Carl von Ossietzky Universität Oldenburg

PPRE

8 — Synchronous Machines

a primer in

Electric Power Systems

Chapter 8 of 8

Learning Objectives

After processing this chapter you will be able to

- describe how a synchronous machine is built;
- list the conditions to connect a generator to a grid;
- recall how to start a synchronous motor;
- paraphrase the power and torque characteristics;
- review how power factor can be controlled;
- compute an SM drive being used additionally for power factor compensation.

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Synchronous machines rotate at a constant synchronous speed in steady state. Unlike induction machines, the rotating stator field and the rotor rotate at the same speed. They are primarily used as generators in all kind of power stations. Like most rotating machines, the synchronous machine can operate as both a generator and a motor. An important feature of a synchronous machine is its ability to draw/supply either lagging or leading reactive current from/to the AC power system. Without such a feature any varying reactive power consumption would impact the constancy of a generated voltage. How the reactive power supply can be adjusted within the synchronous generator will be shown in this chapter.

8.1 Construction

The stator of a synchronous machine carries a set of 3-phase distributed windings similar to that of an induction machine. The number of poles varies as well. The stator windings (also called armature windings) are connected to the AC supply. The rotor carries the field winding which is fed from an external DC source through slip rings and brushes (Fig. 8.1).

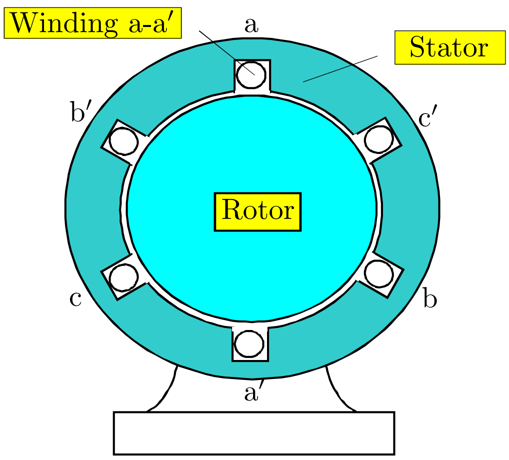

Figure 8.1: Construction of a synchronous machine

The design of synchronous generators varies tremendously depending from the rotor speed. The turbines of a hydro power station rotate comparatively slowly, in contrary to those of a thermal power station where the high speed of the rotor requires distributed masses around the rotor surface, therefore the rotors have different shapes.

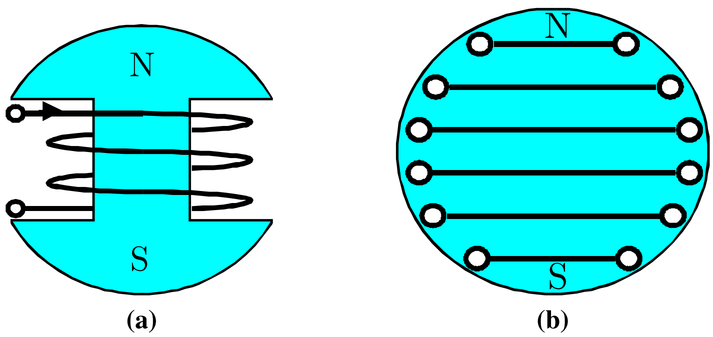

Figure 8.2: **(a)** Rotor with salient pole for low speed machines. **(b)** Rotor with cylindrical or non-salient pole for high speed machines

8.2 Synchronous Generators

The rotor of the synchronous generator is moved by a prime mover (turbine, diesel engine, DC motor, wind drive). The current through the field winding I_f produces a so-called **excitation field**, its flux rotates in the air gap. This rotating flux induces a voltage in the three stator windings called **excitation voltages** E_f which are phase-shifted by 120° electrically (Fig. 8.3).

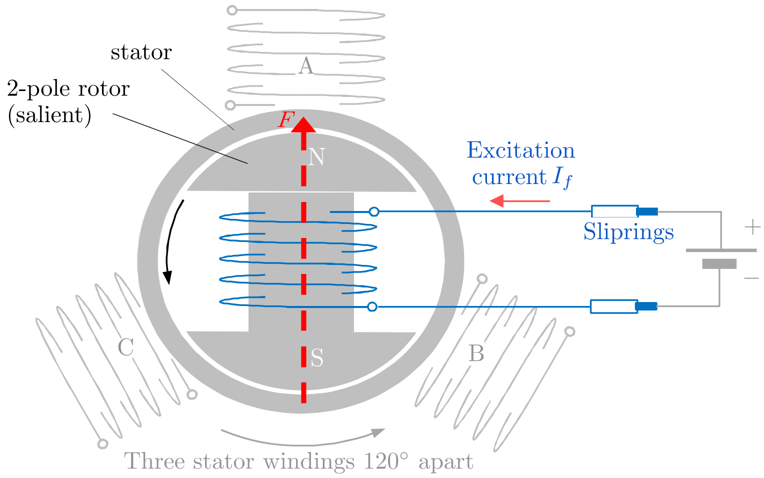

Figure 8.3: The turning rotor produces a rotating excitation field

The rotor speed and the frequency of the induced voltages are related by:

$$n = \frac{120 \cdot f}{p} \tag{8.1}$$

$$f = \frac{n \cdot p}{120} \tag{8.2}$$

where n: rotor speed [rpm]
f: frequency of the 3P stator current [Hz]
p: number of poles {2, 4, 6, 8, ...}

8.3 Infinite Bus (or Grid)

Synchronous generators are applied individually, but mainly they are connected to a power supply system called infinite bus or grid (Fig. 8.4). Due to the large number of generators connected, voltage and frequency of the grid hardly change. Transmission of energy is at higher voltage levels to achieve a better efficiency.

The operation of connecting a synchronous generator to the infinite bus is known as **paralleling with the infinite bus**. Before this connection can be performed, both the generator and the infinite bus must have the same:

1. voltage.
2. frequency.

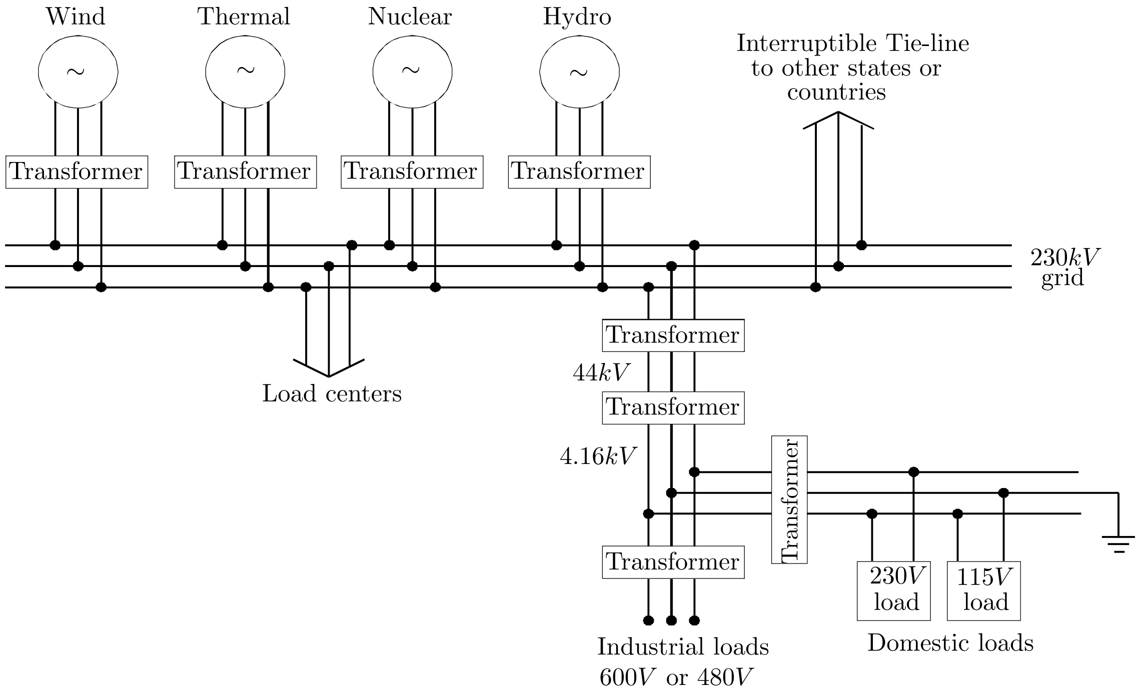

Figure 8.4: Typical infinite bus system (North America)

3. phase sequence.
4. phase angle.

In power plants these conditions are checked by a so-called **synchroscope**. In practice a set of **synchronizing lamps** may be sufficient. Deviating from any of the above mentioned conditions the lamps will glow (or flicker) anyway. The connecting circuit breaker should not be closed before all lamps are dark permanently (Fig. 8.5).

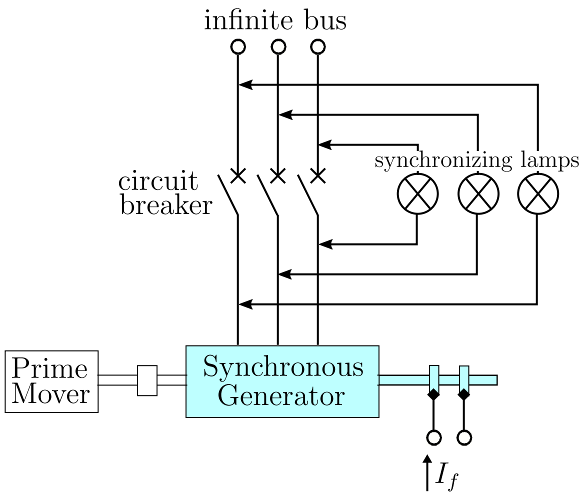

Figure 8.5: Paralleling of a synchronous generator with the infinite bus

After the connection the speed of the generator cannot be changed further. However, the real power transfer from the generator to the infinite bus can be controlled by adjusting the prime mover. Even the controlling of the reactive power (i.e. the machine PF) is possible by adjusting the field current as we will see later.

8.4 Synchronous Motors

When a synchronous machine is used as a motor, it is not able to self-start as induction and DC machines do. If the rotor field is excited by a DC current and the stator terminals are connected to the AC supply, the motor will only vibrate but not start. The stator field is rotating so fast that the rotor poles cannot catch up or lock onto it, in contrary to an induction machine where the rotor field moves with synchronous speed with respect to the stator, i.e. with the same speed as the stator field does. There are two commonly used methods to start a synchronous motor:

Start with Variable-Frequency Supply

The frequency converter starts with a low frequency allowing the poles of the rotor to follow. Afterward it is gradually increased to the synchronous speed. Those converters are expensive and so this method is mostly applied where the synchronous motor has to run at variable speed (Fig. 8.6).

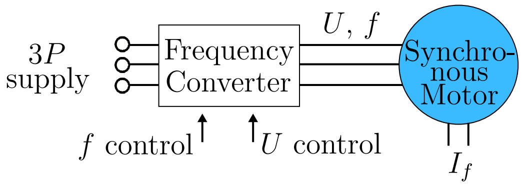

Figure 8.6: Starting of a synchronous motor by a variable frequency supply

Start as an Induction Motor

The rotor of the synchronous motor carries an additional winding, which resembles the cage of an induction motor, known as **damper** or **amortisseur winding** (Fig. 8.7). To start the motor the regular field winding is left unexcited (often just shunted by a resistor). The stator windings connected to the AC source accelerate the rotor until approaching the synchronous speed. Now if the field winding is excited by a DC source, the rotor poles, closely to the speed of the stator poles, will be locked to them. The rotor will then run at synchronous speed.

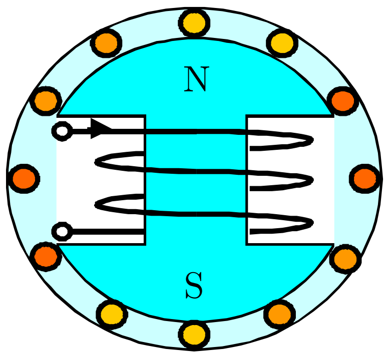

Figure 8.7: Squirrel cage damper winding on the rotor of a synchronous machine

At synchronous speed no current will be induced in the damper winding. Nevertheless, if the speed differs from the synchronous speed because of sudden load changes, a current will be induced in the damper winding to produce a torque to restore the synchronous speed. This restorative torque gives the name "damper". This effect may also be used in generators (carrying an apparently useless damper winding because it is not needed for start) to damp out transient oscillations!

8.5 Power and Torque Characteristic

A synchronous machine is normally connected to a fixed-voltage bus system. It operates at constant speed. There is a limit on the power a generator can deliver to the infinite bus and on the torque applied to a motor without losing synchronism. In the per-phase equivalent circuit (Fig. 8.8), the constant bus voltage U_1 (or terminal voltage) is considered as the reference phasor (Eq. 8.3). The excitation voltage E_f is phase-shifted against U_1 by the power angle δ (Eq. 8.4) and the impedance is dominated by the synchronous reactance X_s (Eq. 8.5). The stator resistance is negligible.

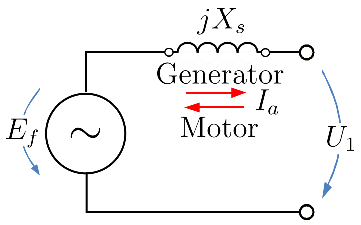

Figure 8.8: Per phase equivalent circuit

$$\underline{U}_1 = U_1 \angle 0^\circ \tag{8.3}$$
$$\underline{E}_f = E_f \angle \delta \tag{8.4}$$
$$\underline{Z}_s = jX_s = X_s \angle 90^\circ \tag{8.5}$$

where
- U_1: terminal voltage (stator) [V]
- E_f: excitation voltage induced by the rotor field [V]
- Z_s: synchronous impedance [Ω]
- X_s: synchronous reactance [Ω]
- δ: power or torque angle (between E_f and U_1)

Solitary Generator

In a solitary application of a synchronous generator (Fig. 8.9a), the phase displacement φ of the armature current is determined by the power factor of the load Z. If the excitation current in the rotor is increased, the generated voltage increases to E'_f which causes a larger terminal voltage U'_1 and more current (I'_a), but phase and load angles remain the same (Fig. 8.9b).

In such an isolated system the stabilizing conditions of a grid, where frequency and voltage remain constant, are not available. The negative consequence is that the terminal voltage tends to change with varying load. This dependency is demonstrated in Figure 8.10, for which the field current (i.e. the excitation voltage E_f) is held constant. To maintain a constant terminal voltage in case of varying load parameters (I_a/I_{aRated} and/or $\cos(\varphi)$), it is necessary to sense permanently the terminal voltage and consequently to adjust the field current appropriately. In practice such a control job is done by an automatic voltage regulator.

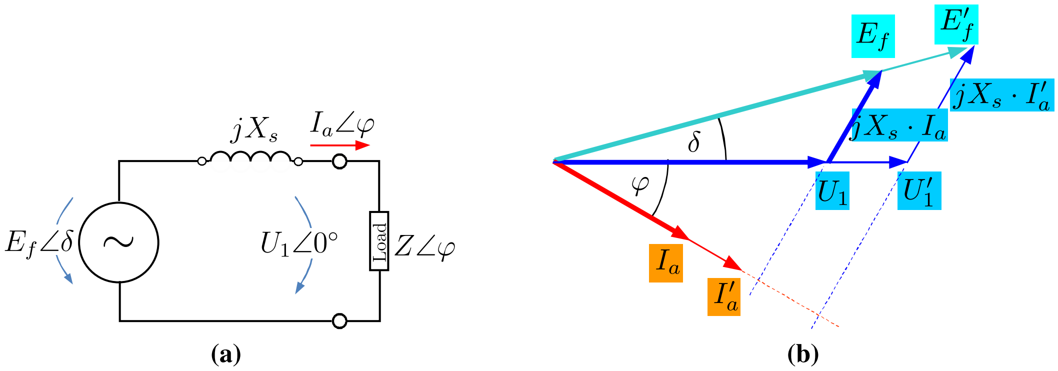

Figure 8.9: **(a)** Isolated SM generator. **(b)** Phasor diagram of a solitary generator with different excitation voltages

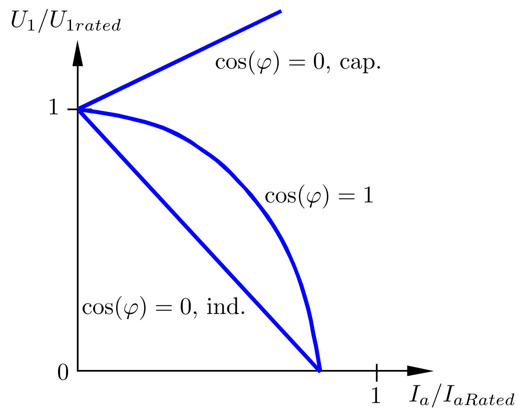

Figure 8.10: Output voltage of a solitary synchronous generator at constant field current but varying load

Utility Case

After having accomplished the paralleling with the infinite bus (see section 8.3) the terminal voltage and frequency of a generator is determined by the grid (Fig. 8.11a). The amount of electric power (real power!) for a 3P synchronous generator (Fig. 8.11b) supplied to the grid is given by the following equation:

$$P = 3 \cdot U_1 \cdot I_a \cdot \cos(\varphi) = 3 \cdot U_1 \cdot I_a \cdot \frac{E_f \cdot \sin(\delta)}{X_s \cdot I_a} = \frac{3 \cdot U_1 \cdot E_f}{X_s} \cdot \sin(\delta) \tag{8.6}$$

If the stator losses are neglected, the power developed at the terminals is also the air gap power, i.e. the power developed by the prime mover (turbine, diesel engine etc.) driving the generator (Fig. 8.12a). Then the mechanical torque is:

$$T = \frac{P}{\omega_s} = \frac{3 \cdot U_1 \cdot E_f}{\omega_s \cdot X_s} \cdot \sin(\delta) \tag{8.7}$$

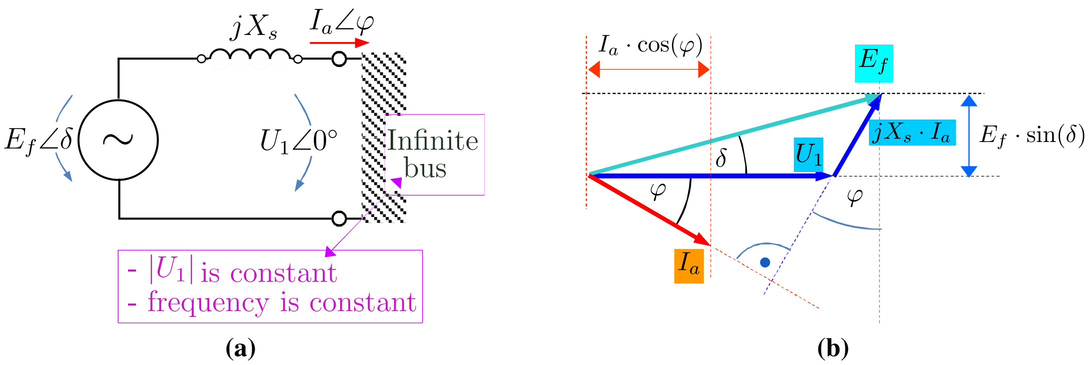

Figure 8.11: **(a)** Synchronous generator connected to a grid (utility). **(b)** Phasor diagram showing the parameters for the real power calculation

where P: (el.) power of the machine [W]
T: mechanical torque [N m]
ω_s: synchr. angular frequency [s^{-1}]
δ: power or torque angle

In contrary to the sometimes very strange torque-speed characteristics of the machine types discussed previously that of the synchronous machine is represented by a simple straight line (Fig. 8.12b). The fact that this curve is far away from the zero-speed reveals the inability to start "naturally" (see section 8.4).

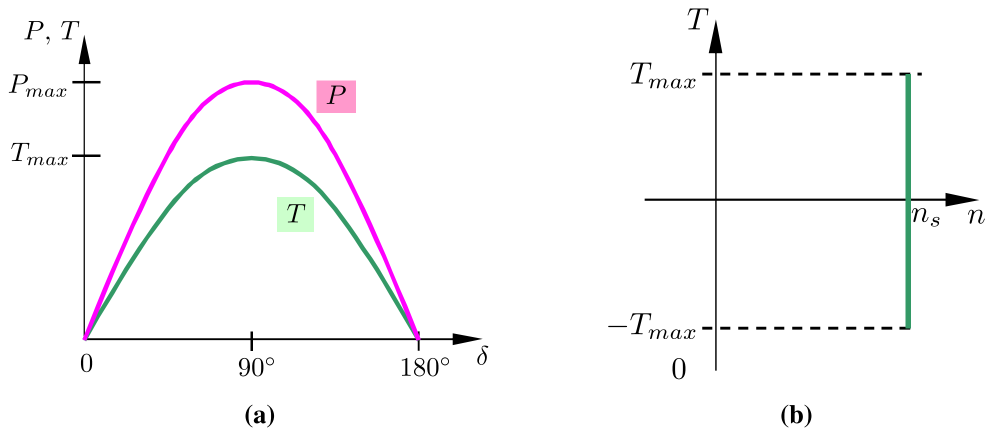

Figure 8.12: **(a)** Power and torque angle characteristics. **(b)** Torque-speed characteristics

8.6 Power Factor Control

An exclusive advantage of the synchronous machine is that its power factor can be **controlled as being lagging or leading** by varying the field current.

This behaviour can be explained by means of the phasor diagrams of machine voltages and currents. Assume a synchronous generator connected to an infinite bus is operating with constant real power visualized by the loci in Figure 8.13. For a 3-phase machine the real power transfer is:

$$P = 3 \cdot U_1 \cdot I_a \cdot \cos(\varphi) \tag{8.8}$$

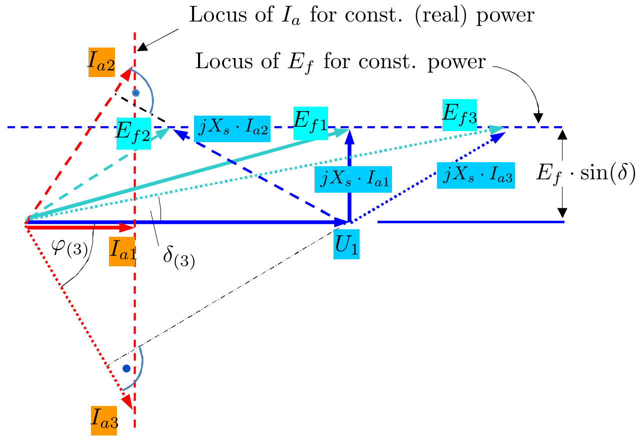

Figure 8.13: phasor diagram for different power factors

For U_1=const follows $I_a \cdot \cos(\varphi)$=const , i.e. the in-phase component (or real part) of the stator current on the U_1 axis is constant (see phasor diagram Figure 8.13). The diagram shows 3 different situations:

1. $I_a = I_{a1}$ in phase with U_1
2. $I_a = I_{a2}$ leading U_1
3. $I_a = I_{a3}$ lagging U_1

The relationship of the voltage phasors for a generator is as follows:

$$\underline{E}_f = \underline{U}_1 + jX_s \cdot \underline{I}_a \tag{8.9}$$

The excitation voltage E_f changes linearly with the field current I_f. Therefore, as I_f is changed, E_f will change along the locus of E_f and I_a will follow along its proper locus thus leading to a change of the power factor. The variation of the stator current with the field current for constant-power operation of a synchronous motor is shown in the so-called **V-curves** in Figure 8.14. It is valid also for generators but with reverse signs.

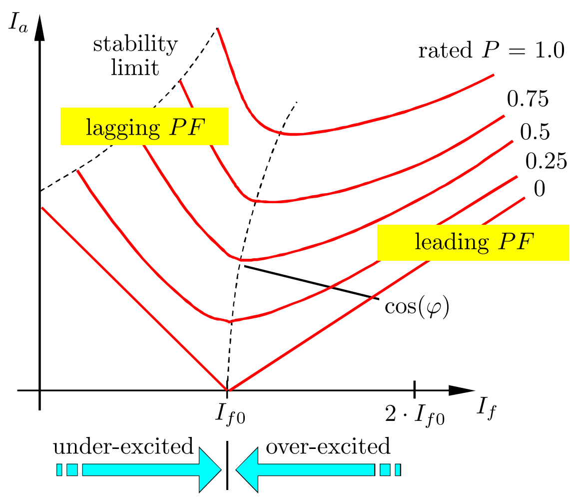

Figure 8.14: V-curves for a synchronous motor at different real power loads

This unique feature of power factor control by the field current can be utilized to improve the power factor of a plant as demonstrated in the next example.

Example 8.1

In a factory a 3-phase, 4 kV, 400 kVA, synchronous machine is installed along with other induction motors. The SM is used as motor. The loads of them all are:
Induction motors: 500 kVA at 0.8 *PF lagging*.
Synchronous motor: 300 kVA at 1.0 *PF*.

(a) Calculate the overall power factor of the factory loads.

$$\underline{S}_F = \underline{S}_{IM} + \underline{S}_{SM} = S_{IM}\angle \arccos(PF_{IM}) + S_{SM}\angle \arccos(PF_{SM})$$
$$\underline{S}_F = 500\angle \arccos(0.8) + 300\angle \arccos(1.0) = 500\angle 36.9^\circ + 300\angle 0^\circ$$
$$\underline{S}_F = 761.6\,\text{kVA}\angle 23.2^\circ$$
$$PF_F = \cos(23.2^\circ) = 0.92\,\textit{(lagging)}$$

(b) To improve the factory *PF* the synchronous machine will be over-excited (to draw leading current) without any change in its real load (Fig. 8.15). To what extent can the *PF* of the factory be improved?
(Approach: the rated power of the SM is higher than the actually connected mechanical load. So, there is a reserve of power which shall be used for compensation!)
Remark: synchronous machines (similar to transformers) are always rated by apparent power with $S = 3 \cdot U_{ph} \cdot I_{ph}$. Its design limits are given by the maximum current per phase! The final power factor doesn't matter.
The semicircle in the figure above shows all operational points for the rated apparent power phasor of the SM ($S_{SM_{max}} = 400$). Under the given real power load the possible S phasors are limited to the locus of the real power ($P = 300$). The position of phasor $\underline{S}_{SM\#}$ reflects the maximum leading reactive power consumption. It is calculated as follows:

$$\underline{S}_{SM\#} = S_{SM_{max}}\angle\varphi_{SM\#} = S_{SM_{max}}\angle \arccos(\frac{P_{SM}}{S_{SM\#}}) = 400\angle \arccos(\frac{300}{400})$$
$$\underline{S}_{SM\#} = 400\,\text{kVA}\angle 41.4^\circ$$

In order to generate leading reactive power the given angle is adjusted to a negative value as shown in the figure above and the new apparent power is given as:

$$\underline{S}_{SM} = 400\,\text{kVA}\angle -41.4^\circ$$

Now the new overall power consumption of the factory is given by:

$$\underline{S}_F = \underline{S}_{IM} + \underline{S}_{SM} = 500\angle 36.9^\circ + 400\angle - 41.4^\circ$$
$$\underline{S}_F = 700.9\,\text{kVA}\angle 2.9^\circ$$

... at a power factor of:

$$PF_F = \cos(\varphi_F) = \cos(2.9^\circ) = 0.99\,\textit{(lagging)}$$

(c) Determine the amount of current (i.e. the line current) of the synchronous motor.

$$I_{SM} = \frac{S_{SM}}{\sqrt{3}\cdot U} = \frac{400\,\text{kVA}}{\sqrt{3}\cdot 4\,\text{kV}} = 57.74\,\text{A}$$

Determine the new PF of the synchronous machine.

$$PF_{SM} = \cos(\varphi_{SM}) = \cos(-41.4^\circ) = 0.75\,\textit{(leading)}$$

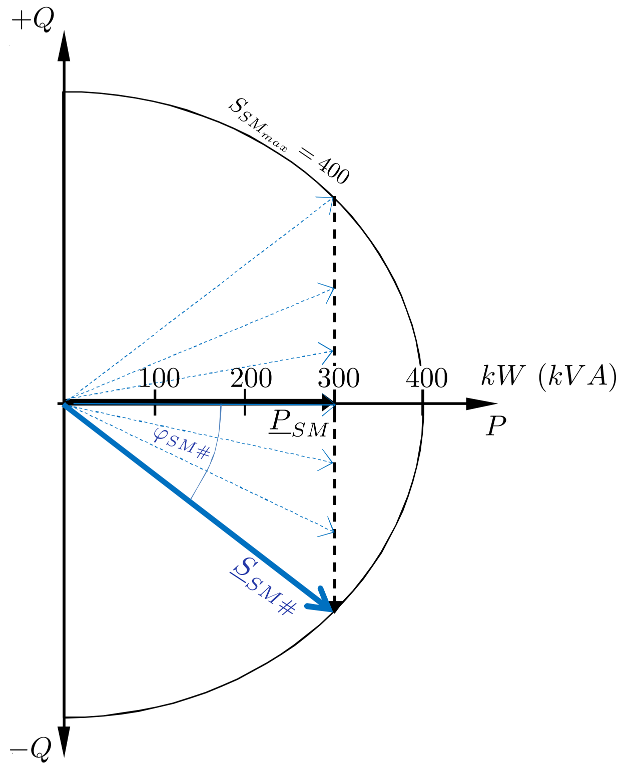

Figure 8.15: Phasor diagram for the "improved" power (apparent, real and reactive) of the SM (Example 8.1)