THE ASYNCHRONOUS GENERATOR IN SMALL POWER PLANTS

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This document is a contribution to the asynchronous machine optimized for generator operation. It refers to the most important design recommendations and its physical background.
With a general description but also by means of specific examples the excellent features of the asynchronous machine as generator at mains parallel operation are explained.

1 GENERAL INFORMATION TO THE ASYNCHRONOUS MACHINE

Numerous advantages made the asynchronous machine to the most frequently used electric driving machine.
It has a simple mechanical configuration with few wear parts. Apart from the special shape of the slipring rotor, the machine neither has sliprings nor brushes. Therefore it requires low maintenance, has a long service life and a robust design. A high efficiency can be achieved at a very favourable price.

1.1 The circle diagram

The so-called circle diagram describes the physical basis of the functioning mode. It is based on the knowledge that the locus curve of the stator current is a near-circular figure. First publications refer to HEYLAND and HEUBACH (1894). The representation of the circle diagram, still applicable today, was indicated by OSSANNA also in 1894 [Figure 1.1]. The current locus curve shows the size and the phase position of the current to the mains voltage in function of the load or the slip s.
The current indicators J_1 are in motor operation ABOVE Line A1, in generator operation BELOW. The distance between the respective circular point and the straight line D is a measure for the torque. The vertical distance between the respective circular point and the straight line A2 is a measure for the output.

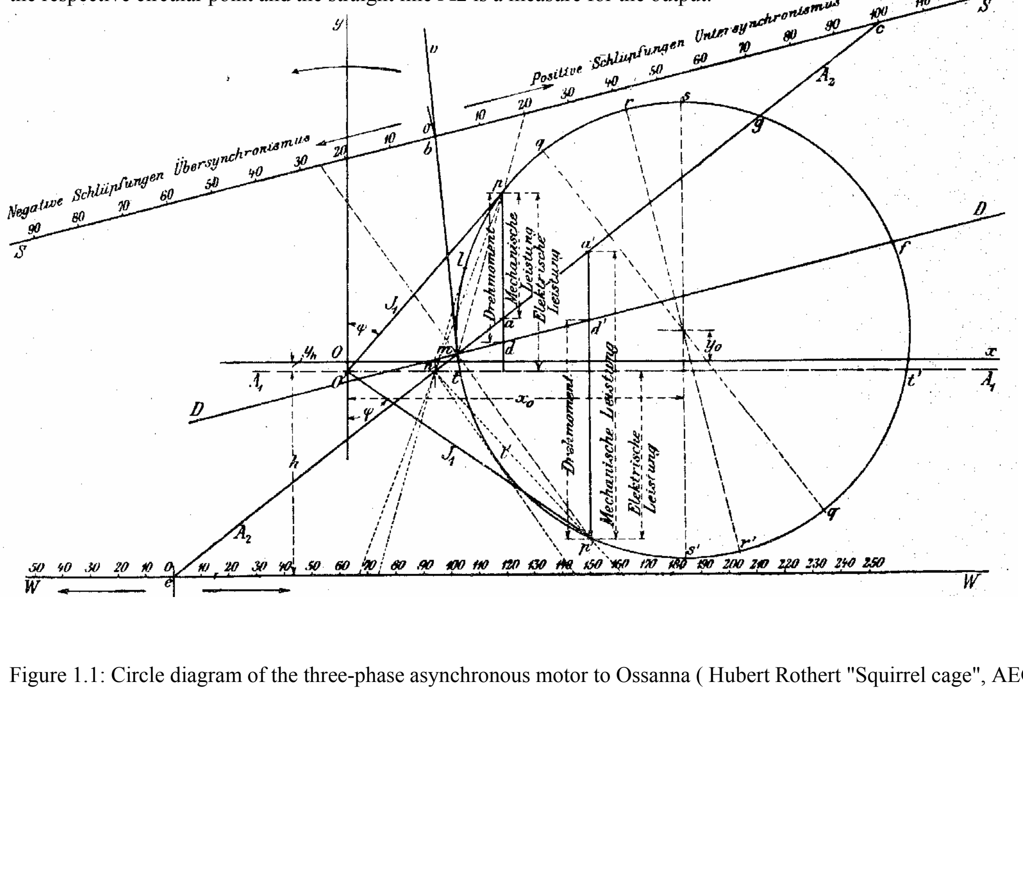

Figure 1.1: Circle diagram of the three-phase asynchronous motor to Ossanna (Hubert Rothert "Squirrel cage", AEG)

1.2 The asynchronous machine as generator

The asynchronous machine is known for more than 100 years. Experience showed that without any special measures the machine can supply electrical energy into the mains when it is driven mechanically beyond its no-load speed. Additionally it is known what to consider for the electrical design obtaining optimum results for generator operation as well.
However the use of asynchronous machines as generators could be found as strongly increasing recently. This depends on various factors, e.g.:

- As per the "Energieeinspeisegesetz" (EEG – Law that regulates feeding of renewable energy into the power supply system) anyone is allowed to supply electrical energy into the three-phase system. Also in case of small plants the power supplying companies are obliged to take the power at a firm price.
- Meanwhile our three-phase systems are linked to such an extent that there is the possibility of power supply even in remote areas.
- The supply systems are of such a high capacity that even for large-sized asynchronous generators the necessary reactive power (cf. 2.4.) is available and the mains connection (cf. 4) is mostly possible without special measures.
- The reliability and the simple control of asynchronous generators meet very much the tendency to an "Attendantless, full automatic small power plant". Plants between some kW and 1500 kW belong to this category today.
- The "Alternative Energy" is gaining more importance. Asynchronous generators are for instance also successfully used in wind power plants.
- When the machine is dimensioned adequately, e.g. accepting the surcharge for a copper cage in the rotor, the efficiency is very high, even at partial load operation (cf. 5.1) .
- There are practically no wear and maintenance parts except the bearings.
- Also special requests can be fulfilled without lot of expenditure: e.g. speed steps by conventional pole-changing, optimum yield of energy in the whole power range (cf. 5.3).
- The current status of inverter technology even offers the possibility of an infinitely variable speed.
- As coming near to the "standardized industrial motor" all constructional special requests being usual there (for instance a selection of the mountings, enclosures and cooling systems of the IEC series) are no problem and available by basic features from all leading manufacturers.

2 MOTOR AND GENERATOR OPERATION OF THE ASYNCHRONOUS MACHINE

2.1 The "not real" asynchronous generators

As already mentioned the asynchronous machine works as generator and supplies the electrical energy into the mains when driven beyond the no-load speed. It is steadily changed between motor and generator operation, e.g. at every pole-changing of an asynchronous motor from high to low speed.
[Figure 2.1]
In this case the kinectic energy of the drive train provides the energy input at the shaft. Immediately upon changing to low speed the machine develops a regenerative (brake) torque which is only fading when the low synchronous speed is reached. The corresponding braking power is fed into the supplying mains as electrical energy as long as it is not higher than the sum of the internal machine losses. This electrical braking does not cause any wear at all and thus possibly reduces the still existing mechanical braking. However in case of frequent braking or high-inertia load the heat loss occurring in the machine is to be considered for designing.

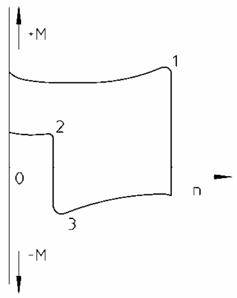

Figure 2.1: typical torque characteristics of a pole-changing asynchronous motor
1: high-speed motor operation, 2: low-speed motor operation, 3: regenerative braking by means of the low-speed winding upon changing from high to low speed.

2.2 The "real" asynchronous generators

These are the asynchronous machines which during their operating time are steadily or mostly running in generator operation. This is already worth-considering for the electrical design and thus to adjust the machine to optimum values in generator operation.

For instance the power factor of the asynchronous generator (compared to the synchronous machine) is load-dependant and that even stronger the lower the breakdown torque is.

Figure 2.2.1 shows the essential torque characteristic of an asynchronous machine, Figure 2.2.2 shows the power flux diagram for motor operation, Figure 2.2.3 shows the power flux for generator operation

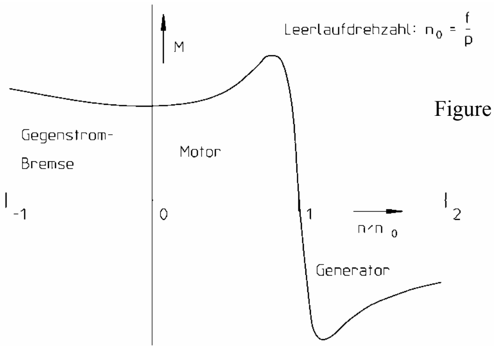

Figure 2.2.1: Typical M-n-characteristic asynchronous machine

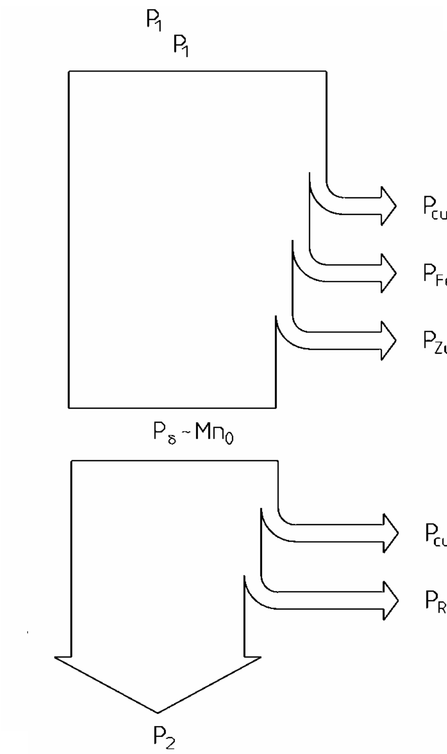

Figure 2.2.2: Power flux for motor operation

P1: Electrically fed (terminal)power

P2: Mechanical (shaft)output

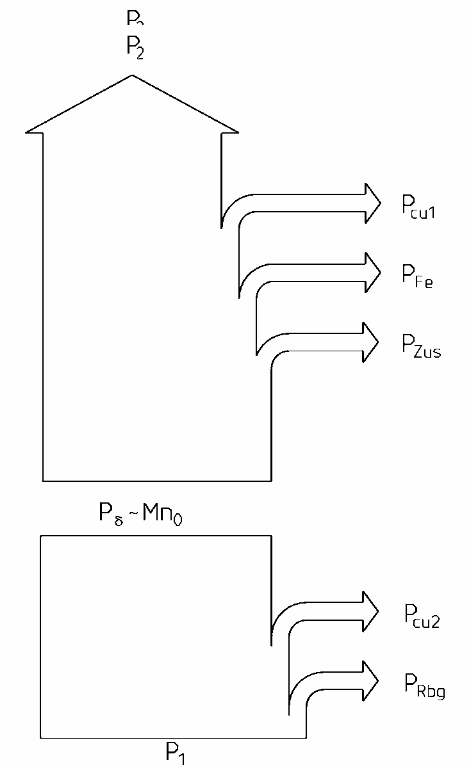

Figure 2.2.3: Power flux for generator operation

P1: Mechanically fed (shaft) input

P2: Electrical (terminal)power

P_{cu1}: Stator copper losses, P_{Fe}: Iron losses, P_{Zus}: Additional losses, P_{cu2}: Rotor copper losses, P_{Rbg}: Friction losses

(Dieter Seifert, Speed variation of asynchronous machines)

2.3 The asynchronous machine in generator operation

As already mentioned at the beginning one of the many advantages of the asynchronous machine is that it can be used as generator without any additional devices, which means an exciter or voltage controller, when it is operated at an existing rigid three-phase mains. As soon as on the machine shaft no torque is taken any more ("Motor") but fed without changing the direction of rotation, an active power flux is applied to the mains, when the fed mechanical power is higher than the machine losses shown in the power flux diagram [Figure 2.2.3]. The speed is over-synchronous, after the equalizing the slip is of a similar size like at motor operation with the same power, only with a negative sign:

$$s = (n_{syn} - n) / n_{syn}$$ (Motor operation: $n < n_{syn}$, $s > 0$
Generator operation: $n > n_{syn}$, $s < 0$)

$$n_{syn} = 120 f / 2 p$$

s = Slip, n_{syn} = Synchronous speed of the machine (1/min), n = Rated speed (1/min)
f = Frequency (Hz), $2 p$ = Number of poles

2.4 The required reactive power for the asynchronous machine

The asynchronous machine needs "reactive power" to build up the magnetic field. It is known that the reactive power is an apparent power not contributing to the direct energy conversion. The current associated with it, which means the reactive current, causes losses in supply and in the machine. The higher the reactive current content in the overall current is, the lower is the power factor „cosφ“.
As already mentioned in 2.2 the power factor can be optimized by an adequate machine design.
Since the asynchronous machine is not "excited" like the synchronous machine it takes the reactive power from the mains. This applies to both motor and generator operation.
Therefore generator operation of the asynchronous machine is NORMALLY NOT possible without the existing ("rigid") three-phase mains. In that case regulable reactive power sources would be required, for example a capacitor bank making available the reactive power for the generator and the load at the respective operating point.
Therefore an asynchronous machine can NOT SO EASILY be used e.g. as an EMERGENCY GENERATING UNIT ("Isolated operation"), also cf. 2.4.1.

2.4.1 Reactive power compensation and self-excitation

One of the few disadvantages of the asynchronous generator is that the required reactive power is to be taken from the mains.

This makes "phase shifting" like for the synchronous machine impossible. However a part of the required reactive power can be compensated by agreement with the power supplying company.

This is done by capacitors which are parallel connected to the motor or generator. It must be observed that the self-excitation limit might be exceeded: This means that the generator produces a voltage even at disconnected mains, it is to a certain extent running at "Isolated operation". This self-excitation process is explained in Figure 2.4.1.1.

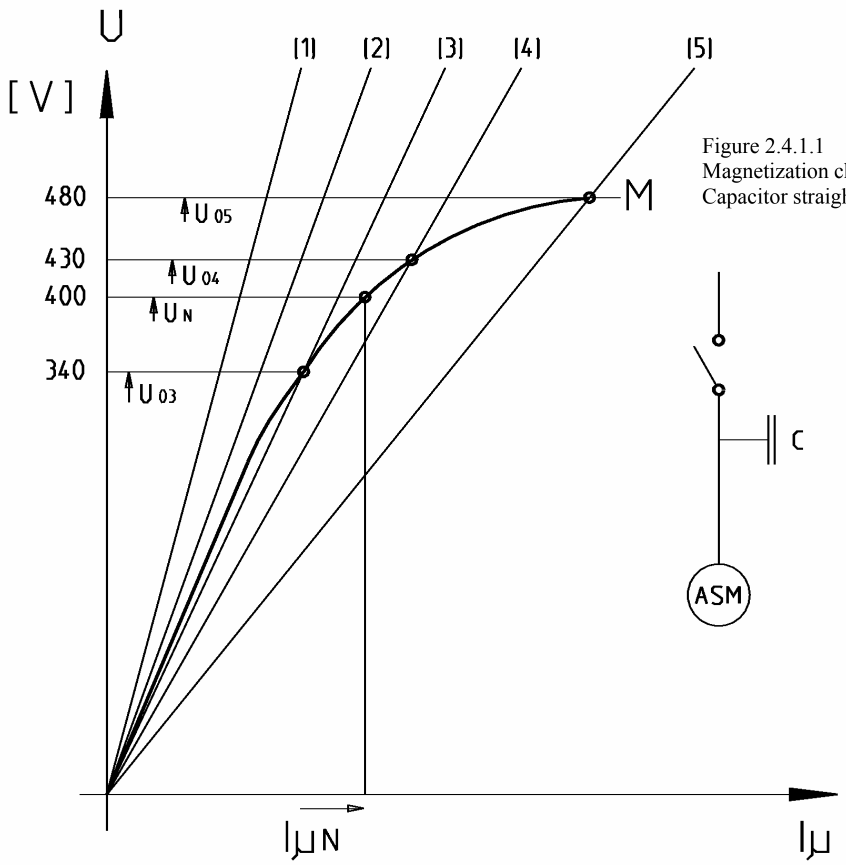

Figure 2.4.1.1
Magnetization characteristic M and Capacitor straight lines (1) – (5)

The magnetization characteristic M is obtained from the chart U= f (Iµ)

For U= U_N the magnetizing current $I_{\mu N}$ flows to cover the required magnetization.

The straight lines (1)- (5) show the so-called capacitor straight lines of the compensating capacitors for different capacitor sizes (capacities):

$Xc = 1/ (\omega \times C) = 1/ (6.28 \times f \times C)$

$Ic = U / Xc = U \times 6.28 \times f \times C$

Ic [A] = Capacitor current U [V] = (Terminal)voltage f [Hz] = Frequency

C [Farad] = Capacity of the capacitor bank

Self-excitation occurs when the capacitor straight line is intersecting the magnetization characteristic. This is not the case for the capacitor straight lines (1) and (2), but for (3), (4) and (5).

On the terminals of the unloaded asynchronous machine which is disconnected from the rigid mains the voltages U03 or U04 or U05 are to be measured as long as the capacitors (3), (4), (5) are parallel connected to it and the speed (frequency) is assumed as constant.
Without three-phase mains the speed and also the frequency are increasing at the generator terminals of the unloaded machine.
However at an increasing frequency the required magnetization of the asynchronous machine decreases and consequently also the magnetizing current, since the machine is quasi operated in the field-weakening range. This means that the magnetization characteristic M in Figure 2.4.1.1 inclines to the left, it is *ascending.*

On the other hand the capacitor straight lines incline to the right, are *descending*, because according to the above formula the capacitor reactance Xc decreases and consequently the capacitor current Ic increases.

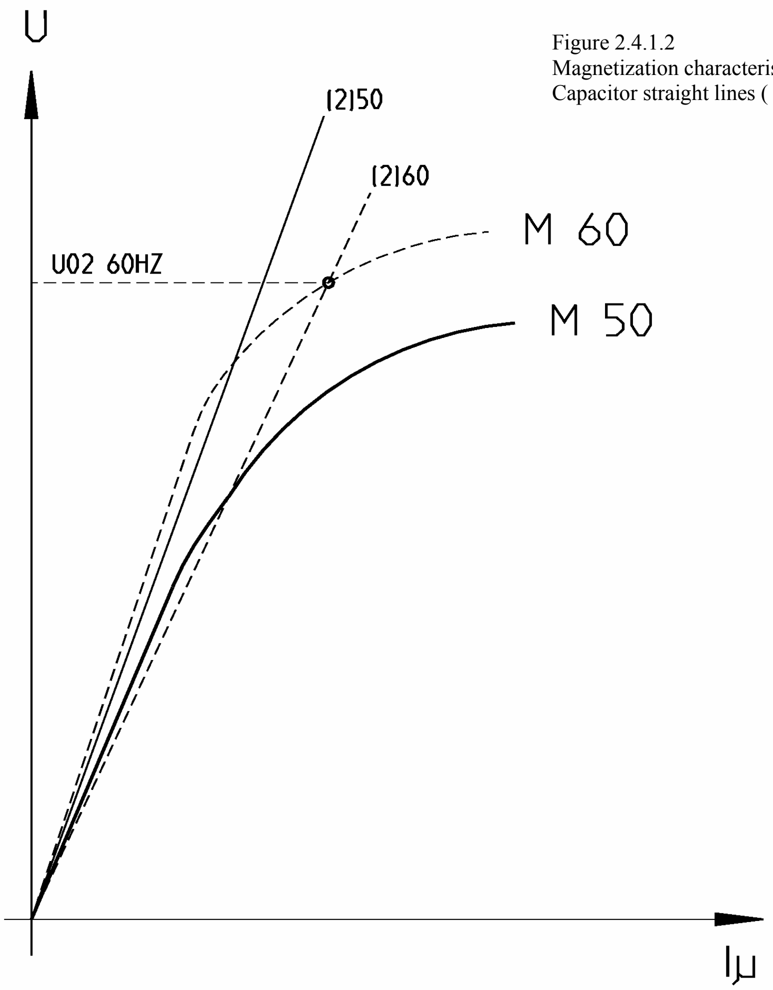

Figure 2.4.1.2
Magnetization characteristics M f. 50 and 60 Hz
Capacitor straight lines (2) for 50 and 60 Hz

Therefore it is possible that:

- at the increasing no-load speed a self-excitation occurs, even if the compensating capacitor is designed such that the self-excitation limit is not reached at rated operation.

In order to avoid possible damages compensated facilities are provided with additional protective devices:

e.g.: Frequency monitoring (today ± 1 Hz possible)
Voltage monitor
Phase displacement angle
Locking of the power switch with the compensating facility
Automatic compensating facility

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By practical experience a degree of compensation of about 0.9 times the no-load reactive power of the generator (manufacturer to be consulted) or a compensation to cos $\varphi \leq 0.96$ at rated operation have proven.
IN ANY CASE it is necessary to contact the competent power supplying company!

Calculation of the required compensating power Q is possible according to the following formula:
Q [kVar] = P GEN [kW] x (tan φ actual – tan φ specified)

e.g.: Generator power = 30 kW, cos φ actual = 0.84, cos φ specified = 0.96, U= 400 V, f= 50 Hz
cos φ actual = 0.84 ⇒ φ = 32.8° ⇒ tan φ actual = 0.646
cos φ specified= 0.96 ⇒ φ = 16.3° ⇒ tan φ specified= 0,292

Q = 30. (0.646 – 0.292) = 10.6 kVAr
Selected is a compensating facility of 12 kVAr, consisting of 3 single capacitors,
a' 4000 VAr (3-phase line !)

Usually it is not necessary to calculate the capacity of the capacitors and to consider a star or delta connection of the compensating capacitors since in practical application the compensating facility is offered as standard part to be purchased and only the generator voltage and the compensating power are to be indicated.

3 POWER FAILURE, REMANENCE AND RUNAWAY SPEED

In accordance with the preceding paragraphs the asynchronous generator normally requires the rigid mains. The mains frequency and the number of poles determine the synchronous speed of the generator (cf. 2.3).
In case of a power failure or power supply interruption the terminal voltage drops (except for the special case of wrongly compensated or wrongly installed equipment).
Only a remanent voltage of some % of the mains voltage is measurable.
No power is supplied by the asynchronous machine any more, only the friction losses are absorbed. The driving machine (turbine, combustion engine,...) and generator try to achieve the RUNAWAY SPEED which depends on the driving machine, on the regulating device as well as well as on the total moment of inertia.
Normally the admissible maximum speeds of asynchronous machines are of the following sizes:

Number of poles	Shaft height [mm]	Enclosure IP	n max. [1/min]
2,4,6,8	≤ 280	23 or 54	6000
2,4,6,8	315-355	23 or 54	4500

Contact the manufacturer for definite values.
In any case the squirrel cage makes the asynchronous machine also unproblematic as to the specific resistance.

In most of the facilities with asynchronous machines the machine unit is by means of the regulating device reset from the runaway speed to the approximate rated speed and kept running at no load until the mains voltage has been restored.

4 MAINS CONNECTION OF ASYNCHRONOUS GENERATORS

As it can be read in paragraph 2.1 even no special measures ought to be required for mains connection of the asynchronous machine. Theoretically it can be connected to the power supply everywhere from standstill to "any" speed. A correctly dimensioned asynchronous machine is pulling the complete machine unit into "synchronism" automatically.
A connection at standstill with non-pressurized turbine could be realized as follows:

4.1 Connection of the asynchronous machine to the power supply

The asynchronous machine starts and accelerates the turbine in motor operation up to almost the no-load speed.
The turbine is pressurized which causes a speed increase above the no-load speed. The energy flow reverses and supplies electric power into the mains.
When the rated torque is reached the rated data are finally set.
Since adequately dimensioned machines have the corresponding breakdown torque, the turbine cannot cause the asynchronous machine to become unstable, even at overloading (e.g. higher water availability):
It is almost acting like a spring converting the given (mechanical) shaft output into electric energy in a very wide range and without any regulation.
If the sudden torque changes occurring at the above mentioned simple connection cannot be accepted considering the coupling, gearbox etc. there are various possibilities for a smoother mains connection:

4.2 Connection at synchronous operation

If the turbine regulator keeps the machine unit operating at no load at the synchronous speed of the asynchronous generator the starting current and the impulse torque are lower than for the connection at non-synchronous speed.
Compared to the synchronous machine it is not necessary to consider the phase position.

4.3 Connection via electric soft starters or via starting transformers

Both devices are functioning according to the principle of a slow voltage rise in the generator winding.
The soft starter regulates the terminal voltage rise at an adjustable "rate" and thus allows a continuous "pulling into synchronism" of the already running machine unit or the motor-operated soft start.

4.4 Connection via starting resistors

The resistors connected in series to the stator winding are (e.g.) reduced step by step. In this way impulse torques and starting current impulses can mostly be avoided as well.

4.5 Star-delta-connection

It is known that the star-delta-starting reduces both the starting current and the starting torque to approx. 1/3 compared to direct starting. However it must be pointed out to the fact that at changing to the delta step a momentarily occurring impulse torque is possible which depending on the machine and the instant of switching can be at least as high as this one at direct starting.

4.6 Use of a frequency inverter

As regards the price of the inverter this solution is only chosen when the input speed must be variable at constant mains frequency. Or if it is e.g. so low that a high-speed generator which supplies into the mains via a frequency inverter is a better solution than the low-speed generator.
The advantage of a connection without current impulses results at inverter application automatically.

4.7 A useful combination from 4. 1 to 6.4 for the respective facility

5 EFFICIENCY AND PARTIAL LOAD CHARACTERISTICS

5.1 Design criteria

The efficiency is especially important for all those machines which are operated at a high cyclic duty factor. Additionally, a good partial load efficiency is essential for machines which are operated at partial load for a longer period.
There are not many machines combining real "continuous operation" and "varying shaft output" so perfectly like hydro-electric generators.
It will still be explained that a special design of the machine and accepting of a higher cost price will pay off soon.
It was mentioned in paragraph 2, that (almost) all asynchronous machines are generally suitable to be operated as generators. Thus it becomes above all for the standard motor range (IEC series up to frame size 315) a common practice to do without an own die set for the generators and only to adapt the winding, but sometimes also this is even not made.
Table 5.1 makes the differences clear

Table 5.1

Load point	$\frac{P_{zu}}{P_{zuN}}$	4/4	3/4	2/4	1/4	Unit
Mechanical power supply	P_{zu}	34	25,5	17	8,5	kW
Mechanical power output	P_{abGen1}	30,8	23,1	15,1	7,1	kW
	P_{abGen2}	31,0	23,3	15,3	7,2	kW
	P_{abGen3}	31,3	23,5	15,5	7,3	kW
Difference of the electric power	$P_{abGen3} - P_{abGen1}$	500	400	400	200	~~k~~W
Difference of the energy generated in one year	$W_{Gen3} - W_{Gen1}$	4400	3500	3500	1750	kWh

Gen1: Standard motor, data for generator operation
Gen2: Standard motor with special winding for generator operation
Gen3: For generator operation optimized asynchronous machine with improved sheet quality, special winding and copper cage.
For Table 5.1 an asynchronous machine acc. to CEMEP- Classification eff 2, which means an upgraded industrial motor standard for 30 kW with $\eta \geq 91.4$ %, was taken as basis.

All of the three machines are driven at the same shaft output and speed.

Loher’s asynchronous generators are available from the standard range, which means up to frame size 315, in two series:

- Unchanged die set, but without exception special winding.
- Special die set, copper cage in the rotor and special winding

From frame size 315 only copper rotors and special winding will be used.

EVERY FURTHER PERCENT IN EFFICIENCY RESULTS IN A HIGHER YIELD AND THUS IN READY CASH.
The extra costs for special measures will mostly pay off within a short time: The extra costs for Generator 3 compared to Generator 1 from Table 5.1 amortized e.g. in 1 to 1 ½ year.

Since most time of the year the water flow to the power plant is below the designed water volume the generators are mostly operated below their rated output and therefore the partial load efficiency should always be considered as well. Loher's generators are designed such that the efficiency at ¾ load is of a comparable height like the efficiency at full load or even higher.

In principle less importance should therefore be attached to the cost price than to the service life-specific cost-benefit accounting!

Special rotor with copper cage for efficiency increase

5.2 Efficiency and power factor

Paragraph 2.4 refers to the reactive power compensation. The higher the reactive power component is, the larger and more expensive is the compensating facility to reduce the mains-specific reactive power component. Emphasis is put on "mains-specific". In the machine itself nothing will change by the (external) parallel connection of the capacitors. The reactive power required by it remains unaffected.
The higher the reactive power component at a specified operating point in the machine is, the higher will be the machine current. However a higher machine current means higher losses. For this reason the power factor "cos φ" is also a criterion for the machine quality. Especially in partial load operation the usual decrease of the power factor can lead to a relative deterioration of the loss balance. In particular cases where generators are used in extreme partial load operation for longer periods there are improvement measures of the manufacturer available, see 5.3

5.3 Long-time operation at small partial load

In some cases it pays to realize the generators with power-changing stator winding. This results at a great extent in better matching of the required magnetization, which means the reactive power of the machine to the actually required active power.

Loher uses for such special requests besides the so-called "combined connections" very often the "good old star-delta connection" with great success.

An example is a hydro-electric plant in the Allgäu (region in Germany): Based on the water flow data there is a half-year operation with up to max. 30 kW. During the other half of the year the turbine produces up to 120 kW, always at 750 1/min.

The problem was solved with a multi-jet Pelton turbine and an asynchronous generator the stator winding of which is "star" or "delta"-connected. The star connection covers the range between 20 and 40 kW, the delta connection between 35 and 130 kW.

Changing is made manually or automatically via the power measurement.

An **8-pole** generator was built the efficiency of which between 20 and 130 kW in the entire output range is **not below 93%** (optimum 95%), and with a power factor in the entire range **not below 0.7**
(optimum 0.8).

6 MEASURED VALUES AND TYPE TEST

All prototypes are subject to an acceptance test at Loher. The test includes the measurement of the most important partial load points (5/4, 4/4, 3/4, 2/4, 1/4) in generator operation. All specified data must be within the tolerance range of the IEC/ VDE. Furthermore a heat run is made at rated operation (4/4- load). The generator winding is in insulation class F, thermal utilization to B (exceptions are marked).

Every following machine is at least subject to a no-load measurement. Resistance measurement and continuous quality inspection during production are obligatory.

7 SUMMARY

For smaller up to medium-sized (hydro-electric) power plants in the output range from 3 kW to 1500 kW the asynchronous generators are simple and low-cost energy producers.
Loher profits by the decades of experience in electrical engineering to consider the special features of generator operation already in the planning phase and thus to assure optimum results.
By various special measures the parameters of the generators, e.g. efficiency and power factor can be increased beyond the already favourable original values.
Loher asynchronous generators are available for all turbine systems like e.g. in hydro-electric and wind power plants ("Winergy").

Loher asynchronous generators cover the outputs from some kW up to the MW-range.

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Ruhstorf, in March 2004