in loading profiles and nature of power factor has been established. This relationship will estimate the amount of capacitor bank required for reactive power compensation without modelling the DISCOM network. The aggregated compensation identified at DISCOM level is compared with compensation identified at TRANSCOM level. It is found that empirical relationship gives a good estimate for capacitor bank requirement for DISCOM networks for reactive power management and voltage control within IEGC operation limits.

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