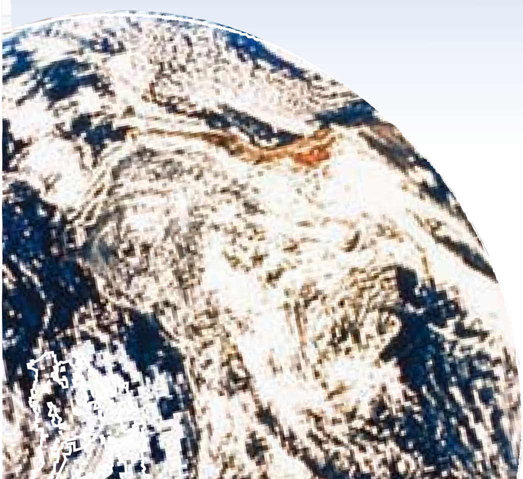
Improving Energy Efficiency by Power Factor Correction



It's all about saving your money!

Performance lagging

Contents

1. Objective and contents

Conservation of resources is a fundamental objective, and increasing energy efficiency a core aim of European policy.

For that purpose, the Commission of the European Communities published the Green Paper on Energy Efficiency[1]. That paper calls upon all levels of society to make contributions.

This position paper identifies potentials for increasing energy efficiency which result from power factor correction on the consumer side in the industry and service sectors.

With the systematic use of power factor correction,

- energy losses in the electrical transmission and distribution networks can be significantly reduced, with a corresponding reduction in the CO_2 emissions involved in generating that lost energy;
- energy transmission and distribution networks can be used more efficiently, for instance for the transmission of regenerative energy;
- the reliability of planning for future energy networks can be increased.

The potential savings in energy consumption are set out on the European scale (EU 25).

The necessary technical equipment is identified.

A study is proposed to determine the actual status in the year 2006.

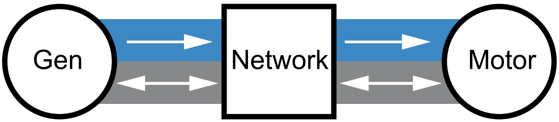
Recommendations are made in this position paper on how the aims of the EU Green Paper on increasing energy efficiency can be effectively supported.

[1] Commission of the European Communities: Green Paper on Energy Efficiency or Doing More with Less, COM(2005) 265 final/2

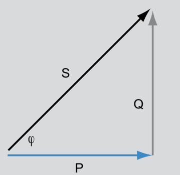
2. The principle of power factor correction

2.1 Origin and effects of reactive power

Many electrical devices, such as AC single-phase and 3-phase motors, require both active power and reactive power. The active power is converted into useful mechanical power, while the reactive power is needed to maintain the device's magnetic fields. This reactive power is transferred periodically in both directions between the generator and the load.



Vector addition of the active power P and the reactive power Q gives the apparent power S. Power generation utilities and network operators must make this apparent power available and transmit it. This means that generators, transformers, power lines, switchgear, etc. must be sized for greater power ratings than if the load only drew active power. Power supply companies are therefore faced with extra expenditure on equipment and additional power losses. They therefore make additional charges for reactive power if this exceeds a certain threshold. Usually a certain target power factor cos φ of between 1.0 and 0.9 (lagging) is specified.



Apparent power
$S^2 = P^2 + Q^2$

Active power
$P = S \cdot \cos \varphi$

Reactive power
$Q = S \cdot \sin \varphi$

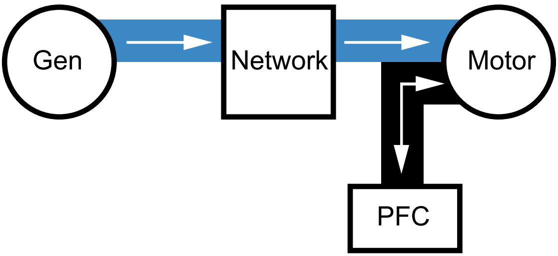
Example: 3-phase motor

Active power	500kW
Reactive power	510kVAr (ind)
Resulting apparent power	714kVA

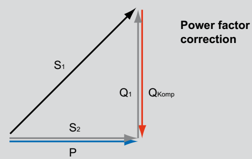
Although the motor's mechanical power output only calls for 500 kW, the supply network loading is an apparent power of 714 kVA, i.e. it has to transmit 143% of the active power.

2.2 Power factor correction

If the lagging power factor is corrected, for example by installing a capacitor at the load, this totally or partially eliminates the reactive power draw at the power supply company. Power factor correction is at its most effective when it is physically near to the load and uses state-of-the-art technology.



The inductive reactive power Q_1 is compensated for totally or partially by the capacitive reactive power Q_{comp}, the apparent power thus being reduced from S_1 to S_2.



Example: 3-phase motor with power factor correction (PFC)

Active power	500 kW
Reactive power	510 kVAr (lagging)
Power factor correction	510 kVAr (leading)
Resultant reactive power	0 kVAr
giving apparent power	500 kVA

The motor draws an active power of 500 kW as before, but its reactive power is fully compensated for and the supply network needs to transmit an apparent power of 500 kVA, i.e. 100% of the active power. Power factor correction in this case therefore reduces the transmission load by 43% of the nominal active power (i.e. from 143% to 100%).

3. Increasing energy efficiency by power factor correction

With power factor correction, a situation can be achieved in which only the necessary active power is transported, both in the transmission and distribution networks and in the customers' networks. The current in the network drops, and this has two advantages:

- Current-dependent network losses are reduced, and require no compensation by increased power generation with corresponding CO_2 emissions. This applies both to customers' networks and public transmission and distribution networks.
- Additional transmission capacities are made available, for instance for the transmission of renewable energy.

The following sections show:

- How high is the consumption of electrical energy by the individual consumer sectors in the EU? What (estimated) actual power factors do the individual consumer sectors have?
- Which consumer sectors are the main causes of reactive energy? How high should the target power factor be?
- How are the shares in losses of the transmission and distribution networks composed?
- How high are the network losses in customers' networks?
- How high are the losses within the power factor correction systems?

The answers to these questions are then used to calculate the increase in energy efficiency:

- What potential savings of network losses are achieved in principle by power factor correction?
- To what extent is the load on the transmission and distribution networks relieved by power factor correction?

3.1 Consumption of electrical energy in the EU 25

The consumption of electrical energy in the EU 25[2] in 2002, comprising 2,641 TWh plus 195 TWh network losses, is shown in Appendix 10.1. The largest consumer sectors are industry with 1,168 TWh (44%), households with 717 TWh (27%) and services with 620 TWh (23%). These three sectors together account for around 94% of consumption.

3.2 Main causes of reactive energy and target power factor

In order to determine which consumer sectors are mainly responsible for reactive power, the estimated power factors of the relevant sectors have been entered in Appendix 10.2. Appendix 10.2 shows the consumer sectors with their estimated[3] power factors.

The sectors of industry and service account for approximately 94% of the reactive power demand. It is proposed that power factor correction should be concentrated on these sectors, industry and service.

The target proposed is a realistic power factor of 0.95 (lagging). This gives the power factor correction systems in service sufficient control capability without going into capacitive overcompensation.

Appendix 10.3 shows the consumption of electrical energy when a target power factor of 0.95 is maintained in the consumer sectors of industry and service. The (vector) sum of active energy and reactive energy then falls from 3,173 TVAh without correction to 2,730 TVAh with power factor correction. This drop of 443 TVAh (15%) leads to a reduction in network losses and reduces the load on the networks.

[2] EURELECTRIC: Statistics and prospects for the European electricity sector (1980-1990, 2000-2020), Table 2.2.31, Brussels 2004
[3] ZVEI estimate

3.3 Network losses in transmission and distribution networks

Power factor correction reduces the current load and thus the purely current-dependent losses in the networks. Appendix 10.4 makes it clear that the current-dependent losses in the transmission and distribution networks amount to around 66%. The division of the network losses into transmission and distribution losses was taken from the Green Paper on energy efficiency[4], and the division into current-dependent and non-current-dependent losses follows an estimate by ZVEI.

3.4 Network losses in customers' networks

There are also network losses in customers' networks. They are not included in the power supply companies' statistics, as they arise behind the point of coupling with the customer and are paid for by the customer. Here too, power factor correction contributes to a reduction in current-dependent losses and increases energy efficiency.

The example in Appendix 10.5 shows that with an improvement in the power factor cos φ from 0.73 to 0.95, around 0.6% of the annual consumption of electrical energy can be saved. The figure of 0.73 corresponds to the power factor in the consumer sectors industry and service from Appendix 10.2.

3.5 Internal losses in power factor correction systems

As with all electrical equipment, power factor correction systems have their own intrinsic losses. These are composed of dielectric, wiring, switchgear and connection cable losses. Appendix 10.6 shows a typical example with specific loss energy of 8.6 kWh/kvar with an annual period of use of 3,600 h.

[4] Commission of the European Communities: Green Paper on Energy Efficiency or Doing More with Less, COM(2005) 265 final/2, Chapter 2.1 Regulation of network activities, Brussels 2005

4. Calculation of the energy savings potential

Three scenarios are contrasted in order to determine the energy savings potential.

Scenario 1: Without power factor correction
Scenario 2: Estimated level in the year 2002
Scenario 3: With power factor correction on cos φ 0.95 for the industry and service sectors.

A model calculation for the network losses in the transmission and distribution networks and in the customers' networks for industry and service, based on the calculations presented above, has been established in Appendix 10.7.
The enclosed calculations show that power factor correction with a specified power factor cos φ of 0.95 for the consumer sectors of industry and service results in a fundamental energy savings potential of 48 TWh per annum. This calculation is based on the consumption data for 2002; with forecast growth of 16%[5] up to the year 2010, this potential is likely to be rather greater.
There are already stipulations of particular power factors in a number of EU countries. Part of this potential will therefore already have been exploited. The authors of this paper do not, however, possess any firm data on the degree of exploitation.

The following comparisons are intended to illustrate what potential an increase in energy efficiency by 48 TWh per annum means:

An increase in energy efficiency of	48	TWh		
means, converted into …				
… CO_2 emissions	0.40	kg/kWh	19	Mt CO_2
… Mtoe	0.086	Mtoe/TWh	4.1	Mtoe
… energy consumption of households	3,525	kWh/a	13.6	million households
… power generation by ...				
wind power generators, 3 MW 3,600 h/a	11	GWh/a	4,444	wind power generators
gas power stations with 450 MW, 7,000 h/a	3,150	GWh/a	15	gas-fired power stations
nuclear power stations with 1600 MW, 8,000 h/a	12,800	GWh/a	4	nuclear power stations

[5] EURELECTRIC: Statistics and prospects for the European electricity sector (1980-1990, 2000-2020), Table 2.1.31, Brussels 2004

5. Calculation of the load relief on the transmission and distribution networks

In Appendix 10.8, Scenario 1 (without power factor correction, PF correction) is presented together with Scenario 2 (estimate for 2002) and Scenario 3 (power factor 0.95 for the consumer sectors industry and service).

It becomes apparent that power factor correction reduces the load on the transmission and distribution networks by around 15%, and by around 6% in relation to the estimated 2002 level.
This additional transmission capacity would assist in the indispensable network expansion for renewable energies and electricity trading in Europe.

6. Cost-effectiveness

If savings of 48 TWh network losses are to be achieved, suitable PF correction systems will have to be erected and installed. The size of the systems is directly proportional to the reactive power for which compensation is required.

For that purpose, the sum of all systems must provide a capacity of 297 Gvar. At 2006 prices, power factor correction systems require an investment of 15 €/kvar. The resulting total investment is therefore € 4.4 billion. See Appendix 10.9, “Costs of power factor correction”.

The systems are durable with service lives significantly longer than 10 years, and have a low maintenance requirement. A portion of this investment has already been made, and the systems are working satisfactorily. The authors of this position paper are not however in possession of any firm data on the number and ratings of the systems. Scenario 2 does, however, reflect the estimates of experts from the manufacturers represented in ZVEI on the basis of their experience of the market from time to time.

7. Necessary technology and regional implementation

7.1 Low voltage capacitor technology and power factor correction systems

Power factor correction systems are low voltage systems which are erected in the course of building installation. They are to be regarded as self-contained units. The systems are connected to the existing building installation and can also be extended without any major adaptations.
Power factor correction systems and their applications are already to be regarded as tried, tested and mature technology.

Figure 3: Complete panel for power factor correction

Monitoring and control of the system are performed independently by corresponding controllers which are normally integrated in the system. These controllers automatically regulate the reactive power factor to the target cos φ entered.

Figure 4: Power factor control relay and Power factor correction capacitor

Correction itself is performed by the PF correction capacitors installed in the system. These capacitors are specially developed and manufactured for this application. The capacitors are of the film type and have low losses.

Power factor correction must take place rapidly and close to the load, i.e. near by the machine generating the reactive power, so that reduction of the load on the transmission channels and thus reduction of losses are optimally effective.

7.2 Regional implementation

The maximum effect is achieved when correction takes place directly at the load, i.e. on the low voltage side.

This also means that different power factors in different regions cannot be set off against each other. It is, of course, the objective to achieve the savings by reducing the load on transmission channels. “Reactive power tourism” from one region with a “good” power factor to another with a “poor” power factor would put an additional load on the transmission lines and have exactly the opposite effect.

Power factor correction systems for low voltage application are at present mainly produced by regional suppliers. The supplier structure is characterised by medium sized enterprises. The systems have a low maintenance requirement and function automatically. Testing to verify correct function is performed locally at site. A considerable portion of value addition takes place in the individual states and regions.

8. ZVEI recommendations on implementation

If the originator of reactive energy is not subject to charges, there is little incentive for him to invest in power factor correction. In that case the costs of network transmission and the additional network losses are borne exclusively by the public and not by those responsible for the additional costs.

Many power supply companies therefore charge a fee in the amount of around one quarter of the costs of active energy to cover the drawing of reactive energy when the latter exceeds a certain level.

ZVEI therefore recommends:

Performance of a study to ascertain what the existing power factor is in the various member states. This will reveal the further potential for increasing energy efficiency in the EU 25.

Stipulation

- **of a power factor cos φ of 0.95 *and***
- **stipulation of an appropriate fee for reactive energy drawn by the consumer sectors of industry and service when the specified power factor is not maintained.**


Get more out of your
supply network

9. Summary

The position paper “Improving Energy Efficiency by Power Factor Correction” refers to the EU Commission’s Green Paper on energy efficiency, COM(2005) 265.

It is shown that power factor correction in the EU 25

- reduces the energy losses in the transmission and distribution networks and in the customers’ networks of the industry and service sectors by 48 TWh per annum, and
- reduces the power to be transmitted in the transmission and distribution networks by 15%.

Part of this potential has already been exploited. The authors of this position paper are not, however, in possession of firm data on the degree of exploitation.

The following conversions illustrate what an increase in energy efficiency means: 48 TWh per annum corresponds to the energy consumed or generated by

- over 13 million households
- over 4,000 wind power generators
- around 15 gas-fired power stations
- around 4 nuclear power stations

ZVEI therefore recommends:

- Performance of a study to ascertain what the existing power factor is in each country, in order to determine what potential for increasing energy efficiency in the EU 25 exists today.

- Stipulation
  - of a power factor cos φ of 0.95 and
  - stipulation of an appropriate fee for reactive power drawn by the consumer sectors of industry and service when the specified power factor is not maintained.

The advantage of this recommendation is that the costs of network transmission and the additional network losses are not to be borne by the public at large, but by the persons and organisations responsible for causing those costs.

The costs of power factor correction are approximately € 0.0062 per kilowatt hour of energy saved (see Appendix 10.9). The investment in the equipment therefore pays for itself even without taking additional costs for avoidance of CO_2 emissions into account.

Power factor correction is to be regarded as a tried, tested and mature technology which is regionally available in all the countries of the EU 25. For optimum effect, power factor correction is to be applied rapidly and close to the load. The major part of value addition must therefore take place regionally in the individual countries.

10. Appendices

10.1 Consumption of electrical energy in the EU 25 by consumer sectors

Total electricity demand all users in EU 25-2002	active energy TWh /1/				
Industry	1,168				
Transport	78				
Service	620				
Domestic	717				
Others	58				
Total consumption	2,641				
T&D net losses	195				
Total demand	2,836				
(T&D net losses)/(Total consumption)	7.4%				
(T&D net losses)/(Total demand)	6.9%				

/1/ EURELECTRIC Statistic and prospects for the European electricity sector (1980-1990, 2000-2020) Table 2.2.31, Brussels 2004

10.2 Consumption of electrical energy in the EU 25 with estimated actual power factor

Total electricity demand all users in EU 25-2002 with estimated power factor	active energy TWh		cos φ /2/	reactive energy Tvarh	apparent energy TvAh
Industry	1,168		0.70	1,192	1,669
Transport	78		0.80	59	98
Service	620		0.80	465	775
Domestic	717		1.00	0	717
Others	58		0.80	44	73
Total consumption	2,641		**0.83**	1,759	3,173
Industry	1,168		0.70	1,192	1,669
Service	620		0.80	465	775
Consumption of Industry & Service only	1,788		**0.73**	1,657	2,437
Transport	78		0.80	59	98
Domestic	717		1.00	0	717
Others	58		0.80	44	73
Consumption of other sectors only	853		**0.99**	102	859

/2/ estimation ZVEI

10.3 Consumption of electrical energy in the EU 25 with target power factor

Total electricity consumption all users in EU 25-2002 with target power factor	active energy TWh		cos φ /3/	reactive energy Tvarh	apparent energy TvAh
Target power factor for Industry & (part of) Services			0.95		
Industry	1,168		0.95	384	1,229
Transport	78		0.80	59	98
Service	620		0.95	204	653
Domestic	717		1.00	0	717
Others	58		0.80	44	73
Total consumption	2,641		**0.97**	690	2,730

/3/ proposed target power factor

10.4 Network losses in transmission and distribution networks

Losses T&D net current dependant losses		share of losses /4/	share of losses /5/	current depend.	not current depend.
Share of the losses in the transportnet		20%			
thereof current dependant			90%	18%	
thereof not current dependant			10%		2%
Share of the losses in the distributionnet		80%			
thereof current dependant			60%	48%	
thereof not current dependant			40%		32%
Losses of the T&D net		100%			
thereof current dependant				66%	
thereof not current dependant					34%
Losses of the T&D net		195			
thereof current dependant				**129**	
thereof not current dependant					**66%**

/4/ Commision of European Communities: GREENPAPER on energy efficiency or doing more with less, 2.1 of regulations of network activities, COM (2005) 265 final, Brussels 2005
/5/ estimation ZVEI

10.5 Network losses in customers' networks

Losses customer net with & without reactive power compensation Example with a typical load			load without comp.	load comp. /7/	
Load active power /6/			500	500	kW
Load cos φ without compensation Ind+Ser			0.73		
Load cos φ with target power factor				0.95	
Load apparent power			681	526	kVA
(Load apparent power)/(transformer rated p.)			85%	66%	
Transformer rated power /6/	800	kVA			
Transformer Fe-losses at noload /8/	1.94	kW	1.9	1.9	kW
Transformer Cu-losses at 100% load /8/	8.20	kW	6.0	3.5	kW
Wiring HV Cu-losses at 100% load /9/	0.15	kW	0.1	0.1	kW
Wiring LV Cu-losses at 100% load /10/	1.82	kW	1.3	0.8	kW
Losses total			9.3	6.3	kW
thereof losses not current depend.			1.9	1.9	kW
thereof losses current dependant			7.4	4.4	kW
(losses current dependant)/(losses total)			79%	69%	
Saving of losses by compensation				3,0	kW
(Saving of losses)/(Losses without compensation)				**0.60%**	
Specific saving of losses (Sav. of losses)/(load active p.)					

/7/ target power factor 0.95 /9/ Cu-wires 20m, 3.0 A/mm²
/8/ ABB transformer databook /10/Cu-cables 20m, 1.5 A/mm²

10.6 Internal losses in power factor correction systems

Losses of reactive power compensation capacitor bank, cable					
Losses of capacitor bank /11/	1.5	W/kvar			
Remark: Loss of dielectric 0,2 W/kvar					
Losses of connection cable /12/	0.9	W/kvar			
Specific loss of capacitor bank incl. connect.	2.4	W/kvar			
Average annual usage /13/	3,600	h			
Specific loss energy of capacitor bank	**8.6**	kWh/kvar			

/11/ technical data ZVEI
/12/ Cu-cable 10 m, 1.5 A/mm²
/13/ 2 shifts of 8 h per day × 5 days per week × 45 weeks per year

10.7 Overall model of network losses

Basic data from calculation before	active energy TWh		cos φ uncomp.	cos φ partial comp.	cos φ comp.
Industry and Service	1,788		0.73	0.85	0.95
Others	853		0.99	0.99	0.99
T&D net losses current dependant 2002	129				
Customer net losses current dep. % of load			1.5%	1.1%	0.9%
Annual usage of capacitor bank	3,600	h			
Specific loss energy of capacitor bank	8.6	kWh/kvar			
Scenario 1: Uncompensated	active energy TWh		cos φ	reactive energy Tvarh	apparent energy TVAh
Industry and Service	1,788		0.73	1,657	2,437
Others	853		0.99	102	859
Total	2,641		0.83	1,759	3,173
Reactive energy for compensation				0	Tvarh
Average annual usage				3,600	h
Reactive Power for compensation				0	Gvar
Specific loss energy of capacitor bank				8.6	kWh/kvar
T&D net losses current dependant	154				
Customer net losses Ind+Ser cur. depend.	26				
Losses of capacitor bank	0				
Total losses current dependant	180				
Scenario 2: Estimation 2002 /14/	active energy TWh		cos φ	reactive energy Tvarh	apparent energy TVAh
Industry and Service	1,788		0.85	1,108	2,104
Others	853		0.99	102	859
Total	2,641		0.91	1,210	2,905
Reactive energy for compensation				548	Tvarh
Average annual usage				3,600	h
Reactive Power for compensation				152	Gvar
Specific loss energy of capacitor bank				8.6	kWh/kvar
T&D net losses current dependant	129				
Customer net losses Ind+Ser cur. depend.	20				
Losses of capacitor bank	1				
Total losses current dependant	150				

Scenario 3: With reactive power compensation to Target Power Factor	active energy TWh		cos φ	reactive energy Tvarh	apparent energy TVAh
Industry and Service	1,788		0.95	588	1,882
Others	853		0.99	102	859
Total	2,641		0.97	690	2,730
Reactive energy for compensation				1,069	Tvarh
Average annual usage				3,600	h
Reactive Power for compensation				297	Gvar
Specific loss energy of capacitor bank				8.6	kWh/kvar
T&D net losses current dependant	114				
Customer net losses Ind+Ser cur. depend.	16				
Losses of capacitor bank	3				
Total losses current dependant	132				
Saving of losses by reactive power compensation	active energy TWh				
Scenario 1 - Scenario 3	**48**				
/14/ Estimation ZVEI					

10.8 Load relief on transmission and distribution networks

Transport capability of the T&D net				apparent energy TVAh	
Scenario 1: Uncompensated				**3,173**	109%
Scenario 2: Estimate 2002				**2,905**	100%
Scenario 3: With reactive power comp.				**2,730**	94%
Scenario 1 - Scenario 3				**443**	15%

10.9 Costs of power factor correction

Cost of reactive power compensation					
Scenario 3 - Scenario 1					
Reactive energy required	1,069	Tvarh			
Average annual usage	3,600	h			
Reactive power required	291	Gvar			
Cost of reactive power compensation /15/	13.0	€/kvar			
Plus installation approx 15% /16/	2.0	€/kvar			
Total cost including installation	15.0	€/kvar			
Invest for reactive power compensation	4.4	billion €			
Energy saving	48	TWh			
Average lifetime of power compensation unit	15	years			
Invest related to energy saving	0.0062	€/kWh			
Electricity price for industry EU 25 /17/	0.055	€/kWh			
The invest into energy saving pays by itself					

/15/ Estimation ZVEI /16/ Estimation ZVEI
/17/ EU energy and transport in figures. Statistic pocketbook 2004. 2.5.3; Source: Eurostat

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