ELECTRONICS AND ELECTRICAL ENGINEERING
ISSN 1392 – 1215 2012. No. 2(118)
ELEKTRONIKA IR ELEKTROTECHNIKA

ELECTRICAL ENGINEERING
T 190
ELEKTROS INŽINERIJA

Improvement of Power Factor. Technoeconomical Application in a Case Study at the Industrial Area of Kavala

P. Adoniadis, N. Vordos, D. V. Bandekas, A. Ioannou
Department of Electrical Engineering, Kavala Institute of Technology,
St. Loukas, 654 04, Greece, phone: 0030-2510-462272, e-mail: vordosn@yahoo.com

crossref http://dx.doi.org/10.5755/j01.eee.118.2.1170

Introduction

Modern power systems are characterized by problems of increased losses and stability trends related to the availability of reactive power. The reactive power is a non-productive one, necessary for the operation of the interconnected cargo and as well as the operation of distribution networks and transmission of electricity. The importance of reactive power is also shown by the great blackout "Great Northeast" in 2003 due to the loss of it. [1] The degree of reactive power consumption is expressed by the quantity cosφ, called power factor (PF). The power factor is the ratio of RMS power to the apparent one. The power factor is calculated as follow:

$$P = \sqrt{3}UI\cos\phi\,, \quad (1)$$

$$S = \sqrt{3}UI\,, \quad (2)$$

$$Q = \sqrt{3}UIsin\phi\,, \quad (3)$$

$$PF = \frac{P}{S} = \cos\phi\,, \quad (4)$$

where P is the active power (watt), U is the voltage (Volt), I is the current (A), φ is the phase difference between voltage and current, S is the apparent power (VA) and Q is the reactive power (VAR).

The most serious problem appears in systems with inductive engines and lighting - air conditioning and heating units. In order to solve these problems, kinds of compensation are used as following:

1. Individual compensation;
2. Central compensation.

In the central compensation is installed an array of capacitors in the entrance of the installation which is monitored by an electronic controller. The national electric generation, in order to encourage industrial users to optimize the power factor, has imposes penalties on their behalf.

In order to save energy and to optimize the cosφ, a range of actions is necessary such as, proper optimization of capacitors to be used, the procedure for the installation and more over the check if it is useful investment of this kind or not economically.

The pricing is divided into three main categories:

1. with low voltage,
2. with medium voltage,
3. with high voltage.

The main charges are G22 billing for domestic use and for industrial B1, B2, B1B and B2B one. The relations for the charge are: Billing G22.

According to the cosf there are the following cases:
If cosφ <0.95, the xz is given by the following equation

$$XZ = KMZ \times \left[1 + \left(\frac{0,95}{\cos f} - 1\right)\right] \times 1,6\,, \quad (5)$$

where XZ is the demand charge (kW) and KMZ is the recorded maximum demand (kW)

If cosφ < 0.95, the xz is given by the following equation

$$XZ = KMZ\,. \quad (6)$$

The billings B1, B2, B1B and B2B are given by the following equations, according to cosφ:

- If cosφ <0.95

$$XZ = KMZ \times \left[1 + \left(\frac{0,87}{\cos f} - 1\right)\right] \times 1,25\,. \quad (7)$$

- If cosφ >0.95

$$XZ = KMZ \times \left[1 + \left(\frac{0,87}{\cos f}\right)\right]. \quad (8)$$

Modeling process to improve the cosf

The reactive power is a critical point for the operation of power systems. For proper use of capacitors or range of capacitors, are used different algorithms for the proper choice. Some of these algorithms use the method of analytical hierarchy [2] and can be used models as shown in Fig. 1.

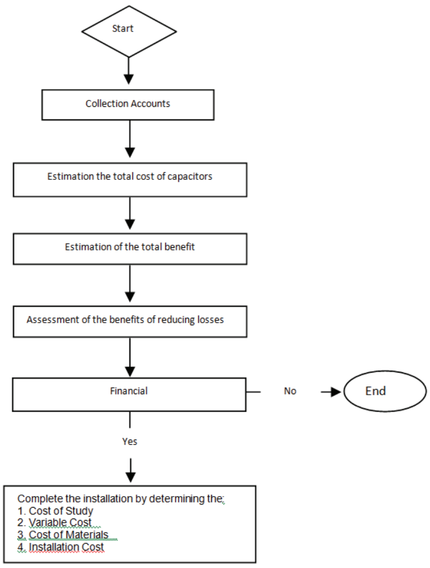

Fig. 1. Decision flowchart

In order to optimize the capacity of capacitors, the cosφ must be maximized, the losses of transfer lines must minimized and the gain of transfer line must maximized. According to this concept the capacitor C1 must calculated as follow [3]:

$$PF = \frac{P_L}{V_L I_S}, \tag{9}$$

$$LL = \sum I_{sn}^2 R_{th}, \tag{10}$$

$$n = \frac{P_L}{P_C}, \tag{11}$$

where P_L: power load; V_L: the RMS voltage of the load; I_s: the RMS value of the current; I_{sn}: the value of current with harmonic h; R_{th}: the resistance of the load.

In practice the choice of the capacity of each capacitor will be used, in order to improve cosφ, proceed as follows:

1. Convert mechanical power into electrical.
2. Calculation of absorbed electrical power

$$P_{el} = \frac{Pmech}{n}. \tag{12}$$

3. Calculation of total absorbed power

$$P_{all} = \sum P_{el}. \tag{13}$$

4. Calculation of the reactive power for each engine

$$P_{bn} = P_{el} \times \tan f. \tag{14}$$

5. Calculation of the total reactive power

$$P_{ball} = \sum P_{bn}. \tag{15}$$

6. Calculation of tan f

$$\tan f = \frac{P_{ball}}{P_{el}}. \tag{16}$$

7. Calculation of reactive power per phase for cosφ in (1)

$$P_b = \frac{1}{3} P_{all} \left(\tan 1 - \tan 2\right). \tag{17}$$

8. Calculation of the capacity of each capacitor

$$C_\Delta = \frac{P_b}{2\pi f U_{\pi o\lambda}^2}. \tag{18}$$

Economic analysis of the capacitor selection

The benefits from the improving of power factor is not only qualitative but mainly economically in the industry [4]. Several economic methods have developed over time, in order to study the economic gain due to the improvement in the consumption of reactive power such as the relation (19) [1].

$$B_T = B_1 + B_2 + B_3, \tag{19}$$

where B_T: the total benefit of using capacitors; B_1: the benefit of reducing the account; B_2 : the benefit of using the actual force; B_3: the benefits of increasing portability force.

Another equation, used by the international literature, on the base of the minimization of reactive power using capacitors, is

$$\sum Cc_j \left(Qc_j\right) + C_{ploss}, \tag{20}$$

where Qc the reactive power of capacitors; $Cc_j\left(Qc_j\right)$ the cosφ of capacitors; C_{ploss} the cost of line losses.

The use of capacitors in an industrial application and the benefit due to this, is

$$CcQc = rQc, \tag{21}$$

where Qc the cost of installation and r the cost of reactive power which is given by

$$r = \frac{operation\ \cos t}{operating\ \text{hours}}. \tag{22}$$

The annual cost of energy is

$$C_a = \beta P_{av} T_{an}, \tag{23}$$

where β the cost of electric energy.

The implementation of any system in order to optimize the power factor requires expenditure of money. The total cost is the result of the total cost of each work as it is shown in relationship (24)

$$TC = \sum C_1 + \sum C_2, \tag{24}$$

where $\sum C_1$ cost of materials (capacitors, electronic units, panel, relay, little u); $\sum C_2$: cost of the assembly, design, installation.

Due to the high cost of the initial installation of the system improving the cosφ, the depreciation of the system must also take into account and is given by relationship (25).

$$T_c^{'} = c_o + c_o \frac{1}{(1+i)^1} + c_o \frac{1}{(1+i)^2} + ... + c_o \frac{1}{(1+i)^N}, \quad (25)$$

where c_o :amortization dose; i: interest rate; N: the number of doses

Case study in the industrial area of Kavala

Kavala is the capital of the prefecture and geographically is located in North Eastern Greece (Fig. 2). The population growth is the result of the industrial development. The majority of the city residents are employed in service sector output. Here there is the only company in Greece where oil and desulphurise are extracted (Kavala Oil AE). Beyond the deposit of black gold, in Thassos/Kavala there is the only Phosphate Fertilizer Manufacturing in Greece. Dozens of other units in the industrial district, with major units of marble and glass, offer thousands of jobs (most famous are the ASCO SA and KRE.KA. SA).

In this paper, are presented two industrial enterprises (company A and company B) of Kavala in combination of loads (resistive, inductive and capacitive). The accounts of the electricity and the power factor for a year are used in the studied companies. Then, an estimation is done based on relationships (5), (6) and (7), of the capacitors array used to offset the cosφ. Moreover, a prediction of the power factor is taking into account and the cost of installations of the capacitor's arrays is calculated and performance analysis of financial results is obtained.

Fig. 2. Indrustrial area of Kavala (Greece)

Company A

The first undertaking study presents the curves of the energy consumed during one year (Fig. 3) and the variation of cosφ is presented. (Fig. 4). As it shown in Fig. 4, the values of cosφ have a range between 0.6 and 1. This variation leads to absorption of reactive power and consequently the economic burden. The company is a craft wood one and is carried out from 2008. The Company operates a working one system of shift 8 hours.

The company (tables 1 and 2) is characterized by annual working time (H) 7260, 123200 kW average load, reactive power before the improvement 216000 kVAR, total installation of capacitors 120 kVAR, total cost of power before the improvement 23687 €, total cost of power after the improvement 22628 € and total profit of 1059 €

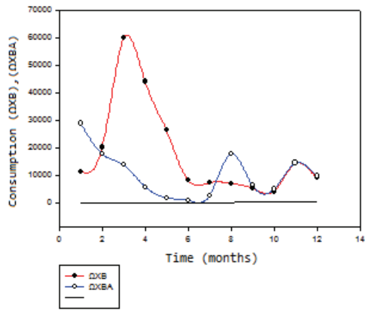

Fig. 3. The consumption of energy of company A during a year

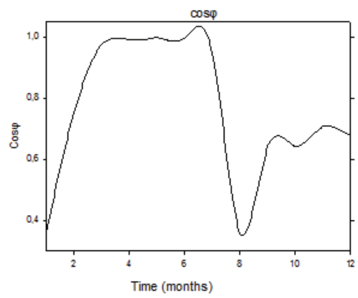

Fig. 4. The cosφ of company A in one year

A vital function of management of a company is the planning for the future. So for any future development and decision, a key tool it is used. To make the prediction, relationships (26), (27) and (28) are used:

$$Y_1 = b_0 + b_1 X_i , \quad (26)$$

$$b_1 = \frac{\sum X_i Y_i - v\bar{X}\bar{Y}}{\sum X_i^2 - v\bar{X}^2}, \quad (27)$$

$$b_0 = \bar{Y} - b_1 \bar{X}, \quad (28)$$

where X is cosφ and Y is the number of days.

Table 1. Recording power consumption of company A

From	Until	Days	ΩXB	ΩXBA	Demanded Days	Demanded Peak	Cosφ
5/12/08	13/1/09	38	11200	28800	45	45	0,362
8/11/08	5/12/08	24	20000	17600	106	80	0,751
8/10/08	8/11/08	33	60000	13600	155	129	0,975
10/9/08	8/10/08	28	44000	5600	158	139	0,992
13/8/08	10/9/08	27	26400	1600	106	94	0,998
14/7/08	13/8/08	29	8000	800	58	50	0,995
9/6/08	14/7/08	35	7200	2400	19	14	0,949
12/5/08	9/6/08	27	6797	17757	31	23	0,357
8/4/08	12/5/08	34	5203	6243	11	8	0,64
24/3/08	8/4/08	14	4000	4800	28	23	0,64
8/2/08	24/3/08	46	14400	14400	40	28	0,707
10/1/08	8/2/08	28	8800	9600	31	30	0,676

Note: ΩXB is the reactive power and ΩXBA is the active power

Applying relations (26) and (27) in the relationship Y1=0,7535-0,00527Xi are produced.

Using this one, the value of power factor for a future month can be predicted and estimated. Choosing the invoice of 15 months and 30 months the values of power factor will be 0.6745 and 0.5954 respectively. Observing the values derived from the model prediction, the values of power factor are much less than the unit and are: $Y_{15} = 0.6745 \quad Y_{30} = 0.5954$.

The big divergence that appears in the power factor from 1, requires the use of capacitor's array and according to relationships (9), (10) and (11) must be placed in case study A capacitor of about 120 KVar.

The total cost of installing the array of capacitors is as follows:

- Price battery capacitor C1 = 2647 € + VAT 21%;
- Cost Regulator 12 Steps C2 = 647 € + VAT 21%;
- Cost Relay C3 = 652 € + VAT 21%;
- Cost Table C4 = 200 € + VAT 21%;
- Cost of small equipment C5 = 110 € + VAT 21%;
- Cost of work and study C6 = 1000 € + VAT 21%.

Thus the relationship (24) becomes $TC = \sum C_1 + \sum C_2 =$ 5256€+ VAT 21%=6359,76€ .

Using the relationship (25) with the rate of 4.5% the extinction of installation of capacitor arrays will be in 23 months while, if they are placed in the first year, the results would be those in Table 2 and the first year would have saved 1059 €.

Table 2. Recording power consumption of the company A by placing capacitors

From	Until	Days	ΩXB	ΩXBA	Demanded Days	Demanded Peak	Cosφ	Value Current	New Cosφ	Required .KVAR	Economic gain
5/12/08	13/1/09	38	11200	28800	45	45	0,362	1737	1	120	485
8/11/08	5/12/08	24	20000	17600	106	80	0,751	2270	1	100	129
8/10/08	8/11/08	33	60000	13600	155	129	0,975	6240	1	40	15
10/9/08	8/10/08	28	44000	5600	158	139	0,992	4658	1	30	4
13/8/08	10/9/08	27	26400	1600	106	94	0,998	2818	1	10	1
14/7/08	13/8/08	29	8000	800	58	50	0,995	963	1	10	1
9/6/08	14/7/08	35	7200	2400	19	14	0,949	753	1	10	4
12/5/08	9/6/08	27	6797	17757	31	23	0,357	866	1	90	195
8/4/08	12/5/08	34	5203	6243	11	8	0,64	516	1	20	28
24/3/08	8/4/08	14	4000	4800	28	23	0,64	418	1	40	31
8/2/08	24/3/08	46	14400	14400	40	28	0,707	1525	1	40	102
10/1/08	8/2/08	28	8800	9600	31	30	0,676	923	1	40	64

Note: total profit from their accounts 1059,00 €

Company B

The first undertaking study presents the curves of the energy consumed during one year (Fig. 5) and the variation of cosφ is presented. (Fig. 6). Company B (Table 3 and Table. 4) is a small one with a working system of one unit of 8 hours, annual working time (H) 7260, 63200 kW average load, reactive power before the improvement 94400 kVAR, total installation of capacitors 100 kVAR, total cost of power before the improvement 8277 €, total power cost improvement after 6892 € and total gain of 1385 €.

The prediction equation is: $Y_1 = 0.5281 + 0.00543X_i$

The price estimates for 15 and 30 months are $Y_{15} = 0.6095 \quad . Y_{30} = 0.6883$

The capacitors should be 100 KVar and the purchase and installation cost are $TC = \sum C_1 + \sum C_2 = 4950$ € + VAT 21%=5989.5€

Table 3. Power consumption of the company B

From	Until	Days	ΩXB	ΩXBA	Demanded Days	Demanded Peak	Cosφ
12/12/08	20/1/09	38	5600	8800	18	18	0,537
17/11/08	12/12/08	25	5600	4800	18	18	0,759
14/10/08	17/11/08	33	4000	8000	14	11	0,447
16/9/08	14/10/08	28	3200	6400	9	6	0,447
21/8/08	16/9/08	25	2400	5600	10	10	0,394
18/7/08	21/8/08	33	3200	7200	14	14	0,406
13/6/08	18/7/08	35	4800	10400	16	15	0,419
19/5/08	13/6/08	24	2400	5600	42	42	0,394
14/4/08	19/5/08	35	5600	10400	39	37	0,474
31/3/08	14/4/08	13	3200	4000	52	44	0,625
15/2/08	31/3/08	46	13600	15200	70	55	0,667
21/1/08	15/2/08	24	9600	8000	63	56	0,768

Table 4. Recording power consumption of the company B by placing capacitors

			TOTAL GAIN FROM THEIR ACCOUNTS								1385,00
From	Until	Days	ΩXB	ΩXBA	Demand Days	Demand Peak	Cosφ	Value Current	New Cosφ	Required .KVAR	Economic Gain
12/12/08	20/1/09	38	5600	8800	18	18	0,537	703	1	30	97
17/11/08	12/12/08	25	5600	4800	18	18	0,759	604	1	20	25
14/10/08	17/11/08	33	4000	8000	14	11	0,447	507	1	30	82
16/9/08	14/10/08	28	3200	6400	9	6	0,447	365	1	20	41
21/8/08	16/9/08	25	2400	5600	10	10	0,394	317	1	30	62
18/7/08	21/8/08	33	3200	7200	14	14	0,406	464	1	40	109
13/6/08	18/7/08	35	4800	10400	16	15	0,419	636	1	40	121
19/5/08	13/6/08	24	2400	5600	42	42	0,394	549	1	100	232
14/4/08	19/5/08	35	5600	10400	39	37	0,474	863	1	80	228
31/3/08	14/4/08	13	3200	4000	52	44	0,625	414	1	70	62
15/2/08	31/3/08	46	13600	15200	70	55	0,667	1782	1	80	251
21/1/08	15/2/08	24	9600	8000	63	56	0,768	1073	1	60	75

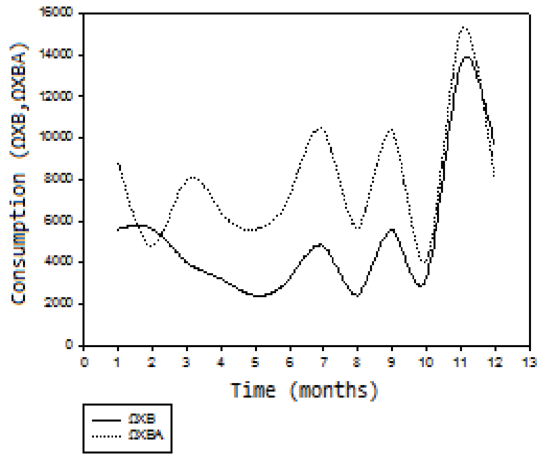

Fig. 5. The consumption of energy of company B during a year

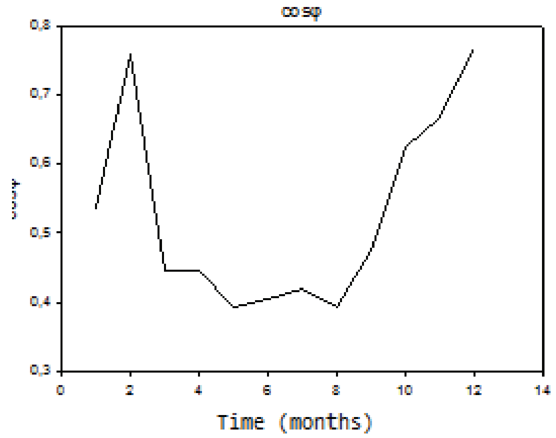

Fig. 6. The cosf of company B in one year

Conclusions

The electrical networks consume active and reactive power caused by the magnetic fields of motors and power transformers, impedance of the transmission and distribution lines, coils, fluorescent lighting and all inductive circuits. The main reasons for making the decision to install capacitor arrays for improving the power factor of a load, for the best technoeconomical solution, are mainly the cost of excessive consumption of reactive power, the decrease of energy and power losses, the increase of the available power at the substation, the best planning of a new substation in the network, the increase or regulation of the voltage scales, the facilitating to start of large motors at the edge very charged distribution lines.

The placement of capacitor's arrays in the two companies in Kavala, showed a reduction in the consumption of reactive power, power factor improvement, energy and money saving and reducing emissions. The depreciation of the capacitor array installation takes place in a relatively short period of about two years.

References

1. **Fangxing Li, Wenjuan Zhang, Tolbert L. M., Kueck J. D., Rizy D. T.** Assessment of the Economic Benefits from Reactive Power Compensation // Power Systems Conference and Exposition (PSCE'06). – IEEE PES, 2006. – P. 1767–1773.
2. **Jizhong Zhu, Momoh J. A.,** Optimal VAr pricing and Var placement using analytic hierarchical process // Electric power systems research, 1998. – Vol. 48. – No. 1. – P. 11–17.
3. . **Abdel Aziz M. M., Abou Elzahab E. E., Ibrahim A. M., Zobaa A. F.** Sizing of capacitors to optimize the power factor at non–sinusoidal frequencies // Electric Power Systems Research, 2003. – Vol. 64. – Iss. 1. – P. 81–85
4. **Thomas R. J., Mount T. D., Schuler R., Schulze W., Zimmerman R., Alvarado F., et al,** "Efficient and Reliable Reactive–Power Supply and Consumption: Insights from an Integrated Program of Engineering and Economic Research" // The Electricity Journal, 2008. – Vol. 21. – Iss. 1. – P. 70–81.

Received 2010 12 09
Accepted after revision 2011 10 20

P. Adoniadis, N. Vordos, D. V. Bandekas, A. Ioannou. Improvement of Power Factor. Technoeconomical Application in a Case Study at the Industrial Area of Kavala // Electronics and Electrical Engineering. – Kaunas: Technologija, 2012. – No. 2(118). – P. 38–42.

The reduction of energy supplies, the increase of the problems of environmental pollution and generally the negative effects of electrical energy production, necessitate the energy saving. The optimization of the power factor saves energy in industrial applications. This paper aims to study the cosφ using compensations capacitors, the benefits of replacement them, the method of optimization using these capacitors, in order to succeed the best technoeconomical solution and a case study in Industry Campus of Kavala. Ill. 6, bibl. 4, tabl. 4 (in English; abstracts in English and Lithuanian).

P. Adoniadis, N. Vordos, D. V. Bandekas, A. Ioannou. Galios koeficiento padidinimas. Techninė ekonominė galimybių studijos aplikacija industrinėje Kavalos srityje // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2012. – Nr. 2(118). – P. 38–42.

Energijos išteklių mažėjimas, aplinkos taršos problemos ir neigiami elektros energijos gamybos veiksniai verčia taupyti energiją. Galios koeficiento optimizavimas leidžia taupyti energiją pramonėje. Naudojant kompensavimo kondensatorius, analizuojamas cosφ ir tiriama, kokios naudos galima gauti pakeičiant juos kito tipo kondensatoriais. Ieškant geriausio techninio-ekonominio sprendimo, atliekama optimizacija naudojant minėtus kondensatorius ir tuo tikslu pramoniniame Kavala rajone atlikta galimybių studija. Il. 6, bibl. 4, lent. 4 (anglų kalba; santraukos anglų ir lietuvių k.).