THE TECHNICAL AND ECONOMIC ADVANTAGES OF
POWER FACTOR CORRECTION

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Abstract: The paper presents an analysis of the power factor from a technical and economic point of view. Power factor correction aims to improve power factor and therefore power quality by using capacitors to compensate for the usually inductive loads, for example motors. Power factor correction systems increase the efficiency of electricity supply, offering immediate cost savings.

Keywords: advantages, analysis, correction, load, power factor, solution.

1. INTRODUCTION

In electrical engineering, the power factor of an AC system is defined as the ratio of the true power absorbed by the load and the apparent power flowing in the circuit and is a dimensionless number in the closed range of −1 to 1\textsuperscript{5}.

Therefore, the power factor is a measure of the efficient use of the input power in the electrical system and is defined as the ratio between the true power and total apparent power, where \textsuperscript{6}, \textsuperscript{7}:

- True power is the power that effectively supplies the equipment and performs useful and productive work.
- Reactive power is required by some equipment (e.g. transformers, motors and relays) to produce a magnetic field for operation; however, he does not perform any real work.
- The apparent power is the vector sum of the true and reactive power and corresponds to the total power required to produce the equivalent amount of true power for the load, see figure 1.

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Fig.1. Power factor correction

Power factor correction may be required when a system has a power factor of less than 90% (or 0.9). A low power factor can contribute to the instability and malfunction of the equipment, as well as significantly higher energy costs than necessary, because it means that more current is needed to perform the same amount of work [2], [4], [10]. By optimizing and improving the power factor, the quality of the power is improved, reducing the load on the electricity distribution system, see fig.2 [3].

Fig.2. PFC Equipment

2. POWER FACTOR IMPROVEMENT

Improving the power factor is a solution that allows technical and economic advantages, in fact, management of a low-energy installation implies an increase in costs
for the authority that supplies electricity, which consequently applies a tariff structure that penalizes the withdrawal of energy with reduced power factors [1].

Legislative measures in force in different countries allow national energy authorities to create a more or less detailed tariff system, without going into too much detail, such a system is structured so that the absorbed reactive energy exceeds the value corresponding to \( \cos \phi \) equal to 0.9 must be paid based on amounts defined according to the voltage level of the supply (low, medium or high) and the power factor [9].

As mentioned above, by correcting the power factor of an installation that provides the required reactive power locally, at the same level of required output power, it is possible to reduce the current value and therefore the total power absorbed on the load side, this implies many advantages, including a better use of the electric machines (generators and transformers) and of the electric lines (transmission and distribution lines), fig.3.

In the case of sinusoidal waveforms, the reactive power required to switch from a power factor \( \cos \phi_1 \) to a power factor \( \cos \phi_2 \) is given by the relation (valid for both three-phase and single-phase systems), see relation (1):

\[
Q_c = Q_1 - Q_2 = P \cdot (\tan \phi_1 - \tan \phi_2)
\]

Where:
- \( P \) is active power
- \( Q_1, \phi_1 \) are the reactive power and the phase shift angle before the power factor correction;
- \( Q_2, \phi_2 \) are the reactive power and the phase shift angle after the power factor correction;
- \( Q_c \) is the reactive power for power factor correction.

Let us presume that we want to increase the power factor from 0.8 to 0.93 in a three-phase installation (\( U_n = 400 \text{ V} \)) absorbing an average power of 300 kW. Relation (2) shows the absorbed current will be:
By applying the formula described above, the reactive power generated locally by $Q_c$ can be obtained in relation (3):

$$ Q_c = P \cdot (\tan \phi_1 - \tan \phi_2) = 300 \cdot (0.75 - 0.39) = 108[kVA] $$

Due to the power factor correction effect, the absorbed current decreases from 540 A to relation (4):

$$ I_1 = \frac{P}{\sqrt{3} \cdot U_n \cdot \cos \phi_1} = \frac{300 \cdot 10^3}{\sqrt{3} \cdot 400 \cdot 0.8} = 540[A] $$

$$ I_1 = \frac{P}{\sqrt{3} \cdot U_n \cdot \cos \phi_2} = \frac{300 \cdot 10^3}{\sqrt{3} \cdot 400 \cdot 0.93} = 465[A] \quad (\approx 15\% \text{ reduction}) $$

For the above, the main benefits of power factor correction can be summarized as follows:
- better use of electric machines;
- better use of power lines;
- reducing losses;
- reduction of voltage drops.

a) Better use of electric machines

By improving the power factor of the installation, these electric machines can be dimensioned for a seemingly lower power, but still provide the same active power [8].

The table 1 presents the variation of transmissible power for MV / LV three-phase transformers as a function for $\cos \phi$:

<table>
<thead>
<tr>
<th>Power of the transformer [kVA]</th>
<th>Power of the transformer [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>63</td>
<td>32</td>
</tr>
<tr>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>125</td>
<td>63</td>
</tr>
<tr>
<td>160</td>
<td>80</td>
</tr>
<tr>
<td>200</td>
<td>100</td>
</tr>
<tr>
<td>250</td>
<td>125</td>
</tr>
<tr>
<td>315</td>
<td>158</td>
</tr>
</tbody>
</table>

Table 1. The variation of transmissible power for MV / LV three-phase transformers
### The Technical and Economic Advantages of Power Factor Correction

<table>
<thead>
<tr>
<th>kW</th>
<th>200</th>
<th>240</th>
<th>280</th>
<th>320</th>
<th>360</th>
<th>400</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>630</td>
<td>315</td>
<td>378</td>
<td>441</td>
<td>504</td>
<td>567</td>
<td>630</td>
</tr>
<tr>
<td>800</td>
<td>400</td>
<td>480</td>
<td>560</td>
<td>640</td>
<td>720</td>
<td>800</td>
</tr>
<tr>
<td>1000</td>
<td>500</td>
<td>600</td>
<td>700</td>
<td>800</td>
<td>900</td>
<td>1000</td>
</tr>
<tr>
<td>1250</td>
<td>625</td>
<td>750</td>
<td>875</td>
<td>1000</td>
<td>1125</td>
<td>1250</td>
</tr>
</tbody>
</table>

From the previous chart it turns out that in order to provide a total power of 170 kW with $\cos \varphi = 0.7$ for a series of loads, a 250 kVA transformer must be used. If the loads would absorb the same power with $\cos \varphi = 0.9$, instead of 0.7, it would be sufficient to use a 200 kVA transformer. It is also valid for generators.

**b) Better use of power lines**

The correction of the power factor allows to obtain advantages for the sizing of the cables. In fact, as previously stated, at the same output power, by increasing the power factor the current decreases. This reduction of current can be such as to allow the choice of conductors with a lower cross section.

**c) Reducing losses**

The power losses of an electric conductor depend on the resistance of the conductor itself and the square of current flowing through it; since, with the same value of the active power transmitted, the higher the $\cos \varphi$, the smaller the current, it turns out that when the power factor increases, the losses in the conductor in the power part of the point where the correction of the factor of power has been made will decrease.

**d) Reduction of voltage drops**

The voltage drop from line to line in a three-phase line can be expressed as follows, in relation (5):

$$
\Delta U = \sqrt{3} \cdot I \cdot (R \cos \varphi + X \sin \varphi) = \frac{P}{U_n} \cdot (R + X \tan \varphi)
$$

Where:
- $R$ and $X$ are respectively the resistance and reactance of the line;
- $P$ is the transmitted active power;
- $I$ is the current;
- $U$ is the rated voltage.

At the same transmitted active power level, the lower the voltage drop, the higher the power factor.
3. THE ADVANTAGES OF POWER FACTOR CORRECTION ECONOMICALLY

In general, the contractual clauses of electricity supply require the payment of the reactive energy absorbed when the power factor is included in the range 0.7 and 0.9, while nothing is due if it is greater than 0.9. For \( \cos \phi < 0.7 \), energy distributors can force consumers to make power factor corrections.

The cost that the consumer incurs on an annual basis when drawing a reactive energy exceeding the value corresponding to a power factor equal to 0.9 can be expressed by the following relation (6):

\[
C_{EQ} = (E_Q - 0.5 \cdot E_p) \cdot C
\]  

(6)

Where:
- \( C_{EQ} \) is the cost of the reactive energy per year in €;
- \( E_Q \) is the reactive energy consumed per year in kVArh;
- \( E_p \) is the active energy consumed per year in kWh;
- \( E_Q - 0.5 \cdot E_p \) is the amount of reactive energy to be paid;
- \( c \) is the unit cost of the reactive energy in €/kVArh.

Consumer savings are in relation (7):

\[
C_{EQ} - C_{Qc} = (E_Q - 0.5 \cdot E_p) \cdot c - Q_c \cdot c_c
\]  

(7)

Where:
- \( C_{Qc} \) is the yearly cost in € to get a power factor equal to 0.9;
- \( Q_c \) is the power of the capacitor bank necessary to have a \( \cos \phi \) of 0.9, in kVAr;
- \( c_c \) is the yearly installation cost of the capacitor bank in €/kVAr.

In fact, a precise analysis of an investment involves the use of economic parameters that go beyond the purposes of this technical application document.

The following is an example of the energy consumption of a company. A company absorbs the active and reactive energy according to the table 2:

<table>
<thead>
<tr>
<th>Month</th>
<th>Active energy [kWh]</th>
<th>Reactive energy [kvarh]</th>
<th>Monthly average pf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>7221</td>
<td>6119</td>
<td>0,76</td>
</tr>
<tr>
<td>Feb</td>
<td>8664</td>
<td>5802</td>
<td>0,83</td>
</tr>
<tr>
<td>Mar</td>
<td>5306</td>
<td>3858</td>
<td>0,81</td>
</tr>
<tr>
<td>Apr</td>
<td>8312</td>
<td>6375</td>
<td>0,79</td>
</tr>
<tr>
<td>May</td>
<td>5000</td>
<td>3948</td>
<td>0,78</td>
</tr>
<tr>
<td>June</td>
<td>9896</td>
<td>8966</td>
<td>0,74</td>
</tr>
<tr>
<td>July</td>
<td>10800</td>
<td>10001</td>
<td>0,73</td>
</tr>
</tbody>
</table>
THE TECHNICAL AND ECONOMIC ADVANTAGES OF POWER FACTOR CORRECTION

<table>
<thead>
<tr>
<th>Month</th>
<th>Active energy [kWh]</th>
<th>Average pf</th>
<th>Operating hours</th>
<th>Active power P [kW]</th>
<th>Qc=P-(tanφ=0.484)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aug</td>
<td>9170</td>
<td>0.72</td>
<td>160</td>
<td>45.1</td>
<td>16.4</td>
</tr>
<tr>
<td>Sep</td>
<td>5339</td>
<td>0.76</td>
<td>160</td>
<td>54.2</td>
<td>10.0</td>
</tr>
<tr>
<td>Oct</td>
<td>7560</td>
<td>0.78</td>
<td>160</td>
<td>33.2</td>
<td>8.1</td>
</tr>
<tr>
<td>Nov</td>
<td>9700</td>
<td>0.74</td>
<td>160</td>
<td>52.0</td>
<td>14.7</td>
</tr>
<tr>
<td>Dec</td>
<td>6778</td>
<td>0.78</td>
<td>160</td>
<td>31.3</td>
<td>9.5</td>
</tr>
<tr>
<td>Total</td>
<td>93746</td>
<td>0.76</td>
<td>160</td>
<td>57.3</td>
<td>26.1</td>
</tr>
</tbody>
</table>

If a bank of automatic capacitors controlled for the correction of the power factor with Qc = 30 kVAR, compared to a total installation cost of 25 € / kVAR, a total cost of 750 € is obtained. Consumer savings, regardless of depreciation and financial costs, must be in relation (8):

\[ C_{EQ} - C_{QC} = 1370 - 750 = 620€ \]  (8)

4. CONCLUSIONS

According to the tariff system applied, the consumer can determine the amount of his own additional tax and, therefore, can evaluate the savings to the penalties to be paid in comparison with the cost of an installation for the correction of the power factors.

Electricity distributors apply a tariff system that imposes penalties for energy consumption with an average monthly power factor of less than 0.9. The contracts applied are different from one country to another and may also vary depending on the client's typology: consequently, the following observations should be considered as a
simple didactic and indicative information, showing the economic benefits that can be obtained due to the correction of the power factor.

It is important to note that the capacitor bank represents an "installation cost" which must be appropriately divided for years of life of the installation, applying one or more economic coefficients; in practice, the savings obtained by correcting the power factor allow to recover the cost of installing the capacitor bank in the first years of use.

Also, too much capacity in an AC circuit will result in a low power factor, as in the case of too much inductance. We must therefore be very careful when performing the power factor correction, in order not to over-correct the circuit.

REFERENCES


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