Three-phase drives

Products with well-balanced energetic parameters

- Asynchronous motors
- Asynchronous motors according to DIN
- Asnchronous motors with a low mass-output ratio and standard fixing dimensions
- Energy efficient motors with standard fixing dimensions
- Asynchronous compact motors with optimized mass-output ratio
- Three-phase compact drives with integrated frequency converter

What do we understand by well-balanced energetic parameters ?

The costs of the electromechanical energy conversion will be determined by the

- manufacturing costs and the operating costs of the electromechanical energy transducer,

but the costs of the technological process will be determined through the

- manufacturing costs and the operating costs of that plant in which is integrated the electromechanical energy transducer.

Our objective is to place such electric drives at our customer's disposal which influence the complete process at cost optimum, in fact on a high technical level, with a low environmental pollution and a with maximum operating safety.

We produce motors which have energy-consciously well-balanced properties regarding their

- efficiency η_n
- power factor cos (φ_n)
- mass-output ratio M/Pn
- partial load behaviour cos (φ) and η at $P < P_n$.

The optimization according to only one of these parameters (e.g. efficiency), which have an effect on the costs, results only in partially optimum solutions.

We offer our customers complete drive solutions being adapted to the technological process optimally:

- variable-speed three-phase drives for the optimum process management
- drive solutions with the possibility to recover electrical energy by utilizing regenerative energy potentials
- compact drives, i.e. three-phase motors with integrated frequency converters

We determine the optimum drive dimensioning by using our modern project planning means.

Economic evaluation of the energetic parameters Efficiency and power factor

The efficiencies at design operation η_n of the European and American standard motors deviate from the mean value only to a minimal extent - in the output range of up to 11 kW by approx. ± 4 % and beyond it only just ± 1 %. But the deviations of the power factors in the design point cos φ_n amount up to ± 6 % in the complete output range.

The deviations in the efficiency are resulting from different design aspects and target criteria.

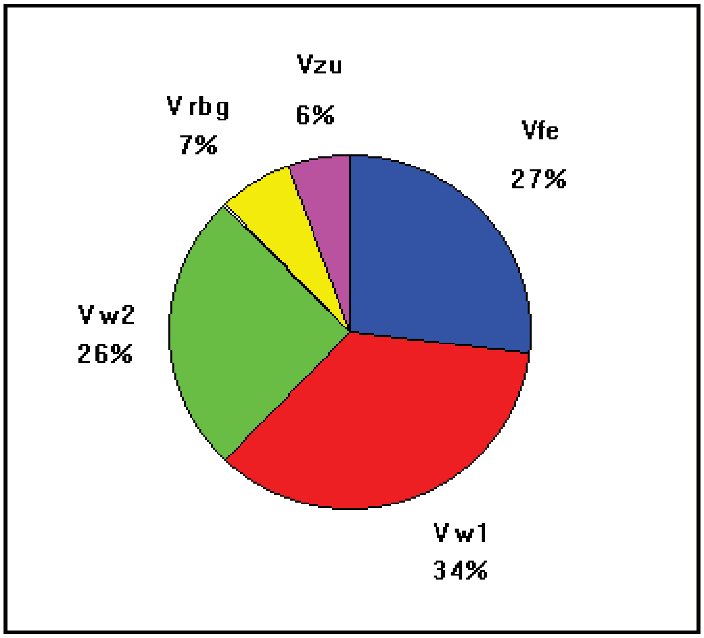
The efficiency describes the ratio of power output P_{out} to power input P_{in} :

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out} + V}$$

The power loss in a three-phase motor is consisting of the virtually load-independent but not speed-independent iron loss in the cores, in the housing and in the shaft V_{fe}, of the load-dependent and the speed-dependent winding loss in the stator winding V_{w1} and in the rotor cage V_{w2}, of the speed-dependent windage and friction
loss V_{frict} and of the load-dependent stray load loss.

$$V = V_{fe} + V_{w1} + V_{w2} + V_{frict} + V_{stray}$$

The percentages of the individual loss to the total loss of a 22 kW-motor are to be taken from the Illustration 1.



V_{frict}
V_{w2}
V_{w1}
V_{fe}
V_{stray}

Illustration 1 : Loss distribution in a 22 kW-standard motor (p=2)

The power factor describes the ratio of the electrical active power P_{el} to the apparent power S_{el} :

$$\cos\varphi = \frac{P_{el}}{S_{el}} = \frac{P_{el}}{\sqrt{3} \cdot U \cdot I}$$

By reason of the design principle, the power factor for asynchronous machines is always lower than One. The phase displacement of the stator current compared with the terminal voltage will be caused in the range of small slip values s

$$s = \frac{n_0 - n}{n_0}$$

$n_0 = \frac{f}{p}$ synchronous speed,

in particular through the magnetizing current. The magnitude of the magnetizing current depends on the intensity of the magnetic flux and on the resulting magnetic resistance of the magnetic circuit. The magnetizing current is a pure reactive current. Phase position and magnitude of the stator current are described by means of the current circle diagram (see Illustration 2).

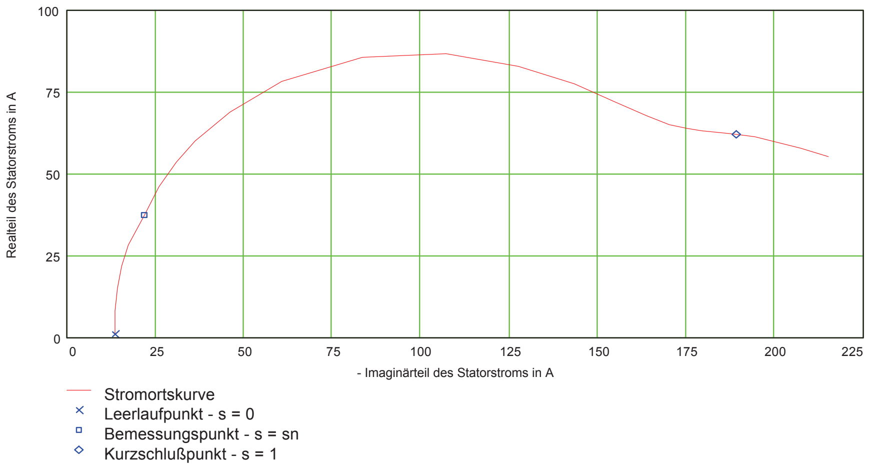


Illustration 2 : Current circle diagram

Realteil des Statorstromes in A	real part of the stator current in A
Imaginärteil des Statorstromes in A	imaginary part of the stator current in A
Stromortkurve	current circle diagram
Leerlaufpunkt	no-load point
Bemessungspunkt	design point
Kurzschlußpunkt	short-circuit point

Electric motors as electromechanical energy transducers have also considerable part in the total electrical energy consumption. In accordance with a study of the ZVEI, the industry in Germany consumes approx. a third of the total energy (see Illustration 3). Approx. 50 % of it need the electric drives. In the electric drive, a part of the required energy will be converted, as power loos, into heat. Here, the complete drive consists of the electronic actuator, of the motor, of a possibly flanged gear and of a directly attached set (e.g. pump. compressor, blower etc.) - the efficiencies of all components determine the total efficiency of the drive.

$\eta_{overall} = \eta_{le}\ \text{ú}\ \eta_{em}\ \text{ú}\ \eta_{gear}\ \text{ú}\ \eta_{am}$

$\eta_{overall}$ - overall efficiency

η_{le} - resulting efficiency of the power-electronic actuators

η_{em} - resulting efficiency of the electric machines

η_{gear} - resulting efficiency of the gears

η_{am} - resulting efficiency of the driven machine

So, an important basis for the energy-conscious evaluation of investment projects is inter alia the determination of the operating costs of the electric drives. The operating costs result from the consumption of the electrical active power and reactive power.

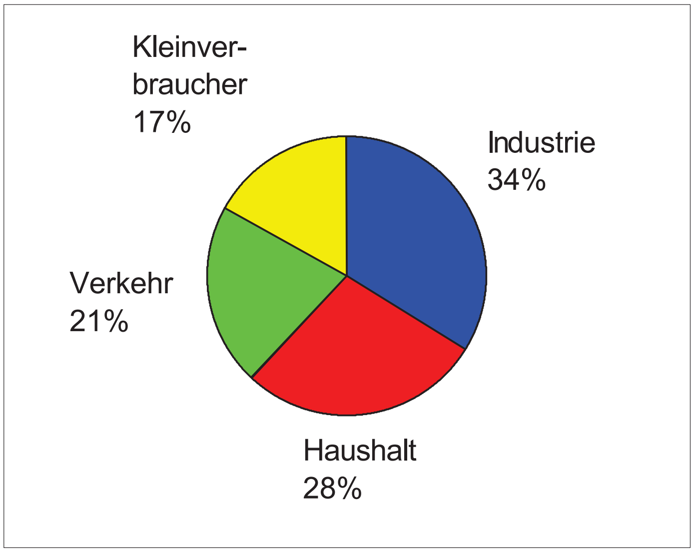


Illustration 3 : Energy consumption in Germany

Kleinverbraucher	small consumer
Industrie	industry
Haushalt	household
Verkehr	traffic

Operating cost for the consumption of the active power

$$KbW = (KE \cdot tb + KW) \cdot \left(\frac{P_{tech}}{\eta_{ges}} + V_{üb} \right) \qquad (7)$$

with $P_{tech} = P_{auf} \cdot \eta_{ges}$ driving power required technological process (8)

$$V_{üb} = S_n \cdot \left(\frac{I}{I_n} \right)^2 \cdot \Delta u_r = \frac{P_{tech.n}}{\cos(\phi_n) \cdot \eta_{ges.n}} \cdot \left(\frac{I}{I_n} \right)^2 \cdot \Delta u_r$$

transmission power loss (9)

$\Delta u_r = \frac{\sqrt{3 \cdot I_n \cdot R_L}}{U_n}$ ohmic voltage drop on the transmission length

R_L - resistance of the transmission length between the power counter and the drive

KE - specific electric energy price in DM/kWh (in dependence on the bought quantity and on the delivery times - night rate or main rate)

KW - specific price per kilowatt in DM/kW for the available installed load

tB - annual operating time in h

index "n" - data at design operation

With (7) and (9) the operating costs for the consumption of active power are als follows:

$$KbW = (KE \cdot tB + KW) \cdot \frac{P_{tech}}{\eta_{ges}} \cdot \left[1 + \frac{P_{tech.n}}{P_{tech}} \cdot \frac{\eta_{ges}}{\eta_{ges.n}} \cdot \frac{1}{\cos(\phi_n)} \cdot \left(\frac{I}{I_n} \right)^2 \cdot \Delta u_r \right]$$

$$KbW = (KE \cdot tB + KW) \cdot \frac{P_{tech}}{\eta_{ges}} \cdot \left[1 + \frac{1}{\cos(\phi)} \cdot \left(\frac{I}{I_n} \right) \cdot \Delta u_r \right] \tag{11}$$

The operating costs arising through power loss in the electric motor will be calculated from :

$$KbWV = (KE \cdot tB + KW) \cdot \frac{P_{tech}}{\eta_{ges}} \cdot \left[1 + \frac{1}{\cos(\phi)} \cdot \left(\frac{I}{I_n} \right) \cdot \Delta u_r \right] \cdot (1 - \eta) \tag{12}$$

Operating cost for the consumption of the reactive power :

$$\mathrm{KbB} = \mathrm{KBl} \cdot \mathrm{tB} \cdot \frac{\tan\varphi}{\eta_{\mathrm{overall}}} \cdot \mathrm{P}_{\mathrm{tech}}$$

with :
Kbl - specific "reactive power"
- price in DM (kVAr*h)
(in dependence on the power factor)

In Table 1 are specified the results of the cost effectiveness analysis for a midsize industrial untertaking. The influence of the motor efficiency η_{em} and of the power factor $\cos\varphi$ will be specified in the tables 2 and 3. The indicated parameters are resulting values being valid for the complete operation. A comparison of the results proves the stronger influence of the efficiency on the complete operating costs - it has approx. 3,5 times the value for the example to be inspected. But the calculation makes also clear that the influence of the power factor cannot be ignored.

High reserves for saving operating costs are in the improvement of the efficiency of the technological process directly influenced by the electric drive.

$KE := 0.123 \cdot \frac{DM}{kW \cdot h}$ $KW := 230 \cdot \frac{DM}{kW}$ $KBl := 0.02 \cdot \frac{DM}{kVar \cdot h}$

$P_{tech} := 3200 \cdot kW$ $tB := 3500 \cdot h$ $\frac{I}{I_n} = 1$

$\eta_{ges} := 60 \cdot \%$ $\eta := 90 \cdot \%$

$\cos(\phi) = 0.81$ $\tan(\phi) = 0.73$ $\Delta u_r := 3 \cdot \%$

Betriebskosten in einem Jahr:

$Kb_{ges} = 3924537 \cdot DM$

Betriebskosten für den Wirkleistungsverbrauch

$KbW = 3653294 \cdot DM$ **93,1 %**

Betriebskosten für den Blindleistungsverbrauch:

$KbB = 271243 \cdot DM$ 6**,9 %**

Betriebskosten für die Übertragungsverluste $KbW_{üb} = 130628 \cdot DM$ **3,3 %**

Betriebskosten für die Motorverluste $KbWV = 365329 \cdot DM$ **9,3 %**

Table 1 : Calculation of the operating costs for a midsize company

Betriebskosten in einem Jahr	operating cost in one year
Betriebskosten für den Wirkleistungsverbrauch	operating cost for the consumption of active power
Betriebskosten für den Blindleistungsverbrauch	operating cost for the consumption of reactive power
Betriebskosten für die Übertragungsverluste	operating cost for the transmission loss
Betriebskosten für die Motorverluste	operating cost for the motor loss

$\eta_{ges1} = 59.4 \cdot \%$ $\eta_{1} = 89.1 \cdot \%$ $\frac{I_{1}}{I_{n}} = 1.01$

Zunahme der gesamten Betriebskosten:

$\Delta Kb_{ges.\eta} = 1.1 \cdot \%$

Zunahme der Betriebskosten für den Wirkleistungsverbrauch:

$\Delta KbW_{\eta} = 1.1 \cdot \%$

Zunahme der Betriebskosten für den Blindleistungsverbrauch:

$\Delta KbB_{\eta} = 1 \cdot \%$

Zunahme der Betriebskosten für die Übertragungsverluste : $\Delta KbW_{üb.\eta} = 3 \cdot \%$

Zunahme der Betriebskosten für die Motorverluste : $\Delta KbWV_{\eta} = 10.2 \cdot \%$

Table 2 : Increase of the operating cost with a reduction of the efficiency by 1 %

Zunahme der gesamten Betriebskosten	Increase of the complete operating cost
Zunahme der Betriebskosten für den Wirkleistungsverbrauch	Increase of the operating cost for the consumption of active power
Zunahme der Betriebskosten für den Blindleistungsverbrauch	Increase of the operating cost for the consumption of reactive power
Zunahme der Betriebskosten für die Übertragungsverluste	Increase of the operating cost for the transmission loss
Zunahme der Betriebskosten für die Motorverluste	Increase of the operating cost for the motor loss

$\cos(\phi_1) = 0.801$ $\tan(\phi_1) = 0.748$ $\frac{I_1}{I_n} = 1.01$

Zunahme der gesamten Betriebskosten:

$\Delta Kb_{ges.\phi} = 0.3 \cdot \%$

Zunahme der Betriebskosten für den Wirkleistungsverbrauch:

$\Delta KbW_{\phi} = 0.1 \cdot \%$

Zunahme der Betriebskosten für den Blindleistungsverbrauch:

$\Delta KbB_{\phi} = 2.9 \cdot \%$

Zunahme der Betriebskosten für die Übertragungsverluste $\Delta KbW_{üb.\phi} = 3 \cdot \%$

Zunahme der Betriebskosten für die Motorverluste: $\Delta KbWV_{\phi} = 0.1 \cdot \%$

Table 3 : Increase of the operating cost with a reduction of the power factor by 1 %

Zunahme der gesamten Betriebskosten	Increase of the complete operating cost
Zunahme der Betriebskosten für den Wirkleistungsverbrauch	Increase of the operating cost for the consumption of active power
Zunahme der Betriebskosten für den Blindleistungsverbrauch	Increase of the operating cost for the consumption of reactive power
Zunahme der Betriebskosten für die Übertragungsverluste	Increase of the operating cost for the transmission loss
Zunahme der Betriebskosten für die Motorverluste	Increase of the operating cost for the motor loss

On the basis of the results specified in the tables 2 and 3, the following quality factor can be introduced for the energy-conscious evaluation of an asynchronous standard motor :

$$GF = \frac{1}{WF + 1} \cdot \left(WF \cdot \eta_n + \cos(\phi_n) \right) \tag{14}$$

With the weithing factor:

$$WF = \frac{\Delta Kb_{ges.\ \eta}}{\Delta Kb_{ges.\ \phi}} \tag{15}$$

The following factors are resulting for the figure example specified in the margin :

WF = 3,58 - weighting factor

GF = 88 % - quality factor

with : η_n = 90 %
$\cos\varphi_n$ = 0,81

Influence of the overdimensioning of the electric drives on the operating cost

The overdimensioning of a drive has two economic aspects :

- Higher specific operating costs (costs referred to the work realized) through reduction of the efficiencies and of the power factors of the drives

- Reduced utilization of the drives - higher investments

Usually, the standard motors, in particular those in the lower output range (approx. up to 100 kW), will not be utilized relatively much concerning their load and their annual operating time in the different branches of industry (see Table 4).

Range of application	ζ	**T**
Ventilation systems	70 %	12 %
Pumps and compressors	63 %	52 %
Agricultural machines	60 %	25 %
Machine tools	20 %	45 %

Table 4 : Load factor ζ and time utilization T of asynchronous standard motors in the range of up to 100 kW

If the operating system or the technological process requires an operation of the drives with different loads, the drives in the projecting phase are to be selected in such a manner that they are adapted to this mode of operation optimally. An important auxiliary means for the drive-oriented adaption is the configuration software of the VEM motors GmbH.

Illustration 4 shows the operating characteristic curves of a four-pole 22 kW standard motors. The motor is dimensioned in such a manner that the efficiency, also in case of partial load (up to approx. 50 %), doesn't deviate much from the maximum efficiency appearing near to the design power. This dimensioning has an energy-conscious advantage as a result of the frequent partial load operation.

In contrast to the efficiency, the power factor drops, in depence on the principle, relatively strongly in the complete underload range. Therefore, seen from the point of the partial load operation, the incorporation of the power factor is very important for the energy-conscious evaluation of the motor.

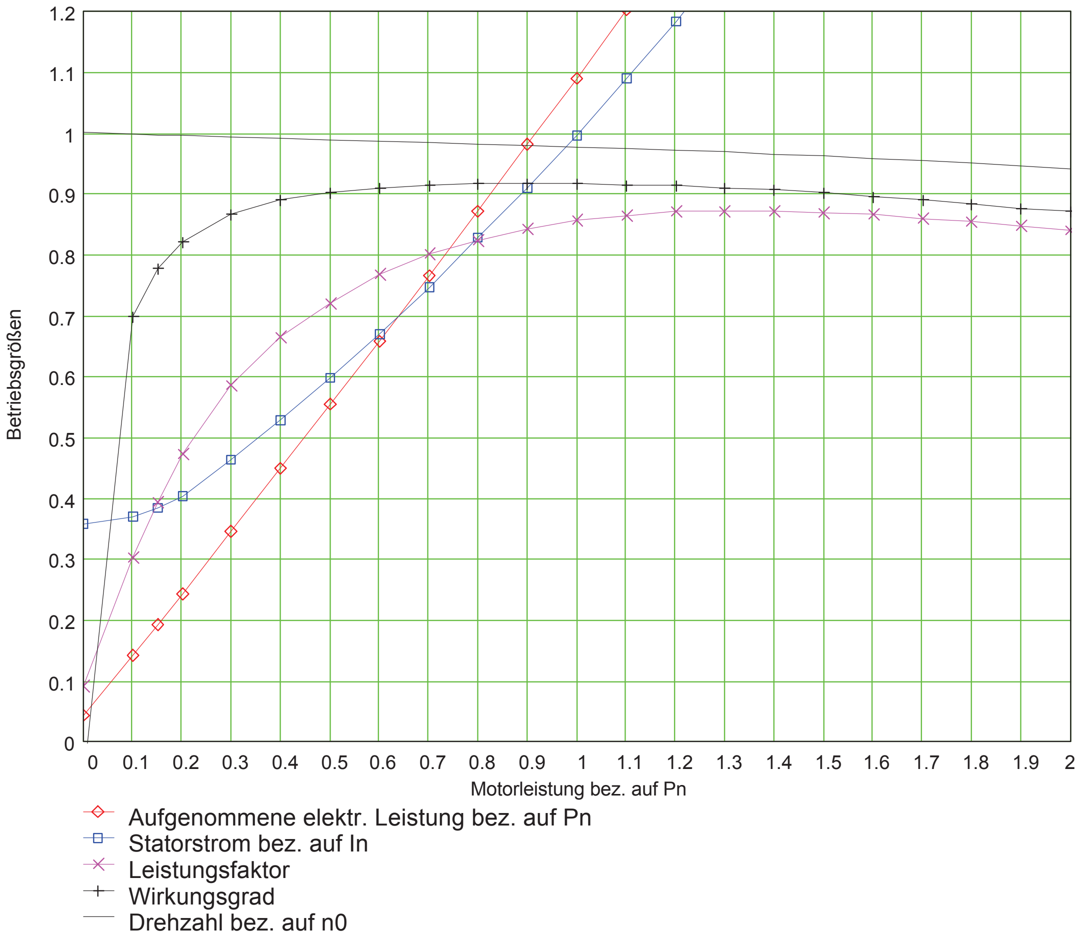


Illustration 4 : Operating characteristic curves of a four-pole 22 kW standard motor

Betriebsgrößen	performance quantities
Motorleistung bez. auf Pn	motor output with reference to Pn
Aufgenommene elektr. Leistung bez. auf Pn	Absorbed electrical power input with reference to Pn

Statorstrom bez. auf In	Stator current with reference to Pn
Wirkungsgrad	Efficiency
Drehzal bez. auf n0	Speed with reference to n0

Table 5 informs about the influence of an overdimensioning of the installed driving power. The calculations are based on the assumption that the drives are utilized with only 50 %; in the example, the mean technologically required driving powerP_{tech} amounts only to 1600 kW, bu the installed driving power comes to 3200 kW. Whereas the resulting efficiency of the motors doesn't change much, the resulting power factor reduces to a considerably higher degree.

The consequence are higher specific operating costs for the used electric energy. In particular, these operating costs result from the increase of the operating costs for the consumption of reactive power.

The operating costs would be essentially higher if the driving machines are also overdimensioned, having then a considerably lower partial load efficiency.

$KE := 0.123 \cdot \frac{DM}{kW \cdot h}$ $\quad KW := 230 \cdot \frac{DM}{kW}$ $\quad KBl := 0.02 \cdot \frac{DM}{kVar \cdot h}$

$P_{tech} := 1600 \cdot kW$ $\quad tB := 3500 \cdot h$ $\quad \frac{I}{I_n} = \frac{1}{2} \cdot \frac{1}{\eta_{ges} \cdot \cos(\phi)}$

$\eta_{ges} := 58.6 \cdot \%$ $\quad \eta := 88 \cdot \%$ $\quad \frac{I}{I_n} = 0.591$

mit: $\eta_{le} * \eta_{getr} * \eta_{am}$ **= 66,7 %** wie bei Vollast

$\cos(\phi) = 0.68$ $\quad \tan(\phi) = 1.06$ $\quad \Delta u_r := 3 \cdot \%$

Betriebskosten in einem Jahr:

$Kb_{ges} = 2053651 \cdot DM$ **52,3 % der Betriebskosten bei Vollast (Tafel 1)**

Betriebskosten für den Wirkleistungsverbrauch

$KbW = 1850122 \cdot DM$ **50,6 % der Kosten bei Vollast (Tafel 1)**

Betriebskosten für den Blindleistungsverbrauch:

$KbB = 203529 \cdot DM$ **75 % der Kosten bei Vollast (Tafel 1)**

Table 5 : Operating costs at a load factor ζ of 50 %

mit	with
.....wie bei Vollast	......such as in case of full load
Betriebskosten in einem Jahr	Operating cost in one year
Kb_{ges}	$Kb_{overall}$
52,3 % der Betriebskosten	52,3 % of the operating cost
bei Vollast (Tafel 1)	at full load (Table 1)
Betriebskosten für den Wirkleistungsverbrauch	Operating cost for the consumption of active power
50,6 % der Kosten bei Vollast (Tafel 1)	50,6 % of the operating cost at full load (Table 1)
Betriebskosten für den Blindleistungsverbrauch	Operating cost for the consumption of reactive power
75 % der Kosten bei Vollast (Tafel 1)	75 % of the operating cost at full load (Table 1)

Investments, pay-back time and operating cost considering the laws of growth

The efficiency and the power factor of asynchronous motors dependen not only on the load but also on the size - they are subject to laws of growth. The illustrations 5 and 6 are showing efficiency and power factor characteristic curves of four-pole standard motors of different output.

In the lower output range of up to 50 kW, the transition to motors with higher design outputs leads to an increase of efficiency and power; i.e., only for motors with a design output of above 50 kW, the use of overdimensioned drives working in the partial load range is uneconomical from the beginning.

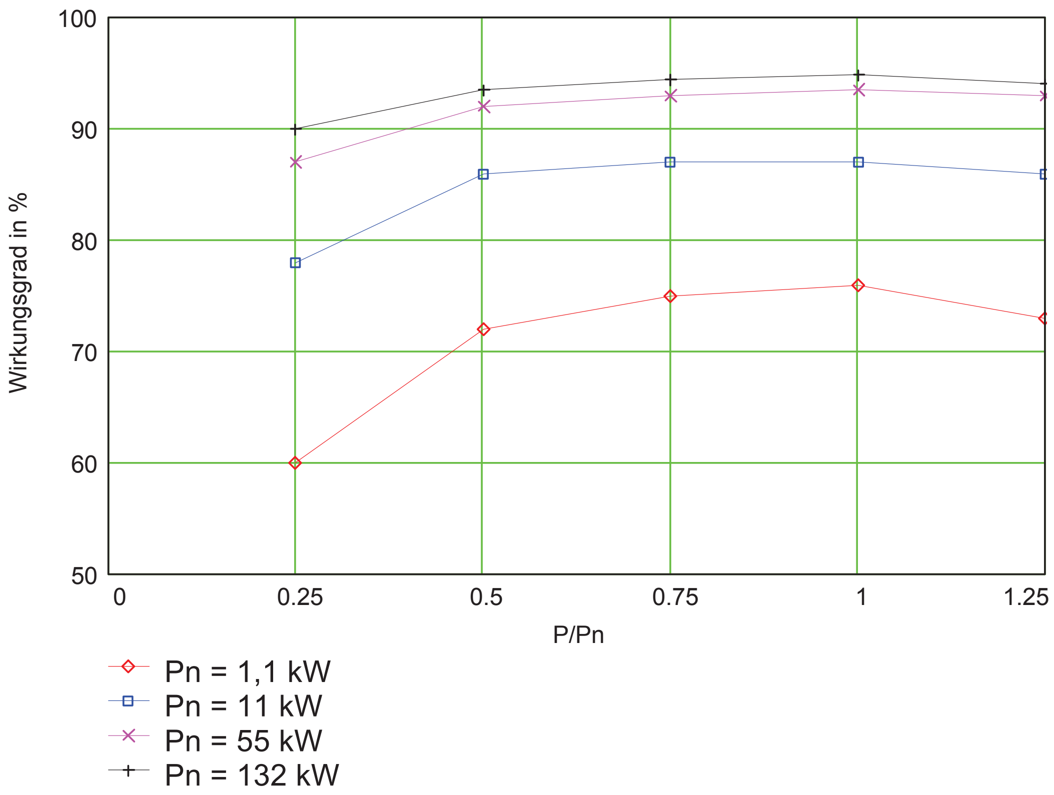


Illustration 5 : Efficiecy characteristic curves of standard motors

Wirkungsgrad in %	efficiency in %

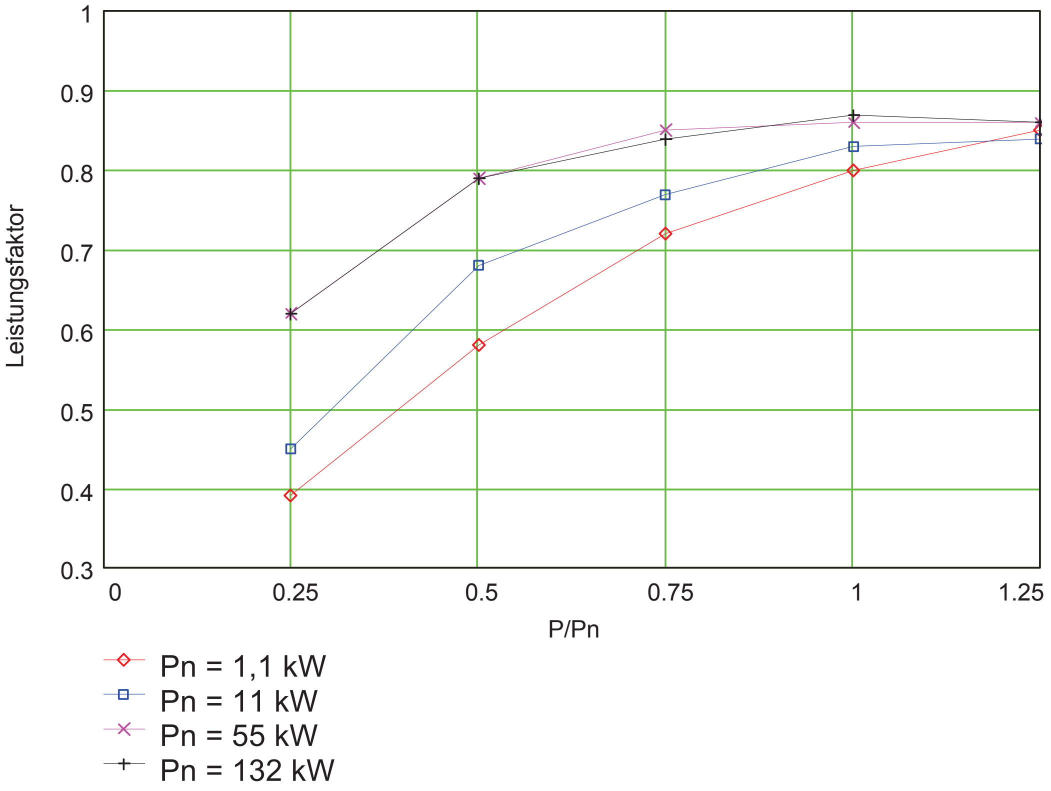


Illustration 6 : Power factor characteristic curves of standard motors

Leistungsfaktor	power factor

The investment costs and the operating costs are important for evaluating economically a drive design. Higher investments ΔI, resulting, for instance, from the installation of overdimensioned or energy efficient motors, have to amortize within an acceptable time t_a by saving operating costs ΔKb.

$$T_a = \frac{\Delta I}{\Delta Kb} \quad \text{pay-back time}$$

with :

ΔI - difference of the investment costs

ΔKb - difference of the operating costs per year

Influence of the motor efficiency in the partial load range on the operating costs

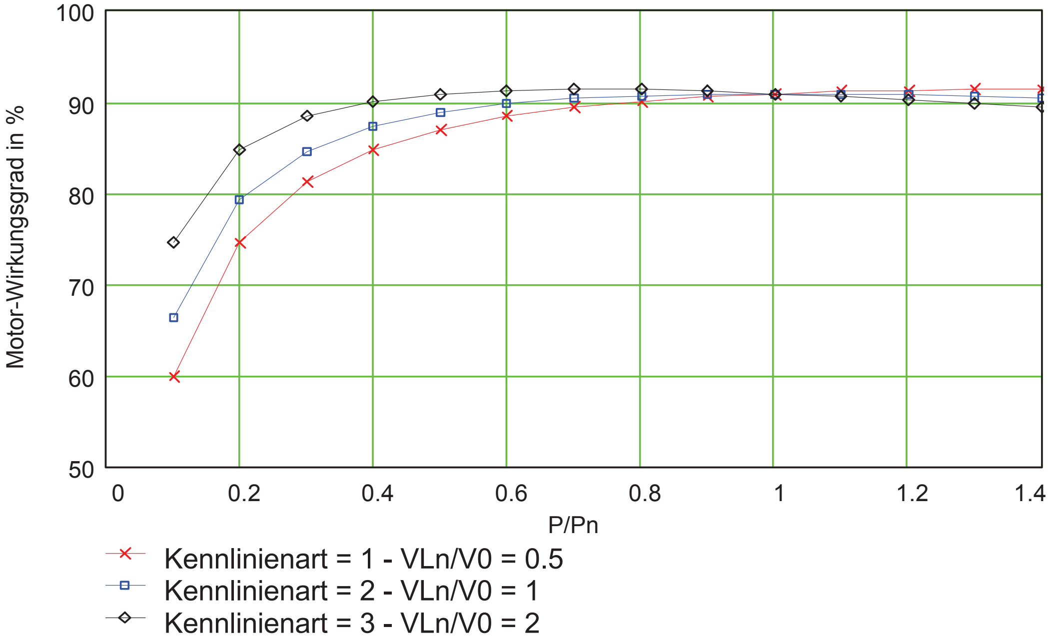


Illustration 7 : Efficieny characteristic curves of an asynchronous motor at different loss distributions

Motor-Wirkungsgrad in %	motor efficiency in %
Kennlinienart	type of characteristic curve

The load-dependence of the efficiency depends on the degree of the load-dependent loss V_L and of the load-independent loss V_0. For the following consideration will be assumed that the load loss increases squarely with the motor output P :

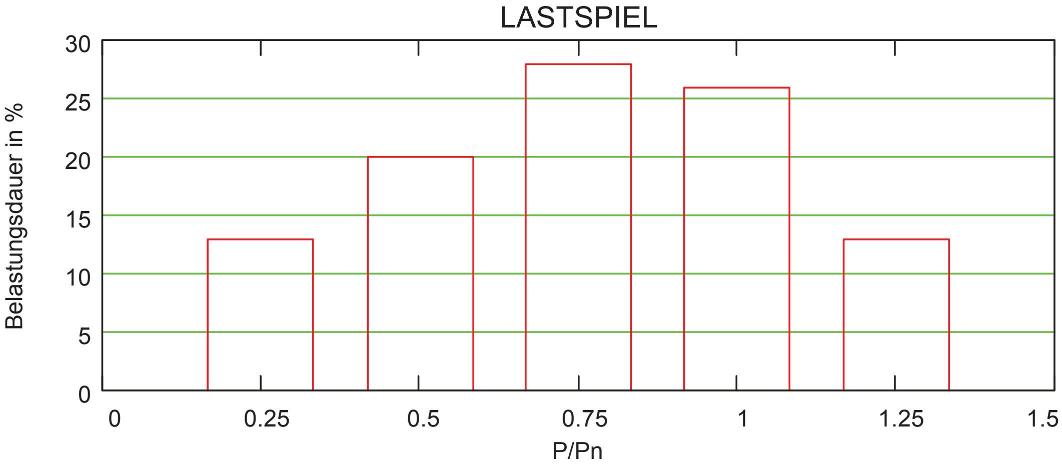
$$V_L = V_{Ln} \cdot \left(\frac{P}{P_n}\right)^2 \qquad (17)$$

With this assumption as well as on the consideration of uniformly high losses in the design point, there are resulting the efficiency characteristic curves, shown in the Illustration 7, in fact at different values for the load-dependent loss - in particular winding loss V_{w1} and V_{w2} - and load-independent loss - in particular mechanical loss and iron loss V_{frct} and V_{te}.

The influence of the type of characteristic curve on the operating costs at a load cycle with considerable shares in the partial load range will be explained in the Illustration 8. For these cases of operation, the efficiency characteristic curves, elevated in the partial load range, lead to noticeable cost cuttings. (The operating costs for the transmission losses and for the reactive power consumption have not been considered for the calculations.)

$P_n = 22 \cdot kW \quad KE := 0.123 \cdot \frac{DM}{kW \cdot h} \quad KW := 230 \cdot \frac{DM}{kW} \quad tB = 3500 \cdot h$

$$KbWV = \left[\sum_{j=1}^{5} \left[\left[\left(KE \cdot T_j \cdot tB + KW \right) \cdot \frac{p_j \cdot P_n}{\eta1_j} \right] \cdot \left(1 - \eta_j \right) \right] \right]$$



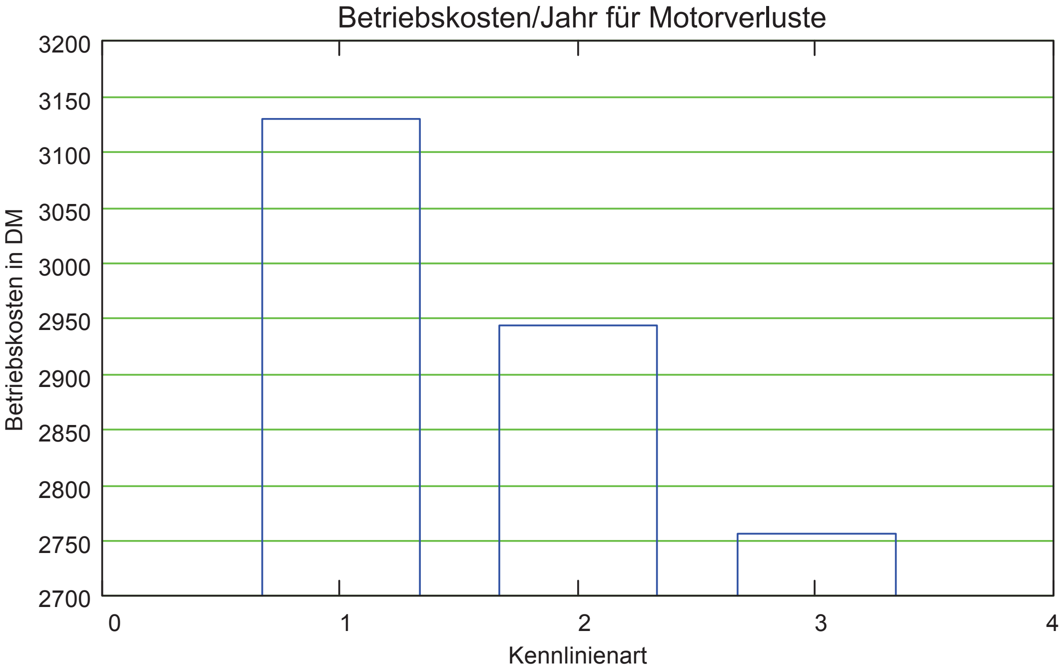


Illustration 8 : Annual operating costs for the loss in a 22 kW motor withdifferent efficiency characteristic curves

Belastungsdauer in %	loading period in %
Betriebskosten in DM	operating cost in DM
Kennlinienart	Type of characteristic curve

Variable-speed three-phase drives for the optimum process management

A large part of processes and drive applications can be optimized energy-consciously through frequency converters by using variable-speed electric drives with a low-loss speed regulation.

Approximately the half of the installed motor output will be required for the operation of pumps, compressors and blowers. Often, the required volumetric flow rate doesn't be constant.
The ratio of volumetric delivery rate Q to absorbed electric power input P_{in} will be influenced considerably through the mode of the volumetric flow rate control - in this case, the motor efficiency has an influence to be neglected. In a fan plant, the traditional regulation of the delivery rate will be realized through throttle valves or through variable-inlet guide vanes. In the partial load range, the efficiency of these plants is very low. The efficiency of fan plants with a speed control is more advantageous. Illustration 9 shows the electric power absorption of a radial fan in the partial load range for the specified possibilities of the delivery rate control.

If the load profile of the radial fan, shown in Illustration 10, will be assumed, the energy savings at a speed control of the radial fan amount to approx. 30 % compared with the throttle valve control and go to approx. 12 % compared with the variable-inlet guide vane control (see table 6).

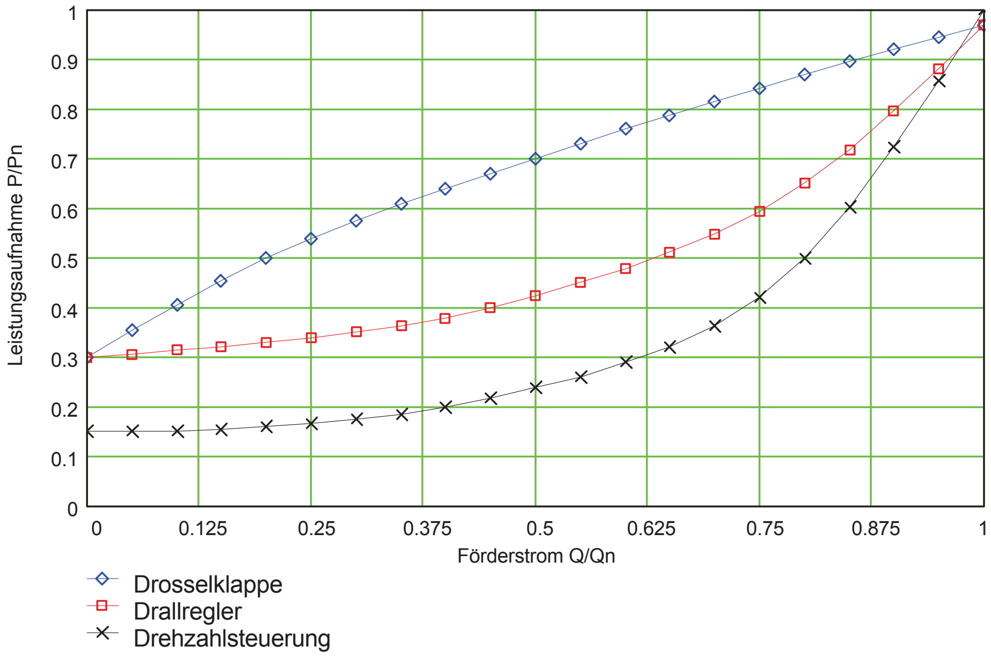


Illustration 9 : Power absorption of a radial fan

Leistungsaufnahme	power absorption
Förderstrom	delivery rate
Drosselklappe	throttle valve
Drallregler	variable-inlet guide vane
Drehzahlsteuerung	speed control

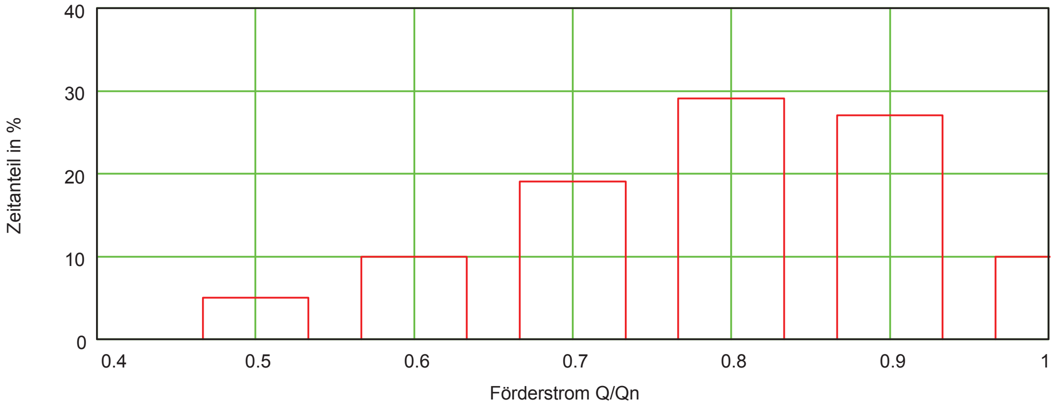


Illustration 10 : Load profile of a radial fan

Förderstrom	delivery rate

Energy saving at speed control in %

compared with the throttle valve control : $\Delta e1 = 31{,}3 \cdot \%$
compared with the variable-inlet guide vane control : $\Delta e2 = 12{,}3 \cdot \%$

Energy saving at speed control in kW

Figure example :

$P_n = 22 \cdot kW$ design output
$tB = 8000 \cdot h$ operating time per year
$\Delta E = \Delta e \cdot Pn \cdot tB$

compared with the throttle valve control : $\Delta E1 = 55164 \cdot kW \cdot h$
compared with the variable-inlet guide vane control : $\Delta E2 = 21730 \cdot kW \cdot h$

Annual operating cost saving at speed control :

$KE = 0{,}123 \cdot \frac{DM}{kW \cdot h}$ $\Delta KbW = KE \cdot \Delta E$
compared with the throttle valve control : $\Delta KbW1 = 6785 \cdot DM$
compared with the variable-inlet guide vane control : $\Delta KbW2 = 2673 \cdot DM$

Table 6 : Operating cost saving at speed control of a radial fan

Influence of voltage fluctuations of the mains on the operating cost

Up to the year 2003, the admissible tolerances of the 400 V mains will amount to ± 10 %. The current, resulting if the mains voltage deviates from the design value or from the mean design value of 400 V, is a function of the power factor in the design point. The current changes result from the energetic-oriented adaption of the active current and from the modification of the magnetizing current influenced from the saturation state. Illustration 11 shows how the motor current changes at voltage deviations of ± 5 % with reference to its design value. The current values are between both represented limit characteristic curves for highly and lowly saturated machines.

By reason of the laws of growth, the power factors in the design point are dependent on the size (see also Illustration 6), i.e., the high power factors belong also to bigger shaft heights.

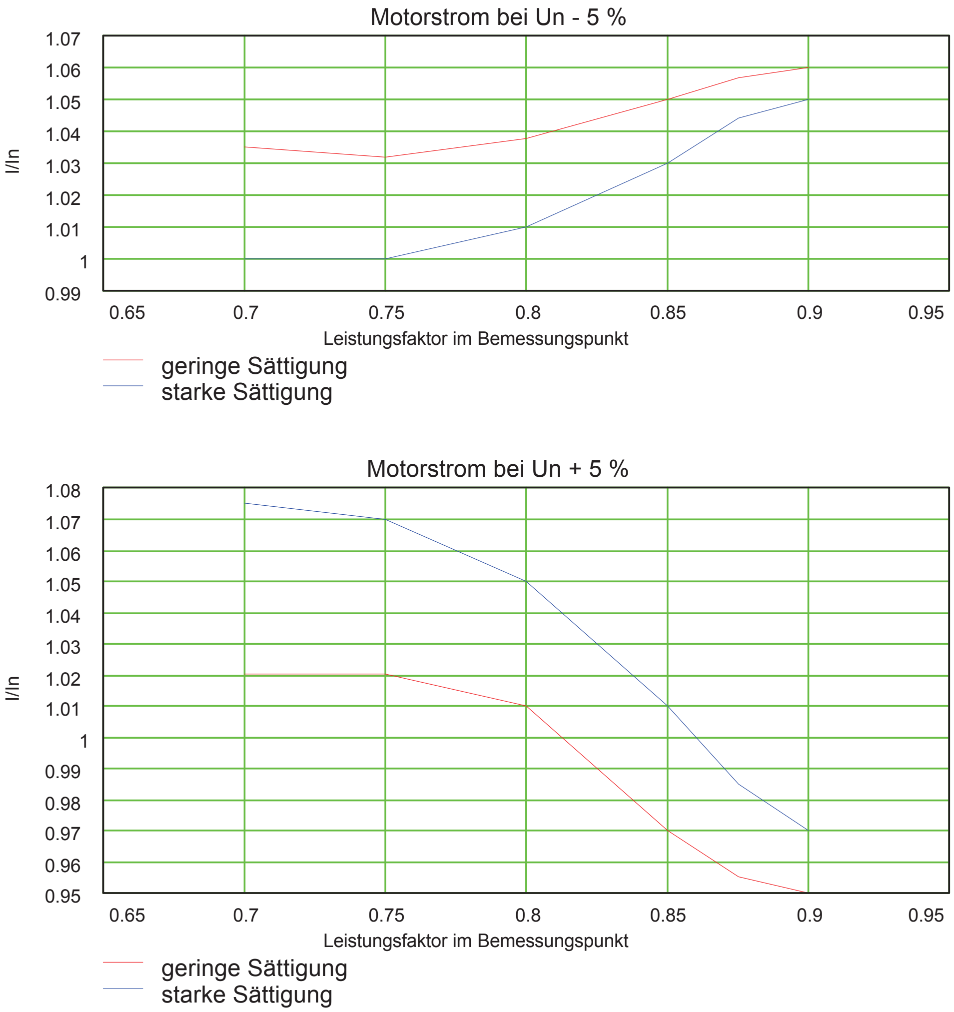


Illustration 11 : Deviation of the motor current from the design value at mains voltage variations by ± 5 %

Motorstrom bei	motor current at
Leistungsfaktor im Bemessungspunkt	power factor in the design point
geringe Sättigung	low saturation
starke Sättigung	high saturation

The influence of the mains voltage variation on the motor efficiency will be shown in Illustration 12. Here has been assumed a continuous loss distribution in accordance with Illustration 1, temperature changes haven't been considered. The results make clear that, in particular in case of motors with a low power factor and a highly utilized magnetic circuit, a voltage rise leads to a considerable reduction of the efficiency.

The statement of this section emphasizes that, in case of the energy-conscious evaluation of a motor, not only the efficiency in the design point but also the power factor, the partial load behaviour and the target criteria are important for the motor dimensioning.

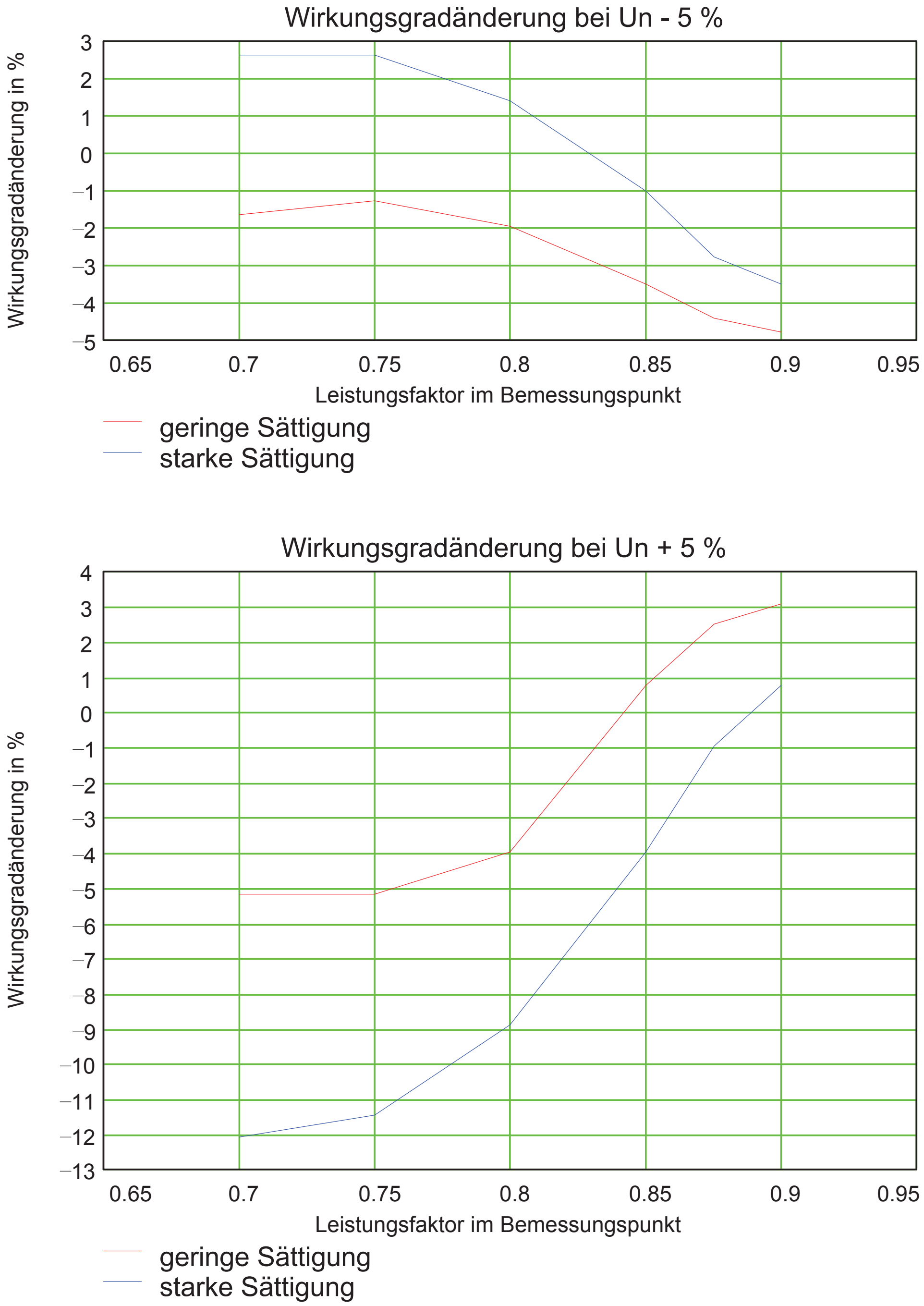


Illustration 12 : Deviation of the efficiency from the design value at mains voltage variation by ± 5 %.

Wirkungsgradänderung bei	Modification of the efficiency at
Wirkungsgradänderung in %	modification of the efficiency in %
Leistungsfaktor im Bemessungspunkt	power factor in the design point
geringe Sättigung	low saturation
starke Sättigung	high saturation