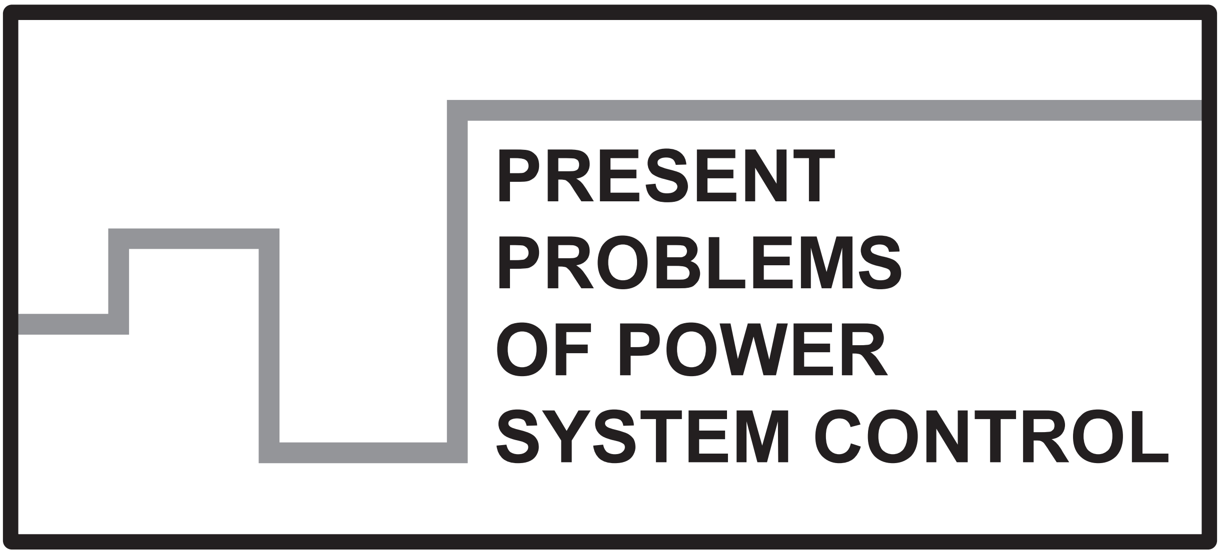
**Scientific Papers of
the Department of Electrical Power Engineering of
the Wrocław University of Technology**



PRESENT PROBLEMS OF POWER SYSTEM CONTROL

7

Wrocław 2016

Guest Reviewers

Ivan DUDURYCH
Tahir LAZIMOV
Murari M. SAHA

Editorial Board

Cover design

Piotr PIERZ

Printed in the camera ready form

Department of Electrical Power Engineering
Wrocław University of Science and Technology
Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland
phone: +48 71 320 35 41
www: http://www.weny.pwr.edu.pl/instytuty,52.dhtml; http://www.psc.pwr.edu.pl
e-mail: wydz.elektryczny@pwr.edu.pl

OFICYNA WYDAWNICZA POLITECHNIKI WROCŁAWSKIEJ
Wybrzeże Wyspiańskiego 27, 50-370 Wrocław
http://www.oficyna.pwr.edu.pl
e-mail: oficwyd@pwr.edu.pl
zamawianie.ksiazek@pwr.edu.pl

ISSN 2084-2201

Print and binding: beta-druk, www.betadruk.pl

capacitor bank, power loss,
voltage profile, distribution system,
MATLAB

Sunny KATYARA*, Madad Ali SHAH*,
Jan IŻYKOWSKI**

POWER LOSS REDUCTION WITH OPTIMAL SIZE AND LOCATION OF CAPACITOR BANKS INSTALLED AT 132 kV GRID STATION QASIMABAD HYDERABAD

With growing concerns about voltage profile and power factor at distribution networks, the capacitor banks are invariably installed for reactive power compensation. The reactive power supplied by capacitor banks is proportional to square of their rated loading voltage. Capacitor banks eventually increase the loading capacity of feeders, so as to supply more customers through same line section. Capacitor banks can be installed anywhere on the network.

The idea of this paper is to reduce total power loss and ensure greater availability of capacitor bank installed at 132 kV grid station Qasimabad Hyderabad, for reactive power compensation, even under worst conditions on distribution system. This is achieved by enhancing its location and size. At present capacitor bank of full size, i.e. of 1.21 Mvar is installed at 11 kV bus of 132 kV grid station Qasimabad Hyderabad. Moreover this paper suggests small sized capacitor banks that would be installed at different feeders instead of one large size capacitor bank at 11 kV bus. The voltage profile and power losses with present sized capacitor bank and the proposed small sized capacitor banks are compared in this work. The distribution network has been simulated by using MATLAB Simulink.

1. INTRODUCTION

Modern power distribution systems experience rise in power losses during summer period [1]–[2]. This is mainly related to the excessive use of reactive loads. Such rise in this nature of load is supplemented with stumpy power factor (~78%) so it requires large reactive power transfer from the utility via network. The prime

---

* Sukkur Institute of Business Administration, Pakistan.
** Wrocław University of Science and Technology.

disadvantage of this issue is the rise of network losses and discount of voltage profile. Low voltage profile leads to malfunctioning or reduction in the lifetime of electric devices and increases the internal losses of cables and motors; hence decreases the efficiency [3]. For reactive power reparation, shunt capacitors are invariably installed at grid station. The main purpose of these capacitor banks is to lessen line and energy losses, sustain paramount voltage regulations at load buses and advance power network safety [4]. The extent of compensation delivered is highly associated to the location of capacitors in the utility network which fundamentally is the investigation of the position, size, numeral and sort of capacitors to be installed in the network [5]. A diverse range of investigation has already been performed on capacitor bank's placement and size problem in the past. But in this our research work we have presented a new technique for capacitor bank location and size so as to lessen total power loss to a greater extent.

Since power distribution network of 132 kV grid station Qasimabad Hyderabad has four transformers and 25 feeders, spreading geographically to supply major parts of Hyderabad city. The capacitor banks of 1.21 Mvar are invariably installed at four transformers buses for reactive power compensation of all feeders. The voltage levels of distribution feeders have greater voltage drop under the substantial load circumstances. Subsequently it offers unproductive facility to its users [6]. Procedures to resolve this issue are considering different techniques such as indigenous capacitor discrepancy, loss bargaining through capacitor installations, installation of synchronous generator, improvement through three phase balancing of utility system, constructing new substations, erecting new feeders and load balancing among feeders or incorporating photo voltaic production to distribution networks [7]–[8]. Capacitor bank position is the usual technique to decrease line losses and to sustain voltage profile beneath the restraints due to economy, modest connection and unpretentious apparatus [9].

However if a big size capacitor bank installed at 11 kV bus fails then regulation for whole feeder would be lost. Therefore proposed idea is to install small sized capacitor banks on each individual feeders. The size of this small sized capacitor bank would be calculated on the basis of reactive power demand of that particular feeder. With this arrangement not only total power loss reduces but also high availability of capacitor banks and accurate voltage regulation can be achieved. Means if any of capacitor bank at any feeder fails then it would not affect the regulation of other feeders as with the failure of large sized single bank installed at 11 kV bus. Although the cost of replacing large size capacitor bank installed at 11 kV bus by small sized capacitor banks installed at individual feeders is more [10] which is actually a disadvantage but mercy is that the transient produced by small sized capacitor banks are less than that of large sized capacitor banks. So the power loss contributed by these small sized capacitor banks would also be small. Therefore the money saved on these losses by small sized capacitor banks is approximately same as cumulative extra cost invested on these small sized capacitor banks for installation.

In this research work, investigative methods have been implemented to examine the capacitor bank's position and its size for decimation of total line losses and cost discount in utility feeders. Also if the location of capacitor is changed from bus with large capacitor bank to individual feeders with small sized capacitor banks then either the voltage profile of system is maintained or not. And also it has been analyzed that whether the system is balanced or unbalanced, it would not affect the system regulation if individual small banks are being installed at different feeders [11]. All these consequences have analyzed through MATLAB simulations.

2. DISTRIBUTION NETWORK CHARACTERISTICS

2.1. OBJECTIVE FUNCTION AND LINE LOSS ESTIMATION

Mathematically, an objective function is used to express the network's characteristics. It is used to minimize the power loss and deviation in the voltage [1]–[2]. This objective function is given by the expression (1):

$$F = W_1 P_{\text{loss}} + W_2 \sum_n (1 - V_i)^2 \tag{1}$$

where W_1 and W_2 are the coefficients of the objective function for the line power losses and voltage deviation, P_{loss} is the total power loss on the distribution network and V_i is the magnitude of the voltage on the i-th feeder.

The complex power at any bus, let say at the i-th bus, can be estimated by the expression (2):

$$P_k + jQ_k = V_k I_k \tag{2}$$

where P_k – real power of the k-th feeder, Q_k – reactive power of the k-th feeder, V_k – voltage at the k-th bus.

Gauss-Seidel iterative method can be used for calculating bus voltage and line losses by using the formula (3) [12]:

$$V_i(k+1) = \frac{1}{Y_{kk}}\left(\frac{P_i - jQ_i}{V_i(k)} - \sum_{n=1}^{m} Y_{in} V_n\right) \tag{3}$$

where $V_i(k)$ voltage at i-th bus after 1st iteration, P_k, Q_k – active and reactive powers at k-th bus, $Y_{m,n} = y_{m,n}$ with $m \neq n$ and $Y_{k,k} = y_{k,m-1} + y_{k,m+1} + y_{ji}$ with $m = n$.

In the line section the power loss between the buses i and $i + 1$, at the power frequency can be calculated by equation (4) [12]:

$$P_{\text{loss}}(i,\, i+1) = R_{i,i+1}\left[\left|V_{i-1} - V_i\right| \cdot \left|y_{i,i-1}\right|\right]^2 \tag{4}$$

where $Y_{m,i+1} = \dfrac{1}{R_{i,i+1} + jX_{i,i+1}}$ – admittance of the line section between buses $i + 1$ and m, $R_{i,i+1}$ – line connection bus resistance i and $i+1$, $X_{i,i+1}$ – line connection bus reactance i and $i + 1$.

The total power loss then can be calculated by using equation (5):

$$P_{\text{loss}} = \sum P_{\text{loss}}(i, i+1) \tag{5}$$

3. NETWORK REPRESENTATION

Figure 1 represents the 132 kV network of Qasimabad grid station Hyderabad which is consisting of two 132 kV lines, one is coming from Halla and other from Jamshoro. The 132 kV voltages are stepped down to 11 kV voltages at grid station by means of four Transformers, one of the transformer is rated at 40 MVA and other three are of 26 MVA. It is then distributed to Hyderabad city through 25 feeders. The 11 kV voltage of the feeder is actually its RMS value, the results calculated below are based on peak value which would be (11 kV * √2 = 15.554 kV). When there is heavy load on feeders then a considerable drop of voltage would be observed. For improving the voltage of system, the capacitor banks are installed at the buses before the feeders as shown in Fig. 1.

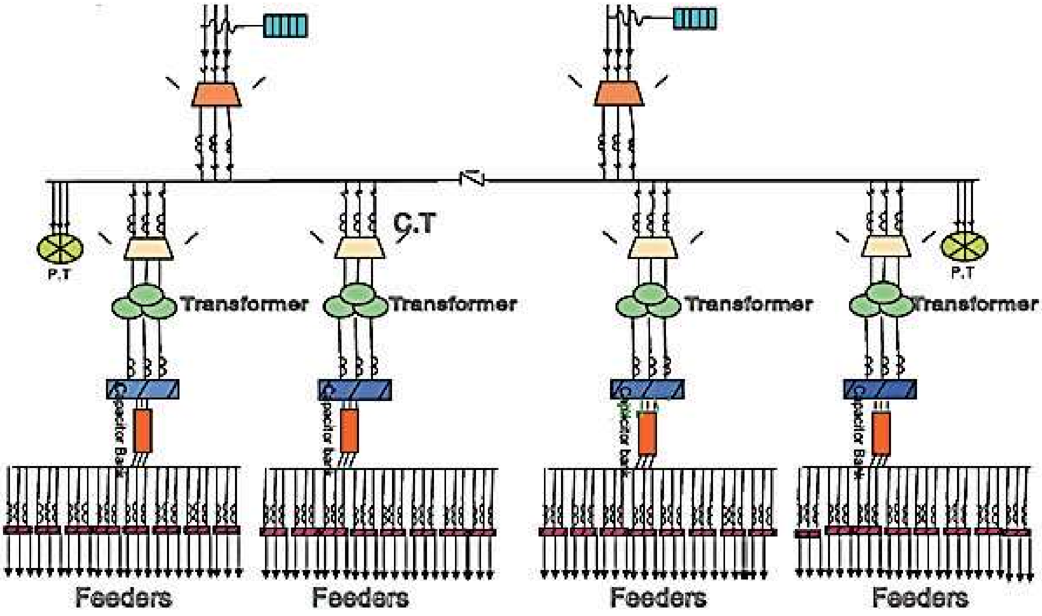


Fig. 1. Graphical illustration of 132 kV grid station Qasimabad, Hyderabad

4. POWER SYSTEM SIMULINK REPRESENTATION

Figure 2 presents the Simulink model of 132 kV grid station Qasimabad Hyderabad. The system was simulated with load of 10 MVA at a 0.87 lagging power factor. These standards were comprised in our MATLAB/SIMULINK model along with line inductances, capacitances, and resistances. The most significant components linked to the buses at the grid station is the static capacitor banks of 1.21 Mvar.

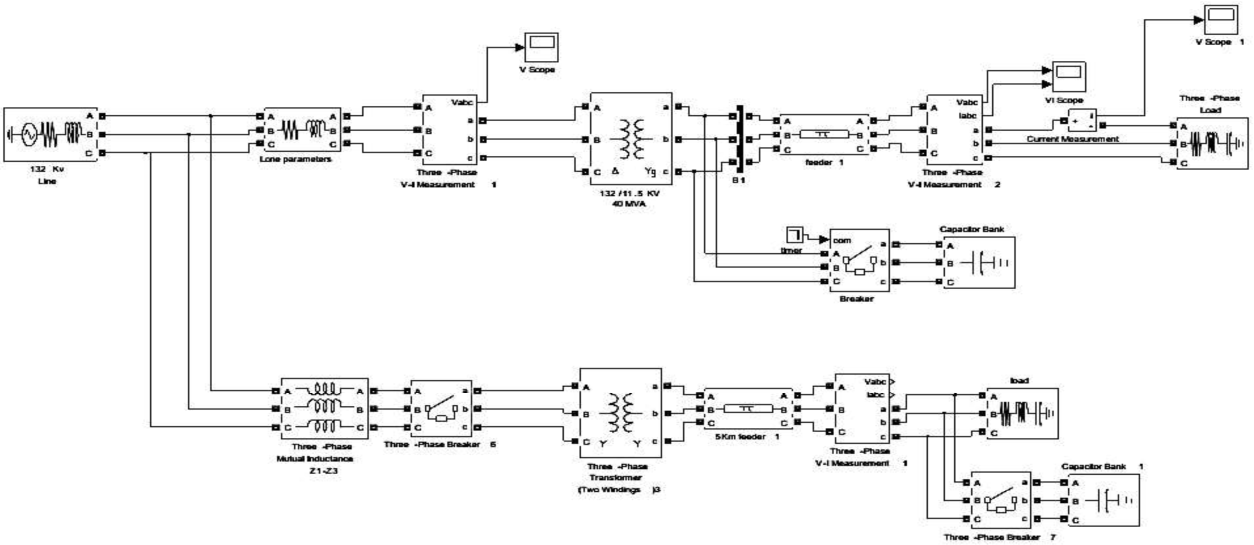


Fig. 2. Simulink model of 132 kV Qasimabad, Hyderabad grid station

5. RESULTS AND DISCISSION

The capacitors banks are normally installed at the buses on the grid station because the numbers of feeders which carry the actual load are connected to them. If we install a large capacitor bank at the bus in order to improve the voltage profile then the feeders which have normal rated loads will get shoot up in their voltages and may cause damage to associated equipments. Capacitors are always designed for largest length of feeders so as to maintain voltage at the far end of it. Since the reactive power supplied by the capacitor is proportional to square of its voltage. When the system voltage is down then reactive power supplied by capacitor will also be low and it is not useful because when we need reactive power then at instant it is not available. It is more convenient to install a separate capacitor bank of small size at each feeder, so that voltage profile could be corrected to the condition of that feeder and unnecessary drop should be avoided [14]. With this configuration the reliability system also increases because if any one of the bank is out of order then it will not influence other neighbouring lines.

5.1. BASE CASE

Initially when no capacitor bank was connected to 0 the system at 132 kV grid station Qasimabad Hyderabad, the system voltage was below the reference value *i*-e 15.554 kV (11 kV RMS) down to 14.14 kV (10 kV RMS) due to reactive power requirement as shown in Fig. 3.

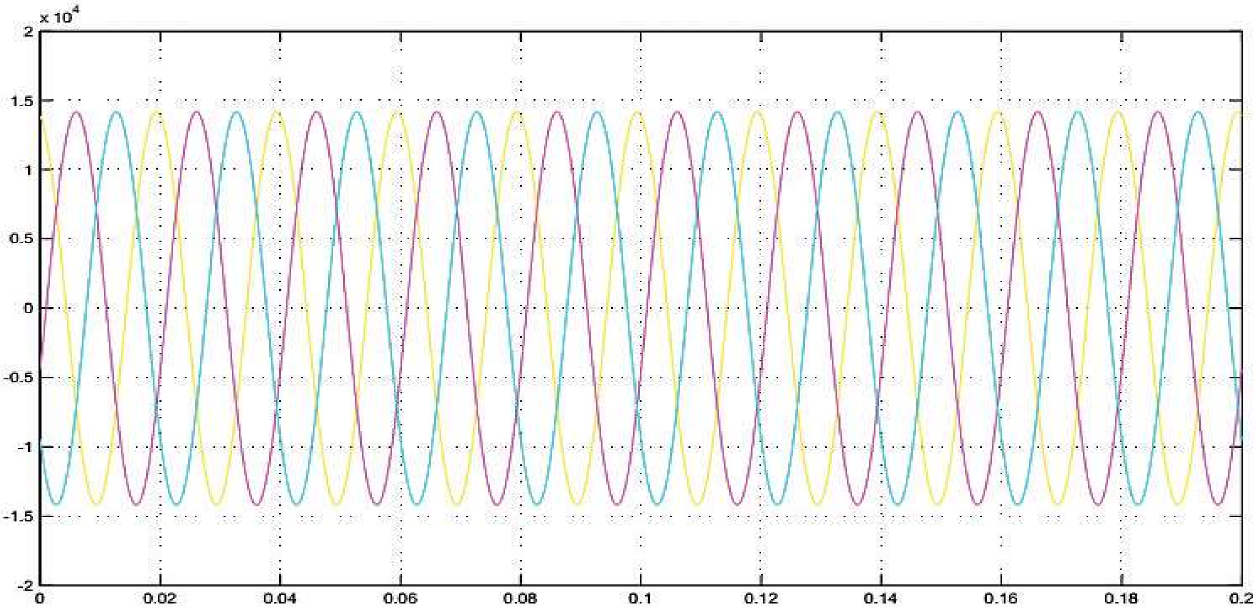


Fig. 3. Voltage at distribution network when no capacitor bank in service

5.2. CAPACITOR BANK (1.21 Mvar) IN SERVICE AT BUS

The size of star connected capacitor bank installed at grid station for reactive power is usually calculated by:

$$\text{Reactive Power} = \frac{V^2}{X_{\text{COMPENSATION}}} \tag{6}$$

Taking $X_{\text{COMPENSATION}} = 100\ \Omega$ would result in Reactive Power = $(11 * 1000)^2/100$ = 1.21 Mvar. When the capacitor banks of 1.21 Mvar were connected to 11 kV buses before the feeders, the voltage was increased from 14.14 kV (10 kV RMS) to 15.554 kV (11 kV RMS) and consequently high frequency transients were also produced at 0.08 sec of supply voltage frequency as shown in Fig. 4. These high frequency transients caused greater power loss in the system. Since now if any of the bank is out of order then, all the feeders connected to bus would lose their voltage regulation. Since the reactive power supplied by capacitor bank is proportional to square of its voltage, so if bus voltage dips below natural line value then power supplied by capacitor banks would reduce four times and it would be unavailable when needed the most.

Therefore it became necessary to install individual small sized capacitor banks at each feeder according to its own reactive power demand. Since the load on each feeder is not same, so the different voltage regulation would be needed for all individuals.

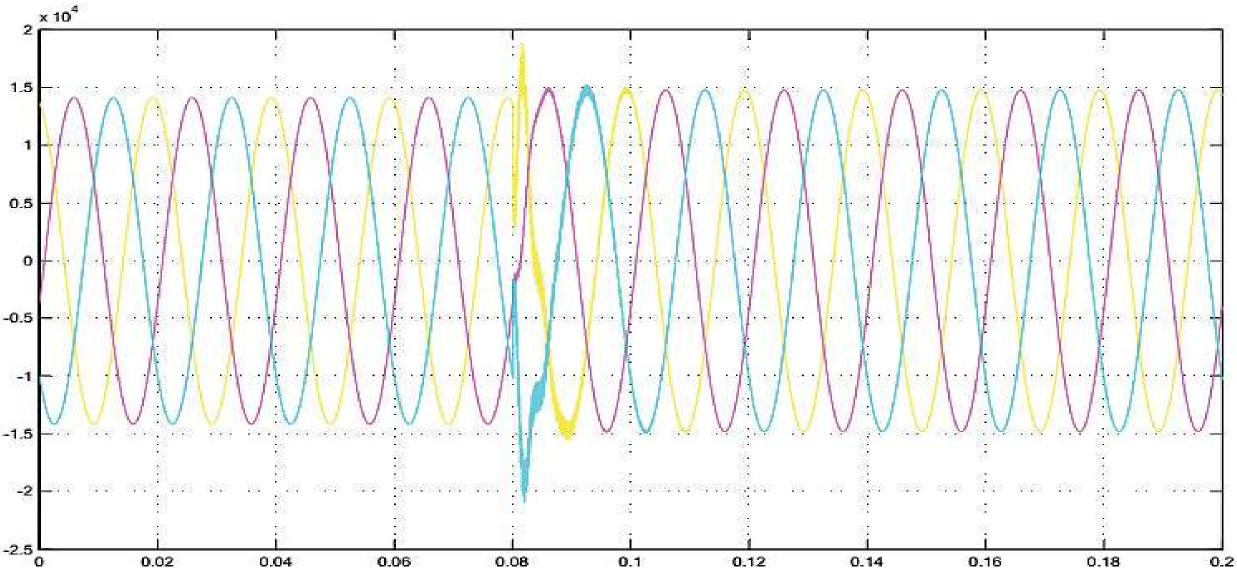


Fig. 4. Voltage at distribution network when capacitors bank is in service

5.3. PROPOSED SMALL CAPACITOR BANK IN SERVICE AT FEEDER

Our suggested way for calculating reactive power of small sized capacitor banks which would be installed individually at feeders is:

$$Q_{\text{bank}} = S_{\text{load}}(p.f_{\text{required}} - p.f_{\text{load}}) \tag{7}$$

Taking: $S_{\text{load}} = 3$ MVA, p.f.$_{\text{load}} = 0.87$, p.f.$_{\text{required}} = 0.953$ one gets: $Q_{\text{bank}} = 250$ kvar.

When capacitor bank of 250 kvar is connected across the Defence feeder installed at 132 kV grid station Qasimabad having load of 3 MVA with a power factor of 0.87 then its voltage improved to exactly 15.554 kV (11 kV RMS*)* and power factor was corrected to 0.953 as shown in Fig. 5.

Since from our above Table 1 it is proved that we can replace large sized capacitor bank having cost of US $ 8000/unit installed at 11 kV bus of 132 kV grid station Qasimabad Hyderabad at by small sized capacitor banks installed at individual feeders with approximately same price as whole of US $ 900/unit and same performance. Yes it is clear that somewhat cost is high, like for six different feeders on single bus the cumulative cost of all small sized capacitor banks would be: Cost = 900 * 6 = $ 5400, which is greater than $ 4000 for single 1.21 Mvar. Since the price of replacing banks for small sized capacitor is surely greater but the amount of money saved on loss reduction is much more than to it, because this replacement expenditure is just for once, then after saving would be for whole life of capacitor banks. The biggest advantage is that high availability of capacitor bank would have been achieved with this arrangement.

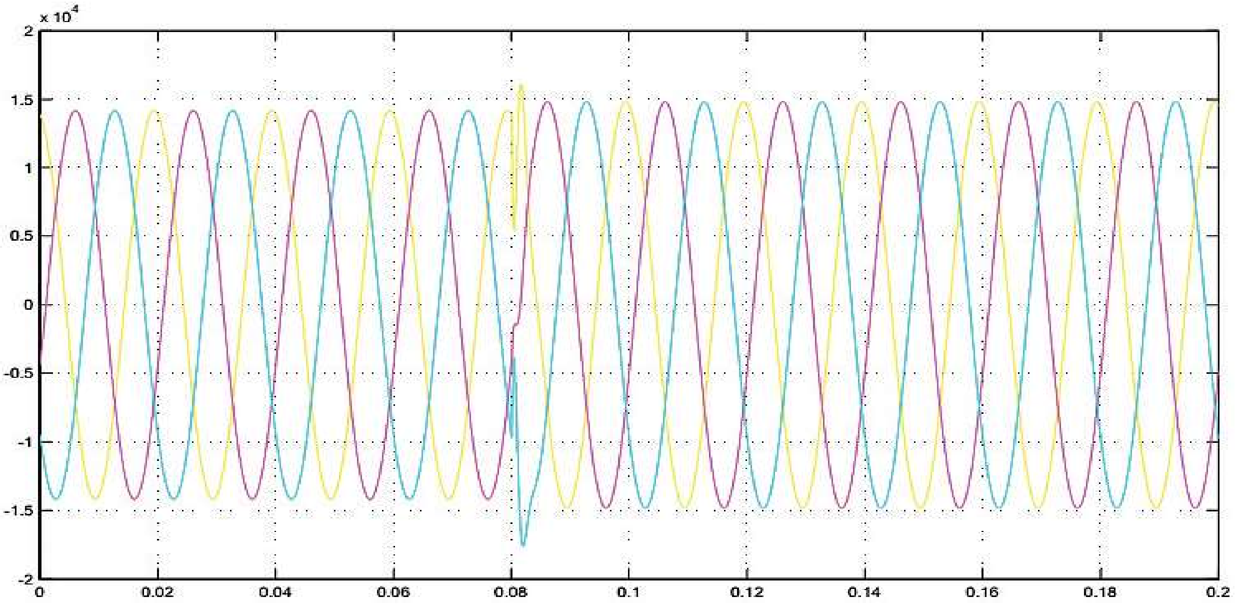


Fig. 5. Voltage at distribution network when small capacitor banks are in service

Table 1. Different companies' capacitor banks with their size and price

S. No.	Name of Brand	Rated Voltage	Rated Power	Price Per Unit
1	TK	11 kV	1.21 Mvar	US $ 4000
2	Daelim	11 kV	1.11 kvar	US $ 7200
3	HV shunt capacitor	1 kV~20 kV	50–800 kvar	US $ 5000–1800000
4	HOMOR	11 kV	100–10 000 kvar	US $ 900
5	ZHIYUE	11 kV	30–334 kvar	US $ 50–450
6	JCKN	11 kV	250 kvar	US $ 100–1000
7	ONLYSTAR	6.3–12 kV	50–500 kvar	US $ 200–2000
8	WIRUN	300 V–12000 V	100–500 kvar	US $ 20–1500

Table 2 shows the characteristic of Defence feeder with old installed capacitor bank and new proposed capacitor bank. It is perceived that total line loss for the utility feeder is 185564 W and loss discount is 12.364% with installed capacitor bank of 1.21 Mvar. But with the proposed capacitor bank the total power loss reduces to

169892 W and loss reduction comes to 12.982%. It is therefore less than total power loss of system. The cost per kvar is also less than that of installed bank. All these results are being calculated and generated by using equations (3), (4) and (5), which are stated above and results are being verified by means of simulations shown above. Thus proposed method offers more accurate reactive power compensation and more loss decimation for a utility feeder.

Table 2. Comparative analysis between installed and proposed capacitor banks

Particulars	Without Capacitor Bank	With Capacitor Bank	
		1.21 Mvar	250 kvar
Maximum Voltage in kV	10.76	11	11.03
Minimum Voltage in kV	10	10.87	10.98
Total loss in (kW)	191.431	185.564	169.892
Cost/kvar $	0.512	0.353	0.312
Loss reduction (%)	0	12.364	12.982

The proposed method offers more accurate reactive power compensation, effective loss reduction and perfect balance of voltage profile for each distribution feeder. This idea was implemented over all 25 feeders and resulting characteristics were illustrated in Table 3. It shows the loading ability of different feeders and on this basis size of capacitor bank was evaluated. With this proposed bank, the associated percentage loss reduction and limit of voltage profile for all 25 feeders is shown in Table 3.

Table 3. Characteristics analysis of different feeders at 132 kV grid station Qasimabad Hyderabad

Sr. No.	Load of Feeder (MVA)	Proposed Capacitor Bank Size (kvar)	Power Loss Reduction (%)	Voltage Profile (p.u.)
1	2	3	4	5
1	4.5	375	12.657	1.003
2	2.8	235	12.432	1.002
3	1.5	125	11.987	1.007
4	3	250	12.982	1.006
5	0.55	46	12.232	1.008
6	0.88	75	12.752	1.005
7	3.85	320	11.879	1.004
8	0.44	38	12.675	1.005
9	1.76	150	12.314	1.008
10	0.99	85	13.123	1.006
11	1.65	140	12.573	1.000
12	1.76	148	12.773	1.001

1	2	3	4	5
13	0.11	10	12.586	1.002
14	2.09	175	11.921	1.000
15	0.11	10	13.142	1.003
16	2.09	175	12.148	1.006
17	1.1	95	12.865	1.009
18	1.32	110	12.554	1.000
19	0.99	85	12.813	1.003
20	1.43	120	11.971	1.005
21	1.43	120	12.745	1.002
22	1.1	95	12.963	1.005
23	1.87	160	12.461	1.007
24	0.88	75	11.978	1.004
25	0.11	10	12.785	1.003

6. CONCLUSION

Since the enhancement of voltage profile, the reduction of line losses and their prices at 132 kV grid station Qasimabad Hyderabad were discussed in this research work by augmenting the size and location of the capacitor bank. It was analysed and calculated that installed capacitor banks of 1.21 Mvar at 132 kV grid station Qasimabad Hyderabad should be replaced with small sized bank of about 250 kvar calculated according to feeder load, which is different for different feeders. This proposed bank is to be installed at individual feeders, so that regulation characteristics on each it can be obtained precisely according to its reactive power demand. This technique also facilitates the high availability of capacitor banks which should be met during the peak load hours. Also with small sized capacitor banks less amplitude and low frequency transients would be produced, so the power losses in the system were found to be least. The cost of small sized capacitor banks with the sum to approximate the large sized single capacitor bank was high but the loss reduction and function of high availability obtained through the small sized capacitor banks were more outstanding than that of cost difference. It is therefore can be concluded that the results from suggested technique were preeminent; which guarantees the dominance of this proposed effort.

7. FUTURE RECOMMENDATIONS

Practical implementation of the capacitor bank placement technique requires further cost benefit analysis which in turn depends upon cost of capacitor bank and energy saving. Also the repeated simulation results could be used to develop a model using any artificial intelligence technique. This technique can accurately predict the location and size of capacitor bank for any load conditions without making any delay. It gives the great edge to implement our proposed technique practically.

ACKNOWLEDGEMENT

Associated authors are gratified to Mehran University of Engineering and Technology Jamshoro Pakistan for supporting our research work and providing free hand access to their laboratories. Authors are also thankful to technical staff of 132 kV grid station Qasimabad Hyderabad for helping to get required data. First author is very much thankful to Prof. Dr. Ashfaque Ahmed Hashmani and Prof. Dr. Bhawani Shankar Chowdhary for supporting and motivating our research work.

REFERENCES

[1] MILLER T.J, *Reactive power control in electric system*, John Wiley & Sons, Inc., New York 1982.
[2] BARAN M.E., WU F.F, *Optimal capacitor placement on radial distribution system*, IEEE Transaction on Power Delivery, Vol. 4, No. 1, January 1989, 725–734.
[3] CHEN C.S., SHU C.T., YAN Y.H., *Optimal distribution feeder capacitor placement considering mutual coupling effect of conductors*, IEEE Transactions on Power Delivery, Vol. 10, No. 2, April 1995, 987–994.
[4] GONEN T., *Electric power distribution system engineering*, McGraw-Hill, 1986.
[5] AL-HINAI S., ELLITHY K., AL-BADI A., AL-NOFLI A., AL-HATMI S., *Determination of optimal rating and location of shunt Var compensation for SQU distribution network*, Proceeding of GCC Cigré 13th Annual Seminar, Muscat, Oman, October 2002, 205–212.
[6] COELHO DE CASTRO C.L.C., DA SILVA M.G., RODRIGUES A.B., *Inclusion of voltage drop and feeder loading constraints in the evaluation of reliability indices for radial distribution networks*, Generation, Transmission and Distribution, IEE Proceedings, Vol. 4, No. 6, November 2006, 661–669.
[7] HAMADA M.M., WAHAB A., EL-SAYED M., RAMADAN A., *A proposed strategy for capacitor allocation in radial distribution feeders*, Power Systems Conference Proceedings, Vol. 4, No. 5, March 2006, 146–151.
[8] KYU-HO KIM, SEOK-KU YOU, *Voltage profile improvement by capacitor placement and control in unbalanced distribution systems using GA*, IEEE Power Engineering Society Summer Meeting, Vol. 2, No. 4, July 1999, 800–805.
[9] HSIAO-DONG CHIANG, JIN-CHENG WANG, JIANZHONG TONG, DARLING G., *Optimal capacitor placement, replacement and control in large-scale unbalanced distribution systems: system solution algorithm and numerical studies*, IEEE Transactions on Power Systems, Vol. 10, No. 1, February 1995, 363–369.
[10] NG H.N., SALAMA M.M.A., CHIKHANI A.Y., *Capacitor allocation by approximate reasoning fuzzy capacitor placement*, IEEE Transaction on Power Delivery, Vol. 15, No.1, January 2000, 393–397.

[11] KHODR H.M., ZERPA I.J., DE OLIVEIRA-DE JESUS P.M., MATOS M.A., *Optimal phase balancing in distribution system using mixed-integer linear programming*, Transmission and Distribution Conference Proceedings, August 2006, 1–5.

[12] MALANGE F.C.V., ALVES D.A., DA SILVA L.C.P., CASTRO C.A., DA COSTA G.R.M., *Real power losses reduction and loading margin improvement via continuation method*, IEEE Transactions on Power Systems, Vol. 19, No. 5, August 2004, 1690–1692.

[13] CHANDRA A., AGARWAL T., *Capacitor bank designing for power factor improvement*, ISSN 2250-2459, ISO 9001:2008 Certified Journal, Vol. 4, Iss. 8, August 2014.

[14] NATRAJAN R., *Power system capacitors*, Taylor & Francis Group, LLC, International Standard Book Number-I 0:1-57444-710-6, USA, May 1996, 45–67.

[15] MUHUMMAD A., MASOUM S., LADJEVARDI M., JAFARIAN A., FUCHS E., *Optimal placement, replacement and sizing of capacitor banks in distorted distribution networks by genetic algorithms*, IEEE Transactions on Power Delivery, Vol. 19, No. 4, October 2004, 1794–1801.