A Comparative Study of Power Factor Improvement in Pakistani Industry Using Different Strategies; A Case Study

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Abstract—Most of the industrial machines have reactive power during operation due to which these machines are facing low power factor. One of the important existing public sector industries (where heavy mechanical products are manufactured) of Pakistan is under study, which has a very low power factor i.e. in the range of 0.60 to 0.75. This low power factor not only increase the cost (when there is extra bill and power factor penalty in the rate clause) but also decrease electrical capacity of power distribution system. In the public sector organization, there are five loads in the public sector industry i.e. machine shop load, heat treatment shop load, non-ferrous shop load, gal/forge shop load and fabrication shop.

In the proposed thesis, we have utilized capacitor bank in the existing distribution network .We investigated the shunt capacitor banks for Power Factor Correction (PFC). After analysis of the proposed distribution network in Matlab/Simulink software, it was found that using shunt capacitor bank in parallel with load, the power factor increased to 0.95, due to which proposed system and devices efficiency increased. The power losses decreased tremendously. Voltage drop has been reduced. Reduction in size of a conductor and cable reduced cost of the copper. Three different strategies (Central PFC, Regional PFC, Local PFC) are followed in this power factor improvement study and each one is then compared with the previous system.

Keywords— Machines, Capacitor bank, Transformer, bus bar, distribution parameters, Power Factor Correction (PFC).

I. INTRODUCTION

The power that runs in the power systems is a combination of active and reactive power. As an example, for the proper functioning of a motor in a fan, a specific amount of active power P and reactive power Q are to be supplied to the fan. The process of rotation of fan requires the magnetization of the winding and the rotation of the fan. The former is achieved through the reactive power and the latter is accomplished through the active power. One of the problems that normally take place in such scenarios is that the load takes up a lot more of the reactive power as compared to the normal conditions or rated values. Majority of the load at the consumer end is inductive load.

The voltage slumps at the load whenever the demand for the reactive power increases. This scenario is always catered for by introducing the capacitive components in the circuit like a capacitor bank or a FACTs device. A black out is always on the cards if the reactive power compensation is not provided immediately within a fraction of seconds.

Motors are undoubtedly the most commonly and massively existing and installed inductive load in the industry globally. Their inductive nature causes the phase between current and angle to shift such that current lags and voltage leads as shown in Figure 1.
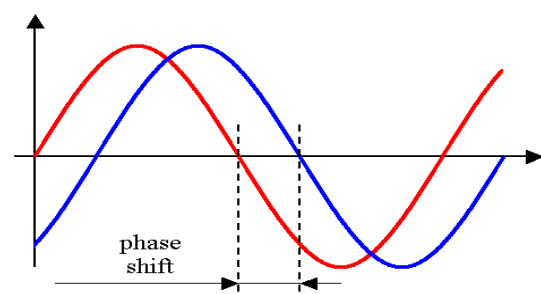

Figure 1. Phase shift

Current is said to be in an advanced state and voltage in a delayed state if it leads, mainly in a capacitive load. On the other hand voltage is said to be in an advanced state and current in a delayed state if it is an inductive load. The change in this difference of the angles of current and voltage result as a decreased value of the usable power or the real power P, as compared to the supplied power that is kVA or MVA.

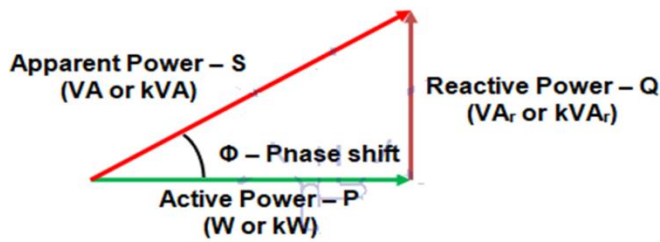Representing those powers by vectors, the "power triangle" may be as shown in figure. 2.

Figure 2. Power triangle

The trigonometric ratio cosine, when applied to the difference of the angles of current and voltage, denoted by Φ, gives the power factor.

$P = S * \cos \Phi$

$Q = S * \sin \Phi$

If the power factor is low then the following unwanted phenomena can take place such as:

a) Massive drops in voltages.
b) Massive current flow in the lines.
c) Higher losses by Joule effect in the conductors.

Majority of the countries follow a strict rule that does not permit power factor to drop short of 0.9 Else, many penalties and fines are imposed for the violation. The process of power factor correction, at the clients' end, involves the reduction in the apparent power by shrinking the power demand at the substation when operating at the peak hours where load is at its maximum. It is at this stage where the vacated capacity of the system is employed for delivering more power to the load. This inherently improves the system by increasing its efficiency. The improvement of power factor also comes with many advantages such as savings in terms of money because the wire can now be used of a smaller cross sectional area.

Capacitors are commonly found in distribution circuits. By freeing up some space for capacity, reducing the end losses and by making up for the loss of the voltage, the capacitors, as a result, amplify the performance of a distribution system. Mainly they are employed for power factor correction, voltage regulation and reduce the losses. Just like dams store water, capacitors store reactive power, which is readily supplied to the reactive load in case of need. Distribution capacitors are generally pad mounted and pole mounted but mostly the pole mounted is followed. A switch ON and OFF mechanism is usually followed to initiate and terminate respectively the charging process of a capacitor. The capacitors which do not have such a switch are always ON or OFF.

Capacitors bank provide benefits to the distribution system, it can devise a condition in which a best location and sizing of the capacitor is achieved i.e.

1- Power Factor Correction.
2- Increase the voltage of the load bus.
3- Reduce transmission losses ($I^2 R$).
4- Improve bus-voltage stabilization /regulation.

5- Release of system capacity.
6- Reduce the lagging component of the circuit current.
7 - Efficient power utilization.
8- Reduce electricity billing cost based on kVA demand.

Although capacitors provide benefits to distribution systems, when not properly employed they can create losses and over voltages. The scenario when a capacitor is completely or nearly completely charge, the closing of the capacitor results in the form of generation of transient inrush current. A transient response gets introduced in the circuit whenever a sudden change is encountered such as that of switching ON or OFF.

As stated above, Capacitor Bank can be fixed or controllable nature. Fixed Capacitor Banks are typically only switched on or off a few times during their useful lifespan, leading to few transients. In contrast, switched capacitor banks offer a greater threat of generating transients in distribution circuits since these banks may switch on and off several times during the day, each time generating a transient. In this study we are installing fixed capacitor banks.

The points that need to be taken care of while performing the installation of capacitor banks are as under:

a) Careful selection of the control mechanism to be employed in the system.
b) Cautiously determining the location to install the capacitor bank.
c) Calculation of the bank size (the size of a capacitor bank in kVAR)

A special type of relay is also used in capacitor bank for the protection and supervision of capacitor banks. The one shown in diagram is "ABB" made "REV615". They are responsible for monitoring the safety levels and in response perform the switching operation in the network in real time as quickly as possible which is shown in Figure 3.

Figure 3. VAR relay

The equation below helps calculate the size of the required capacitor for compensation.

$Q [kVAR] = P [kW] \times (\tan \Phi 1 - \tan \Phi 2)$

Here P refers to the real component of the power at the installation node. $\Phi 1$ and $\Phi 2$ represent the phase shifts of voltage and current at the installation and the desired one respectively. In order to characterize the location of installation of the capacitor bank, there are three schemes that are

dominantly in use. Which technique to be used depends upon the location where the load is inductive and the real power that is to be sent.

A. *Centralized correction*

In this scheme there is only one capacitor bank which is installed close to the main incoming switchboard as shown in figure 4.
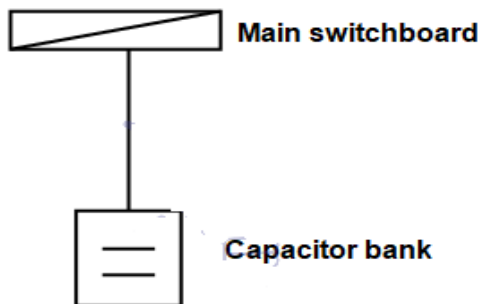

Figure 4.   Centralized Power Factor (P.f) correction

B. *Regional correction:*

This scheme proposes the installation of capacitor banks in proximity of the distribution switchboards. These are responsible for furnishing the required energy to the most important consumers that cause the degradation of the power factor as shown in figure 5.
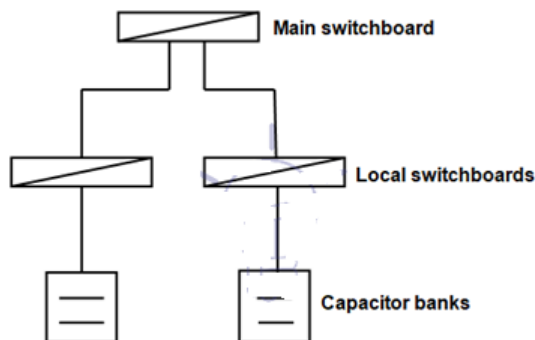

Figure 5.   Regional Power Factor correction

C. *Local correction*

Suggests that capacitor banks be installed in the neighborhood of the individual consumers as shown in Figure 6.
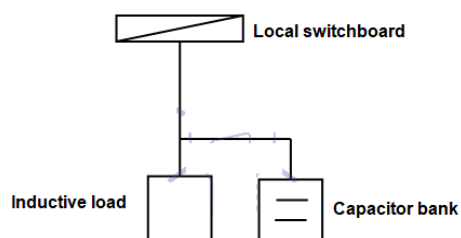

Figure 6.   Local correction

II.   LITERATURE OVERVIEW

Power factor is actually cosine of the angle between voltage and current phase shift. It ranges between 0 and 1. If the load is purely resistive (ideal), the angle between voltage and current becomes zero, therefore the cosine of this zero, which is the power factor, becomes 1 [1,2]. It is an ideal condition. In case, if the load is not resistive, then it is either capacitive or inductive, broadly classified as reactive. In such case the angle difference between the voltage and current is 90O, therefore the power factor, cosine of 90O becomes equal to zero thus rendering the worst possible value of the power factor. Power factor is leading in capacitive load and lagging in inductive load. Where the power factor is leading, it implies that the load is generating the reactive power. If the power factor is lagging then it means that VARs are being consumed by the load. [3]. The value of Power factor cannot be zero or unity and will always be higher than zero or less than one [4].

When an increase in reactive power happens, the value of the voltage in the line drops meanwhile increase in the current is observed. In order to get rid of such a situation, it is inherently important that power factor be maintained in the range of 0.8 to a maximum value of 1 at all times. If not, the equipment at the user end might go out of order causing millions in losses [5]. Harmonics generated in the system distort the voltage and current waveform and consequently distort the power factor. The power factor distortion can be obtained by considering the total harmonic distortion of the voltage and current [6]. The root mean square of voltage or current harmonics over the fundamental voltage or current computes the total harmonic distortion. The extent of disfigurement caused to the power factor can be found out by finding the ratio of the fundamental voltage and current to the total values of voltage and current. [6,7]

A large phase shift and harmonics create low power factor displacement and distortion. A capacitor is useful to correct the power factor displacement in linear loads. But when dealing with the loads that are non-linear, harmonic filter is widely preferred since power resonance generates mighty values of the higher order harmonics [8]. While talking about industries, almost half of the load is of Induction Motors [9]. Mechanical resistance and magnetization reactance are in direct proportion in an induction motor. Even a slight change in the values of the above mentioned two considerations, mechanical resistance and magnetization reactance, results as a huge variation in the value of the power factor.[10][12]. In an industry load as well as power factor is changing at every instant hence requires immediate and sharp catering for. To solve this problem, reactive power compensation is required by the user. A capacitors bank is a substantial solution to generate reactive power [13, 14, 15].

To find out the value of the reactive power needed for the motor, research works have depicted that the reactive component of the no load current is always equals to the nine tenth of the current in the no load case. However, if full load current is available, the no-load current can be predicted as 30% of the full-load current. Then, 90% of the full-load current

provides the required reactive power in VAR [16]. However, this method is not sufficient to determine the proper size of capacitor because it only provides an approximation, in particular at fixed load. Therefore, this empirical technique may create under- or over-correction at operating time, where under-correction causes a penalty charge for the user while overcorrection produces self-excitation, which is harmful for the induction motor winding [17].

The study found that the power factor correction equation is a suitable technique to calculate the exact amount of reactive power required at any loading point in individual or group induction motors, or even at a point of common coupling. This method took three factors into consideration which were the power factor before any device, the power factor to reach and the power at the input.[18][19]. One method to find the exact value of capacitor is also carried out in MATLAB/Simulink. It renders a value of kVAr which is the required capacitor value for compensation. [13]. Another methodology comes with the installation of a device that is called a power analyzer. It is responsible for the measurement and saving of the parameters which are power factors, current, voltage and power.[14][20][21]

The method known as Measured Current and Manufacturer's Data (MCMD) has been used for the calculation of power factor of an induction motor with rated power of 2200 W. It is calculated at many loads. It takes into account a mathematical equation for the sake of providing an optimal, feasible and practical solution [14]. In this approach, the measured current method is used to obtain the load. The results of the proposed method are compared with the instantaneous power method and zero crossing method, and show errors of + 0.04 at the full-load condition and -0.18 at the no-load condition [14]. Kriging and regression are also techniques for estimation of power factor mostly for the residential houses. In the regression method, a locally weighted regression technique with an exponential function has been used. The Kriging method with a semivariogram model is considered.[24,25]. In case of small induction motor (mostly under 250 W) A zero crossing method and instantaneous power method are presented to determine the power factor from no-load to full-load conditions. Also, using equivalent circuit parameters in the induction motor can be a great way to determine the power factor because the total resistances over impedance obtain the power factor [11][23]. The Kriging method is also applied in this induction motor to estimate the power factor. For the motor ,mentioned above, results showed that the zero crossing and instantaneous method produced errors of 22% and 35%. However, the Kriging method created an average error of 14% [22]. In this induction motor, MCMD and Kriging are also applied to estimate the power factor from no-load to full-load conditions [26]. However, the Kriging and regression methods were not able to estimate the power factor from full-load to over-load conditions because both methods are interpolation techniques and cannot extrapolate unseen points.

ANN is an intelligent technique used to estimate the power factor in distribution systems by analyzing the real parameters of the power system. In a research made by power distribution company in Victoria (Australia), the results showed that the ANN is able to estimate the power factor at unseen points with an accuracy of 93% [27].

We can have some economic benefits by improving power factors.

- Benefits due to increase in generation capacity of the system

- Benefits due to energy conservation or reduction of energy losses

- Benefits due to increase in the capacity of distribution substation

- Benefits due to reduction of system voltage drops (or we can say voltage improvement)

- Benefits due to increase in the capacity of feeder

- Benefits due to increase in the transmission capacity of the system

The total benefits we can avail due to installation of shunt capacitor banks can be summarized as shown in Eq. (1).

$$\sum \Delta\$ = \Delta\$_G + \Delta\$_T + \Delta\$_S + \Delta\$_F + \Delta\$_{ACE} + \Delta\$_{GBCE} \text{ --------(1)}$$

Where:

$\Delta\$_G =$ Annual benefits due to increase in generation capacity $/yr

$\Delta\$_S =$ Annual benefits due to increase in substation capacity, $/yr

$\Delta\$_F =$ Annual benefits because of increasing feeder capacity, $/yr

$\Delta\$_{ACE} =$ Annual benefits due to conservation of energy, $/yr

$\Delta\$_{GBCE} =$ Additional annual revenue due to increase in the consumption of kWh energy, $/yr

$\Delta\$_T =$ Annual benefits because of increasing transmission capacity, $/yr [28]

We can calculate the approximate value of the percent voltage rise (%VR) along the line can be calculated as given in equation (2):

$$\%VR = \frac{Q_{C,3\phi} \times l}{10 \times V_{L-L}^2} \tag{2}$$

By putting the values in the above equation we can easily calculate the percent voltage rise along the line [28].

Capacitor Bank

A capacitor, also known as "condenser" is an electrical element with two electrical conductors separated by an insulator material (dielectric), as shown in Figure 7.
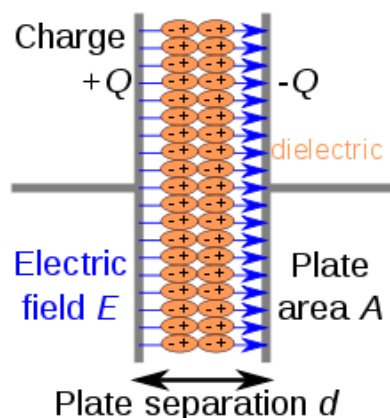
Figure 7.   Simplified scheme of a capacitor

The multipurpose device known as the capacitors that fall under the requirements of the IEEE standards which are namely 60871 60143, standard 824 are in use for the research purpose [1]. The primary applications and advantages of capacitors are:

a) Power factor correction and reactive power compensation requirements which arise due to MV and LV consumers.
b) The induction effect of transmission lines which are either overhead or underground.
c) Achieving voltage regulation in HV transmission lines. [3]
d) Starting the 1φ motor (Squirrel Cage-Low Voltage).

The capacitors are amassed either in a series or a parallel combination. Capacitors are either connected in a delta formation or a Y formation depending upon the nature of the distribution network. An MV distribution network is equipped with a delta formation of capacitors, so does the LV network.

Figure. 8 shows casing of above mentioned capacitors.

When capacitors remain in use for a longer period of time, then being a charge storage device, they preserve the charge in them. This turns the capacitors into a two way sword which can even cause the connected devices to get a sudden and unexpected charge resulting in them burning out and requiring an immediate maintenance or often replacement. Sometimes capacitors come with internally integrated resistors to discharge the stored charges and causing the other devices to remain safe [4].
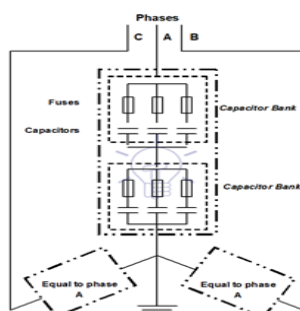

Figure 8.   Schematic diagram of a capacitor bank

III.   METHODOLOGY

Simulation is done with Matlab/Simulink of the existing power system of the case industry and the existing parameters and other relevant data(current, voltage, power, power factor etc) are in study. Three different strategies of capacitor bank installation for the purpose of power factor correction are under study.

1) Centralized correction(strategy 01)
2) Regional correction (strategy 02)
3) Local correction (strategy 03)

Each sytem involving the above mentioned strategy is then simulated in Matlab/Simulink. All the relevant output data and power parameters of these strategies are compared with the data of the system without capacitor bank. Also the output data and power parameters of each strategy are also compared among each other in the end.

Methods used for power factor correction:
Method1:
$\theta 1 = Cos^{-1}(0.XX)$; Tan $\theta 1$
$\theta 2 = Cos^{-1}(0.95)$; Tan $\theta 2$
So the Required Capacitor kVAR to improve P.F from 0.XX to 0.95
Required Capacitor kVAR = Q (Tan $\theta 1$ – Tan $\theta 2$)
Method 2:
Multiplier to improve PF from 0.XX to 0.95 and load rated power will result the desired Capacitor kVAR to improve power factor to 0.95
Required Capacitor KVAR = P(w) x Multiplier of 0.XX and 0.95 as shown in Table I.
Where Multiplier = crossing point to existing and desired P.F.

TABLE I.   KVAR MULTIPLYING FACTOR OF 0.XX AND 0.95

cosφ	tg φ	Multiplying factor for KVAR 0.93	0.94	0.95
		0.40	0.36	0.33
0.40	2.29	1.895	1.924	1.959
0.41	2.22	1.831	1.840	1.896
0.42	2.16	1.771	1.800	1.836
0.43	2.10	1.713	1.742	1.778
0.44	2.04	1.647	1.677	1.712
0.45	1.98	1.592	1.626	1.659
0.46	1.93	1.533	1.567	1.600
0.47	1.88	1.485	1.519	1.532
0.48	1.83	1.430	1.464	1.467
0.49	1.78	1.386	1.420	1.453
0.50	1.73	1.337	1.369	1.403
0.51	1.69	1.291	1.323	1.357
0.52	1.64	1.249	1.281	1.315
0.53	1.60	1.205	1.237	1.271
0.54	1.56	1.164	1.196	1.230
0.55	1.52	1.124	1.156	1.190
0.56	1.48	1.085	1.117	1.151
0.57	1.44	1.047	1.079	1.113
0.58	1.40	1.010	1.042	1.073
0.59	1.37	0.973	1.005	1.039
0.60	1.33	0.909	0.971	1.005
0.61	1.30	0.904	0.936	0.970
0.62	1.27	0.870	0.902	0.936
0.63	1.23	0.838	0.870	0.904
0.64	1.20	0.805	0.837	0.871
0.65	1.17	0.774	0.806	0.840
0.66	1.14	0.743	0.775	0.809
0.67	1.11	0.713	0.745	0.779
0.68	1.08	0.684	0.716	0.750
0.69	1.05	0.654	0.686	0.720
0.70	1.02	0.625	0.657	0.691
0.71	0.99	0.597	0.629	0.663
0.72	0.96	0.568	0.600	0.634
0.73	0.94	0.541	0.573	0.607
0.74	0.91	0.514	0.546	0.580
0.75	0.88	0.487	0.519	0.553
0.76	0.86	0.460	0.492	0.526
0.77	0.83	0.434	0.466	0.500
0.78	0.80	0.408	0.440	0.474
0.79	0.78	0.381	0.413	0.447
0.80	0.75	0.355	0.387	0.421

Method 3:

Required KVAR = S x (sin (cos (θv – θI))

Where S is the induction motor apparent power and θv – θI is the angle difference between voltage and current.

B. Existing Distribution Network

The three phase source was being used to provide 11kv/50Hz generation to consumers via transformer and distribution line. The transformer is being used to step down the 11kv voltage to 440v at the distribution side to provide consumer's appliances. In existing factory, large motors have been used to manufacture products but as we know that the induction motors power factor were lagging and draws high current so that reactance factor has been increased.

Here in this public sector organization which is under study, there is load of five workshops:

i) Machine shop
ii) Heat treatment shop
iii) Non-Ferrous shop
iv) Gal/Forge shop
v) Fabrication shop

The data of the existing system is given in Table II.

TABLE II. DATA SHEET OF ALL SHOPS WITHOUT CAPACITOR BANK

Machine/ Shop No.	P.F	KW	KVAR	KVA	I(LV)	I(HV)(Line	I(HV)(Phase)
MACHINE SHOP	0.71	4035	4002	5683	8202	516.64	298.2822
FAB SHOP	0.69	4207	4408	6097	8800.4	554.282	320.0149
HEAT TREATMENT	0.7	2200	2244.3	3142.8	4536	285.71	164.9547
NON FERROUS	0.74	405	368.114	547.3	789.95	49.7543	28.72566
GAL/FORGE	0.75	1464	1291	1952	2817.47	177.455	102.4534

IV. SIMULATION AND RESULTS

This existing system is implemented in MATLAB/Simulink. We have seen that without capacitor bank, there is a large gap between voltages and current angle so due to which if we take power factor into account; the cosine angle between voltage and current is power factor. If the voltage and current cosine angle difference will be large so power factor will lag. So in the existing system, the system power factor is lagging nearly 0.7 due to which system draws large current from the source via three phase transformer. In addition, Power losses have been increased. The simulations and its results are shown in Table III and Table IV.

TABLE III. SIMULATION RESULTS FOR POWER SYSTEM OF THE CASE INDUSTRY

		RMS						
SHOPS		Vph (volts)	VL (volts)	Iph/IL (Amps)	S (VA)	Total GEN (VA)	Q (VAR)	Total Q (VAR)
WITHOUT CAPACITOR BANK	NFS	232.85	403.308	796.36	556297.278		373831.771	
	M/S	230.21	398.7354	8176.91	5647219.35	17380250.63	3975642.42	12279613.59
	H/T	231.53	401.0217	4546.46	3157925.65		2254758.92	
	G/F	232.08	401.9744	2831.29	1971257.35		1303001.11	
	F/B	230.07	398.4929	8761.9	6047551		4372379.37	

TABLE IV. SIMULATION RESULTS FOR POWER SYSTEM OF THE CASE INDUSTRY

SHOPS	P.F	P with respective P.F (Watts)	P with unity P.F (Watts)	P Loss (Watts)	Total Loss (Watts)
WITHOUT CAPACITOR BANK					
NFS	0.74	411659.9857	556297.278	144637.2923	
M/S	0.71	4009525.741	5647219.353	1637693.612	
H/T	0.7	2210547.956	3157925.651	947377.6954	5097263.747
G/F	0.75	1478443.012	1971257.35	492814.3374	
F/B	0.69	4172810.189	6047550.999	1874740.81	

PROPOSED DISTRIBUTION NETWORK

To improve the power factor we are using static capacitor banks in parallel with each load. A capacitor bank is a grouping of several identical capacitors interconnected in parallel or in series with one another. These groups of capacitors are typically used to correct or counteract undesirable characteristics, such as power factor lag or phase shifts inherent in Alternating Current (AC) electrical power supplies. Capacitor banks may also be used in Direct Current (DC) power supplies to increase stored energy and improve the ripple current capacity of the power supply. We have used different strategies of placing capacitor at the system to check the behavior of power factor and reactive power.

Strategy 1 (One Capacitor bank with combined Load or Centralized Correction):

In this type, single capacitor bank is connected to the bus bars of the main LV distribution board for the installation, and remains in service during the period of normal load.

For this scenario the value of capacitor bank required is calculated to achieve power factor of 0.95. The data is shown in Table V.

TABLE V. EXISTING OVERALL LOAD VALUES AND REQUIRED CAPACITOR BANK FOR 0.95 PF

OVERALL SHOPS						
S/NO	LOAD NO	KWA	P.F	KVA	KVAR	REQ CAP
1	L_M1	12331	0.72	17126.39	11885.27	7830.185

Simulation and Results

We have combined all of the loads and installed one capacitor bank to analyze the behavior of the proposed distribution network system, as suggested in strategy 01. It is implemented in the MATLAB/Simulink. The generating source is providing 11kv .The three phase transformer steps down the 11kv to 440kv which is useful for the industry induction motors. The main purpose of providing capacitor bank in case of power system is to supply reactive power to the system and they are installed at the receiver end, this is also called as VAR Compensation. Figure 9 below shows the system designed in Matlab/Simulink for centralized compensation. The capacitor banks here used are Static VAR Compensator. The result shown in table below shows that the power factor has been increased from 0.7 to 0.95.
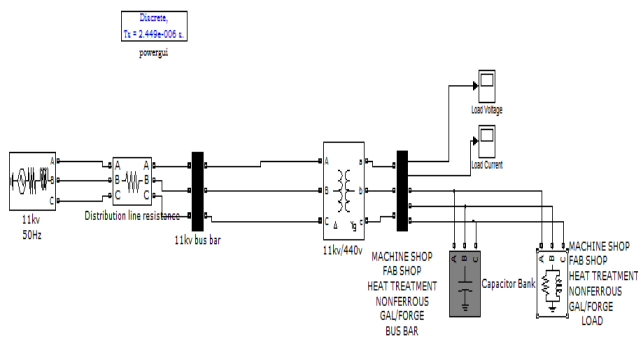

Figure 9.   Strategy 1 (One Capacitor bank with overall Load)

TABLE VI.   STRATEGY 1 (ONE CAPACITOR BANK WITH OVERALL LOAD)

		RMS						
	SHOPS	Vph (volts)	VL (volts)	Iph/IL (Amps)	S (VA)	Total GEN (VA)	Q (VAR)	Total Q (VAR)
STRATEGY 1	Overall	231.34	400.6926	18736.32	13003380.8	13003380.81	4060304.36	4060304.355

TABLE VII.   STRATEGY 1 (ONE CAPACITOR BANK WITH OVERALL LOAD)

	SHOPS	P.F	P with respective P.F (Watts)	P with unity P.F (Watts)	P Loss (Watts)	Total Loss (Watts)
STRATEGY 1	Overall	0.95	12353211.77	13003380.81	650169.0403	650169.0403

Strategy 2 (De-Centralized or Regional Correction):

In this strategy, Capacitor banks are connected to bus bars of each Regional distribution board of each workshop discussed lately. In this system a significant part of the system take benefits from this arrangement, mainly the feeder cables from the main distribution board to each of the regional distribution boards at which the power factor compensation is required.

For this scenario the value of capacitor bank required is calculated to achieve power factor of 0.95. The data is shown in Table VIII.

TABLE VIII.   EXISTING REGIONAL LOAD AND REQUIRED CAPACITOR BANK TO ACHIEVE 0.95 PF

PARAMETERS WITH DESIRED POWER FACTORS

Machine/ Shop No.	P.F	KW	KVAR	KVA	I(LV)	I(HV)(Line	I(HV)(Phas	Required KVAR
MACHINE SHOP	0.95	4035	1326.03	4247.37	6130.55	386.124	222.929	2675
FAB SHOP	0.95	4207	1382.55	4428.42	6391.88	402.584	232.432	3029
HEAT TREATMENT	0.95	2200	722.989	2315.79	3342.55	210.526	121.547	1520
NON FERROUS	0.95	405	133.096	426.316	615.334	38.756	22.3758	235
GAL/FORGE	0.95	1464	481.117	1541.05	2224.32	140.096	80.8843	810

Simulation and Results

In strategy 2, we have isolated all loads (each shop is isolated) and installed capacitor bank with individual load(workshop) to analyze the behavior of the proposed distribution network. We have investigated that the power factor has been increased smoothly to 0.95. Moreover, the power loss has been reduced from 5MW to 0.66 MW. Figure 10 shows the system designed in Matlab/Simulink for de-centralized   or regional compensation. The capacitor banks here used are Static VAR Compensator. The design is shown in figure 10 and the resultant data after simulation is also shown in the Table IX and Table X.

TABLE IX.   STRATEGY 2 (FIVE CAPACITOR BANKS WITH SEPARATE LOAD)

			RMS					
	SHOPS	Vph (volts)	VL (volts)	Iph/IL (Amps)	S (VA)	Total GEN (VA)	Q (VAR)	Total Q (VAR)
STRATEGY 2	NFS	234.93	406.9107	625.9	441128.061		137631.955	
	M/S	232.44	402.5979	6170.8	4303022.26		1342542.94	
	H/T	233.69	404.763	3382.33	2371250.09	13180429.66	739830.029	4112294.055
	G/F	234.2	405.6463	2255.59	1584777.53		494450.591	
	F/B	232.33	402.4074	6428	4480251.72		1397838.54	

TABLE X.   STRATEGY 2 (FIVE CAPACITOR BANKS WITH SEPARATE LOAD)

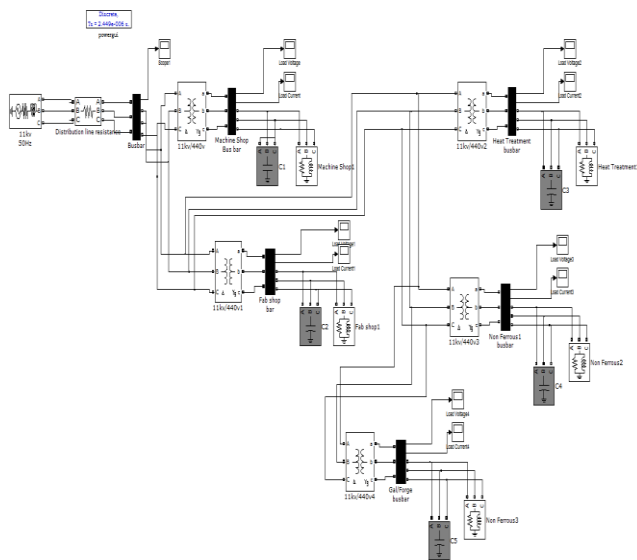|	SHOPS	P.F	P with respective P.F (Watts)	P with unity P.F (Watts)	P Loss (Watts)	Total Loss (Watts)
STRATEGY 2	NFS	0.95	419071.658	441128.061	22056.40305	
	M/S	0.95	4087871.143	4303022.256	215151.1128	
	H/T	0.95	2252687.588	2371250.093	118562.5047	659021.4832
	G/F	0.95	1505538.657	1584777.534	79238.8767	
	F/B	0.95	4256239.134	4480251.72	224012.586	

Figure 10. Strategy 2 (Regional correction)

Strategy 3 (Capacitor banks with Individual Load or Local Correction):

In this strategy, Capacitor banks are directly connected to the terminals of each inductive load(or small group of loads).

As in this public sector organization, there are five shops (regional loads) i.e. machine shop load, heat treatment shop load, nonferrous shop load, gal/forge shop load and Fabrication shop. Here in this strategy we install the capacitor banks to each load of every shop. Table XI shows the existing system and the proposed capacitor banks values, after calculation, for separate loads of each shop(one shop is mentioned)to achieve the power factor of 0.95. Table XII and XIII shows the simulation results after capacitror bank installation.

TABLE XI.   EXISTING DATA OF H/T SHOP AND REQUIRED CAPACITOR BANK FOR 0.95 PF

			HEAT TRT			
S.No	Load	KW	P.F	KVA	KVAR	REQ CAP KVAR
1	L_HT1	200	0.71	281.6901	198.3667	132.6
2	L_HT2	186	0.72	258.3333	179.2766	118.11
3	L_HT3	224	0.7	320	228.5257	154.784
4	L_HT4	250	0.74	337.8378	227.2321	145
5	L_HT5	160	0.68	235.2941	172.5205	127.04
6	L_HT6	240	0.72	333.3333	231.3247	152.4
7	L_HT7	250	0.66	378.7879	284.5703	202.25
8	L_HT8	90	0.68	132.3529	97.04278	71.46
9	L_HT9	160	0.69	231.8841	167.8399	115.2
10	L_HT10	140	0.65	215.3846	163.6781	117.6
11	L_HT11	190	0.73	260.274	177.8835	115.33
12	L_HT12	110	0.7	157.1429	112.2224	76.01

Simulation and Results

In Strategy 3, the case is slightly different. We isolated following loads in each shop and installed capacitor bank with

individual load in order to analyze the behavior of the proposed distribution network for strategy 03. We have investigated that the power factor has increased rapidly to 0.95.

The design is shown in figure 11 and results in Table XII and Table XIII.
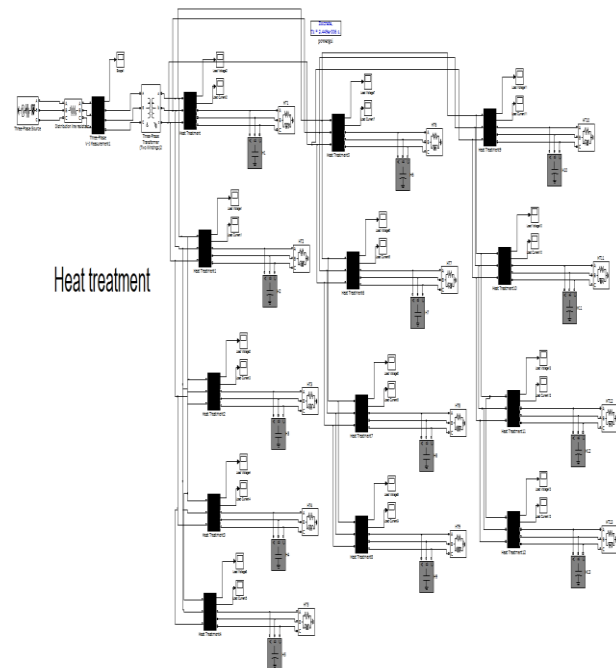

Figure 11. Strategy 3 (Capacitor bank for H/T shop Local Correction

TABLE XII.   STRATEGY 3 (CAPACITOR BANKS WITH INDIVIDUAL LOAD)

		RMS						
	SHOPS	Vph (volts)	VL (volts)	Iph/IL (Amps)	S (VA)	Total GEN (VA)	Q (VAR)	Total Q (VAR)
STRATEGY 3	NFS	234.8	406.6855	626.65	441412.26		140369.099	
	M/S	232.66	402.9789	7022	4901215.56		1558586.55	
	H/T	233.68	404.7456	3767	2640817.68	14901259.53	839780.022	4666137.631
	G/F	234.37	405.9407	2501	1758478.11		548645.17	
	F/B	232.78	403.1868	7388	5159335.92		1578756.79	

TABLE XIII.   STRATEGY 3 (CAPACITOR BANKS WITH INDIVIDUAL LOAD)

	SHOPS	P.F	P with respective P.F (Watts)	P with unity P.F (Watts)	P Loss (Watts)	Total Loss (Watts)
STRATEGY 3	NFS	0.948	418458.8225	441412.26	22953.43752	
	M/S	0.948	4646352.351	4901215.56	254863.2091	
	H/T	0.948	2503495.161	2640817.68	137322.5194	750711.1957
	G/F	0.95	1670554.205	1758478.11	87923.9055	
	F/B	0.952	4911687.796	5159335.92	247648.1242	

A. Comparison between Existing and Proposed Distribution Network

If we summarize all the strategies, we know that in our daily use electrical systems we use lot of devices (actuators) most of which run by the help of motors. All the rotating devices are

based upon coil that and their working and proper functioning is always governed by the Principle of Electromagnetic Induction. The impedance component of an inductor is always taken as a positive value whenever solving the circuit and the impedance component of the capacitive element is taken with a negative sign. Addition of extra inductive devices or components results as an enlarged reactive power in the circuit.

Hence the circuit faces a huge drop in the power factor because the value obtained as a result of the division of real power P by apparent power S. this in turn causes an increase in the value of the apparent power because the latter is a complex sum of P and Q. But the power factor of a system should always and essentially be high. This is advisable for the reason that it will end up maintaining the efficiency of the system. The incorporation of the capacitive element causes a decline in the Q which in turn makes S to drop also. Concomitantly the power factor rises. This new value of the power factor is then maintained at the acceptable value. Hence it can be extracted from the above few lines that the capacitor bank responsibly performs the reactive power compensation.

The Table XIV and Table XV clearly show us that without capacitor, the system efficiency will reduce, draws large current and lagged the power factor. We investigated that the static capacitor bank achieved our goal to increase power factor to 0.95 .Furthermore, increasing in power factor nearly unity have reduced the power losses.

As shown in Table XV , the power losses have been reduced from 5MW to .65MW in strategy 1 strategy 2 and 0.75 MW in strategy 3.Slightly higher value of power loss in strategy 3 is because of not exact values of capacitor banks (as we are using standards). A high value of the power factor means that there will be a very small requirement of the amount of reactive power compensation. This will mean that a very minute amount of current will be obtained from the supply. In this case the copper loss that is the I2R loss will decline. The losses also fade when the power factor is high owing to the less values of the reactive devices.

Furthermore, the reactive power has been reduced from 12MVAR to 4MVAR.Power that is used up by the load is referred to as true, real or active power. Active or real power is denoted by P, the power that is reflected, because load is reactive, back into the system is known as reactive power. The sum of P and Q is the apparent power denoted by the letter S. In an analogy of a triangle, if theta is the angle between P and Q, where neither P nor Q is the hypotenuse, S will be the hypotenuse of the triangle.

The apparent power is also reduced from 17MVA to 13 MVA. When capacitive and inductive components are attached in a parallel assembly, the resultant current is zero. That is to say that the amount of current that flows through the inductor flows in a direction opposite to that of the one flowing through the capacitor. Hence the cancellation results as zero current. The reactive devices capacitors and inductors, when placed in a circuit, generate and consume the reactive power respectively.

The theory of power factor control orbits around this mechanism. In practical observation and usage, the load always has active, capacitive and inductive elements. Hence the power S that flows to the load also carries active and reactive components to deliver to the loads.

Multiplication of voltage and the conjugate of electric current render the reactive power Q. A major use of apparent power is that it can generate a very close estimate of the size of the electric equipment. A proper and accurate value of the sum of S component of several loads can only be made if the value of angle leading or that of angle lagging between voltage and current is the same or to say that they both have the same power factors.

TABLE XIV.   COMPARISON BETWEEEN EXISTING AND PROPOSED SYSTEM

| | | RMS | | | | | | |
	SHOPS	Vph (volts)	VL (volts)	Iph/IL (Amps)	S (VA)	Total GEN (VA)	Q (VAR)	Total Q (VAR)
WITHOUT CAPACITOR BANK	NFS	232.85	403.308	796.36	556297.278		373831.771	
	M/S	230.21	398.7354	8176.91	5647219.35		3975642.42	
	H/T	231.53	401.0217	4546.46	3157925.65	17380250.63	2254758.92	12279613.59
	G/F	232.08	401.9744	2831.29	1971257.35		1303001.11	
	F/B	230.07	398.4929	8761.9	6047551		4372379.37	
STRATEGY 1	Overall	231.34	400.6926	18736.32	13003380.8	13003380.81	4060304.36	4060304.355
	NFS	234.93	406.9107	625.9	441128.061		137631.955	
	M/S	232.44	402.5979	6170.8	4303022.26		1342542.94	
STRATEGY 2	H/T	233.69	404.763	3382.33	2371250.09	13180429.66	739830.029	4112294.055
	G/F	234.2	405.6463	2255.59	1584777.53		494450.591	
	F/B	232.33	402.4074	6428	4480251.72		1397838.54	
	NFS	234.8	406.6855	626.65	441412.26		140369.099	
	M/S	232.66	402.9789	7022	4901215.56		1558586.55	
STRATEGY 3	H/T	233.68	404.7456	3767	2640817.68	14901259.53	839780.022	4666137.631
	G/F	234.37	405.9407	2501	1758478.11		548645.17	
	F/B	232.78	403.1868	7388	5159335.92		1578756.79	

TABLE XV.   COMPARISON BETWEEEN EXISTING AND PROPOSED SYSTEM

	P.F	P with respective P.F (Watts)	P with unity P.F (Watts)	P Loss (Watts)	Total Loss (Watts)
WITHOUT CAPACITOR BANK	0.74	411659.9857	556297.278	144637.2923	
	0.71	4009525.741	5647219.353	1637693.612	
	0.7	2210547.956	3157925.651	947377.6954	5097263.747
	0.75	1478443.012	1971257.35	492814.3374	
	0.69	4172810.189	6047550.999	1874740.81	
STRATEGY 1	0.95	12353211.77	13003380.81	650169.0403	650169.0403
	0.95	419071.658	441128.061	22056.40305	
	0.95	4087871.143	4303022.256	215151.1128	
STRATEGY 2	0.95	2252687.588	2371250.093	118562.5047	659021.4832
	0.95	1505538.657	1584777.534	79238.8767	
	0.95	4256239.134	4480251.72	224012.586	
	0.948	418458.8225	441412.26	22953.43752	
	0.948	4646352.351	4901215.56	254863.2091	
STRATEGY 3	0.948	2503495.161	2640817.68	137322.5194	750711.1957
	0.95	1670554.205	1758478.11	87923.9055	
	0.952	4911687.796	5159335.92	247648.1242	

CONCUSLION

Capacitor banks are good devices for improving the network and are already used in the industries. In this thesis a solution to the Optimal Capacitor Problem (OCP) applied to a particular distribution network. The reactive power compensation plays very important role, especially for the industry. Nowadays, there are many power electronic devices that are used such as converters, inverters, UPS systems etc. They all generate

distortions to the supplying voltage and current waveforms. In order to avoid poor power quality, it is necessary to apply reactive power compensating device minimizing reactive power consumption.

In the proposed thesis, we have utilized capacitor bank in the existing distribution network where power factor was tremendously on the lower side .We have investigated using static shunt capacitor banks for Power Factor Correction (PFC). A comparative analysis of the strategy 1(Centralized Correction), Strategy 2(De-Centralized Correction or Regional Correction) and Strategy 3 (Local Correction) have been carried out to focus the aforementioned research problem and then each of one is compared with the previous system. Good and Bad things of every system is discussed. Any industrialist in Pakistan can have benefit from this research and can opt a better strategy after studying this study keeping in view the nature of his installed industry, power system setup and his economic status.

Furthermore, after analysis of the proposed distribution network in Matlab/Simulink software, it was found that using shunt capacitor bank in parallel with load, the power factor increased to 0.95 due to which proposed system and devices efficiency increased as current requirement reduced. Active power (P),Reactive Power (Q), Current and Voltage at LV side of each shop was simulated and results was displayed in the form of tables and graphs which clearly shows the increase in the efficiency in the power system of each shop. The power losses reduced from 5MW to the range of 0.65MW. Voltage drop also reduced. Reduction in size of a conductor and cable reduced the cost of the whole system. After PFC, system becomes able to manage more loads with the same capacity.Moreover in future, the proposed system can be automated the capacitor banks using switching devices, for betterment of the power system performance. Instead of static capacitor banks, simulations can be done for automatic capacitor banks. Also other power factor improvement devices like synchronous condenser, phase advancers (individually or in mixed form) can be used and results can be simulated for these devices respectively. Simulations can be done for PFC at the HV side of the transformer and the result can be compiled. PID, Fuzzy Logic and SMC controllers can be used to get optimal values so that we can prevent our system from any unpredictable bad event.

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