Energy saving in electromechanical equipment with power coefficient correction

Dimitris Al. Katsaprakakis
Aeolian Land S.A.
www.aiolikigi.gr

Greece - Bulgaria 2007-2013
INVESTING IN OUR FUTURE
The project is co-funded by the European Union (ERDF) and National Funds of Greece and Bulgaria under the European Territorial Cooperation Programme

Introduction

- Electricity production companies (utilities) provide consumers with active and reactive power for the electrical devives operation.
- Reactive power is mainly consumed by motors, for the creation of the required electromagnetic field for their operation.
- Reactive power is also consumed by transformers, fluorescent lamps, welding machines etc.
- The production and the transportation of reactive power implies extra loads for power generators, transmission lines, transformers, etc, leading to overloading of the electricity production and distribution system and the limitation of its ability for active power production and transportation.
- The electricity transportation losses and the voltage drops are also increased with the reactive power consumption.

Greece - Bulgaria 2007-2013
INVESTING IN OUR FUTURE
The project is co-funded by the European Union (ERDF) and National Funds of Greece and Bulgaria under the European Territorial Cooperation Programme

Introduction

- The most common electrical devices that consume reactive power are met in asynchronous motors, employed in industrial production lines, as well in several devices met in the domestic and commercial sector, such as:
    - lifts
    - escalators
    - electrical pumping stations
    - wind turbines
    - electrical vehicles
    - air conditions
    - refrigerators
    - clothes’ washers and dryes.

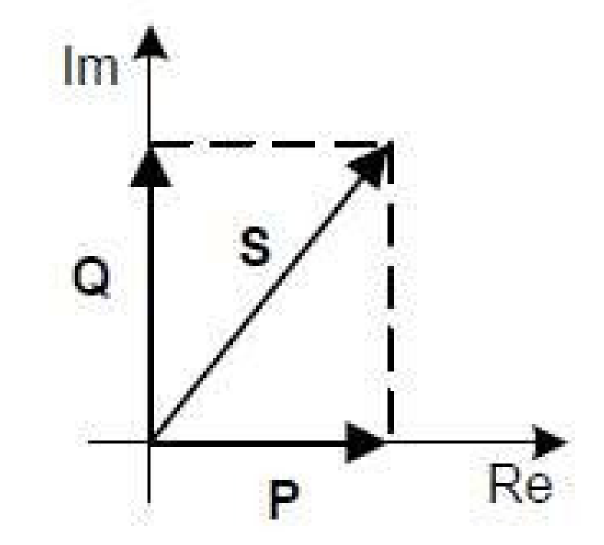
Power coefficient

- If P is the active and Q the reactive power consumption in an electric system, the power coefficient of that system is defined as the ratio of the active power consumption over the "apparent" power, that is the vector sum of the active and reactive power:

$$\cos\varphi = \frac{P}{\sqrt{P^2 + Q^2}} \Leftrightarrow \cos\varphi = \frac{1}{\sqrt{1 + \tan^2\varphi}}$$

where the apparent power is defined as $\vec{S} = \vec{P} + \vec{Q}$

and $\tan\varphi = \dfrac{Q}{P}$



Power coefficient

- The power coefficient (cosϕ) consist an index for the reactive power consumption of an electric system.
- A “good” load exhibits power coefficient values close to unity (e.g. 0,95 – 0,99), while a “bad” load exhibits lower power coefficient values.
- For example, an active power demand of 100kW implies the consumption of 48,4 / 32,8 / 14kVA or reactive power if the system’s power coefficient is 0,90 / 0,95 / 0,99, respectively.
- In practice, mean power coefficient values are calculated in electrical systems for certain time intervals, on the basis of the active and reactive energy consumption measurements.

Power coefficient

Mean monthly power coefficient calculation example.

- Let the monthly energy consumptions for an electrical system be as below:
  reactive energy: A = 136.600kVAh
  active energy: W = 105.000kWh.
- The mean monthly power coefficient in that case is:

$$\tan\varphi = \frac{A}{W} \Leftrightarrow \tan\varphi = 1{,}301$$

$$\cos\varphi = \frac{1}{\sqrt{1+\tan^2\varphi}} \Leftrightarrow \frac{1}{\sqrt{1+1{,}301^2}} \Leftrightarrow \cos\varphi = 0{,}609$$

Power coefficient

Mean monthly power coefficient calculation example.

- In the same with the previous example system, reactive power compensation devices are introduced, and the monthly energy consumptions are measured:
  reactive energy: A = 50.000kVAh
  active energy: W = 105.000kWh.
- The mean monthly power coefficient is now modified as:

$$\tan\varphi = \frac{A}{W} \Leftrightarrow \tan\varphi = 0{,}476$$

$$\cos\varphi = \frac{1}{\sqrt{1+\tan^2\varphi}} \Leftrightarrow \frac{1}{\sqrt{1+0{,}476^2}} \Leftrightarrow \cos\varphi = 0{,}903$$

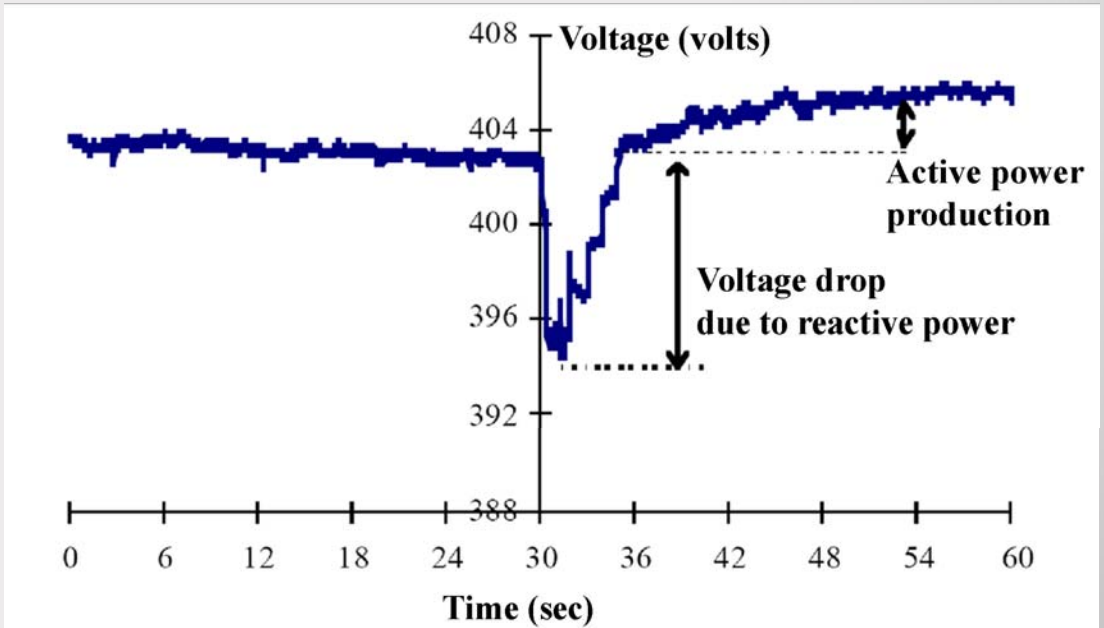
Greece - Bulgaria 2007-2013
INVESTING IN OUR FUTURE
The project is co-funded by the European Union (ERDF) and National Funds of Greece and Bulgaria under the European Territorial Cooperation Programme

Power coefficient

- From the above mentioned it is obvious that the power coefficient is improved, tending to unity, as the reactive power consumption is reduced, compared with the active power demand of the system.
- The power coefficient increase implies several benefits for the electrical system, as it will be analysed farther in this presentation.
- Consequently, the power coefficient correction is achieved with devices that aim at the reduction of the reactive power consumption.
- The transmission of the reactive power is not easy, since the arising transmission losses can be raised to a significant percentage of the initial produced reactive power.
- Hence, the reactive power demand should be faced locally, at the networks specific points where it is consumed.

Power coefficient

- In electrical networks the reactive power affects the system’s nominal voltage.
- The abrupt reactive power consumption, usually met during the powering on of electrical motors, can lead to significant voltage sags in the networks.
- It is so concluded that the reduction of the reactive power consumption and the power coefficient correction the introduction of devices and equipments for the support of the networks’ nominal voltage.
- Such devices are the capacitors.



Benefits from the power coefficient correction

Reduction of the electricity losses

- The reduction of the electricity losses Δp of an electrical system, for constant active power demand, depends on the systems power coefficient.
- The power losses p_R on a resistive resistance R which transfers current I, are given by the relationship:

$$p_R = R \cdot I^2$$

- If V is the voltage on the resistance, cosϕ the system's power coefficient and P the active power transmitted through the resistance, then:

$$P = V \cdot I \cdot \cos\varphi \Leftrightarrow I = \frac{P}{V \cdot \cos\varphi}$$

- Finally, the power losses are written as: $p_R = R \cdot \left(\frac{P}{V \cdot \cos\varphi} \right)^2$

Greece - Bulgaria 2007-2013
INVESTING IN OUR FUTURE
The project is co-funded by the European Union (ERDF) and National Funds of Greece and Bulgaria under the European Territorial Cooperation Programme

ΔΗΜΟΣ ΘΕΡΜΑΪΚΟΥ
AEOLIAN LAND S.A.

Reduction of the electricity losses

- The power losses in an electrical system where the power coefficient is improved from $\cos\phi_1$ to $\cos\phi_2$ will be respectively:

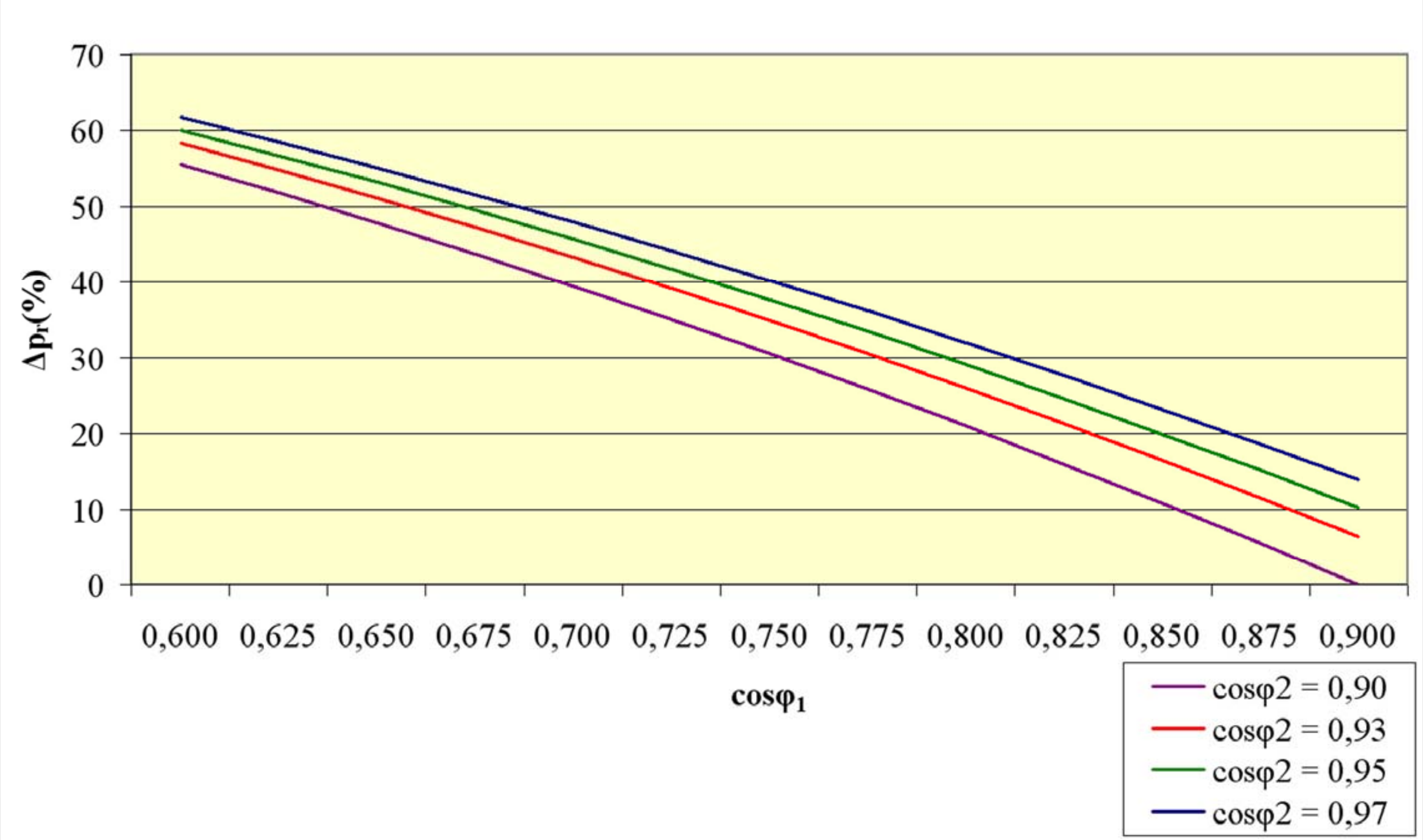
$$p_{R1} = R \cdot \left(\frac{P}{V \cdot \cos\varphi_1} \right)^2 \qquad p_{R2} = R \cdot \left(\frac{P}{V \cdot \cos\varphi_2} \right)^2$$

- The specific power losses variation due to the power coefficient correction will be:

$$\Delta p_R = \frac{p_{R1} - p_{R2}}{p_{R1}} \Leftrightarrow \Delta p_R = 1 - \frac{\cos^2\varphi_1}{\cos^2\varphi_2}$$

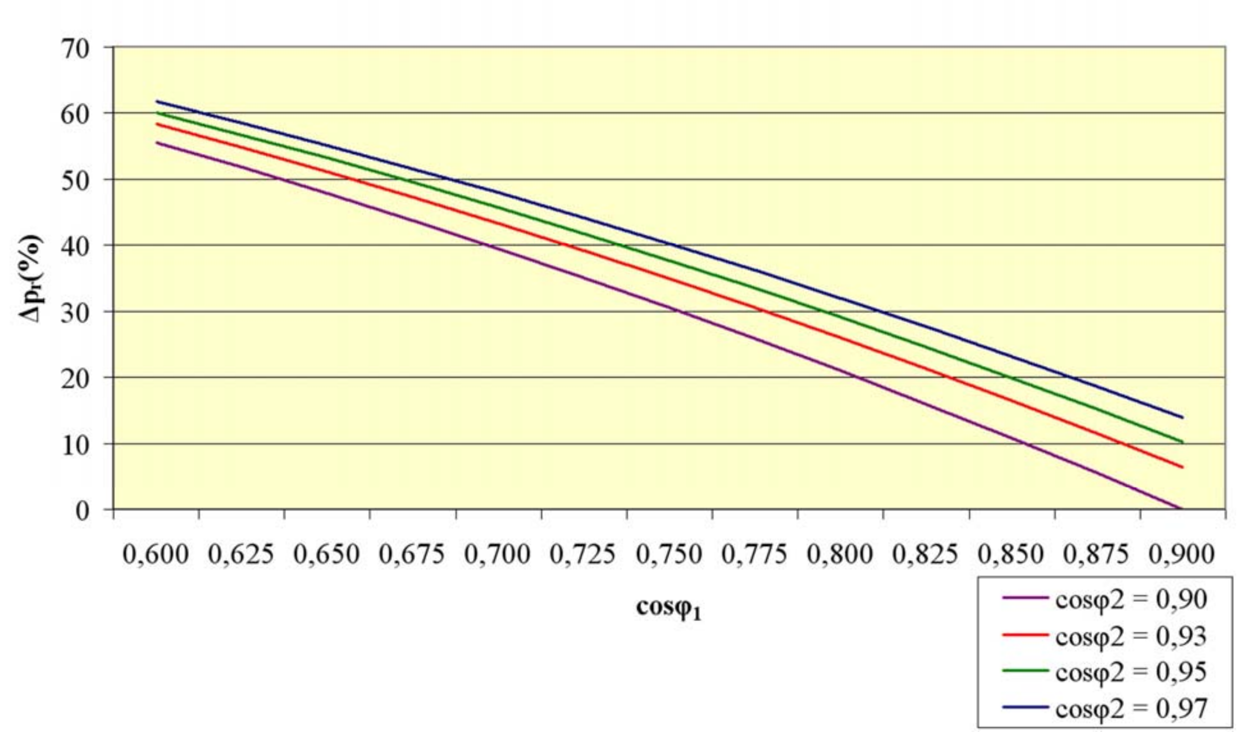
Reduction of the electricity losses

- The graphical representation of the above relationship gives the diagram below:



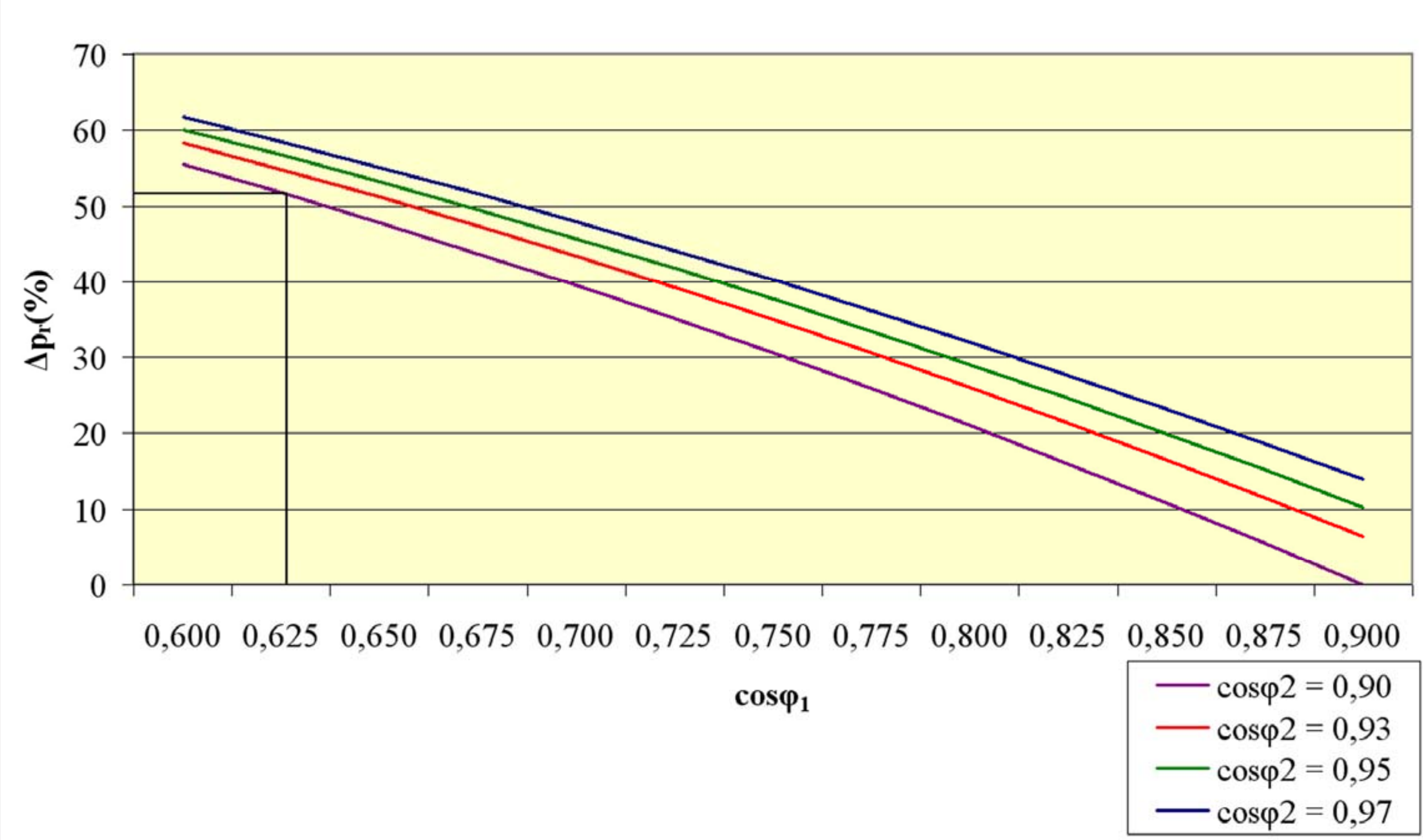
Reduction of the electricity losses

$\cos\varphi_1$	$\cos\varphi_2$			
	0,90	0,93	0,95	0,97
	Δp_r(%)			
0,600	55,56	58,38	60,11	61,74
0,625	51,77	54,84	56,72	58,48
0,650	47,84	51,15	53,19	55,10
0,675	43,75	47,32	49,52	51,58
0,700	39,51	43,35	45,71	47,92
0,725	35,11	39,23	41,76	44,14
0,750	30,56	34,96	37,67	40,22
0,775	25,85	30,56	33,45	36,16
0,800	20,99	26,00	29,09	31,98
0,825	15,97	21,31	24,58	27,66
0,850	10,80	16,46	19,94	23,21
0,875	5,48	11,48	15,17	18,63
0,900	0,00	6,35	10,25	13,91



Reduction of the electricity losses

- Using the above diagram (or table) we could see, for example, that if the power coefficient of a system increases from 62,5% to 90%, a reduction on the power losses of 51,77% will be achieved.



Reduction of the voltage sag

- The power coefficient correction leads to the reduction of the voltage sag on the transformers and the transmission lines installed before the capacitors connection point of the network.
- The voltage sag of a system is calculated using the following relationship:

$$\Delta V = Z \cdot I \Leftrightarrow \Delta V = R \cdot I \cdot \cos\varphi + X \cdot I \cdot \sin\varphi$$

where:

$$Z = R + j \cdot X$$

R and X are the resistive and the inductive component respectively of the complex resistance Z of the transformer or the transmission line.

Reduction of the voltage sag

Example of the voltage sag reduction in an electrical system.

- A transformer operates with the following specifications:
  - nominal power: $S = 630kVA$
  - short circuit voltage: $u_k = 4\%$
  - losses on copper: $P_{cu} = 6.500W$.
- Short circuit voltage in a transformer is the voltage of the primary circuit when the transmitted current is the nominal one and the secondary circuit is shorted. It is given by the relationship:

$$u_k = \sqrt{u_x^2 + u_r^2}$$

where u_r and u_x are the resistive and inductive voltage sag on the transformer.

Reduction of the voltage sag

Example of the voltage sag reduction in an electrical system.

- Resistive voltage sag:

$$u_r = \frac{R \cdot I}{V_{ov.}} = \frac{P_{Cu}}{S} \Leftrightarrow u_r = \frac{6,5}{630} \cdot 100\% \Leftrightarrow u_r = 1,03\%$$

- Inductive voltage sag :

$$u_x = \frac{X \cdot I}{V_{ov.}} = \sqrt{u_k^2 - u_r^2} \Leftrightarrow u_x = 3,87\%$$

- If the power coefficient is $\cos\phi = 0,7$ ($\sin\phi = 0,71$), the voltage sag on the transformer is calculated as:

$$\frac{\Delta V}{V_{ov.}} = \frac{R \cdot I}{V_{ov.}} \cdot \cos\varphi + \frac{X \cdot I}{V_{ov.}} \cdot \sin\varphi = 3,47\%$$

Reduction of the voltage sag

Example of the voltage sag reduction in an electrical system.

- If the power coefficient improves to cosϕ = 0,95 (sinϕ = 0,31), the voltage sag on the transformer is calculated as:

$$\frac{\Delta V}{V_{\text{ον.}}} = \frac{R \cdot I}{V_{\text{ον.}}} \cdot \cos\varphi + \frac{X \cdot I}{V_{\text{ον.}}} \cdot \sin\varphi = 2{,}18\%$$

hence, a reduction of the voltage drop of 1,29% is achieved.

- Although this reduction may seem low, it is rather important.
- Indeed, if the voltage drop in a system is 1,29% higher, this means that, in order to transfer the same power, the current must be raised with the same percentage.

Reduction of the voltage sag

Example of the voltage sag reduction in an electrical system.

- Then, the power losses will increase as:

$$\frac{R \cdot I_2^2 - R \cdot I_1^2}{R \cdot I_1^2} = \frac{I_2^2}{I_1^2} - 1 = \left(1 + \delta I\right)^2 - 1 = 2{,}60\%, \quad \text{where} \quad \delta I = \frac{I_2 - I_1}{I_1} = 1{,}29\%$$

Reduction of the voltage sag

- The voltage drops in transmission lines is not as high as on transformers, because they exhibit lower inductive resistance.
- However, the reactive power transmission in a system with low power coefficient, can cause overloading of the lines and, consequently, important voltage drop, leading finally to significant reduction of the line transmission ability.
- If the power coefficient correction is performed closely to the motors, the lines are relieved from the reactive power transmission and high voltage drops are avoided.

Reduction of the voltage sag

Reduction of voltage drop in power transmission lines versus the system's power coefficient and the cables' size.

Cable's size (mm^2)	System's power coefficient					
	0,5	0,6	0,7	0,8	0,9	1,0
	Transmission line ability (kW)					
3 x 10	20,0	24,0	28,0	32,0	36,0	40,0
3 x 16	27,5	33,0	38,5	44,0	49,5	55,0
3 x 25	33,7	40,5	47,2	54,0	60,8	67,5
3 x 35	41,2	49,5	57,8	66,0	74,2	82,5
3 x 50	50,0	60,0	70,0	80,0	90,0	100,0
3 x 70	61,0	73,2	85,4	97,6	110,0	122,0
3 x 95	73,5	88,0	103,0	117,0	132,0	147,0
3 x 120	85,0	102,0	119,0	136,0	153,0	170,0
3 x 150	97,5	117,0	136,0	156,0	175,0	195,0
3 x 185	111,0	133,0	156,0	178,0	200,0	222,0
3 x 240	128,5	154,0	180,0	206,0	232,0	257,0

Reduction of the voltage sag

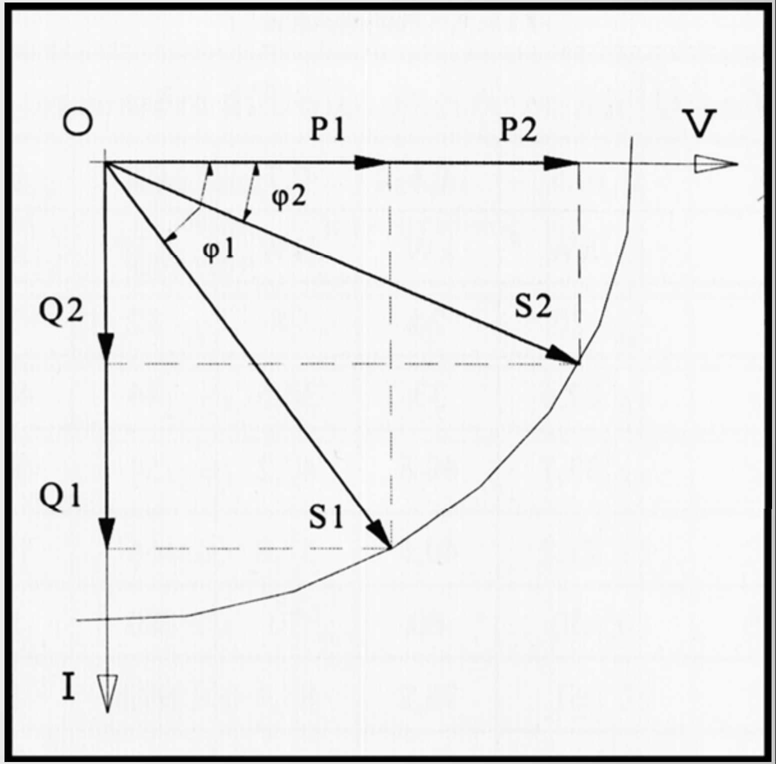
- Generally, the voltage drop in power transmission lines always implies the transmitted current equally percentage increase, for constant transmitted power.
- Since the resistive losses are analogous with the square of the current, the current increase leads to much higher losses increase.

Resistive losses increase versus the system's power coefficient						
Power coefficient	1,0	0,9	0,8	0,7	0,6	0,5
Current over the nominal (%)	100	111	125	143	166	200
Resistive losses over the nominal (%)	100	123	156	205	278	400

- From the above table we can see:
  - If cosφ reduces from 1 to 0,7, the resistive resistances are doubled.
  - If cosφ reduces from 1 to 0,5, the resistive resistances increase four times.

Increase of the systems' transmission ability

- The power coefficient correction can lead to significant increase of the systems' power transmission ability, since the transmitted loads through the lines and the transformers are reduced.
- In the diagram it is obvious that between two operational cases with the same apparent power ($S_1 = S_2$), in the second case, which exhibits higher power coefficient ($\phi_2 < \phi_1$), the active power transmission ability is higher ($P_2 > P_1$).



Increase of the systems' transmission ability

Increase of the transformers′ transmission ability versus the power coefficient						
Transformer′s nominal power (kVA)	System′s power coefficient					
	0,5	0,6	0,7	0,8	0,9	1,0
	Transformer′s active power transmission ability (kW)					
160	80	96	112	128	144	160
250	125	150	175	200	225	250
400	200	240	280	320	360	400
500	250	300	350	400	450	500
630	315	378	441	504	567	630
800	400	480	560	640	720	800
1.000	500	600	700	800	900	1.000
1.600	800	960	1.120	1.280	1.440	1.600

Increase of the systems' transmission ability

Calculation example of the transformers' transmission ability:

- Let's assume a transformer with nominal power of 630kVA that must take over an active power load of 500kW with power coefficient cosϕ = 0,7.
- The transformer's transmission ability with the above power coefficient is: 630kVA x 0,7(kW/kVA) = 441kW. Hence, the transformer is not adequate in this case for the required transmitted active power.
- For the above active power transmission with the specific power coefficient, the required nominal power of the transformer is:
  500kW / 0,7(kW/kVA) = 714,29kVA.
- Depending on the range of the commercially available transormers, we most probably should select a 800kVA or 1.000kVA transformer.
- The purchase of a larger device corresponds to high cost.

Increase of the systems' transmission ability

Calculation example of the transformers' transmission ability :

- If for the same transformer (630kVA) and the same active power demand (500kW), the power coefficient is cosϕ = 0,9, then the transformer's transmission ability is 630kVA x 0,9(kW/kVA) = 567kW. Hence, the transformer is adequate in that case.

Increase of the systems' transmission ability

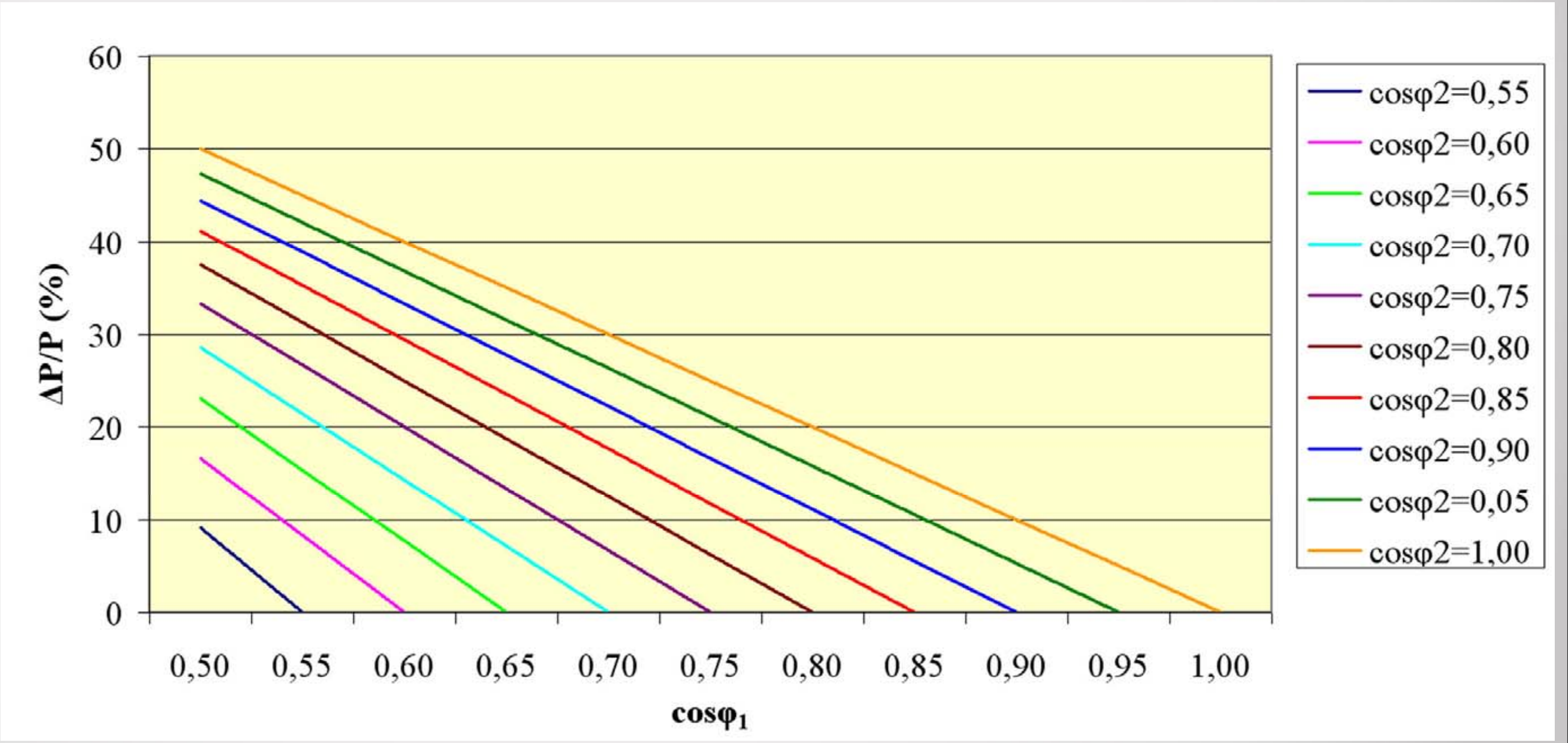
- If $P_1 = V \cdot I \cdot \cos\phi_1$ and $P_2 = V \cdot I \cdot \cos\phi_2$, are the transmitted active power in two cases between which only the power coefficient changes, we can define the specific variation of the transmitted active power versus the system's power coefficient:

$$\frac{\Delta P}{P_2} = \frac{P_2 - P_1}{P_2} = 1 - \frac{\cos\varphi_1}{\cos\varphi_2}$$

- The diagram of the next slide is constructed using the above relationship.

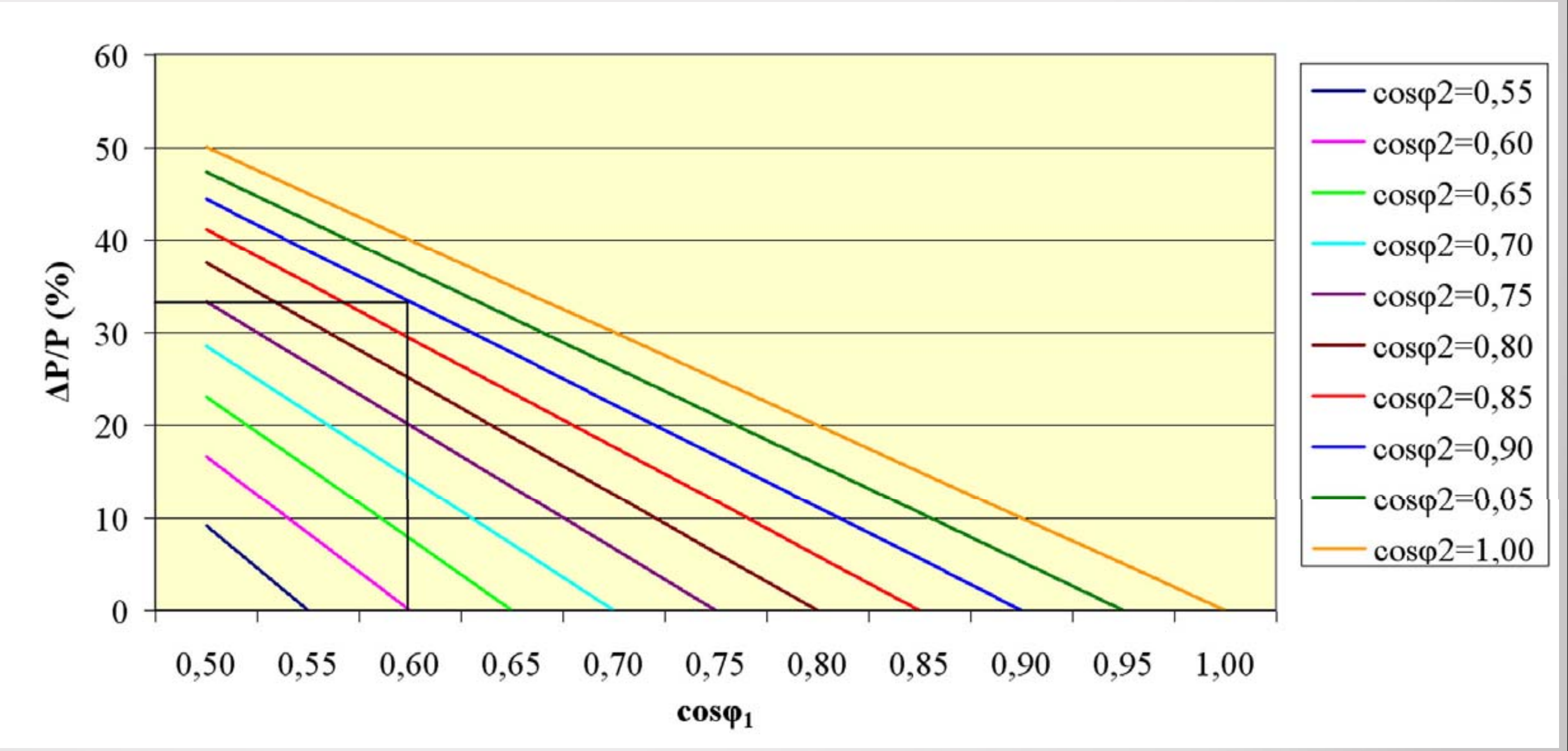
Increase of the systems' transmission ability

Diagram of the system's transmitted ability increase with the power coefficient correction



Increase of the systems' transmission ability

In the previously presented diagram we can estimate, for example, that if the power coefficient of a system increases from 0,60 to 0,90, a relative increase of the system's transmitted ability of 33,33% is achieved.



Increase of the systems' transmission ability

Systems′ transmitted ability increase with the power coefficient correction

$\cos\varphi_1$	$\cos\varphi_2$									
	0,55	0,60	0,65	0,70	0,75	0,80	0,85	0,90	0,95	1,00
	System′s transmitted ability relative increase (%)									
0,50	9,09	16,67	23,08	28,57	33,33	37,50	41,18	44,44	47,37	50,00
0,55	0,00	8,33	15,38	21,43	26,67	31,25	35,29	38,89	42,11	45,00
0,60		0,00	7,69	14,29	20,00	25,00	29,41	33,33	36,84	40,00
0,65			0,00	7,14	13,33	18,75	23,53	27,78	31,58	35,00
0,70				0,00	6,67	12,50	17,65	22,22	26,32	30,00
0,75					0,00	6,25	11,76	16,67	21,05	25,00
0,80						0,00	5,88	11,11	15,79	20,00
0,85							0,00	5,56	10,53	15,00
0,90								0,00	5,26	10,00
0,95									0,00	5,00
1,00										0,00

Methods of power coefficient correction

Power coefficient correction methods

- The power coefficient of a system is improved with the installation of capacitors that provide the consumed reactive power.
- The alternative methods are derived by the networks’ possible locations where the capacitors can be installed and they are:
  - central compensation
  - team compensation
  - local compensation.
- For the selection of capacitors’ optimum installation method, a thorough system’s inspection and evaluation is required.

Power coefficient correction methods

Correction with central compensation.

- The capacitors are installed directly after the power transformer, on the low voltage bar.
- With this method the required capacitors power is the minimum one, compared to the one of the other two methods.
- With this method, the reactive power that passes through the transformer reduces, consequently the voltage drop and the transformer’s losses reduce as well, leading to increase of the transformer’s transmission ability.

Power coefficient correction methods

Correction with team compensation.

- With this method the capacitors are installed before of selected parts of the electrical system.
- This method is selected when large inductive loads are met in system’s points, long distances from the central compensation.
- Central compensation still remains for the rest parts of the system.
- The total required capacitive power with this method is higher than the one of the central compensation.

Power coefficient correction methods

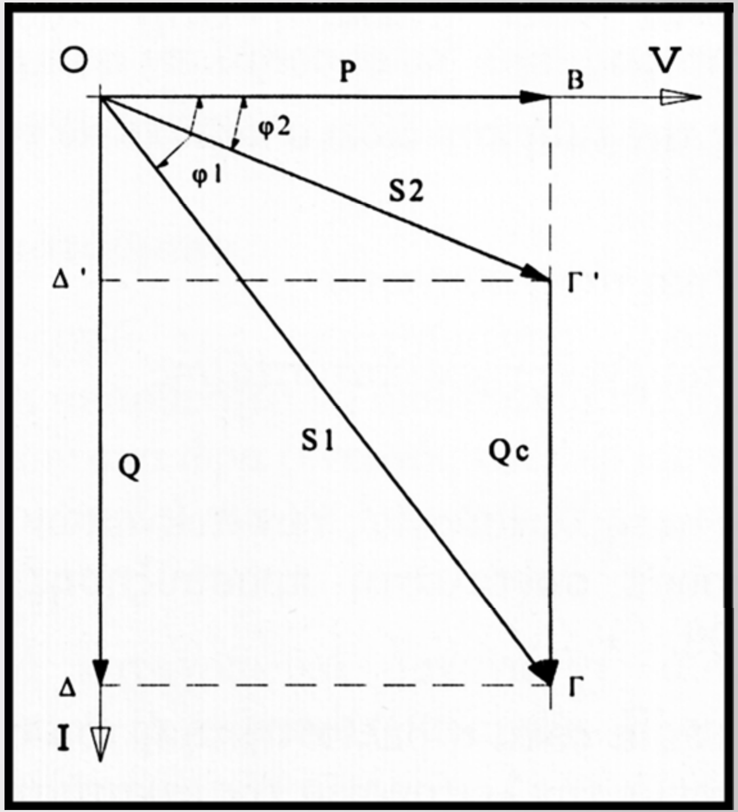
Correction with local compensation.

- It is applied in large loads with constant, or at least long, operational time period.
- It is implemented with the capacitors’ installation at the motors’ poles, with the required support of switches and fuses.
- The required capacitive power is much higher than the one of central compensation, since it is practically calculated on the basis of the peak loads of the devices for which it is applied.
- The total installation cost (capacitors, switches and fuses) is higher than the other two methods.
- For the abovementioned reasons, this method should be selected only in cases of considerably high power consumptions.

Calculation of the capacitors' required nominal power

Calculation of the capacitors' required nominal power

- Let P be the active power demand of a system, S_1 the corresponding apparent power and ϕ_1 the angle between the active and reactive power demand Q.
- To achieve a power coefficient correction from $\cos\phi_1$ to $\cos\phi_2$ the capacitors should provide the system with reactive power Q_c given from the following relationship:



$$Q_c = P \cdot \left(\tan\varphi_1 - \tan\varphi_2\right) \Leftrightarrow$$

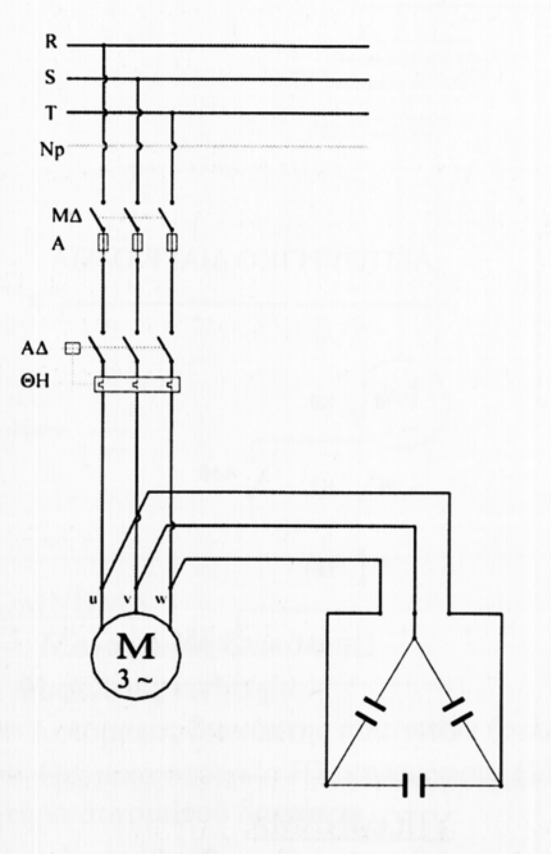
$$Q_c = P \cdot \left(\frac{\sqrt{1-\cos^2\varphi_1}}{\cos\varphi_1} - \frac{\sqrt{1-\cos^2\varphi_2}}{\cos\varphi_2} \right)$$

Calculation of the capacitors' required nominal power

- For triangle connected capacitors, the required capacitive power is given by the relationship:

$$Q_c = 3 \cdot \left(\frac{V_C}{V} \right)^2 \cdot \omega \cdot C$$

where:
V_C the capacitors' polar voltage
V the network's nominal voltage
at the capacitors' connection location
$\omega = 2 \cdot \pi \cdot f$, the network's rotational speed
f the networks' nominal frequency
C the capacitors' total capacity.

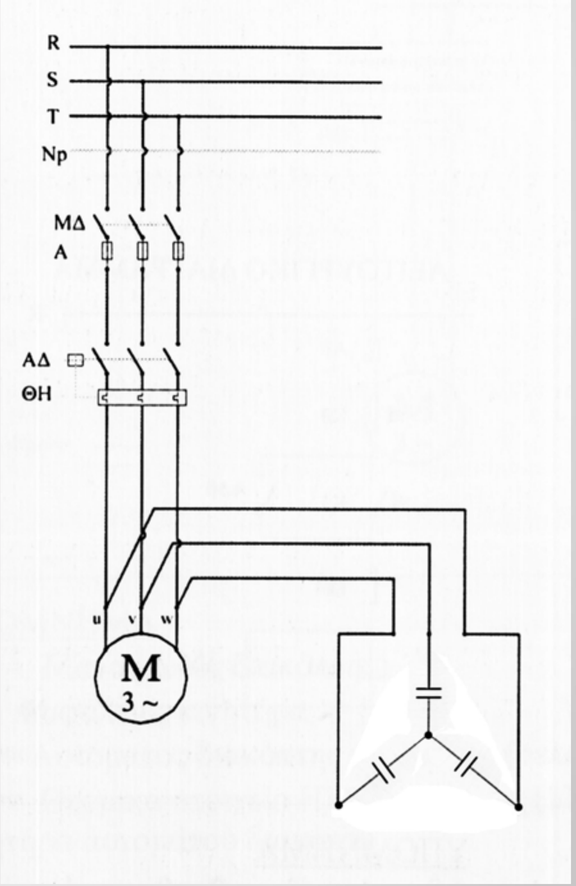


Calculation of the capacitors' required nominal power

- For star connected capacitors, the required capacitive power is given by the relationship:

$$Q_c = \frac{1}{3} \cdot \left(\frac{V_C}{V} \right)^2 \cdot \omega \cdot C$$

- From the above two relationships it is concluded that the required capacitors' capacity with star-connection is three times higher than the one with triangle connection :
  $C_{star} = 3 \cdot C_{delta}$.
- For this reason, in reactive power compensation installations, the triangle connection is always selected for the capacitors.



Calculation of the capacitors' required nominal power

Example of parametric calculation:

- An electrical system operates with power coefficient $\cos\phi_1$=0,70 ($\tan\phi_1$=1,02) and consumes active power P.
- By applying the previous relationship we calculate the required capacitors' power in order to improve the power coefficient as presented in the table below.

$\cos\varphi_2$	0,85	0,90	0,95	1,00
$\tan\varphi_2$	0,62	0,48	0,33	0,00
Q_c	0,40·P	0,54·P	0,69·P	1,02·P

- It is observed that the correction of the power coefficient from 0,90 to 1,00 requires the installation of almost double capacitive power, leading to extremely high installation cost.
- For this reason the power coefficient is usually corrected up to 0,90.

Calculation of the capacitors' required nominal power

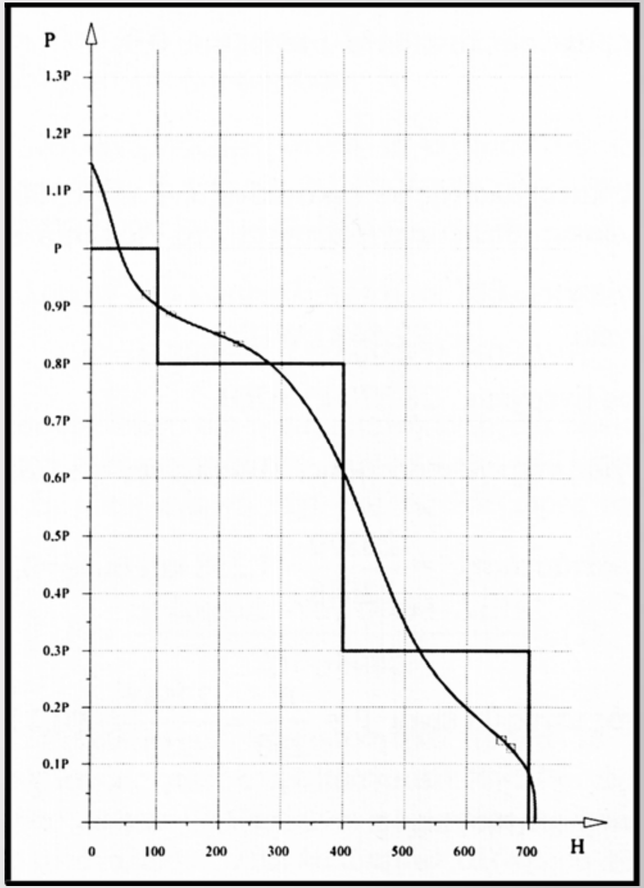
Calculation of capacitors' required power for central compensation:

- In that case, the system's total active power must be known.
- This power usually is derived from the power consumption duration curve.
- If no consumption data is available to get the duration curve, then this curve can be approached with a gradual function.
- The power consumption of the system is finally arisen from the division of the annual electricity consumption, known from the utility measurements, over the total operational hours, taken from the power consumption duration curve.

Calculation of the capacitors' required nominal power

<u>Example of the required capacitors' power for central compensation</u>:

- The annual power consumption duration curve is approached with a three-stages gradual function:
  - stage 1^{o}: operation with active power P for 100h
  - stage 2^{o}: operation with active power 0,80·P for 300h
  - stage 3^{o}: operation with active power 0,30·P for 300h.
- If the annual electricity consumption is W, then W = P·100h + 0,8P·300h + 0,3P·300h ⇔W = P·430h ⇔ P = W/430h.
- If, for example, W = 105.000kWh, then P = 244,19kW.



Calculation of the capacitors' required nominal power

<u>Example of the required capacitors' power for central compensation</u>:

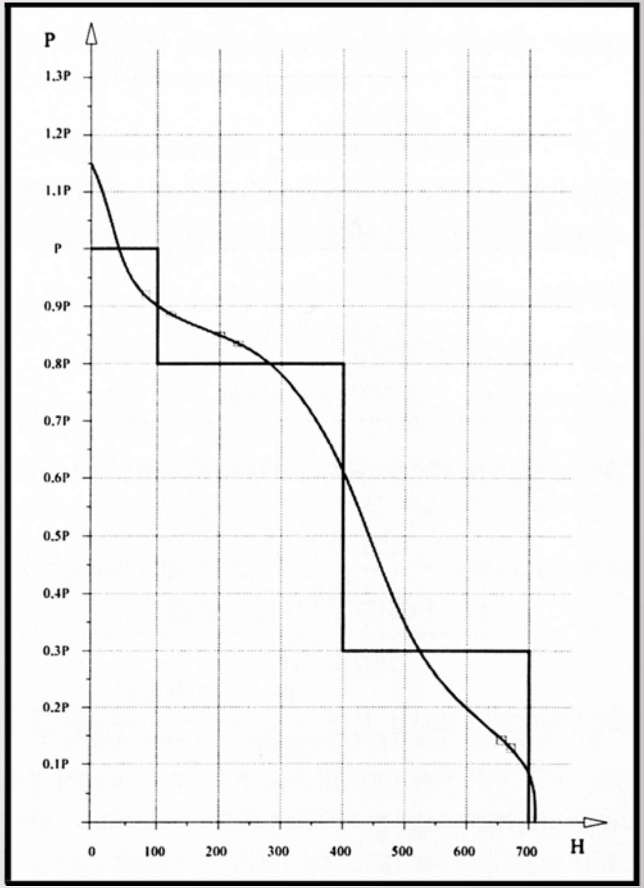
- If the existing power coefficient (before the compensation) is $\cos\phi_1 = 0{,}609$ ($\tan\phi_1 = 1{,}302$), and we aim at its correction at $\cos\phi_2 = 0{,}900$ ($\tan\phi_2 = 0{,}484$), then the capacitors' power should be:

$$Q_c = P \cdot (\tan\varphi_1 - \tan\varphi_2) \Leftrightarrow$$

$$Q_c = 244{,}19 \cdot (1{,}302 - 0{,}484) \Leftrightarrow Q_c = 199{,}75\text{kVAR}$$

- If $V_C = 400$V the capacitors' polar voltage and $V = 380$V the network's voltage, then $(V_C/V)^2 = 1{,}108$.
- The final capacitive power is corrected as:

$$Q_{c2} = Q_{c1} \cdot \left(\frac{V_c}{V}\right)^2 = 221{,}32\text{kVAR}$$



Calculation of the capacitors' required nominal power

Example of the required capacitors' power for team compensation:

- In this case consumption data is required for every part of the system that the team compensation is to be applied.
- For this reason, special devices, named as "network's analysers" must be installed in the particular parts of the system.

Calculation of the capacitors' required nominal power

<u>Example of the required capacitors' power for team compensation</u>:

- In case that the electricity consumption measurements is not possible in the system's parts that we want to apply team compensation, we can work empirically as described below:
    - we find all the necessary data of the particular system's parts (amount and power of the devices, distance from the low voltage bars, cables' sizes)
    - the devices specifications are gathered (power, rotational speeds, cosφ, nominal current)
    - central compensation will be applied for the rest parts of the system, except the ones that team compensation is applied.

Calculation of the capacitors' required nominal power

<u>Example of the required capacitors' power for team compensation</u>:

- The averaged part's power consumption is given by the relationship:

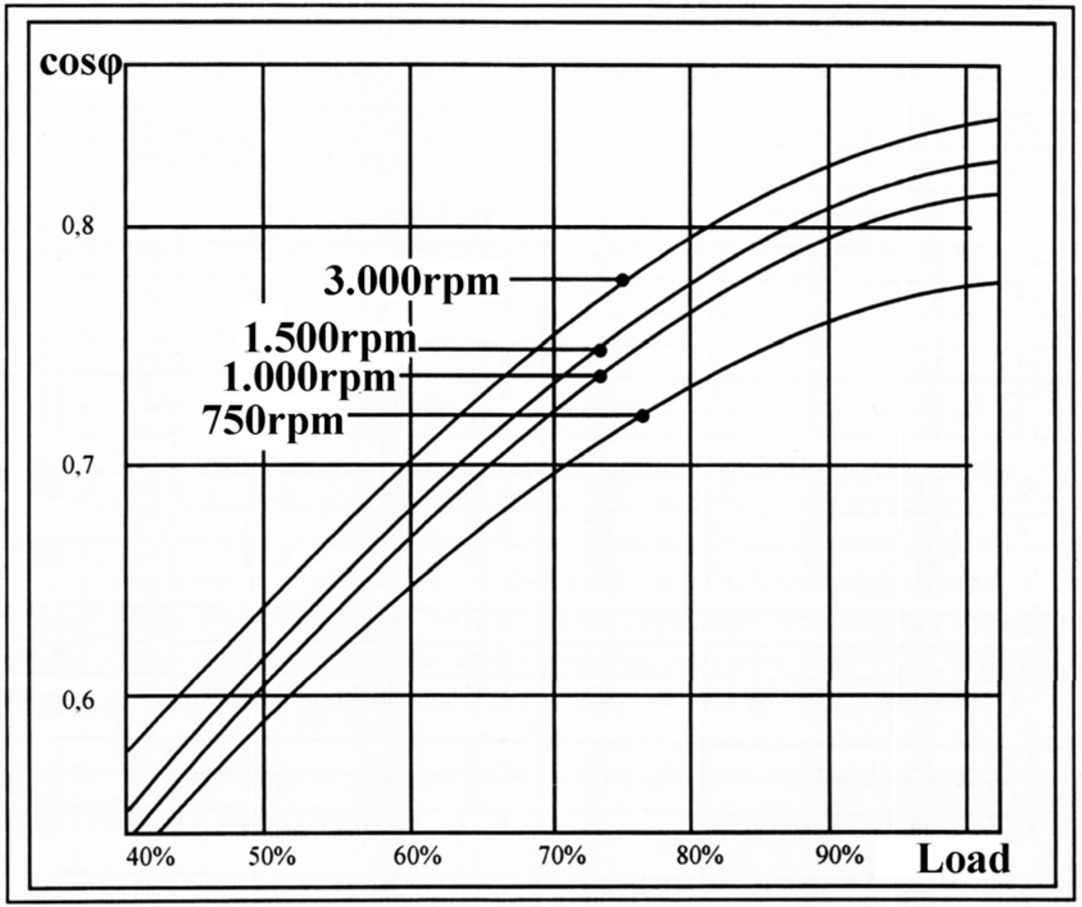
$$P = \kappa \cdot \sum \frac{P_i \cdot \mu_i}{\eta_i}$$

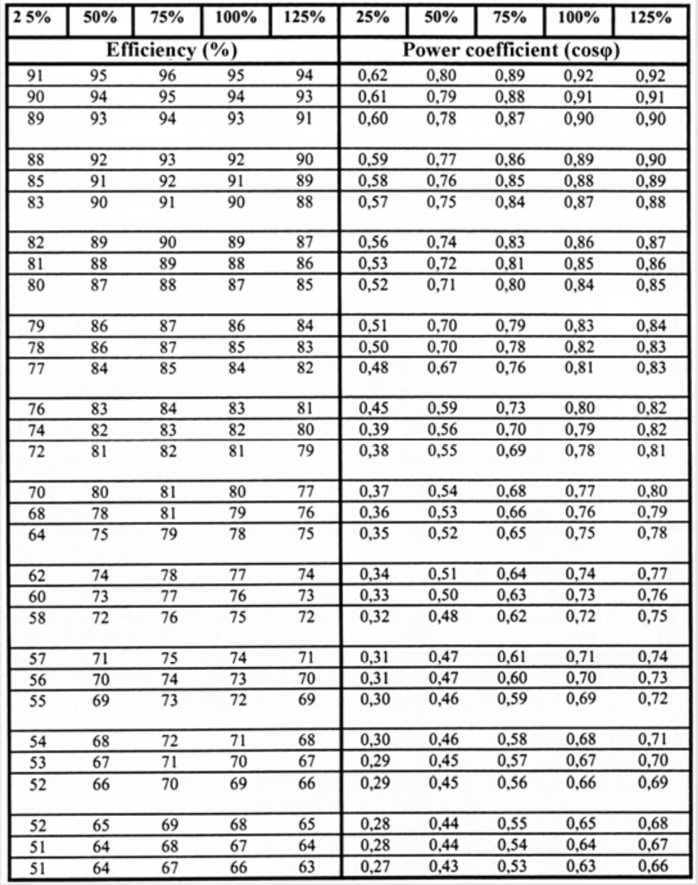
where:

κ: coefficient of simultaneous devices operation
P_i: the nominal power of each device
μ_i: loading coefficient of each device
η_i: efficiency of each device.

Calculation of the capacitors' required nominal power

Calculation of the capacitors' required power in team compensation:





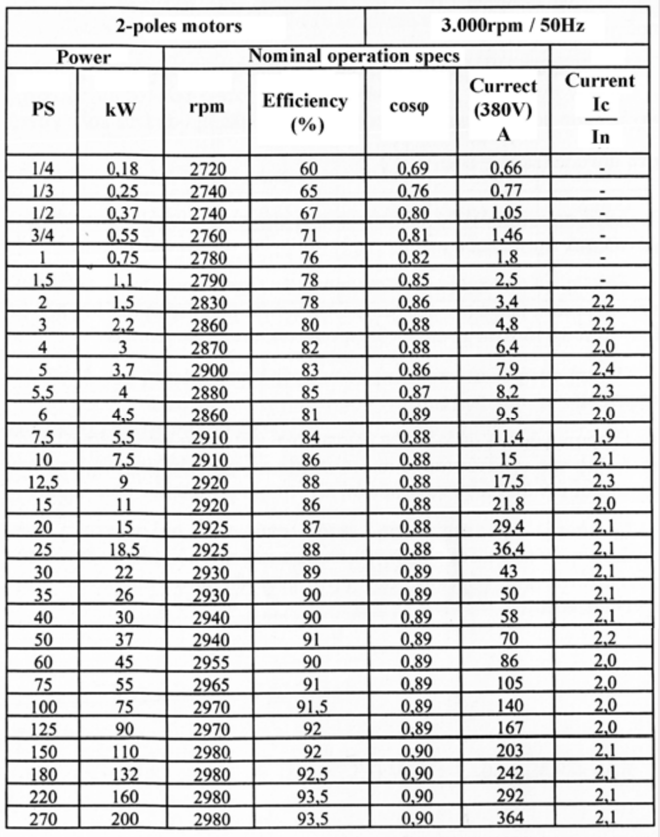
2 5%	50%	75%	100%	125%	25%	50%	75%	100%	125%
Efficiency (%)					Power coefficient (cosφ)				
91	95	96	95	94	0,62	0,80	0,89	0,92	0,92
90	94	95	94	93	0,61	0,79	0,88	0,91	0,91
89	93	94	93	91	0,60	0,78	0,87	0,90	0,90
88	92	93	92	90	0,59	0,77	0,86	0,89	0,90
85	91	92	91	89	0,58	0,76	0,85	0,88	0,89
83	90	91	90	88	0,57	0,75	0,84	0,87	0,88
82	89	90	89	87	0,56	0,74	0,83	0,86	0,87
81	88	89	88	86	0,53	0,72	0,81	0,85	0,86
80	87	88	87	85	0,52	0,71	0,80	0,84	0,85
79	86	87	86	84	0,51	0,70	0,79	0,83	0,84
78	86	87	85	83	0,50	0,70	0,78	0,82	0,83
77	84	85	84	82	0,48	0,67	0,76	0,81	0,83
76	83	84	83	81	0,45	0,59	0,73	0,80	0,82
74	82	83	82	80	0,39	0,56	0,70	0,79	0,82
72	81	82	81	79	0,38	0,55	0,69	0,78	0,81
70	80	81	80	77	0,37	0,54	0,68	0,77	0,80
68	78	81	79	76	0,36	0,53	0,66	0,76	0,79
64	75	79	78	75	0,35	0,52	0,65	0,75	0,78
62	74	78	77	74	0,34	0,51	0,64	0,74	0,77
60	73	77	76	73	0,33	0,50	0,63	0,73	0,76
58	72	76	75	72	0,32	0,48	0,62	0,72	0,75
57	71	75	74	71	0,31	0,47	0,61	0,71	0,74
56	70	74	73	70	0,31	0,47	0,60	0,70	0,73
55	69	73	72	69	0,30	0,46	0,59	0,69	0,72
54	68	72	71	68	0,30	0,46	0,58	0,68	0,71
53	67	71	70	67	0,29	0,45	0,57	0,67	0,70
52	66	70	69	66	0,29	0,45	0,56	0,66	0,69
52	65	69	68	65	0,28	0,44	0,55	0,65	0,68
51	64	68	67	64	0,28	0,44	0,54	0,64	0,67
51	64	67	66	63	0,27	0,43	0,53	0,63	0,66

Power coefficient and efficiency variation of asynchronous motors the motors' load and the rotational speed.

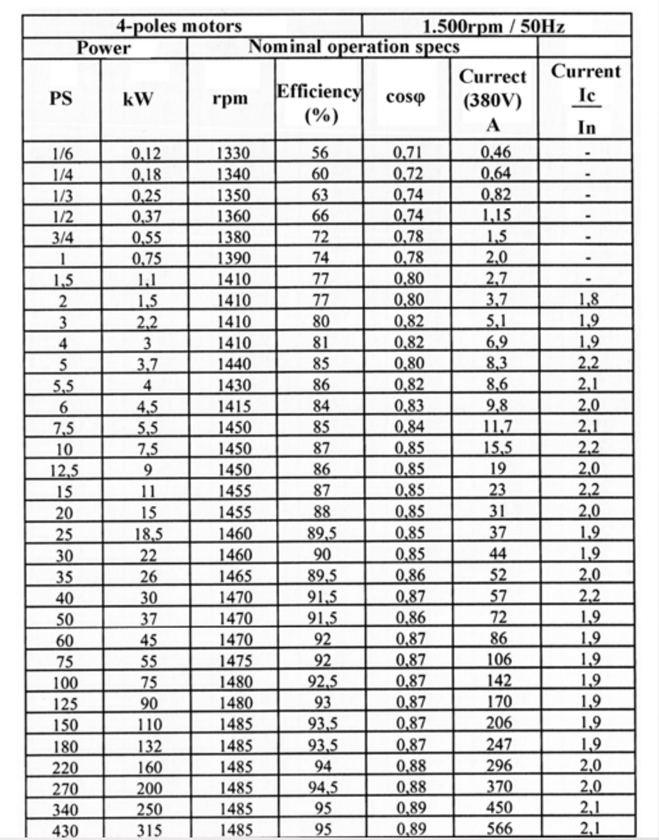
Calculation of the capacitors' required nominal power

Calculation of the capacitors' required power in team compensation:

- Asynchronous motors specifications.



2-poles motors				3.000rpm / 50Hz		
Power		Nominal operation specs				
PS	kW	rpm	Efficiency (%)	cosφ	Currect (380V) A	Current Ic / In
1/4	0,18	2720	60	0,69	0,66	-
1/3	0,25	2740	65	0,76	0,77	-
1/2	0,37	2740	67	0,80	1,05	-
3/4	0,55	2760	71	0,81	1,46	-
1	0,75	2780	76	0,82	1,8	-
1,5	1,1	2790	78	0,85	2,5	-
2	1,5	2830	78	0,86	3,4	2,2
3	2,2	2860	80	0,88	4,8	2,2
4	3	2870	82	0,88	6,4	2,0
5	3,7	2900	83	0,86	7,9	2,4
5,5	4	2880	85	0,87	8,2	2,3
6	4,5	2860	81	0,89	9,5	2,0
7,5	5,5	2910	84	0,88	11,4	1,9
10	7,5	2910	86	0,88	15	2,1
12,5	9	2920	88	0,88	17,5	2,3
15	11	2920	86	0,88	21,8	2,0
20	15	2925	87	0,88	29,4	2,1
25	18,5	2925	88	0,88	36,4	2,1
30	22	2930	89	0,89	43	2,1
35	26	2930	90	0,89	50	2,1
40	30	2940	90	0,89	58	2,1
50	37	2940	91	0,89	70	2,2
60	45	2955	90	0,89	86	2,0
75	55	2965	91	0,89	105	2,0
100	75	2970	91,5	0,89	140	2,0
125	90	2970	92	0,89	167	2,0
150	110	2980	92	0,90	203	2,1
180	132	2980	92,5	0,90	242	2,1
220	160	2980	93,5	0,90	292	2,1
270	200	2980	93,5	0,90	364	2,1

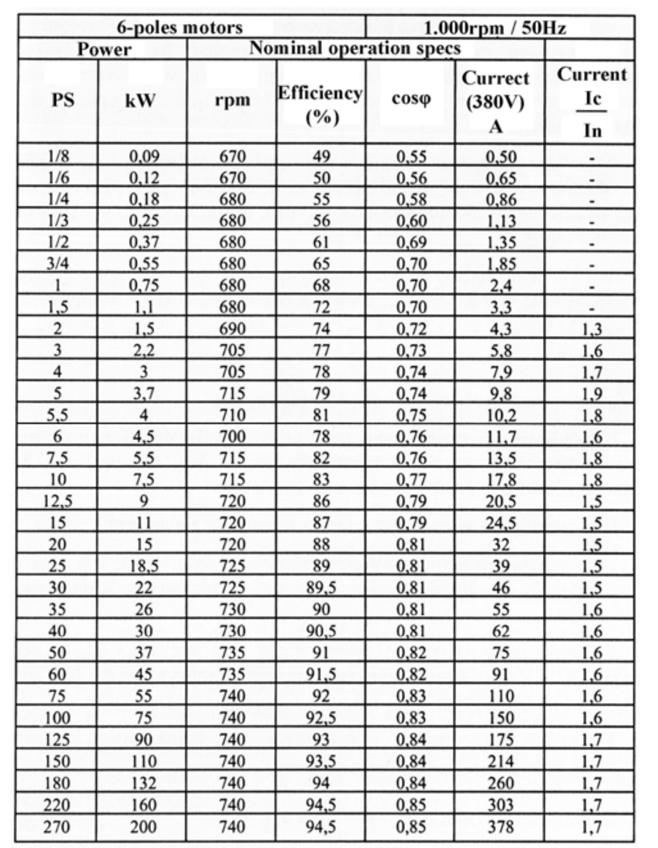


4-poles motors				1.500rpm / 50Hz		
Power		Nominal operation specs				
PS	kW	rpm	Efficiency (%)	cosφ	Currect (380V) A	Current Ic / In
1/6	0,12	1330	56	0,71	0,46	-
1/4	0,18	1340	60	0,72	0,64	-
1/3	0,25	1350	63	0,74	0,82	-
1/2	0,37	1360	66	0,74	1,15	-
3/4	0,55	1380	72	0,78	1,5	-
1	0,75	1390	74	0,78	2,0	-
1,5	1,1	1410	77	0,80	2,7	-
2	1,5	1410	77	0,80	3,7	1,8
3	2,2	1410	80	0,82	5,1	1,9
4	3	1410	81	0,82	6,9	1,9
5	3,7	1440	85	0,80	8,3	2,2
5,5	4	1430	86	0,82	8,6	2,1
6	4,5	1415	84	0,83	9,8	2,0
7,5	5,5	1450	85	0,84	11,7	2,1
10	7,5	1450	87	0,85	15,5	2,2
12,5	9	1450	86	0,85	19	2,0
15	11	1455	87	0,85	23	2,2
20	15	1455	88	0,85	31	2,0
25	18,5	1460	89,5	0,85	37	1,9
30	22	1460	90	0,85	44	1,9
35	26	1465	89,5	0,86	52	2,0
40	30	1470	91,5	0,87	57	2,2
50	37	1470	91,5	0,86	72	1,9
60	45	1470	92	0,87	86	1,9
75	55	1475	92	0,87	106	1,9
100	75	1480	92,5	0,87	142	1,9
125	90	1480	93	0,87	170	1,9
150	110	1485	93,5	0,87	206	1,9
180	132	1485	93,5	0,87	247	1,9
220	160	1485	94	0,88	296	2,0
270	200	1485	94,5	0,88	370	2,0
340	250	1485	95	0,89	450	2,1
430	315	1485	95	0,89	566	2,1

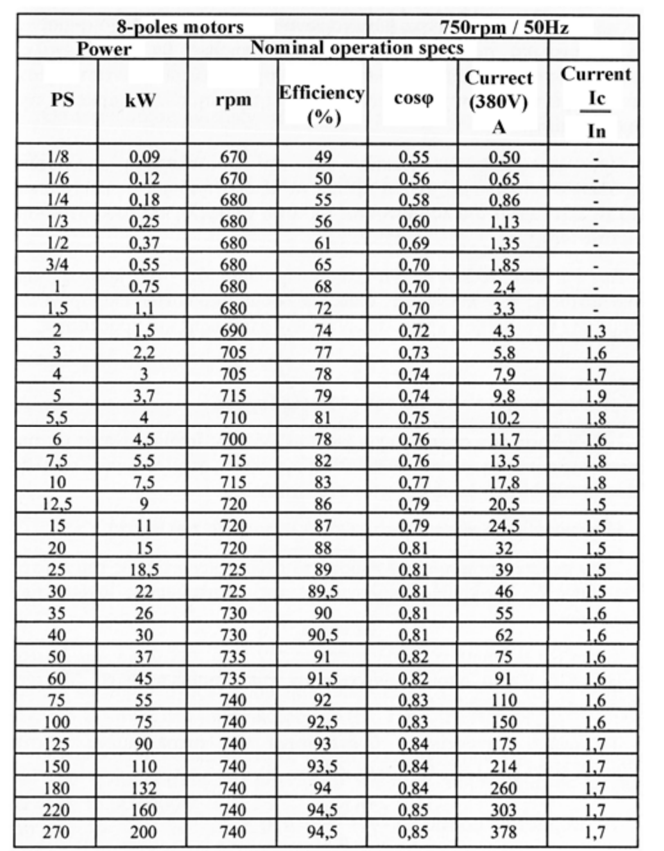
Calculation of the capacitors' required nominal power

<u>Calculation the capacitors' required power in team compensation</u>:

- Asynchronous motors specifications.



6-poles motors				1.000rpm / 50Hz		
Power		Nominal operation specs				
PS	kW	rpm	Efficiency (%)	cosφ	Currect (380V) A	Current $\frac{Ic}{In}$
1/8	0,09	670	49	0,55	0,50	-
1/6	0,12	670	50	0,56	0,65	-
1/4	0,18	680	55	0,58	0,86	-
1/3	0,25	680	56	0,60	1,13	-
1/2	0,37	680	61	0,69	1,35	-
3/4	0,55	680	65	0,70	1,85	-
1	0,75	680	68	0,70	2,4	-
1,5	1,1	680	72	0,70	3,3	-
2	1,5	690	74	0,72	4,3	1,3
3	2,2	705	77	0,73	5,8	1,6
4	3	705	78	0,74	7,9	1,7
5	3,7	715	79	0,74	9,8	1,9
5,5	4	710	81	0,75	10,2	1,8
6	4,5	700	78	0,76	11,7	1,6
7,5	5,5	715	82	0,76	13,5	1,8
10	7,5	715	83	0,77	17,8	1,8
12,5	9	720	86	0,79	20,5	1,5
15	11	720	87	0,79	24,5	1,5
20	15	720	88	0,81	32	1,5
25	18,5	725	89	0,81	39	1,5
30	22	725	89,5	0,81	46	1,5
35	26	730	90	0,81	55	1,6
40	30	730	90,5	0,81	62	1,6
50	37	735	91	0,82	75	1,6
60	45	735	91,5	0,82	91	1,6
75	55	740	92	0,83	110	1,6
100	75	740	92,5	0,83	150	1,6
125	90	740	93	0,84	175	1,7
150	110	740	93,5	0,84	214	1,7
180	132	740	94	0,84	260	1,7
220	160	740	94,5	0,85	303	1,7
270	200	740	94,5	0,85	378	1,7



8-poles motors				750rpm / 50Hz		
Power		Nominal operation specs				
PS	kW	rpm	Efficiency (%)	cosφ	Currect (380V) A	Current $\frac{Ic}{In}$
1/8	0,09	670	49	0,55	0,50	-
1/6	0,12	670	50	0,56	0,65	-
1/4	0,18	680	55	0,58	0,86	-
1/3	0,25	680	56	0,60	1,13	-
1/2	0,37	680	61	0,69	1,35	-
3/4	0,55	680	65	0,70	1,85	-
1	0,75	680	68	0,70	2,4	-
1,5	1,1	680	72	0,70	3,3	-
2	1,5	690	74	0,72	4,3	1,3
3	2,2	705	77	0,73	5,8	1,6
4	3	705	78	0,74	7,9	1,7
5	3,7	715	79	0,74	9,8	1,9
5,5	4	710	81	0,75	10,2	1,8
6	4,5	700	78	0,76	11,7	1,6
7,5	5,5	715	82	0,76	13,5	1,8
10	7,5	715	83	0,77	17,8	1,8
12,5	9	720	86	0,79	20,5	1,5
15	11	720	87	0,79	24,5	1,5
20	15	720	88	0,81	32	1,5
25	18,5	725	89	0,81	39	1,5
30	22	725	89,5	0,81	46	1,5
35	26	730	90	0,81	55	1,6
40	30	730	90,5	0,81	62	1,6
50	37	735	91	0,82	75	1,6
60	45	735	91,5	0,82	91	1,6
75	55	740	92	0,83	110	1,6
100	75	740	92,5	0,83	150	1,6
125	90	740	93	0,84	175	1,7
150	110	740	93,5	0,84	214	1,7
180	132	740	94	0,84	260	1,7
220	160	740	94,5	0,85	303	1,7
270	200	740	94,5	0,85	378	1,7

Calculation of the capacitors' required nominal power

Example for the capacitors' required power in team compensation:

- Let's assume a system's part for which the following table is constructed, after the data gathering and measuring.

Motors number ν	Motors power (kW)	Devices capacity factor μ	Power coefficient cosϕ	Efficiency η	ν·(P·μ)/η	cosϕ·ν·(P·μ)/η
5	3,7	0,60	0,68	0,84	13,21	8,99
2	5,5	0,75	0,78	0,87	9,48	7,40
2	7,5	0,60	0,66	0,81	11,11	7,33
2	9,0	0,65	0,73	0,84	13,93	10,17
1	15,0	0,75	0,74	0,84	13,39	9,91
				Totals	61,13	43,79

Calculation of the capacitors' required nominal power

Example for the capacitors' required power in team compensation:

- If the coefficient of the devices' simultaneous operation is set κ = 0,75, then:

$$P = \kappa \cdot \sum \frac{P_i \cdot \mu_i}{\eta_i} \Leftrightarrow P = 45{,}85\,\mathrm{kW}$$

- For the required capacitive power calculation using the relationship:

$$Q_c = P \cdot \left(\tan\varphi_1 - \tan\varphi_2\right)$$

we should calculate the averaged power coefficient of the system's particular part. This is given by the relationship:

$$\cos\varphi_1 = \frac{\sum \nu_i \cdot \frac{P_i \cdot \mu_i}{\eta_i} \cdot \cos\varphi_i}{\sum \nu_i \cdot \frac{P_i \cdot \mu_i}{\eta_i}} \Leftrightarrow \cos\varphi_1 = 0{,}716$$

Calculation of the capacitors' required nominal power

Example for the capacitors' required power in team compensation:

- For $\cos\phi_1 = 0{,}716$ it will be $\tan\phi_1 = 0{,}975$. If the power coefficient is attempted to be improved at $\cos\phi_2 = 0{,}90$ after the compensation, it will be $\tan\phi_2 = 0{,}484$.
- The required capacitive power is finally calculated by the relationship:

$$Q_c = P \cdot \left(\tan\varphi_1 - \tan\varphi_2\right) \Leftrightarrow$$

$$Q_c = 45{,}83 \cdot \left(0{,}975 - 0{,}484\right) \Leftrightarrow Q_c = 22{,}50\mathrm{kVAR}$$

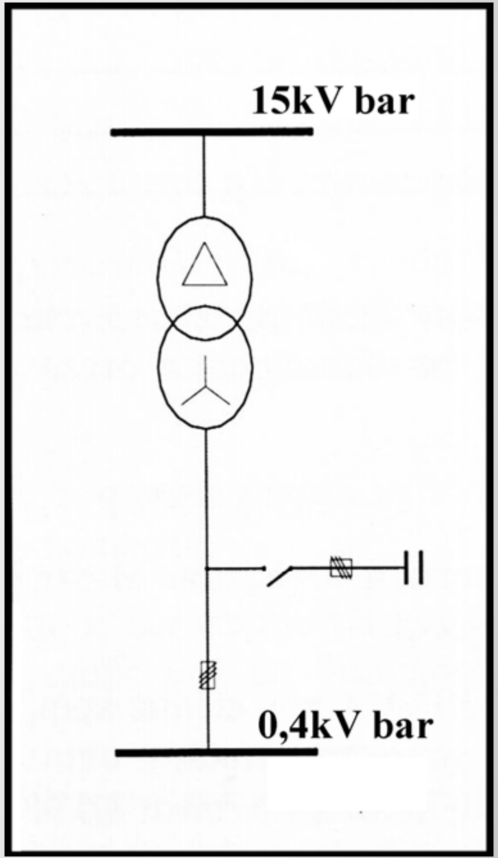
- If $V_C = 400V$ the capacitors' polar voltage and $V = 380V$ the network's, then $(V_C/V)^2 = 1{,}108$.
- The final capacitive power is:

$$Q_{c2} = Q_{c1} \cdot \left(\frac{V_c}{V}\right)^2 = 24{,}93\mathrm{kVAR}$$

Calculation of the capacitors' required nominal power

<u>Capacitors required power for local reactive power compensation on transformers</u>:

- The power coefficient correction is performed with the connection of capacitors with the appropriate power in the transformer's low voltage circuit.
- If the transformer's magnetization current is known it is possible to calculate the required capacitors' power accurately.



Calculation of the capacitors' required nominal power

<u>Capacitors required power for local reactive power compensation on transformers</u>:

- Let's assume a 630kVA nominal power transformer with nominal voltage 400V.
- The magnetization current of the 630kVA transformer, is $I_o = 1{,}8\%$ over the transformer's nominal current.
- The transformer's nominal current is given by the relationship:

$$P = \sqrt{3} \cdot V_{ον} \cdot I_{ον} \Leftrightarrow I_{ον} = \frac{P}{\sqrt{3} \cdot V_{ον}} \Leftrightarrow I_{ον} = \frac{630.000V \cdot A}{\sqrt{3} \cdot 400V} \Leftrightarrow I_{ον} = 909{,}3A$$

- Magnetization current:

$$I_o = 1{,}8\% \cdot I_{ον} \Leftrightarrow I_o = 0{,}018 \cdot 909{,}3A \Leftrightarrow I_o = 16{,}37A$$

Calculation of the capacitors' required nominal power

Capacitors required power for local reactive power compensation on transformers:

- The consumed reactive power by the transformer is:

$$Q_c = \sqrt{3} \cdot V_{ov} \cdot I_o \Leftrightarrow Q_c = \sqrt{3} \cdot 400V \cdot 16{,}37A \Leftrightarrow Q_c = 11{,}34kVAR$$

- It is finally selected to install capacitors of 15kVA nominal power.

Calculation of the capacitors' required nominal power

<u>Capacitors required power for local reactive power compensation on transformers</u>:

- In case that no data are available for the capacitors (e.g. old devices), we can accept that the required capacitors power will be (the lower values correspond to larger transformers):

$$Q_c = \sqrt{3} \cdot V_{ov} \cdot I_o \Leftrightarrow Q_c = 3{,}5 - 5\% \cdot P$$

where P the transformer's nominal power.

- In the previous example transformer, with 630kVA nominal power, the application of this empirical method would give: $Q_C = 0{,}035 \cdot 630\text{kVA} \Leftrightarrow Q_C = 22{,}05\text{kVAR}$, instead of 15kVAR that was previously calculated.

Calculation of the capacitors' required nominal power

Capacitors required power for local reactive power compensation on transformers:

Capacitors required power for local reactive power compensation on transformers 15/0,4kV	
Transformer nominal power (kVA)	Capacitors' power (kVAR)
160	5,0
250	7,5
400	10,0
630	15,0
1.000	20,0
1.600	30,0

Calculation of the capacitors' required nominal power

Example of the calculation of the required capacitors' power for local compensation of welders:

- Resistance or arc type welders consume from the network high quantities of magnetic energy (reactive power).
- For this reason they are equipped with the appropriate capacitors directly by the manufacturer.
- In case this does not happen, and there not any available information regarding the reactive power consumption from a welder, we can assume, to simplify the calculation, a mean power coefficient of cosϕ=0,45.
- Generally, by installing capacitors with nominal power equal to the half of the welder's nominal one, it is achieved acceptable power coefficient correction.

Calculation of the capacitors' required nominal power

Example of the calculation of the required capacitors' power for local compensation of asynchronous motors:

- For the local reactive power compensation on asynchronous motors, the capacitors' power should approach and not exceed the motors' nominal power.
- This is imposed in order to avoid the phenomenon of power flow from the motors to the network (self-excitation) and the causing of overvoltages.
- For this reason the required capacitive power is calculated for the reactive power compensation during motors open circuit operation (lack of load).
- Unfortunately the motors' open circuit current I_o is not often mentioned in the motors' specifications list. Consequently there are certain difficulties regarding the accurate calculation of the required capacitive power for motors' local compensation.

Calculation of the capacitors' required nominal power

Example of the calculation of the required capacitors' power for local compensation of asynchronous motors:

- The consumed reactive power of an asynchronous motor during its powering on, is given by the relationship:

$$Q_c = \sqrt{3} \cdot V_{ον} \cdot I_o$$

- The required capacitive power is calculated with the above relationship, introducing a security coefficient k = 0,85 – 0,90, to avoid motor's self-excitation:

$$Q_c = k \cdot \sqrt{3} \cdot V_{ον} \cdot I_o$$

Calculation of the capacitors' required nominal power

Example of the calculation of the required capacitors' power for local compensation of asynchronous motors:

- Let a motor consumes P = 30kW of active power, operating over a nominal voltage of V = 380V, and exhibiting a current for open circuit current I_o = 18A.
- The required capacitive power is calculated as:

$$Q_c = k \cdot \sqrt{3} \cdot V_{ov} \cdot I_o \Leftrightarrow Q_c = 0{,}9 \cdot \sqrt{3} \cdot 380\mathrm{V} \cdot 18\mathrm{A}$$

$$\Leftrightarrow Q_c = 10{,}66\mathrm{kVAR}$$

Calculation of the capacitors' required power

Capacitors' power for local compensation of asynchronous motors:

Motor power		Rotational velocity (rpm)				
		3.000	1.500	1.000	750	500
HP	kW	Required capacitive power (kVAR)				
10	7,5	5	5	5	7,5	-
20	15	7,5	7,5	7,5	10	10
30	22	7,5	10	10	12,5	15
40	30	10	12,5	15	15	20
50	37	12,5	15	15	20	25
75	55	15	20	20	25	30
100	74	20	25	25	30	40
150	110	30	35	40	45	55
220	162	40	50	60	70	80

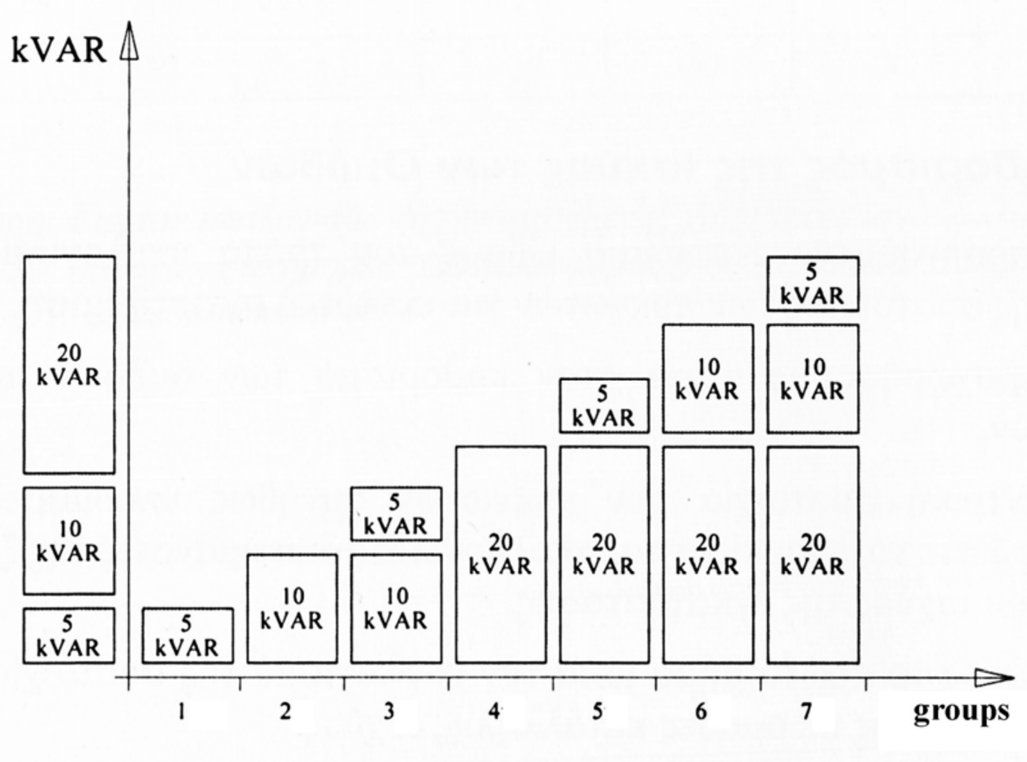
Selection of the capacitors optimum group

Determining the groups power

- The installed capacitors in a system is usually divided into groups, in order to follow the reactive power demand variations.
- For the better presentation of the subject, let’s assume that 35kVAR of capacitors are required for the reactive power compensation in the system.
- Three different capacitors groups formation will be examined:
    - the groups’ power follow the ratio: 1:2:4:8, namely, the power of the following capacitors’ group is double than the power of the previous one
    - the groups’ power follow the ratio: 1:2:2
    - the groups’ power follow the ratio: 1:1:1:1.

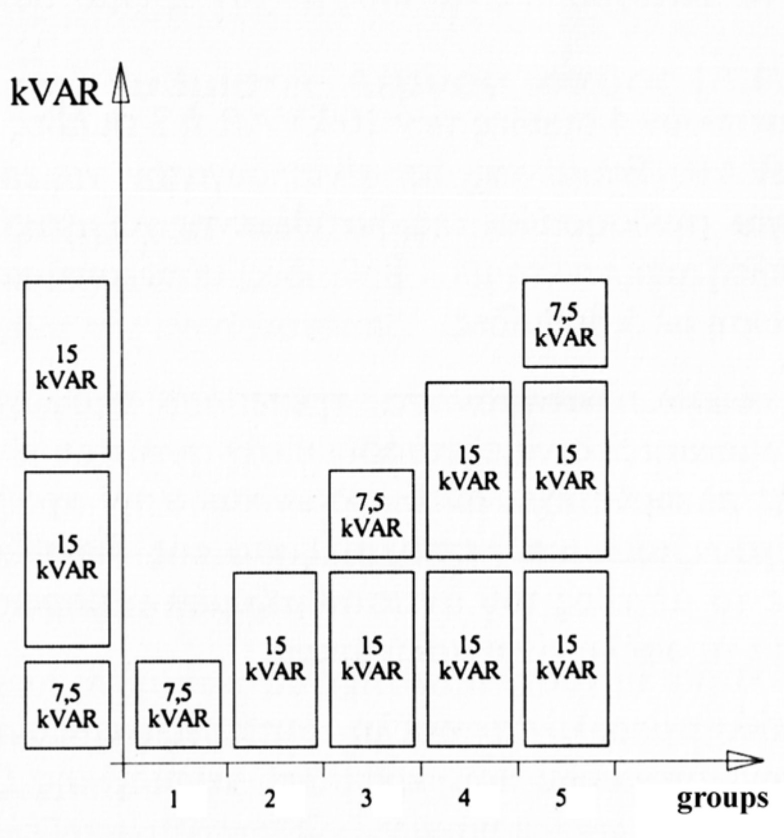
Determining the groups power

- The groups' power follow the ratio: 1:2:4:8.
- In that case we can form three capacitors' groups, with power 5, 10 and 20kVAR, connected to each other with an automatic relay, with the proper interruption power.
- With these groups we can have seven different combinations, regarding the total available capacitive power, with an increase stage of 5kVAR.
- The capacitors can follow quite satisfactorily the reactive power demand of the system.



Determining the groups power

- The groups’ power follow the ratio: 1:2:2.
- If we install three capacitors’ groups with power 7,5, 15 and 15kVAR, we can have five different combinations, regarding the total available capacitive power, with an increase stage of 7,5kVAR.
- The capacitors can follow quite satisfactorily the reactive power demand of the system with this formation as well.



Greece - Bulgaria 2007-2013
INVESTING IN OUR FUTURE
The project is co-funded by the European Union (ERDF) and National Funds of Greece and Bulgaria under the European Territorial Cooperation Programme

ΔΗΜΟΣ ΘΕΡΜΑΪΚΟΥ
AEOLIAN LAND S.A.

Determining the groups power

- The groups' power follow the ratio : 1:1:1:1, namely, they have the same capacitive power.
- The number of the different combinations that we can have is the same with the number of the groups.
- In our specific example, in order to reach the required capacitive power of 35kVAR, we could install four capacitors' groups of 10kVAR or three groups of 10kVAR and one of 5kVAR.
- It is obvious that in this case the reactive power demand variation can not be followed accurately be the compensation device.

Comparison of the above cases

- At a glance it seems that the third solution must be avoided, since the arising capacity power combinations cannot coincide satisfactorily with the possible reactive power demand values.
- The arisen benefits from an accurate regulation of the produced capacitive power depend on the size of the compensated load. For low loads the benefits are poor.
- Moreover, these benefits are lost from the hard capacitors operation conditions (consecutive coupling and decoupling operations), that lead to the shortening of their life period.
- The same stands with the automatic switches, the contacts of which must be frequently maintained, due to the hard operating conditions.
- Consequently, in most cases, the reactive power compensation is approached taking into account an averaged power coefficient value, while the compensation of reactive power values exhibiting during short time intervals is out of interest.

Comparison of the above cases

- In this way, the number of the coupling and decoupling automatic operations is reduced and, more importantly, the number of the instant overvoltages, that harm the capacitors insulation and shorten their life period, is also limited.
- To conclude with, in practice it is usually selected a capacitive power for each capacitors’ group of 15 – 25% of the total required capacitors nominal voltage.

End of presentation

Thank you for your attention

Greece - Bulgaria 2007-2013
INVESTING IN OUR FUTURE
The project is co-funded by the European Union (ERDF) and National Funds of Greece and Bulgaria under the European Territorial Cooperation Programme