Stanisław Gawron

Starting of Synchronous Motors

Abstract: The starting of synchronous motors can be asynchronous or frequency or by using an additional motor. The choice of the starting method requires detailed knowledge related to starting conditions, i.e. load torque during the start and the short-circuit power of the power grid at the motor power supply point. The aforementioned condition is essential to the correct design of the starting system. The article discusses the three above-named starting methods.

Key words: synchronous motor, starting

DOI: 10.32730/mswt.2024.68.5.7

1. Introduction

Synchronous motors are used in drive systems of high-power machinery operating continuously at a constant rotational rate [3]. The advantages of synchronous motors are the following:

- operation with capacitive power factor *cosφ* and the compensation of inductive reactive power compensation, which, in terms of a large number of induction motors in a company, constitutes a significant advantage,
- higher efficiency than that of induction motors.

Synchronous motors are used to drive various types of turbine compressors in technological lines tasked with the production of gases (nitrogen, oxygen, argon, hydrogen), in mine ventilation shafts and other applications.

A difficult moment in the operation of synchronous motors is the start. The starting of synchronous motors can be carried out using one of the methods presented below [3, 8]:

- asynchronous start – motor is connected to the grid directly or through a choking coil,
- frequency start – motor is powered by a frequency-adjustable inverter; at synchronous speed, the motor is synchronised with the grid voltage,
- start involving the use of an additional induction motor coupled to a synchronous motor; at sub-synchronous speed, the motor is synchronised with the grid voltage.

2. Asynchronous start

The asynchronous start requires the satisfaction of the following conditions:

- in terms of its design, the motor must be prepared to generate asynchronous torque,
- power grid at the motor connection point must be characterised by appropriate short-circuit power so that the starting current does not decrease the voltage of the grid below the permissible value, affecting other grid users $U \geq 0.9U_N$ [1].

The article only discusses the motor. In order to start, the motor must generate an asynchronous torque, whereas electrodynamic forces generated by the starting current must not damage the winding [6, 7].

Asynchronous torque T_a is determined by the power of the rotating magnetic field $P\psi$, penetrating the rotor from the gap:

$$T_a = p\frac{P_\psi}{\omega_1}$$

where: p is the number of pole pairs and $\omega_1 = 314$ 1/s is the pulsation of grid voltage.

The rotor must have closed electric circuits in which the rotating magnetic flux induces currents.

The required condition is satisfied using the two methods presented below.

1. The rotor is cylindrical, the core is made of electrotechnical metal sheets. The package of the sheets has double slots, some of which contain the excitation winding, whereas the other ones have a squirrel-cage winding (Fig. 1a), the same as in asynchronous motors.
2. Another variant of the solution involves the use of the salient-pole rotor (Fig. 1b). The core is made of solid steel, excitation winding is located on the pole bodies and the poles are covered with solid steel pole pieces, bolted to the pole bodies. The pole pieces have two functions, i.e. they protect the winding against the action of centrifugal force and enable the generation of asynchronous torque. During the start of the motor, in the pole pieces, the magnetic flux induces current flowing in the circuit between the poles through the pole bodies and the shaft.

The current in the stator winding during start is $I_R \approx 7I_N$, whereas its surge value can reach $I_u \approx 12I_N$. Electrodynamic forces (alternating with a frequency of 100 Hz) affecting the stator winding are proportional to the square of current, which means that they can be more than 100 times greater than forces affecting the winding during steady operation, (at rated current I_N). The stator winding is at risk of being damaged by the above-named forces, at the point where the winding exits the slots (Fig. 2a). The winding faces must be appropriately fixed so that they do not vibrate during the start. In turn, the insulation of the turns at the exit from the slots must be suitably reinforced so that it does not crack during micro-vibrations of the winding faces (Fig. 2b). During motor operation, the winding heats up and must be able to expand so that thermal stresses are not generated in the turns [4, 5].

dr inż. Stanisław Gawron – Łukasiewicz – Upper-Silesian Institute of Technology
Corresponding author: stanislaw.gawron@git.lukasiewicz.gov.pl

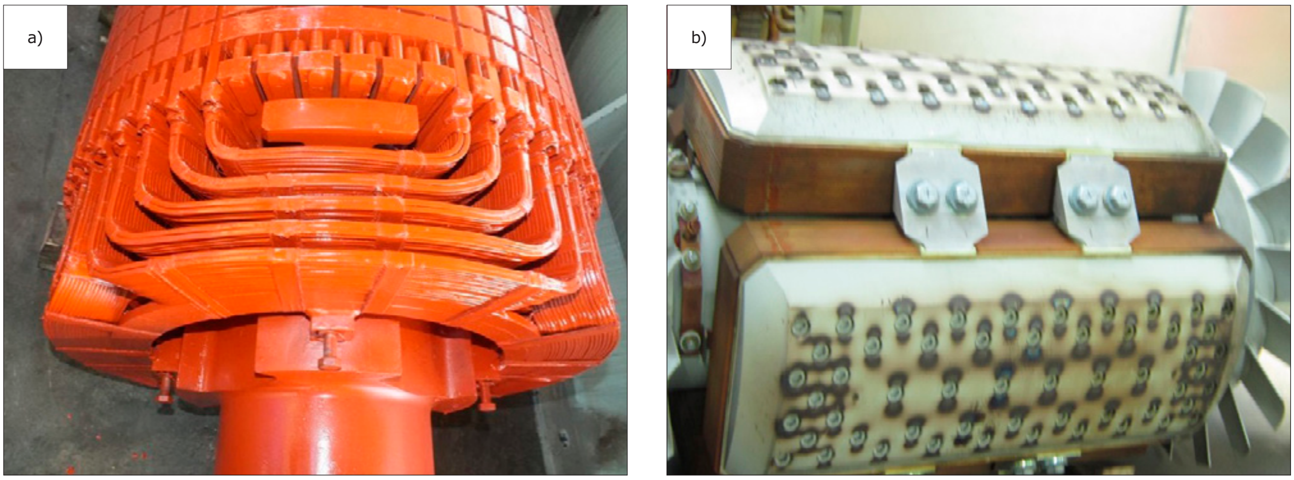

Fig. 1. Rotor of synchronous motor: a) cylindrical and b) salient pole

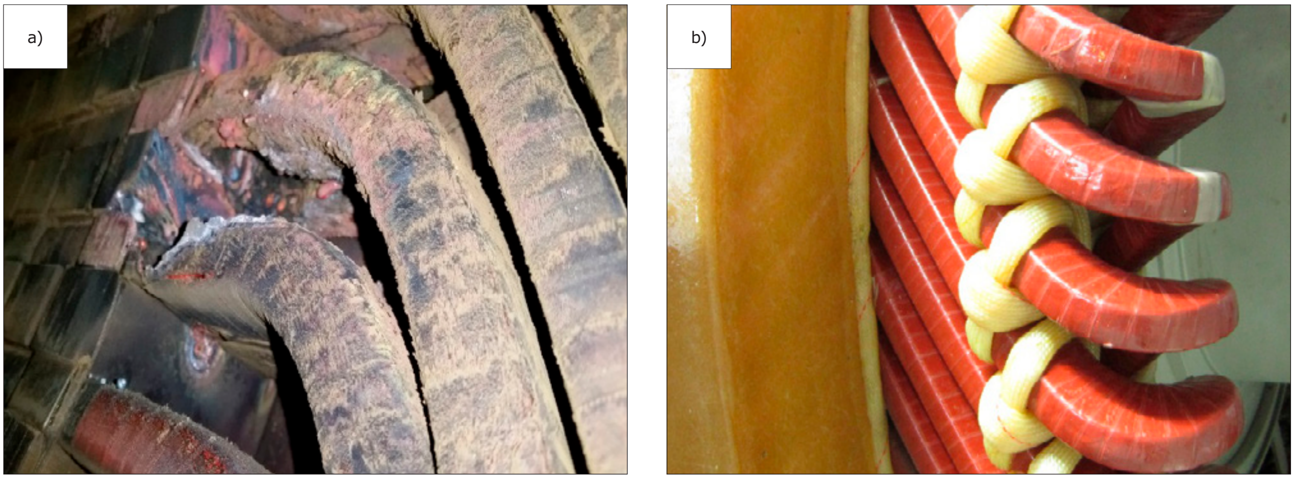

Fig. 2 Exit of the stator winding turns from the slots: a) winding damage and b) winding after replacement (new)

3. Frequency start

The soft start of the synchronous motor can be performed by supplying the motor with a voltage of adjustable frequency. The design of a frequency converter is based on an AC/DC/AC. The adjustment range of voltage is $U = (0.1 \div 1)\ U_N$, whereas of frequency is $f = (3 \div 50)$ Hz, ratio $\frac{E}{f} \approx \frac{U}{f} \approx \frac{U_N}{f_N}$ is constant, where: E denotes rotation voltage and f denotes frequency. The diagram of the motor supply system is presented in Fig. 3.

The start of motor M requires the performance of the following activities:

- starting motor excitation,
- using switch W1 to connect the AC/DC/AC to power grid $U1$,
- using switch W2 to connect inverter 1 with busbars $U2$ and setting voltage of minimum frequency f_{min} on inverter 1,
- using switch W4 to connect motor M to the inverter, the synchronising torque will automatically set the rotor into synchronous rotation

$$n_{\min} = 60\frac{f_{\min}}{p}$$

- continuous increase in frequency and voltage will make the motor reach the synchronous rotational rate

$$n_s = 60\frac{50}{p} = \frac{3000}{p}\ \frac{\text{obr}}{\text{min}}$$

- motor synchronises with power grid $U1$ by correcting the inverter frequency, the synchroniser should be built-in into the inverter,
- when frequency and voltage phases become compatible, switch W3 switch turns on, whereas switch W4 turns off, marking the end of the starting procedure.

If a given plant is in possession of several synchronous motors, they can be started using one inverter.

4. Start with an additional motor

A combined heat and power plant (CHP) was equipped with 2 synchronous generators having a rated active power of 12 MW (apparent power of 15 MVA) and that of 6.4 MW (apparent power of 8 MVA), a rated voltage of 6.3 kV and a rotational rate of 3000 rpm. The above-named plant was in liquidation. Related test results led to the conclusion that the above-named machines could be used as electric motors [2], yet it was necessary to solve a problem connected with their start. The machines had two shaft terminals, i.e. a driving terminal and a terminal for connecting the exciter. The motor exciters were static in terms of power electronics. The shaft terminal to the exciter was used to couple the squirrel-cage induction motor, used to start

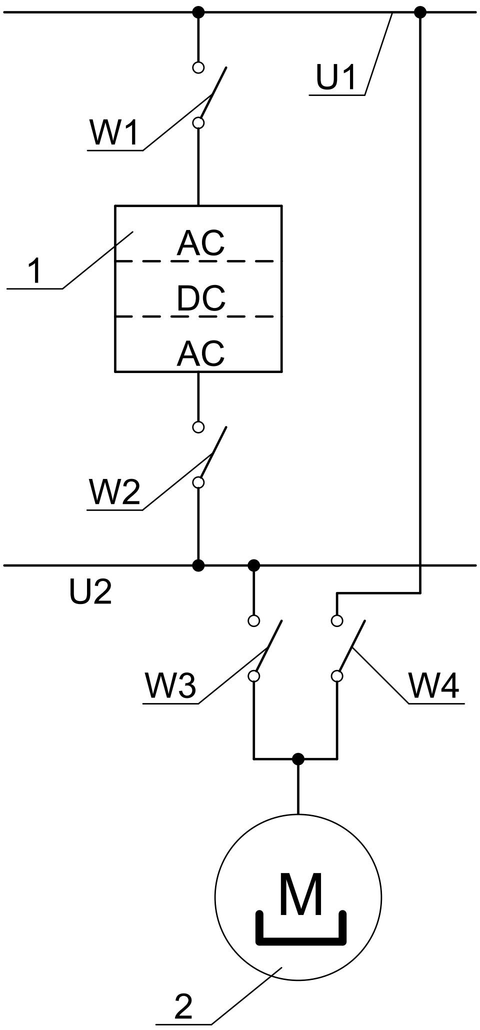

Fig. 3 Schematic diagram of the motor power supply during the start with voltage $U2$ from the AC/DC/AC inverter and during operation with power voltage $U1$

the synchronous motor. The clutch (coupling) could be permanent or disengaging. The induction motor having a lower-rated power was powered by the inverter.

The torque of the induction motor used to start the synchronous motor had to be greater than the load torque, which was the sum of the moment of friction and the ventilation of the synchronous motor and the load torque of the machine coupled with the synchronous motor. During the start, the machine load torque should be minimal. In the case under discussion, it was planned that the synchronous motors would be used as turbocompressors. The start was performed with closed valves, where the load affecting the synchronous motor shaft was only the moment of friction. The friction moment of the unit amounted to between 2 % and 3 % of the rated torque.

Because of the power supply from the 400 V inverter, an induction motor selected to start the synchronous motor (6.4 MW) had a rated power of 400 kW, a voltage of 400 V and $2p = 2$. The cost of the motor drive was approximately 100,000 PLN, whereas that of the inverter amounted to approximately 80,000 PLN. An additional cost was that of a permanent or disengaging clutch.

Due to the power supply from the 400 V inverter, an induction motor selected to start the synchronous motor having a power of 12 MW was characterised by a rated power of 560 kW, a voltage of 400 V and $2p = 2$. The cost of the motor drive amounted to approximately 130,000 PLN, whereas the cost of the inverter was approximately 120,000 PLN. An additional cost was that of a permanent or disengaging clutch.

The connection of the synchronous motor to the grid takes place in the same manner as the start with the inverter (Fig. 3). The induction motor drives the synchronous motor with a steplessly increased rotational rate. Next, at a specific sub-synchronous rate, the excitation current is switched on and, by correcting the rotational rate of the induction motor, it is possible to obtain the compatibility of the frequency and phase of the synchronous motor voltage with a grid voltage of 6 kV. Afterwards, it is possible to connect the motor to the grid and the synchronisation of the synchronous motor is completed. If the motor shafts are coupled with a disengaging clutch, the clutch must be disengaged.

The starting of synchronous motors with an additional induction motor is used, for example, in pumped-storage power plants. The largest Polish pumped-storage power plant (Żarnowiec) is equipped with four major electric machines, i.e. generator-motors, each of them having the following rated parameters: 15.75 kV, $p = 18$, a power of 177 MW in relation to a generator operation 209 of MVA and a power 210 MW in relation to a motor operation of 228 MVA. In the generator mode, the water turbine drives the electric machine and starts it up. In the engine mode, the electric machine drives the turbine pumping water from the lower reservoir to the upper reservoir. The turbine works as a pump and it has the opposite direction of rotation. The transition of the electric machine to motor operation requires a change in the direction of rotation. The starting of the electric machine is achieved using an additional ring induction motor with a water starting resistor. The power plants were built at the turn of the 1970s and 1980s, i.e. when there were no inverters of adequate power.

5. Summary

The starting of the synchronous motor [9, 10] can be asynchronous or frequency or by using an additional motor. The choice of the starting method requires detailed knowledge concerned with the starting conditions of the load torque during the start and the short-circuit power of the power grid at the motor power supply point. The aforementioned condition is essential to the correct design of the starting system.

The asynchronous start is the simplest, yet surge current can reach (7 ÷ 12) I_N and electrodynamic forces can be more than 100 times greater than forces operating at rated current. High starting current can reduce the grid voltage below the permissible value, possibly affecting other electricity consumers supplied from the grid, and triggering problems impacting the operation of other devices.

The frequency start is smooth, yet it requires the purchase of a frequency converter characterised by parameters adjusted to those of the motor. If the motor rotational rate during normal operation is adjusted in accordance with the technological requirements of the working machine, the frequency converter is necessary for the normal operation of the motor. In such a system, the problem of starting is, in a way, solved automatically.

The start involving the use of an additional asynchronous squirrel-cage motor powered by the inverter, the power of which constitutes a few percent of that of the synchronous motor, is also smooth, but can only be designed when the synchronous motor has a second free shaft end and is not loaded during the start.

REFERENCES

[1] Rozporządzenie Ministra Klimatu i Środowiska z dnia 13 października 2023 r., zmieniające rozporządzenie w sprawie szczegółowych warunków funkcjonowania systemu elektroenergetyczne. Dziennik Ustaw RP. Poz. 2280.
[2] Ekspertyza możliwości pracy generatorów synchronicznych o mocach 12 MW i 6,4 MW (6 kV), jako silniki synchroniczne. Opracowanie no. CG4-050147. Instytutu Napędów i Maszyn Elektrycznych, Komel 2016.
[3] Glinka T.: Maszyny elektryczne i transformatory. Wydawnictwo WNT, 2018, ISBN 978-83-01-20115-9, pp. 332.
[4] Glinka T., Szymaniec S.: Eksploatacja i diagnostyka maszyn elektrycznych i transformatorów. Wydawnictwo WNT, 2019. ISBN 978-83-01-20735-9, p. 578.
[5] Drak B.: Zagadnienia elektromechaniczne czół uzwojeń stojanów maszyn elektrycznych dużej mocy prądu przemiennego. Zeszyty Naukowe Pol. Śl. Elektryka z. 163, Gliwice 1998.
[6] Drak B., Glinka T., Kapinos J., Miksiewicz R., Zientek P.: Awaryjność maszyn elektrycznych i transformatorów w energetyce. Wydawca: Instytut Napędów i Maszyn Elektrycznych KOMEL. ISBN 978-83-931909-4-2. Katowice 2013.
[7] Zawilak T.: Rozruch silników synchronicznych dużej mocy przy częściowym zasilaniu uzwojenia stojana. Zeszyty Problemowe – Maszyny Elektryczne 2009, nr 84, s. 33–34.
[8] Concordia C., Crary S.B., Kilbourne C.E., Weygandt C.N.: Synchronous starting of generator and motor. Electrical Engineering, 1945, vol. 64, no. 9, pp. 629–634. DOI: 10.1109/EE.1945.6441256.
[9] LeDoux K., Visser P., Hulin D., Nguyen H.: Starting large synchronous motors in weak power systems. Industry Applications Society 60th Annual Petroleum and Chemical Industry Conference, Chicago, IL, USA, 2013, pp. 1–8. DOI: 10.1109/PCICon.2013.6666022.
[10] Das J.C., Casey J.: Characteristics and analysis of starting of large synchronous motors. 1999 IEEE Industrial and Commercial Power Systems Technical Conference (Cat. No. 99CH36371), Sparks, NV, USA, 1999, p. 10, DOI: 10.1109/ICPS.1999.787222.