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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[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 [6], [7]:

- True power is the power that effectively supplies the equipment and performs useful and productive work.
- Reactive power is required by some equipment (eg. 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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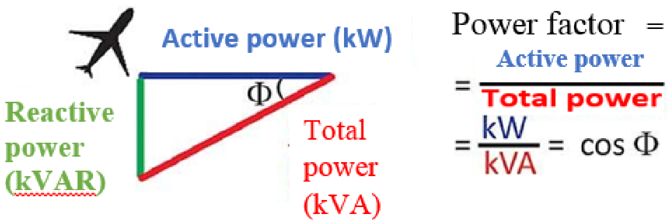

Fig.1. Power factor correction

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].

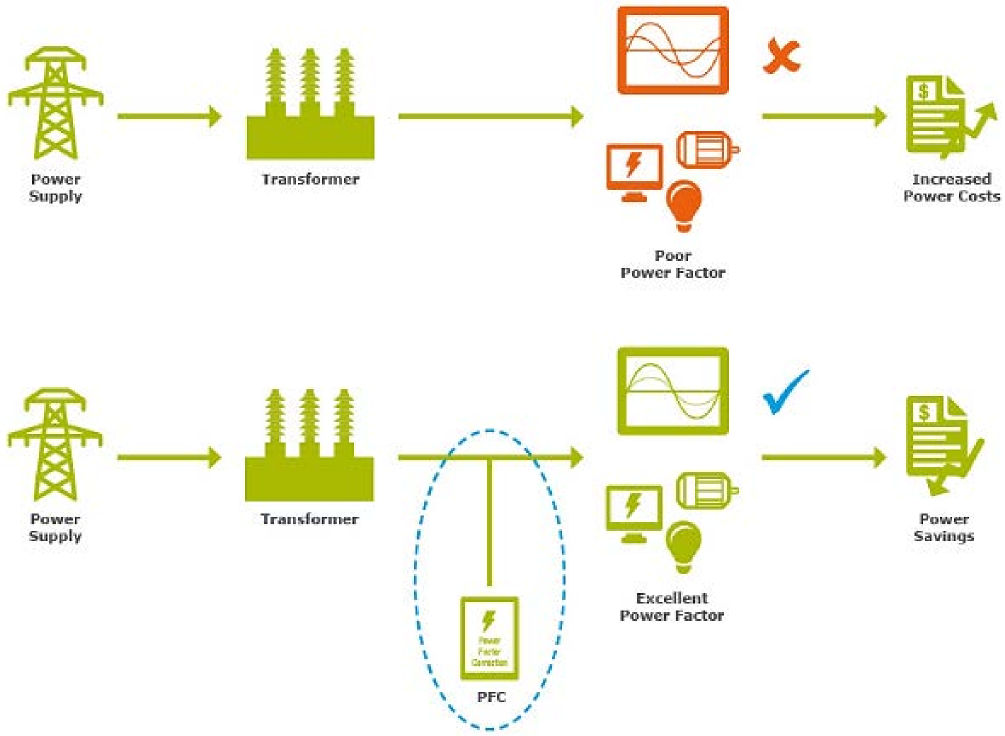

Fig.2. PFC Equipment

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 cosφ 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.

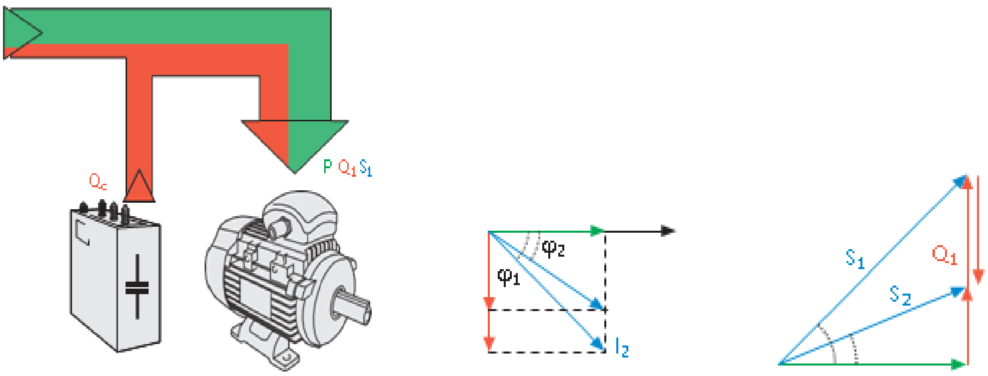

Fig.3. Power factor improvement

In the case of sinusoidal waveforms, the reactive power required to switch from a power factor $\cos\varphi_1$ to a power factor $\cos\varphi_2$ is given by the relation (valid for both three-phase and single-phase systems), see relation (1):

$$Q_c = Q_1 - Q_2 = P \cdot (tg\varphi_1 - tg\varphi_2) \tag{1}$$

Where:

- P is active power
- Q1, φ_1 are the reactive power and the phase shift angle before the power factor correction;
- Q2, φ_2 are the reactive power and the phase shift angle after the power factor correction;
- Qc 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 (Un = 400 V) absorbing an average power of 300 kW.

Relation (2) shows the absorbed current will be:

$$I_1 = \frac{P}{\sqrt{3} \cdot U_n \cdot \cos\varphi_1} = \frac{300 \cdot 10^3}{\sqrt{3} \cdot 400 \cdot 0.8} = 540[A] \tag{2}$$

By applying the formula described above, the reactive power generated locally by Qc can be obtained in relation (3):

$$Q_c = P \cdot (tg\varphi_1 - tg\varphi_2) = 300 \cdot (0{,}75 - 0{,}39) = 108[kVAr] \tag{3}$$

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

$$I_1 = \frac{P}{\sqrt{3} \cdot U_n \cdot \cos\varphi_2} = \frac{300 \cdot 10^3}{\sqrt{3} \cdot 400 \cdot 0.93} = 465[A] \tag{4}$$

(≈15% 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 cosφ:

Table 1. ***The variation of transmissible power for MV / LV three-phase transformers***

Power of the transformer [kVA]	Power of the transformer [kW]					
	cosφ					
	0.5	0.6	0.7	0.8	0.9	1
63	32	38	44	50	57	63
100	50	60	70	80	90	100
125	63	75	88	100	113	125
160	80	96	112	128	144	160
200	100	120	140	160	**180**	200
250	125	150	**175**	200	225	250
315	158	189	221	252	284	315

400	200	240	280	320	360	400
630	315	378	441	504	567	630
800	400	480	560	640	720	800
1000	500	600	700	800	900	1000
1250	625	750	875	1000	1125	1250

From the previous chart it turns out that in order to provide a total power of 170 kW with cosφ = 0.7 for a series of loads, a 250 kVA transformer must be used. If the loads would absorb the same power with cosφ = 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 cosφ, 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):

$$\Delta U = \sqrt{3} \cdot I \cdot (R\cos\varphi + X\sin\varphi) = \frac{P}{U_n} \cdot (R + Xtg\varphi) \quad (5)$$

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 cosφ <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):

$$C_{EQ} = (E_Q - 0{,}5 \cdot E_p) \cdot C \tag{6}$$

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 Ep 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):

$$C_{EQ} - C_{Qc} = (E_Q - 0{,}5 \cdot E_p) \cdot c - Q_c \cdot c_c \tag{7}$$

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 cosφ 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 2. ***Active and reactive energy consumption in one year***

Month	Active energy [kWh]	Reactive energy [kvarh]	Monthly average pf
Jan	7221	6119	0,76
Feb	8664	5802	0,83
Mar	5306	3858	0,81
Apr	8312	6375	0,79
May	5000	3948	0,78
June	9896	8966	0,74
July	10800	10001	0,73

Aug	9170	8910	0,72
Sep	5339	4558	0,76
Oct	7560	6119	0,78
Nov	9700	8870	0,74
Dec	6778	5879	0,76
Total	**93746**	**79405**	**-**

If a bank of automatic capacitors controlled for the correction of the power factor with Q_c = 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 table 3:

Table 3. ***The reactive power necessary to increase the power factor up to 0.9***

Month	Active energy [kWh]	Monthly average pf	Operating hours	Active power P [kW]	Qc=P·(tanϕ-0.484[1])
Jan	7221	0,76	160	45,1	16,4
Feb	8664	0,83	160	54,2	10,0
Mar	5306	0,81	160	33,2	8,1
Apr	8312	0,79	160	52,0	14,7
May	5000	0,78	160	31,3	9,5
June	9896	0,74	160	61,9	26,1
July	10800	0,73	160	67,5	29,8
Aug	9170	0,72	160	57,3	27,9
Sep	5339	0,76	160	33,4	12,3
Oct	7560	0,78	160	47,3	15,4
Nov	9700	0,74	160	60,6	26,1
Dec	6778	0,76	160	42,4	16,2

[1]0.484 is the tangent corresponding to a cosφ equal to 0.9

In the case of a capacitor bank with automatic control for the correction of the power factor with Q_c = 30 kVAr, compared to the total installation cost per year of 25 €/kVAr, a total cost of 750 € is obtained. Consumer savings, regardless of depreciation and financial costs, are presented in relation (8):

$$C_{EQ} - C_{QC} = 1370 - 750 = 620€ \tag{8}$$

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.

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