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Placement of Capacitors in the Electrical Distribution System to Improve the Voltage Profile and Reduce Active Power Losses and Reactive Power Losses

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Abstract

In distribution systems, the generation and transmission of reactive power over long distances are economically impractical. However, this study proposes an efficient solution to meet the demand for reactive power by strategically integrating capacitor banks at load centers. Distribution systems commonly face issues such as high power losses and poor voltage profiles, primarily due to low power factors resulting in increased current and additional active power losses.

This article focuses on assessing the static effects of capacitor bank integration in distribution systems. The study involves the deployment of 3.42MVAr capacitor banks in 20kV, 4-bus-bar systems and 1.164MVar capacitor banks in 0.4kV, 2-bus-bar systems. The impact is thoroughly analyzed through measurements and pre/post-installation studies. Load flow analysis, conducted using Power World software for simulation modeling, predicts power flows, voltage levels, and active power losses across system branches.

We draw a comprehensive comparison between distribution systems with and without capacitor banks, encompassing both technical and economic aspects. The evaluation includes power flow magnitudes, voltage profiles, and active power losses. The proposed approach offers numerous benefits, including power factor correction, reactive power support, reduced losses, and enhanced voltage profiles in the distribution system.

Keywords: Capacitor Bank Placement, Load Flow Analysis, Power Factor Correction, active power and power losses and Voltage Profile

1. Introduction

In the Afghanistan the Electrical distribution systems usually suffers from two major problems, poor voltage profile and high power losses. They define losses as the difference between the energy in the system and the energy used by end users. In a typical power system at peak load conditions, reactive power losses are approximately 8-10 times greater than their active power counterparts because the inductive reactance of high voltage transmission lines is approximately 8-10 times greater than resistances. Also, to transmit large blocks of active power across transmission systems, sufficient reactive (support) power is required to maintain proper transmission voltages and maintain voltage stability under both normal and contingency conditions. Producing reactive power in a power plant and supplying it to a load that is located far away is not economically efficient, but it can be easily supplied by power capacitors located in load centers (Gönen, 2014).

The cause of low power factor is economically undesirable, for example, most induction motors have low lagging power factor, which is very small at light load (0.2-0.3) and reaches (0.8-0.9). The full load is a different load in the power system. Being high in the morning and evening and low at other times. During the low load period, the supply voltage increases, which increases the magnetizing current. This leads to a decrease in the power factor in the field of view. Normally, the total load power factor in the power supply system is less than 0.8. A power factor less than unity leads to many disadvantages, a low power factor is very undesirable because it increases the current, because the increase in current causes a large KVA rating of the equipment, larger conductor size, and high copper losses. Poor voltage regulation, reducing the capacity of the system (Hofmann et al., 2012).

The benefits of the system due to the use of shunt capacitors include power factor correction, reactive power support, line and transformer loss reduction, power system capacity release, energy savings due to increased energy loss, voltage profile improvement, and active power transmission capacity increase. These benefits apply to both distribution and transmission systems (Glover et al., 2017).

1.1. Research Objectives:

1- To Analyze the Voltage Profile of the Distribution System by Evaluate the current voltage profile of the distribution system and Identify areas with voltage drops or fluctuations, and Determine the optimal voltage levels for efficient operation.

2- To Assess how the placement of capacitors affects the voltage profile, and Simulate various scenarios with different capacitor placements, and Compare voltage profiles before and after capacitor placement.

3- To Evaluate the Reduction in Active and Reactive Power Losses, before and after capacitor placement.

1.2. Importance of the research

The importance of the research lies in the importance of its topic, as Proper capacitor placement helps maintain the voltage levels within desired limits throughout the distribution network, ensuring stable and reliable power supply, and minimizes voltage drops across the distribution lines, improving the overall voltage stability of the system.

Also the Capacitors reduce the current flowing through the distribution lines, which directly decreases I^2R losses (active power losses). This leads to more efficient energy distribution, and Reducing Active Power Losses.

The Capacitors provide reactive power locally, which improves the power factor of the system. A better power factor reduces the reactive power losses, leading to more efficient energy delivery.

The importance of the research is also represented in providing a reduction in energy costs and environmental impact, which means lower fuel consumption and reduced greenhouse gas emissions.

1.3. Research methodology

This research is a quantitative research, where measurements, simulations and numerical data are used to evaluate the effects of integrating capacitor banks into distribution systems. The focus is on measurable outcomes such as power flows, voltage levels and active power losses.

And through Simulation Study using Power World software, and Collect data on system parameters, including load profiles, line impedances, existing capacitor placements, and voltage levels, and Gather historical data on voltage fluctuations, power losses, and reactive power demands, then Evaluate the system's performance under different load conditions and contingencies.

2. Benefits due to the application of shunt capacitors

The use of shunt capacitors to supply the forward currents required by the load relieves the generator from supplying that part of the induced current and also achieves the desired KVAR capacity (Gönen, 2014).

2.1. Voltage Profile Improvements

Shunt capacitors reduce the induced current in the electrical circuit. Reducing the line current reduces the IR and IX voltage drops and improves the system voltage level from the capacitor to the source. In both distribution and transmission systems, it is necessary to maintain the voltage between 0.95-1.05 units. Lower system voltage causes induction motors to run at higher currents. At lower voltages, voltage recovery will be slow after the fault is cleared. Therefore, maintaining acceptable voltage levels in the power system is an important goal.

A one-line diagram of a power system for voltage drop analysis is shown in *Fig. 2*. The vector diagram of the system without shunt capacitors is shown in *Fig. 1(Natarajan, 2005)*.

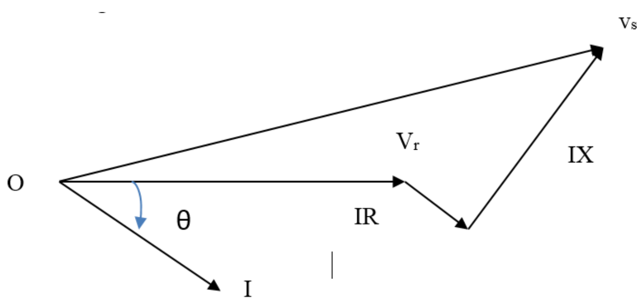

Fig. 1 Phaser diagram of the system without shunt capacitor

The corresponding voltage relations are:

$$V_R = V_s - I(\cos\theta \pm j \sin\theta)(R + jX) \qquad (1)$$

The phasor diagram of the system with shunt capacitors is shown in *Fig. 2*.

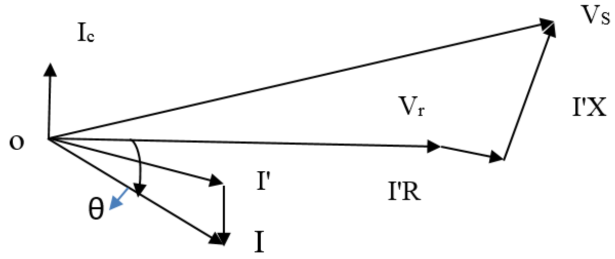

Fig. 2 Phaser diagram of the system with shunt capacitor

The corresponding current relations are:

$$I' = I(\cos\theta \pm j \sin\theta) - j I_c \quad (2)$$

Where the capacitor current is:

$$I_c = \frac{V}{X_c} \quad (3)$$

The improved voltage profile at the load is due to the decrease in the line current and reduced voltage drop.

The best place to support voltage depends on where the voltage is supported. *Fig. 3* shows how the capacitor changes the voltage profile along the circuit. Unlike the regulator, the capacitor changes the characteristics of the upstream voltage of the bank (Short, 2014).

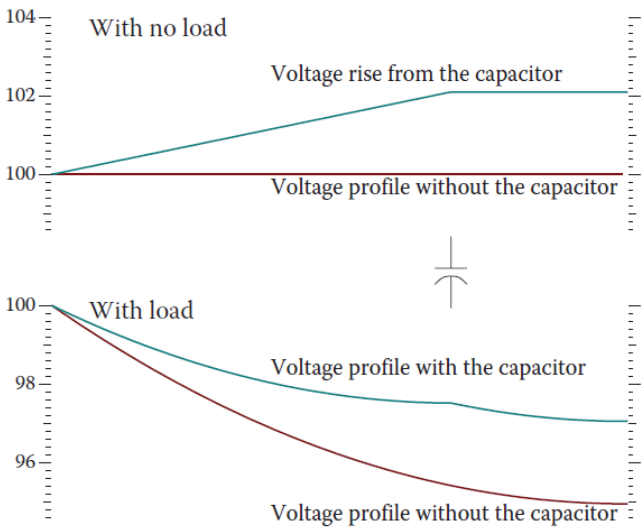

Fig. 3 Voltage profiles after addition of a capacitor bank **Error! Reference source not found.**(Short, 2014).

2.1.1. Voltage rise due to the addition of shunt capacitors

The addition of a shunt capacitor bank raises the voltage at the point of installation. The voltage drop equations without shunt capacitors (VD_1) and with shunt capacitors (VD_2) are (Natarajan, 2005):

$$VD_1 = \frac{KVA_1}{(10)(KV)^2}(R\ Cos\ \theta_1 - j\ X\ Sin\ \theta_1) \quad (4)$$

$$VD_2 = \frac{KVA_2}{(10)(KV)^2}(R\ \cos\theta_2 - jX\ \sin\theta_2) \quad (5)$$

$$VD_1 - VD_2 = \frac{1}{(10)(KV)^2}\{[R(KVA_1\ \cos\theta_1 - KVA_2\ \cos\theta_2)] + jX(KVA_1\ \sin\theta_1 - KVA_2\ \sin\theta_2)]\} \quad (6)$$

$$VD_1 - VD_2 = \frac{KVA_C}{(10)(KV)^2}X \quad (7)$$

Where $(KVA_1\ \cos\theta_1 - KVA_2\ \cos\theta_2)$ is the change in the real power, which is equal to zero. The other component, $(KVA_1\ \sin\theta_1 - KVA_2\ \sin\theta_2)$, is the change in the reactive power due to the addition of reactive power supplied through shunt capacitors.

2.1.2. Voltage rise at the transformer

Every transformer on the power system from the location of the capacitor bank to the generator will experience a voltage rise. This is an important component of the voltage rise due to the shunt capacitor. Since the transformer impedance is always a significant value, the voltage drop due to the transformer reactance in the presence of the shunt capacitor is given by (Natarajan, 2005):

$$VD_1\text{-}VD_2=\frac{KVA_C}{(10)(KV)^2}Xt \tag{8}$$

$$KV_{base}=(MVA_{\ base})\ (X_{base}) \tag{9}$$

$$VD_1\text{-}VD_2=\frac{KVAR_C}{(10)(MVA_{\ base})\ (X_{base})}=\frac{KVAR_C}{10(MVA_{\ base})}\cdot X_T\cdot\ \frac{1}{X_{base}} \tag{10}$$

$$Voltage\ at\ the\ transformer\ location=\frac{KVA\cdot R_C\cdot X_T}{10(KVA_T)} \tag{11}$$

Where X_T is the transformer reactance per unit and KVA_T is the base KVA of the transformer .If the voltage rise is excessive, then tap changers can be used to keep the voltage within acceptable levels.

2.1.3. Reduced voltage drops

The following advantages can be obtained by the installation of capacitors into a circuit (Gönen, 2014):

- The effective line current is reduced, and consequently, both *IR* and *IXL* voltage drops are decreased, which results in improved voltage regulation.
- The power factor improvement further decreases the effect of reactive line voltage drop

The percent voltage drop that occurs in a given circuit can be expressed as:

$$\%VD=\frac{S_{L3\emptyset}(r\times cos\theta+xsin\theta)l}{10\times v^2{}_{L\_L}} \tag{12}$$

The voltage drop that can be calculated from the above Equation is the basis for the application of the capacitors. After using capacitors, the system increases the voltage due to improving the power factor and reducing the effective line current. Therefore, the voltage due to and *IXL* is reduced. The approximate percentage of voltage increase along the line can be calculated as. Follows:

$$\%VR=\frac{Q_{c3\emptyset}.x.l}{10\times v^2{}_{L\_L}} \quad (13)$$

An additional phenomenon of voltage rise on each transformer from the generating source to the capacitors is because of the use of capacitors. It is independent of the load and power factor of the line and can be expressed as.

$$\%VR_T=(\frac{Q_{c,3\emptyset}}{S_{T,3\emptyset}})X_T \quad (14)$$

2.2. Line and transformer loss reductions

When shunt capacitors are installed for power factor correction, the line of current is reduced. Consequently, both I^2R and I^2X losses are reduced. In industrial power systems, I^2R losses range from *3*% to *8*% of rated load current, depending on operating hours at full load, conductor size, feeder circuit length, and transformer impedance. The load on most electrical circuits will vary depending on the time of day. The load factor is defined as (Natarajan, 2005):

$$Load\ factor\ (LDF)=\frac{Average\ KW\ demand}{Peak\ KW\ demand} \quad (15)$$

The current also varies with time. The loss factor is defined in order to estimate the loss in the system. The loss factor is a function of the load factor and is determined by the formula:

$$Loss\ factor(LF)=0.15\ LDF+0.85\ LDF^2 \quad (16)$$

$$Average\ loss\ =3\ (I^2R)\ (Loss\ factor) \quad (17)$$

2.3. Loss Reduction Due to Improved Power Factor

One of the major advantages of using capacitors is that they can reduce distribution line losses. Losses come from current through the resistance of the conductors. Some of this current transfers active power and some flows to provide reactive power. Reactive power provides magnetization for induction motors and other inductive loads. Reactive power does not spin up *KWH* meters and does any useful work, but it must be supplied (Short, 2004).

In industrial plants, the I^2R losses vary from 2 to 7% of the load Kilowatt-hour depending on the duration of the rated load and the light load. In addition, the losses are proportional to the resistance of the circuit and the length of the feeder. When the shunt capacitors are installed, the line current is reduced. The relation can be expressed as (Natarajan, 2005):

$$Loss\ reduction = 1 - \left(\frac{Original\ PF}{Improved\ PF}\right)^2 \quad (18)$$

This relation plotted in *Fig. 4* is based on the assumption that the *kW* load remains the same.

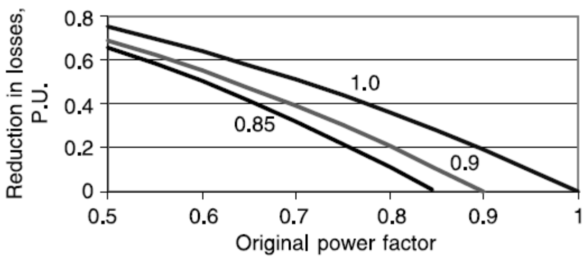

Fig. 4 Reduction in losses due to improved power factor (Gönen, 2014).

2.4. Release of Power System Capacity

Power factor correction capacitors provide the reactive current requirements locally and reduce the line current. Reduced line current means fewer *KVA* for transformers and feeder circuits. Thus, the shunt capacitor compensation helps to reduce the thermal overloads on transformers, transmission lines, generators, and cables (Natarajan, 2005).

3. Power Factor Improvement Equipment

Normally, the power factor of the whole load on a large generating station is near 0.8 to 0.9. However, sometimes it is lower and in such cases, it is desirable to take special measures to improve the power factor. This can be achieved with the following equipment (Mehta & Mehta, 2005):

3.1. Synchronous compensator

An induction motor accepts a leading current when over-excited and therefore behaves like a capacitor. An over-excited, no-load synchronous motor is known as a synchronous capacitor. When such a machine is connected in parallel with a power source, it receives a leading current, which partially neutralizes the lagging reactive component of the load. it improves the power factor.

Advantages:

- By changing the field excitation, the amount of current consumed by the motor can be changed by any amount. This helps to achieve smooth power factor control.
- Motor windings have a high thermal resistance to short-circuit currents.
- Malfunctions are easily eliminated.

Disadvantages:

- Significant engine losses.
- Maintenance costs are high.
- Makes a noise.
- Except for sizes above 500 *KVA*, the cost is higher than static capacitors of the same rating.
- Since a synchronous motor has no self-starting torque, additional equipment must be provided for this purpose.

3.2. Phase advancers

Phase advance is used to improve the power factor of induction motors. The low power factor of an induction motor is because its stator winding consumes an excitation current that lags the supply voltage by 90^{o}. If the excitation ampere-turns can be provided from some other *A.C* source, then the stator winding will be freed from the excitation current and the power factor of the motor can be improved. This work is done with a phase shifter, which is simply an *A.C* exciter. The phase transmitter is mounted on the same shaft as the main motor and is connected to the motor rotor circuit. It provides exciting ampere-turns in the rotor circuit at a slip frequency.

By providing more revolutions of amps, the induction motor can be operated at a driving power factor such as an over-excited synchronous motor.

The phase shifter has two major advantages. First, how the driving ampere-turns are fed. Therefore, at the slip frequency, the lagging *KVAR* consumed by the motor is significantly reduced. Second, the phase shifter is convenient to use where the use of synchronous motors is unacceptable. However, the major disadvantage of phase shifters is that they are uneconomical for engines less than 200 Hp (Mehta & Mehta, 2005).

3.3. Static capacitors

Power factor can be improved by connecting capacitors in parallel with lagging power factor equipment. A capacitor (commonly known as a static capacitor) draws the leading current and partially or completely cancels the lagging reactive component of the load current. This increases

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the power factor of the load. capacitor) consumes the leading current and partially or completely neutralizes the lagging reactive component of the load current. This increases the power factor of the load.

advantages:

- They have low losses.
- They do not require any special maintenance, as they have no rotating parts.
- They are easy to install, as they are lightweight and do not require a foundation.
- They can operate under normal atmospheric conditions.

Disadvantages:

- Have a short service life of 8 to 10 years.
- They can be easily damaged if the voltage exceeds the rated value.
- Once capacitors have been damaged, repairing them is uneconomical.

4. Design of capacitors for distribution system

In *Fig. 5*, several industrial factories connected as primary loop systems, because this system is used where high service reliability is important. The feeder loops around a load area and returns to the distribution substation, especially providing two-way feed from the substation or station.

In this primary loop system, some consumers 20 *KV*, and some consumers 0.4 *KV*. These consumers are powered by two sources, and these sources can be stations or distribution substations.

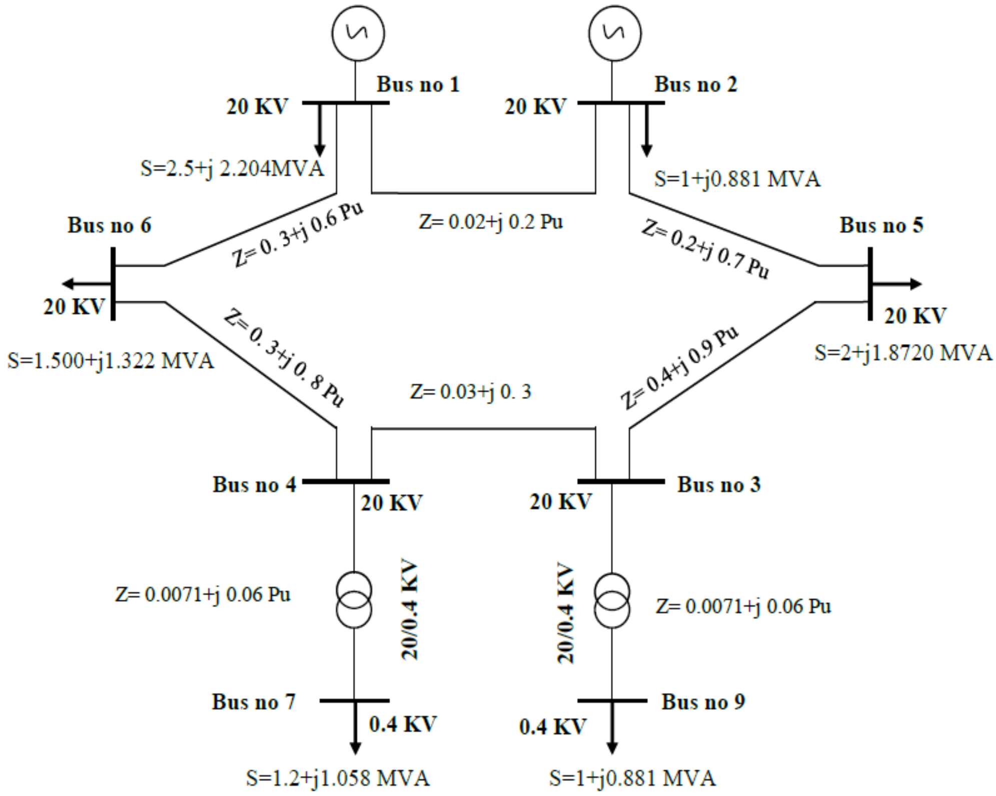


Fig. 5 schema of several industrial factories connected as primary loop systems

4.1. Sizes of capacitors for reactive compensation for 20kv connections (bus-bars)

In this distribution system all capacitors have star connection with bus.

4.1.1. Size of capacitor for reactive compensation for Bus No 1

Total active load ($P = 2500\ KW$) load

$$P\ for\ Bus_{(n)} = Kw/Efficiency \quad (19)$$

$$P\ for\ Bus_{(1)} = 2500/0.99 = 2525.3\ KW$$

Total new apparent power (S) load

$$S_{(before\ P.F\ correction)}\ for\ Bus_{(n)} = KW\ /old\ Power\ Factor \quad (20)$$

$$S_{\ (before\ P.F\ correction)}\ for\ Bus_{(1)} = 2525.3/0.75 = 3367.0\ KVA$$

$$S_{\ (after\ P.F\ correction)}\ for\ Bus_{(n)} = KW\ /New\ Power\ Fact \quad (21)$$

$$S_{(after\ P.F\ correction)}\ for\ Bus_{(1)} = 2525.3/0.95 = 2658.2KVA$$

$$Qc_n = P \times (tan(arcos(cos\varphi_1)) - tan(arcos(cos\varphi_2))) \quad (22)$$

$$Qc_1 = 2525.3 \times (tan(arcos(0.75)) - tan(arcos(0.95))) = 1397.1\ Kvar$$

$$Site\ of\ Capacitor\ bank = 1397.1\ Kvar$$

$$Leading\ qc_n\ supplied\ by\ each\ Phase = Qc_n/No\ of\ Phase \quad (23)$$

$$Leading\ qc_1\ supplied\ by\ each\ Phase = \frac{1397.1}{3} = 465.7\ Kvar$$

$$Capacitor\ Charging\ Current\ (Ic) = (qc_n\ x1000)/(U/(\sqrt{3})) \quad (24)$$

$$Capacitor\ Charging\ Current\ (Ic_1) = (465.7\ x1000)/(20000/(\sqrt{3}))\ =40.32A$$

$$Xc_n=(U/\sqrt{3})/Ic \quad (25)$$

$$Xc_1=(20000/\sqrt{3})/40.329=286.32\ \Omega$$

$$C_n=10^6/(Xc_n \times \omega) \quad (26)$$

$$C_1=10^6/(286.32\times 2\times \Pi \times 50)=11.113\mu F$$

4.1.2. Size of capacitor for Bus No 2

$$P\ for\ Bus_{(2)}=1000/0.99=1010.1\ KW$$

$$S_{(before\ P.F\ correction)}\ for\ Bus_{(2)}=1010.1/0.75=1346.8\ KVA$$

$$total\ Load\ (after\ P.F\ correction)\ for\ Bus\ (2)=1010.1/0.95=1063.3\ KVA$$

$$Qc_2=1010.1\times(tan(arcos(0.75))-tan(arcos(0.95)))=558.82\ Kvar$$

$$Leading\ qc_2\ supplied\ by\ each\ Phase = \frac{558.82}{3} = 186.266\ Kvar$$

$$Capacitor\ Charging\ Current\ (Ic_2) = (186.266\ x1000)/(20000/(\sqrt{3}))\ =16.13A$$

$$Xc_2=(20000/\sqrt{3})/16.13=715.87\ \Omega$$

$$C_2=10^6/(715.87\times 2\times \Pi \times 50)=4.448\mu F$$

4.1.3. Size of capacitor for reactive compensation for Bus No- 5

$$P\ for\ Bus_{(5)}=2000/0.99=2020.2\ KW$$

$$S_{(before\ P.F\ correction)}\ for\ Bus_{(5)}=2020.2/0.75=2693.6\ KVA$$

$$S_{(after\ P.F\ correction)}\ for\ Bus_{(5)}=2020.2/0.95=2126.5\ KVA$$

$$Qc_5=2020.2\times(tan(arcos(0.75))-tan(arcos(0.95)))=1117.64\ Kvar$$

$$Leading\ qc_5\ supplied\ by\ each\ Phase = \frac{1117.64}{3} = 372.54\ Kvar$$

$$Capacitor\ Charging\ Current\ (Ic_5) = (372.54\ x1000)/(20000/(\sqrt{3}))\ =32.26A$$

$$Xc_5=(20000/\sqrt{3})/32.26=354.93\ \Omega$$

$$C_5=10^6/(354.93\times 2\times \Pi \times 50)=8.972\mu F$$

4.1.4. Size of capacitor for reactive compensation for Bus No-6

$P \text{ for } Bus_{(6)} = 1500/0.99 = 1515.2\ KW$

$S_{(before\ P.F\ correction)} \text{ for } Bus_{(6)} = 1515.2/0.75 = 2020.2\ KVA$

$S_{(after\ P.F\ correction)} \text{ for } Bus_{(6)} = 1515.2/0.95 = 1594.9\ KVA$

$Qc_6 = 1515.2 \times (tan(arCos(0.75))\text{-}tan(arCcos(0.95))) = 838.23\ KVar$

$Leading\ q\text{-}c_6 \text{ supplied by each Phase } = \frac{838.23}{3} = 279.41\ KVar$

$Capacitor\ Charging\ Current\ (Ic_6) = (279.41 \times 1000)/(20000/(\sqrt{3}))\ = 24.197A$

$Xc_6 = (20000/\sqrt{3})/24.197 = 477.208\ \Omega$

$C_6 = 10^6/(477.208 \times 2 \times \Pi \times 50) = 6.673\ \mu F$

4.2. Sizes of capacitors for reactive compensation for 0.4kv connections (bus bars)

In this distribution system all capacitors have Wye connection with bus.

4.2.1. Size of capacitor for reactive compensation for Bus No -7

$P \text{ for } Bus_{(7)} = 1200/0.95 = 1263.2\ KW$

$S_{(before\ P.F\ correction)} \text{ for } Bus_{(7)} = 1263.2/0.75 = 1684.2\ KVA$

$S_{(after\ P.F\ correction)} \text{ for } Bus_{(7)} = 1263.2/0.95 = 1329.6\ KV$

$Qc_7 = 1263.2 \times (tan(arcos(0.75))\text{-}tan(arcos(0.95))) = 698.82\ KVAR$

$Leading\ q\text{-}c_7 \text{ supplied by each Phase } = \frac{698.82}{3} = 232.94\ KVA$

$Capacitor\ Charging\ Current\ \left(Ic_7\right) = \left(232.94 \times 1000\right)/(400/(\sqrt{3}))\ = 1008.65A$

$Xc_7 = (400/\sqrt{3})/1008.65 = 0.228\ \Omega$

$C_7 = 10^6/(0.228 \times 2 \times \Pi \times 50) = 13968.04 \mu F$

4.2.2. Size of capacitor for reactive compensation for Bus No -9

$P \text{ for } Bus_{(9)} = 1000/0.95 = 1052.6\ KW$

$S_{(before\ P.F\ correction)} \text{ for } Bus_{(9)} = 1052.6/0.75 = 1403.5\ KVA$

$S_{(after\ P.F\ correction)} \text{ for } Bus_{(9)} = 1052.6/0.95 = 1108.0\ KVA$

$Qc_9 = 1052.6 \times (tan(arcos(0.75))\text{-}tan(arcos(0.95))) = 582.35\ Kvar$

$$\text{Leading } q\text{-}c_9 \text{ supplied by each Phase } = \frac{582.35}{3} = 194.11 \text{ Kvar}$$

$$\text{Capacitor Charging Current } (Ic_9) = (194.11\times1000)/(400/(\sqrt{3})) = 840.52A$$

$$Xc_9 = (400/\sqrt{3})/840.52 = 0.274\ \Omega$$

$$C_9 = 10^6/(0.274\times2\times\Pi\times50) = 11623.04\ \mu F$$

5. Modeling of Simulation of the distribution system by power World software

We put all data into power world software, and we run calculation without and with capacitor, than we can compare voltage profile and reduce active power losses and power losses without and with capacitor.

No	From Name bus	To Name bus	Branch Device Type	R (Pu)	X (Pu)	Lim MVA Phase A,B,C
1	Bus No. 1	Bus No. 2	Line	0.02	0.2	3.5
2	Bus No 1	Bus No 6	Line	0.3	0.6	6.5
3	Bus No 2	Bus No 5	Line	0.2	0.7	7
4	Bus No 4	Bus No 3	Line	0.03	0.3	3.4
5	Bus No 5	Bus No 3	Line	0.4	0.9	4.5
6	Bus No 3	Bus No 9	Transformer	0.00071	0.06	10
7	Bus No 6	Bus No 4	Line	0.3	0.8	5
8	Bus No 4	Bus No 7	Transformer	0.00071	0.06	40

Tab. 1 distribution system branches input without capacitor

No	From Name	To Name	MW From	Mvar From	MVA From	MW Loss	Mvar Loss
1	Bus No. 1	Bus No. 2	0.13	0.013	0.130648	0.000004	0.00004
2	Bus No 1	Bus No 6	2.919	2.519	3.855635	0.0446	0.089
3	Bus No 2	Bus No 5	0.0329	0.1152	0.119806	0.0329	0.1152
4	Bus No 4	Bus No 3	0.16	-0.02	0.161245	0.00001	0.00009

5	Bus No 5	Bus No 3	0.836	-860	860.0004	0.0062	0.014
6	Bus No 3	Bus No 9	1	0.9	1.345362	0.000243	0.001285
7	Bus No 6	Bus No 4	1.36	-1.08	1.736663	0.0098	0.0261
8	Bus No 4	Bus No 7	1.2	1.1	1.627882	0.000243	0.001285
9	Total					0.094	0.247

Tab. 2 distribution system branches state without capacitors

No	Name of bus	Nominal voltage (KV)	Real voltage (KV)	Angle of voltage (Deg)	Load (MW)	Load (Mvar)	Cos φ	Gen (MW)	Gen (Mvar)	Gen (MVA)
1	Bus No 1	20	20	1.46	2.5	2.2	0.75	5.28	4.74	7.095
2	Bus No 2	20	20	1.47	1	0.88	0.75	4.01	3.73	5.47
3	Bus No 3	20	19.256	0.38	–	–	0.75	–	–	–
4	Bus No 4	20	19.258	0.41	–	–	0.75	–	–	–
5	Bus No 5	20	19.487	0.62	2	1.87	0.75	–	–	–
6	Bus No 6	20	19.524	0.87	1.5	1.32	0.75	–	–	–
7	Bus No 7	0.4	0.385	0.36	1.2	1.06	0.75	–	–	–
8	Bus No 9	0.4	0.385	0.34	1	0.88	0.75	–	–	–
9	Total				9.2	8.21	–	9.29	8.47	12.57

Tab. 3 Distribution system buses without capacitors

No	From Name bus	To Name bus	Branch Device Type	R (Pu)	X (Pu)	Lim MVA Phase A,B,C
1	Bus No 1	Bus No 2	Line	0.02	0.2	3.5
2	Bus No 1	Bus No 6	Line	0.3	0.6	6.5
3	Bus No 2	Bus No 5	Line	0.2	0.7	7
4	Bus No 4	Bus No 3	Line	0.03	0.3	3.4
5	Bus No 5	Bus No 3	Line	0.4	0.9	4.5
6	Bus No 3	Bus No 9	Transformer	0.00071	0.06	10
7	Bus No 6	Bus No 4	Line	0.3	0.8	5
8	Bus No 4	Bus No 7	Transformer	0.00071	0.06	40

Tab. 4 Distribution system branches state with capacitors

NO	From Name	To Name	MW From	Mvar From	MVA From	MW Loss	Mvar Loss
1	Bus No 1	Bus No 2	-0.1	0	0.1	1E-06	0.00001
2	Bus No 1	Bus No 6	2.9	1	3	0.0272	0.0543
3	Bus No 2	Bus No 5	2.9	1.2	3.1	0.0197	0.0688
4	Bus No 4	Bus No 3	0.1	-0.1	0.1	0.00001	0.00005
5	Bus No 5	Bus No 3	0.9	0.4	1	0.0039	0.0088
6	Bus No 3	Bus No 9	1	0.4	1.1	0.00014	0.001
7	Bus No 6	Bus No 4	1.3	0.4	1.4	0.0059	0.0157
8	Bus No 4	Bus No 7	1.2	0.4	1.3	0.00014	0.001

9	Total	0.057	0.14966

Tab. 5 distribution system branches state with capacitors

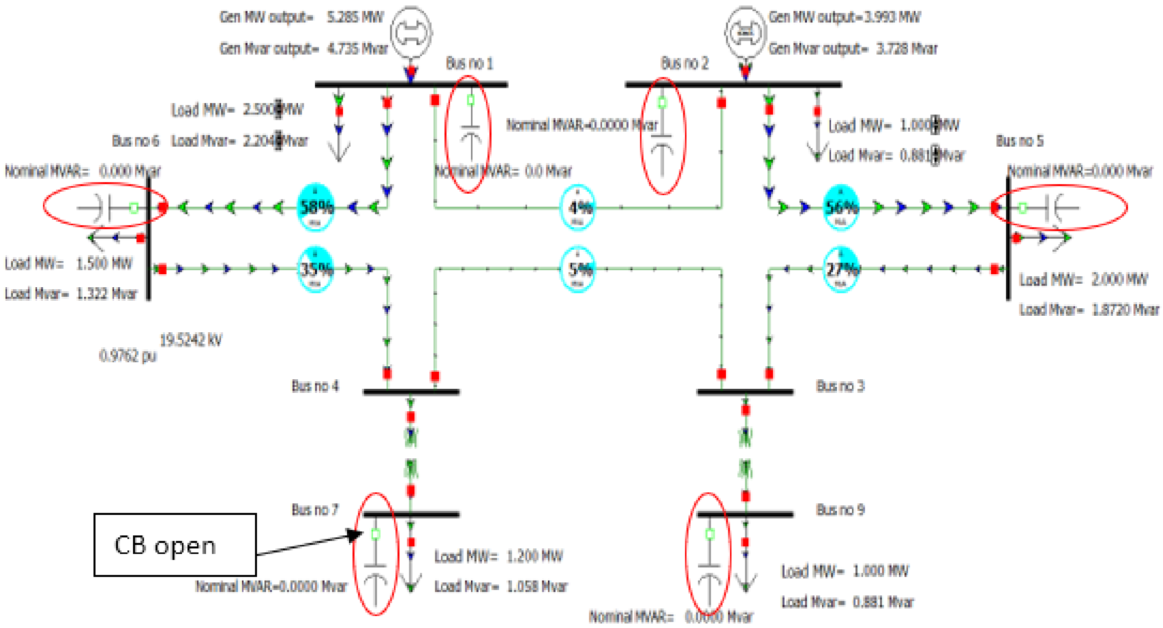


Fig. 6 simulation model of distribution system without capacitors

No	Name of bus	Nominal voltage (KV)	Real voltage (KV)	Angle of voltage (deg)	Shunt capacitor (Mvar)	Load (MW)	Load (Mvar)	cosφ1	cosφ2	Gen (MW)	Gen (MVar)	Gen (MVA)
1	Bus 1	20	20	1.46	0.553	2.5	2.2	0.75	0.95	5.3	2	5.660
2	Bus 2	20	20	1.47	0.881	1	0.88	0.75	0.95	4	1.5	4.249
3	Bus 3	20	19.57	0.05	–	–	–	–	–	–	–	–
4	Bus 4	20	19.57	0.07	–	–	–	–	–	–	–	–
5	Bus 5	20	19.72	0.42	1.182	2	1.87	0.75	0.95	–	–	–
6	Bus 6	20	19.71	0.64	0.806	1.5	1.32	0.75	0.95	–	–	–
7	Bus 7	0.4	0.391	0.03	0.635	1.2	1.06	0.75	0.95	–	–	–

8	Bus 9	0.4	0.391	0.02	0.529	1	0.88	0.75	0.95	–	–	–
9	Total				4.586	9.2	8.21	–	–	9.3	3.5	9.910

Tab. 6 Distribution system buses with capacitor

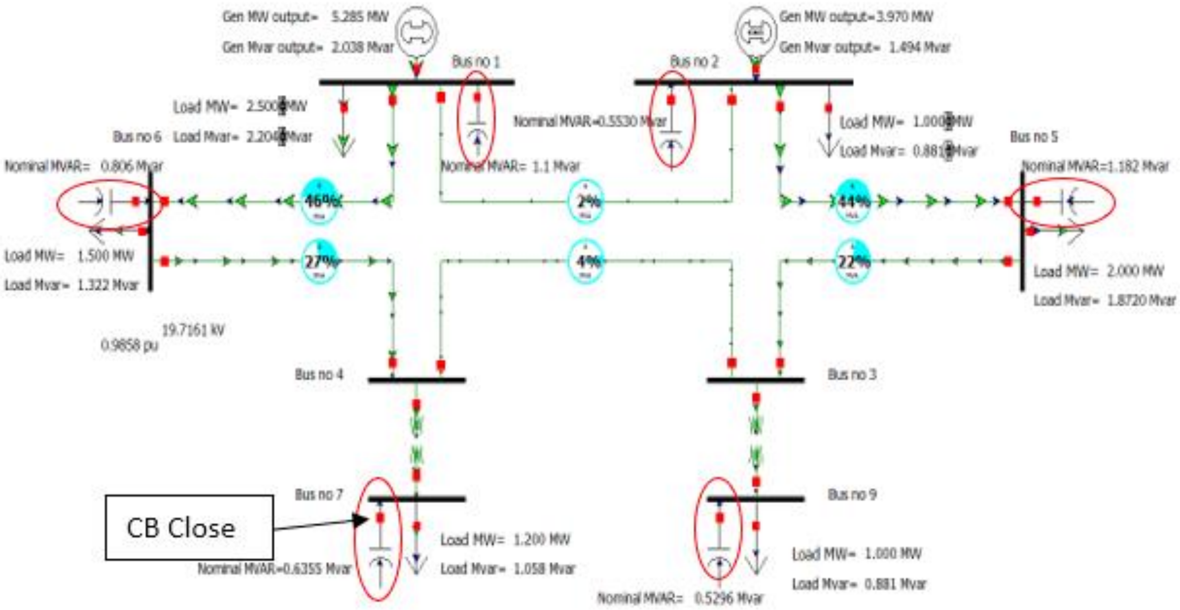
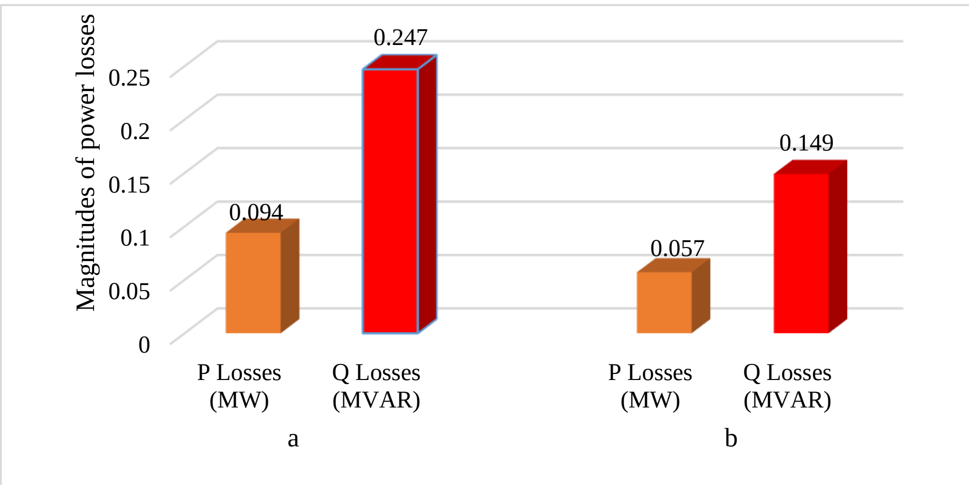


Fig. 7 simulation model of distribution system with capacitors

Fig. 8 P,Q losses in entire distribution system a. before reactive power compensation, b. after reactive power compensation



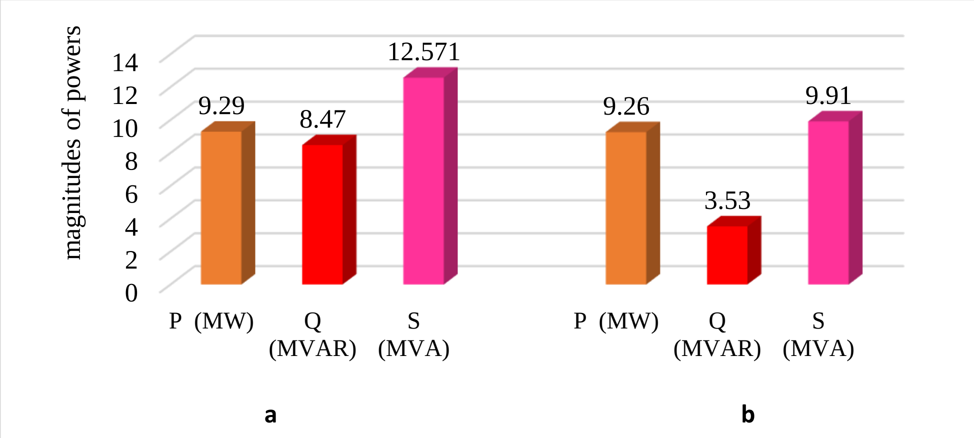


Fig. 9: P,Q, S generator output entire a. before reactive power compensation, b. after reactive power compensation

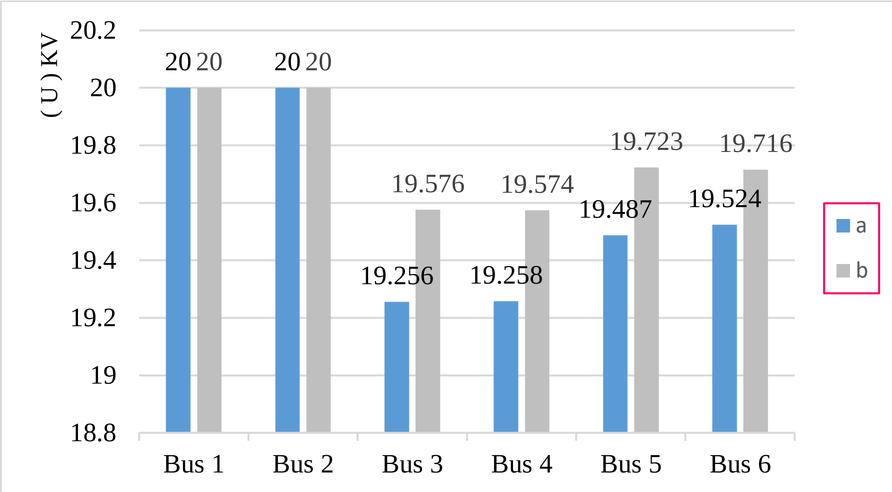


Fig. 10 voltage in distribution 20kv buses a. before reactive power compensation, b. after reactive power compensation

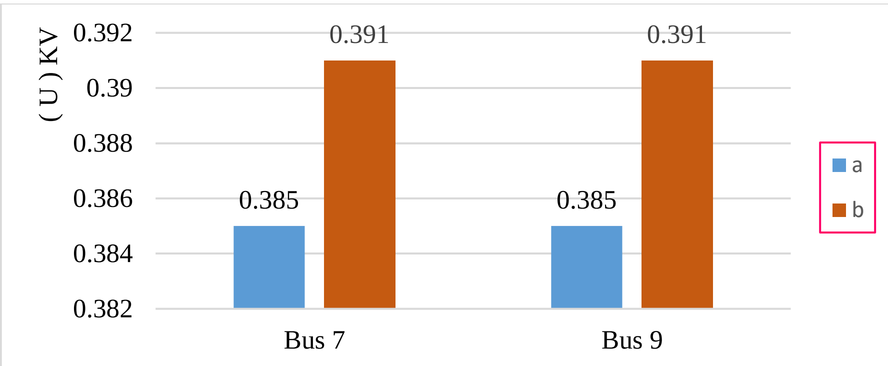


Fig. 11 Voltage in distribution 0.4 KV buses a. before reactive power compensation, b. after reactive power compensation

6. Research results

The results summarized as follows:

- The placement of capacitors resulted in improved voltage levels across the distribution network. Voltage deviations from the nominal value were significantly reduced.
- There was a notable reduction in active power losses (I^2R losses) throughout the distribution lines. The optimized capacitor placement minimized the current flow, thereby reducing resistive losses.
- Capacitors provided local reactive power support, reducing the amount of reactive power that needed to be transmitted over long distances.
- The power factor of the system improved significantly, leading to lower reactive power losses.
- The effective capacity of the distribution lines increased, allowing for the accommodation of additional loads without significant upgrades.

7. Conclusion

Capacitor banks are a common solution for reducing power losses, improving voltage profiles, correcting power factors and increasing system capacity in power distribution systems. The simulation was done on a sample of 4 buses of 20 kV and 2 buses of 0.4 kV distribution system, a comparative study was done for the system without capacitors and with optimal capacitors. Before adding the capacitor, the voltage value at the bus was often poor, also the active power loss and reactive power loss were large, also the Kva magnitude of the station generators was very high because the generators of a power plant are rated in Kva.

Power factor correction is used to bring the power factor back to the nearest unity that is economically feasible. This is usually achieved by adding a capacitor to the electrical distribution system, which compensates for the reactive power of the induced load, thereby reducing the load on the source.

This article describes 3.42MVar capacitor banks in 4 busbars of a 20kv system and 1.164MVar capacitor banks in 2 busbars of a 0.4kv distribution system to provide capacitive reactance compensation or power factor correction. Its installation shows other beneficial effects on the distribution system, such as improving the voltage profile, reducing line current, reducing reactive power losses, reducing active power losses, and freeing up the capacity of the power system in the substation or distribution station. In this thesis, power factor correction is applied to a group of loads in one place. This technique is suitable for municipal or industrial customers with a distributed load, and it is also economical to have one large capacitor bank for reactive compensation instead of several smaller banks for the entire distribution system.

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