Energy Saving by Power Factor Correction: Application to Qatar Industries

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Abstract

The industrial power distribution networks of the State of Qatar would have inductive loads at low power factor. These distribution networks experience increase in power losses especially during the peak summer period. Low power factor is most commonly corrected by connecting shunt VAR compensation such as shunt capacitors bank at the desired location to perform the power factor correction. The power factor correction using shunt capacitors bank produce economic saving in capital expenditures through the reduction of power losses through the distribution network. This paper presents a practical case study of power factor correction for an 11 kV industrial distribution network in the State of Qatar. The network model has been developed using EDSA professional power system software. The energy after adding the shunt capacitors (i.e. after power factor correction) has been determined from the power flow solutions. The on-site measurements have been conducted and the measurements have been verified by the network model that was developed by EDSA software.

Introduction

Industrial power distribution networks experience increase in power losses during summer period. This is mainly related to the excessive use of air conditioning system and motor drives which reflects an increase in the electric load. Such increase in this type of load is accompanied with low power factor (~ 78%) which leads to huge transfer of reactive power from the utility through the network. The main drawback of this problem is increase in the network losses and reduction in the voltage level. 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. Shunt capacitors have been commonly used to provide reactive power compensation in power distribution network. They are provided to minimize power and energy losses, maintain best voltage regulations for load buses and improve power network security. The amount of compensation provided is very much linked to the placement of capacitors in the distribution network which is essentially determination of the location, size, number and type of capacitors to be placed in the system. A large variety of research work has been done on capacitor placement problem in the past.
The main objective of this study is to design an energy saving scheme for an industrial distribution network in Qatar. This can be achieved by decreasing the network losses and improving the main electric load operation to a better efficiency level. The designed scheme is concerned with improving the power factor of the distribution network by adding shunt capacitors to the network at optimal size and location. Load flow modeling is used to simplify the network and to calculate the network losses and the voltage profile. The network model parameters are collected through field measurements and then implemented in Electrical Distribution Software Analysis (EDSA) program. After that, the EDSA modeling is validated by comparing load flow results with power flow field measurements. The size of the capacitor (VAR compensation) is determined and is verified using EDSA software. The designed VAR compensation system will reduce the overall network losses. The field measurements, software analysis, designed VAR compensation system, and overall energy saving are presented in this paper.

**Benefits of Power Factor Correction**

Loads on electric power networks include two components: active power (measured in kilowatts) and reactive power (measured in kilovars). Active power has to be provided by power plants, whereas reactive power can be provided by either power plants or shunt var compensation such as shunt capacitors bank. It is a well-known fact that shunt power capacitors are the most economical source to meet the reactive power requirements of inductive loads and transmission lines operating at a lagging power factor.

**Economic Justification for Capacitors**

When reactive power is provided only by power plants, each system components (i.e., generators, transformers, transmission lines and distribution feeders, switch-gear, and protective equipments) has to be increased in size accordingly. Capacitors can mitigate these conditions by decreasing the reactive power demand all the way back to the generators. Line currents are reduced from capacitors locations all the way back to the generation equipment. As a result, losses and loadings are reduced in distributions feeders, substation transformers, and transmission lines. Depending upon the uncorrected power factor of the system, the installation of shunt capacitors can increase generator and substation capability of additional load at least 30 percent, and can increase individual circuit capability, from the voltage regulation point of view, approximately 30 to 100 percent. Furthermore, the current reduction in transformer and distribution equipment and lines reduces the load on these kilovolt ampere-limited apparatus. In general, the economic benefits force capacitor banks to be installed on the primary distribution network rather than on the secondary. The methods used by the utilities to determine the economic benefits derived from the installation of capacitors vary from company to company, but the determination of the total installed cost of a kilovar of shunt capacitors is easy and straightforward. In general, the economic benefits that can be derived from capacitor installation can be summarized as:

- Benefits due to released generation capacity
- Benefits due to released transmission capacity
- Benefits due to released distribution substation capacity
- Benefits due to reduced voltage drops (voltage improvement)
- Benefits due to released feeder capacity
- Benefits due to reduced energy losses

Therefore the total benefits due to installation of capacitor banks can be summarized as given in Eq. (1).
\[ \sum \Delta\$ = \Delta\$_G + \Delta\$_T + \Delta\$_S + \Delta\$_F + \Delta\$_{ACE} + \Delta\$_{GBCE} \]  \hspace{1cm} (1)

Where:
\( \Delta\$_G \) = annual benefits due to released generation capacity, $/yr
\( \Delta\$_S \) = annual benefits due to distribution substation capacity, $/yr
\( \Delta\$_F \) = annual benefits due to released feeder capacity, $/yr
\( \Delta\$_{ACE} \) = annual benefits due to conserved energy, $/yr
\( \Delta\$_{GBCE} \) = additional annual revenue due to increase kWh energy consumption, $/yr
\( \Delta\$_T \) = annual benefits due to released transmission capacity, $/yr

In our project, we will discuss the benefits of the installation of shunt capacitors from the perspective of reduced energy losses and reduced voltage drops.

**Benefits due to Reduced Energy Losses**

The annual energy losses are reduced as a result of decreasing copper losses due to the installation of capacitors. The conserved energy can be expressed as given in Eq. (2).

\[ \Delta ACE = \frac{Q_{C,3\phi} \cdot R \cdot (2S_{L,3\phi} \sin \theta - Q_{C,3\phi}) \cdot 8760}{1000 \cdot V_{L-L}^2} \text{ kWh/yr} \]  \hspace{1cm} (2)

Where:
\( \Delta ACE \) = annual conserved energy, kWh/yr
\( Q_{C,3\phi} \) = three-phase reactive power due to corrective capacitors applied, kvar
\( R \) = total resistance to load center,
\( S_{L,3\phi} \) = original, i.e., uncorrected three phase load, kVA
\( \sin \theta \) = sine of original (uncorrected) power factor angle
\( V_{L-L} \) = line to line voltage, kV

The annual benefits due to the conserved energy can be calculated as given in Eq. (3).

\[ \Delta\$_{ACE} = \Delta ACE \times EC \]  \hspace{1cm} (3)

Where:
\( \Delta\$_{ACE} \) = annual benefits due to conserved energy, $/yr
\( EC \) = cost of energy, $/kWh

**Benefits due to Reduced Voltage Drops**

The following benefits can be derived from the installation of capacitors from into a circuit:
- 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 approximate value of the percent voltage rise along the line can be calculated as given in equation (4):
\[
\%VR = \frac{Q_{c,3\phi} \times l}{10 \times V_{L-L}^2}
\]

(4)

Also, an additional voltage rise phenomenon through every transformer from the generation source to the capacitors occurs due to the application of capacitors, which is independent of load and power factor of line, and can be expressed as:

\[
\%VR_T = \left( \frac{Q_{c,3\phi} \times l}{S_{T,3\phi}} \right) x_T
\]

(5)

Where:
\%VR_T = percent voltage rise through transformer
\[S_{T,3\phi}\] = total three-phase transformer rating, kVA
\[x_T\] = percent transformer reactance (approximately equal to transformer’s impedance)

**Practical case study: Power Factor Improvement for an Industrial 11 kV Substation**

The power factor correction using shunt capacitors have been applied to an existing 11 kV substation. This substation is a part of power distribution network of Qatar power system. The 11 kV substations have two 66 kV/33 kV transformers that feeds the industrial customers through 12 kV feeders. The single-line diagram of the substation is shown in Figure 1.
The case study consists of three steps:

- Measurements using power quality analyzer (AMEC 3945 PQ Analyzer)
- Computer simulation using professional power system analysis software (EDSA software).
- Calculation of Energy Saving

**Measurements**

The power quality analyzer has been used to measure all the values that needed to simulate the network for power factor correction using EDSA software. The PQ analyzer has been left on the substation for 24hrs recording. The recorded 24hrs power factor at the secondary 11kV secondary side of the transformer is shown in Figure 2(a) and 2(b). The measurements of MW and MVar loads connected to the 11 kV feeders are shown in Figure 1.

![Figure 2(a). Time trends of power factor over 24 hours (summer condition)](image)

![Figure 2(b). Time trends of power factor over 24 hours (winter condition)](image)

From Figures 2(a) and 2(b), it can be seen that power factor of the substation is considered a poor power factor (0.75 to 0.87). The objective of this study is to improve the power factor to 0.95 to minimize the power losses (saving energy) and to reduce the voltage drops (improve
voltage profile). The selection of the shunt capacitors for power factor improvement is determined and it is verified by the EDSA software simulations.

**Computer Simulations**
EDSA power flow program 6 has been used to calculate the total network power losses. Power flow solution has been obtained using Newton-Raphson method. The power flow with shunt capacitors is shown in Figure 4. From Figure 4, it can be observed that the power factor has been improved to 0.9478. The kvar rating of the shunt capacitors have been determined to improve the power factor at each feeder to 95% lagging. The calculated kVar of each shunt capacitor is shown in Figure 4.

**Simulation without adding shunt capacitors**
EDSA power flow program has been used to calculate the total network power losses. Power flow solution has been obtained using Newton-Raphson method. The solution of the power flow without shunt capacitors is shown in Figure 3. From Figure 3, it can be observed that the power factor of the network at bus 2 is 0.79. The value of 0.79 power factor is a poor power factor and the target is to improve it to 0.95.

![Figure 3. Power flow solution without shunt capacitors](image-url)
The summary of power flow results without shunt capacitors are given in Table 1.

Table 1 Summary of Total Generation and Demand
Without shunt capacitors

<table>
<thead>
<tr>
<th></th>
<th>P(MW)</th>
<th>Q(MVAR)</th>
<th>S(MVA)</th>
<th>PF(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swing Buses</td>
<td>10.977</td>
<td>8.986</td>
<td>14.186</td>
<td>77.38</td>
</tr>
<tr>
<td>Generators</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Shunt</td>
<td>0.036</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Static Load</td>
<td>10.95</td>
<td>8.468</td>
<td>13.842</td>
<td>79.1</td>
</tr>
<tr>
<td>Motor Load</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total Loss</td>
<td>0</td>
<td>0.526</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Mismatch</td>
<td>-0.009</td>
<td>-0.008</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From Table 1, the total power losses in the network are 0.036MW (36kW).

Simulation with adding the shunt capacitors
EDSA power flow program has been used to calculate the total network power losses. Power flow solution has been obtained using Newton-Raphson method. The power flow with shunt capacitors is shown in Figure 4. From Figure 4, it can be observed that the power factor has been improved to 0.9478.

Figure 4 Power flow solution with adding shunt capacitors
Table 2 Summary of Total Generation and Demand With Shunt Capacitors

<table>
<thead>
<tr>
<th></th>
<th>P(MW)</th>
<th>Q(MVAR)</th>
<th>S(MVA)</th>
<th>PF(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swing Buses</td>
<td>10.965</td>
<td>4.034</td>
<td>11.683</td>
<td>93.85</td>
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<tr>
<td>Generators</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Shunt</td>
<td>0</td>
<td>4.792</td>
<td>4.792</td>
<td>0</td>
</tr>
<tr>
<td>Static Load</td>
<td>10.95</td>
<td>8.46</td>
<td>13.842</td>
<td>79.1</td>
</tr>
<tr>
<td>Motor Load</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total Loss</td>
<td>0.024</td>
<td>0.356</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mismatch</td>
<td>-0.009</td>
<td>0.001</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From Table 2, the total power losses in the network are 0.036MW (36kW). The losses decreases from 0.036 MW (36kW) to 0.024 MW (24kW)

**Energy Saving Due Power Factor Improvement**

The total reduction in the power losses is calculated as:

$$\Delta P_{\text{loss}} = P_{\text{loss, before cap}} - P_{\text{loss, after cap}}$$

$$\Delta P_{\text{loss}} = 0.036 - 0.024 = 0.012 \text{ MW} = 12kW$$

Table 3 Energy Saving

<table>
<thead>
<tr>
<th>Period</th>
<th>Saved energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>One day</td>
<td>12*24=288 kWhr</td>
</tr>
<tr>
<td>One month</td>
<td>288*30= 8640 kWhr</td>
</tr>
<tr>
<td>One year</td>
<td>8640*12= 103680 kWhr</td>
</tr>
</tbody>
</table>

As shown in Table 3, adding shunt capacitors to the industrial network will save around 103680 kWhr energy every year. The cost of the shunt capacitors can be recovered within few years.

**Conclusions**

This paper presented a power factor correction for an existing industrial power distribution network in the state of Qatar. Shunt capacitors is used for power factor correction. On-site measurements of the network loads and power factor have been conducted using power quality analyzer. A time trend of network power factor has also been measured and recorded over 24 hours. The measurement results show a power factor for all network loads. EDSA power system analysis software has been used to model the network and to determine the network power losses. The determined location and rating of shunt capacitors has reduced the energy losses in the network. The shunt capacitors have been located at the end of each 11 kV feeder. The optimal location of shunt capacitors to minimize the energy losses is one of the future studies.
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References


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