Autonomous mode and parallel operation of an asynchronous generator with the electrical network

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Abstract. This article explains that an asynchronous machine, like other electrical machines, can operate as a motor and generator due to the property of reciprocating motion and that an asynchronous generator is not different in design from an induction motor. The work is devoted to the study of a three-phase asynchronous generator, the magnetic excitation flux of which is formed by a three-phase voltage source and moves relative to the rotor. Ideally, induction generators operate best in a stable region between the idle state and the maximum torque region. In addition, an asynchronous generator connected to a capacitor system can generate sufficient reactive power to operate independently.

1 Introduction

An asynchronous machine, like other electric machines, can operate in motor and generator mode, according to the reversible property of electric machines discovered by E. Lens. The design of an asynchronous generator is no different from an asynchronous motor. To transition from motor mode to generator mode when the stator winding is connected to the network, the rotor of the asynchronous machine is rotated by the prime mover to the rotating side of the stator field so that the rotation frequency of the generator rotor is greater than the frequency of the stator magnetic field ($n_2>n_1$). In this case, the car skids:

$$(s)=(n_1-n_2)/n_1 \tag{1}$$

Will have a negative sign. In practice, in normal operation of an asynchronous generator, there will be (–s)≤(6÷8%).

In the generator mode of an asynchronous machine, the conductors of the stator and rotor windings intersect with the rotating field in seemingly opposite directions. In motor

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mode, these conductors cross in the appropriate direction. Therefore, in the vector diagram of the generator E_{2s} (hence, E'_{2s} both) and the directions of the E_1 vectors should be conditionally placed in the reverse phase.

2 Materials and methods

Considerations regarding rotor current are as follows. General expression for rotor current:

$$I_2 = \frac{E_2 \cdot (-s)}{\sqrt{r_2^2 + (\text{-s})^2 \cdot x_2^2}} \tag{2}$$

Active component of the rotor current:

$$I_{2a} = I_{2a} \cdot \cos\psi_2 = \frac{E_2 \cdot (-s)}{\sqrt{r_2^2 + (\text{-s})^2 \cdot x_2^2}} \cdot \frac{r_2}{\sqrt{r_2^2 + (\text{-s})^2 x_2^2}} = \frac{E_2 \cdot (-s) \cdot r_2}{\left(r_2^2 + (\text{-s})^2 \cdot x_2^2\right)} \tag{3}$$

It changes sign because the glide sign is negative (–s); and the reactive component of the rotor current:

$$I_{2p} = I_{2p} \cdot \cos\psi_2 = \frac{E_2 \cdot (s)}{\sqrt{r_2^2 + (\text{-s})^2 \cdot x_2^2}} \cdot \frac{x_2}{\sqrt{r_2^2 + (\text{-s})^2 x_2^2}} = \frac{E_2 \cdot (s) \cdot x_2}{\left(r_2^2 + (\text{-s})^2 \cdot x_2^2\right)} \tag{4}$$

Does not change its sign (that is, it will be the same as in the motor mode), since $(\text{-s})^2$ is a positive value. Changing the sign of the active component I_{2a} of the rotor current changes the sign of the electromagnetic torque, so it is a braking torque, while the reactive component I_{2r} maintains its sign, creating a magnetic field, as in motor mode, the machine receives magnetizing current from the network.

The vector diagram of the asynchronous generator is shown in Figure 1, a. It looks like the corner is in generator mode $\varphi_1 > \frac{\pi}{2}$, so $P_1 = m_1 U_1 I_1 \cos\varphi_1 < 0$. This indicates that active power is being supplied to the network rather than being consumed.

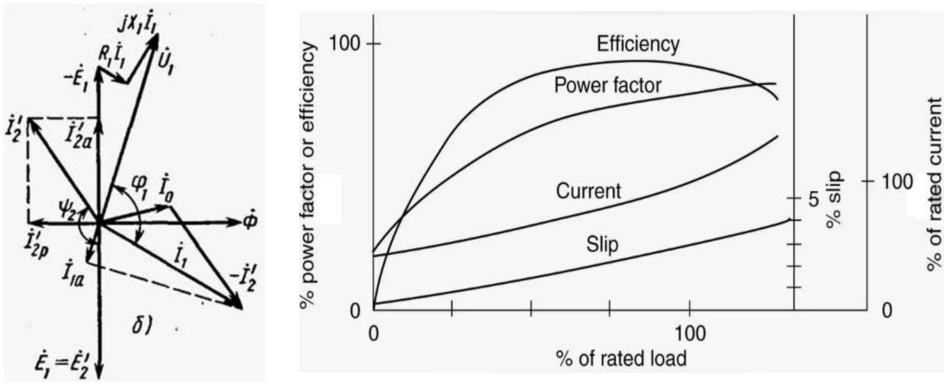
In the vector diagram, the stator current I_1 is found from the current balance equation of the asynchronous machine in the system of equations, namely:

$$I_1 = I_0 + (\text{-I}_2^{'}),$$

Voltage U_1 is also determined from the voltage equation and the EMF in the equation, that is:

$$U_1 = -E_1 + jI_1 x_1 + I_1 \text{r}_1.$$

Vector U_1 represents the mains voltage. The generator voltage vector U_1G, balancing the network voltage, will have the opposite direction, that is, $U_{1G} = -U_1$. Regulation of the active power of the generator to the network is achieved by changing the angular speed of the rotor. The operating characteristics of an asynchronous generator (Figure 1, b) can be determined from the circuit diagram or equivalent circuit. As the load increases, the rotor speed n_2 increases to make the voltage U_{1G}= const.



a b

Fig. 1. Vector diagram (a) and performance characteristics (b) of an asynchronous generator.

2.1 Parallel operation of an asynchronous generator with the power grid

In Figure 2 a, shows a diagram of parallel operation of an asynchronous generator with a synchronous generator. Here, the direction of active (P) and reactive (Q) energies between machines and the network, as well as between machines, is indicated by arrows. Figure 2, b, clearly shows the negative impact of an asynchronous generator on the operating mode of a synchronous generator. The voltage vector U1 should be considered as the voltage U_{1G} of an asynchronous generator (AG) operating in parallel with a common load with a synchronous generator (SG).

In this interpretation, the vector U_{1G} is equal to 180^0 relative to the vector of the mains voltage supplied to the stator winding of the asynchronous machine U_1 must be turned to, then the current vector AG precedes the voltage vector U_1 (Figure 2, b). Due to the presence of a reactive component $I_{r.AG}$ of the current going before U1 in the asynchronous generator, such a current is also present in the synchronous generator, and this vector lags behind the voltage vector U_1. Hence the angle $\varphi'_{SG}>\varphi_{SG}$ as a result, because φ'_{SG} decreases relatively (hereφ_{SG}- when $U_{SG} = U_1$ and the displacement angle of the current vectors I_{SG} in the unconnected state of the asynchronous generator).

Taking reactive energy from the network to drive asynchronous generators is its disadvantage, since, working as a power source, it provides consumers with both active and reactive energy (for example, to create a magnetic field in transformers and asynchronous motors) will be needed. Therefore, asynchronous generators are sometimes used in hydroelectric power plants and low-power wind power plants.

It should be noted that, according to the results of recent scientific research, high-power asynchronous generators in the power system, when used in parallel with synchronous generators, have proven their significant effectiveness in damping low-frequency oscillations.

Since the capacitor S is connected to the stator winding of asynchronous generators, the current I_r=I_c precedes its voltage (Figure 3, b). In the presence of residual magnetic flux ($\Phi_{residual}$) in the stator winding, a small amount of $E_{residual}$ is generated when the rotor rotates (Figure 3, c). Thanks to its effect, the reactive current I_C leads the voltage vector U_1 in the stator winding-capacitor circuit. The reactive component of this current I_r is directed in the same direction as the magnetic flux Φ. Therefore, the magnetic field created by the capacitive current in the stator winding, the MMF, magnetizes the machine.

The self-excitation process continues until the voltages of the asynchronous generator and capacitors are equal, i.e.

$$I_C \omega_1 L_1 = \frac{I_C}{\omega_1 C} \tag{5}$$

Here $L_1 = (x_1 + x_2)/\omega_1$ – inductance of the asynchronous generator; C – capacitance corresponding to one phase.

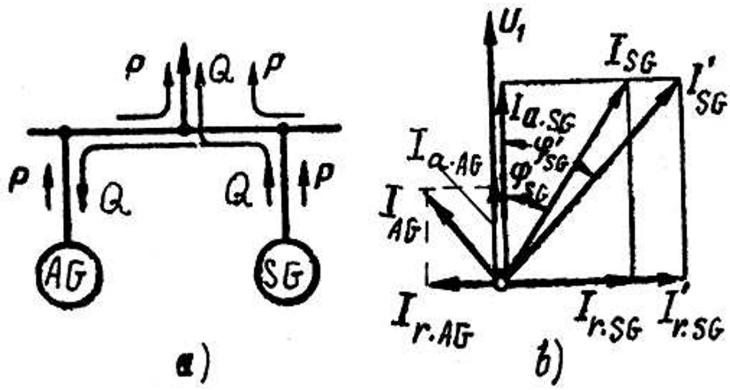


Fig. 2. Parallel operation of asynchronous and synchronous generators (a) and vector diagram (b); Q - reactive power.

If the capacitance of the capacitor is reduced, then the deviation angle α of the characteristic $U_C = I_C x_C$ increases, the voltage of the asynchronous generator decreases, and the asynchronous generator, when the straight line $I_C x_C$ coincides with the straight part of the curve at idle, cannot self-excite (Figure 3, c).

When the rotor of an asynchronous generator with a prime mover rotates and reaches the rotation speed determined by the formula, frequency oscillations occur in the statorω_1, and $\omega_{кр} = \frac{1}{\sqrt{L_k C}}$ - highest critical frequency value$\omega_1 > \omega_{cr}$self-excitation is disrupted.

$$n = \frac{30 \cdot \omega_1}{\pi \cdot p} \tag{6}$$

2.2 Operation of an asynchronous generator with a load

To determine slip using the formula $s = \frac{n_1 - n_2}{n_1}$ it is necessary to change the rotation frequency n in accordance with the change in slip so that the voltage frequency f_1 = const of the asynchronous generator operating with the load. This is difficult to do, since when the rotation speed of the prime mover is fixed by the regulator (setting), the frequency decreases at constant values of the power and load of the asynchronous generator.

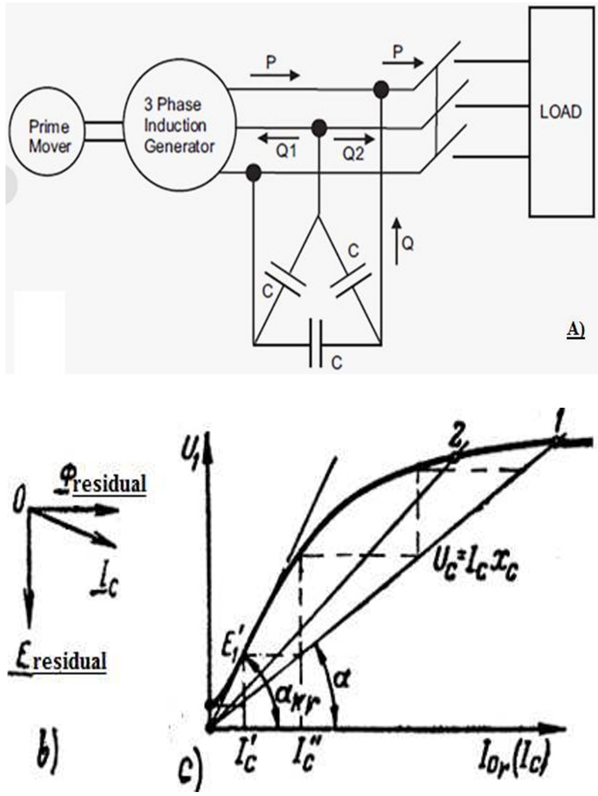


Fig. 3. Self-excited asynchronous generator (a), vector diagram (b) and explanation of the self-excitation process of an asynchronous generator (c).

3 Results and Discussion

This is explained as follows. When an asynchronous generator operates with a load, its voltage decreases slightly due to the voltage drop across the inductive and active resistance of the stator winding. The second reason for this is that when operating with a load, the magnetizing current of the asynchronous generator also decreases somewhat, since part of the capacitor current is used to cover the reactive component of the rotor current and the load current.

A decrease in voltage reduces the saturation level of the magnetic system of the asynchronous generator and, as a result, the inductance L1 of the asynchronous machine increases and its increase according to the formula $\omega_1 = 2\pi f_1$ leads to a decrease in frequency f1, and according to the formula $x_C = \dfrac{1}{2\pi f_1 C}$ the inductive reactance xs of the capacitor increases and as a result the current IS decreases. So, the nature of the load greatly affects the operation of the asynchronous generator.

A decrease in voltage reduces the degree of saturation of the magnetic system of the AG and, as a result, the inductance L1 of the asynchronous machine increases; and its increase $\omega_1 = 2\pi f_1 = \dfrac{1}{\sqrt{L_1 C}}$ according to the formula, frequency causes a decrease in f1 and $x_C = \frac{1}{2\pi f_1 C}$ According to the formula, the inductive reactance xC of the capacitor increases, and as a result, the current IC decreases. Therefore, the nature of the load greatly affects the operation of the asynchronous generator.

If the load of an asynchronous generator is purely active, then the capacitance of the capacitors must be equal to the reactive power of the generator, and with an active - inductive load, it is necessary to increase the capacitance of the capacitor bank in order to provide the load with reactive power.

The capacitance of the capacitor bank of a self-excited asynchronous generator is quite large, i.e. it is 70÷100% of its rated capacity. This increases the cost of the device.

In practice, the applications of asynchronous generators are limited due to the fact that the voltage and frequency variation characteristics are not sufficiently satisfactory when using an asynchronous generator that is not connected to a network with a purely resistive load.

Due to their good starting characteristics, asynchronous machines are used as starters for starting aircraft engines. The generator can then be turned on and used as an AC power source on board the aircraft.

Below in Figure 4. shows an analysis of the balance of active and reactive energy of asynchronous generators operating in parallel with the network.

According to this analysis, it is possible to compensate for the reactive power that the induction generator receives from the grid using a capacitor bank, but it is necessary to take into account the reactive power that the load receives from the grid.

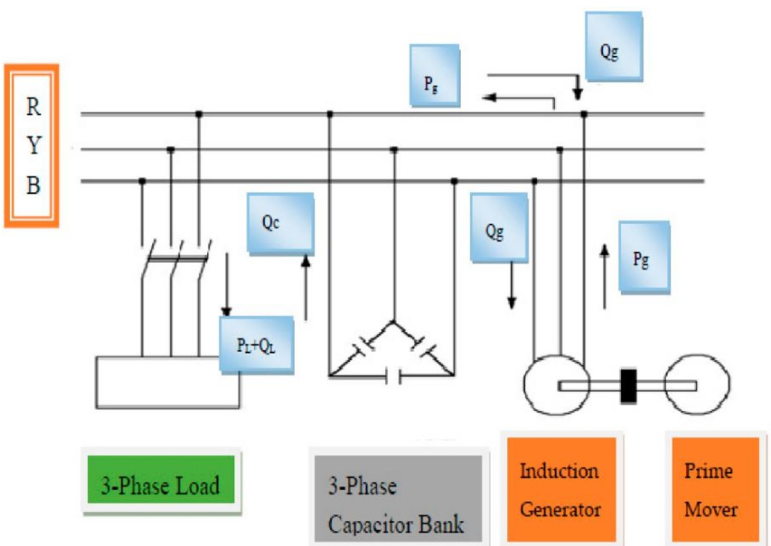


Fig. 4. Analysis of the balance of active and reactive energy of asynchronous generators operating in parallel with the network.

According to Figure 5, the reactive power and active power transmitted by the asynchronous generator from the network depend on the slip. Moreover, the more active power an asynchronous generator transmits to the network, the more reactive power it consumes.

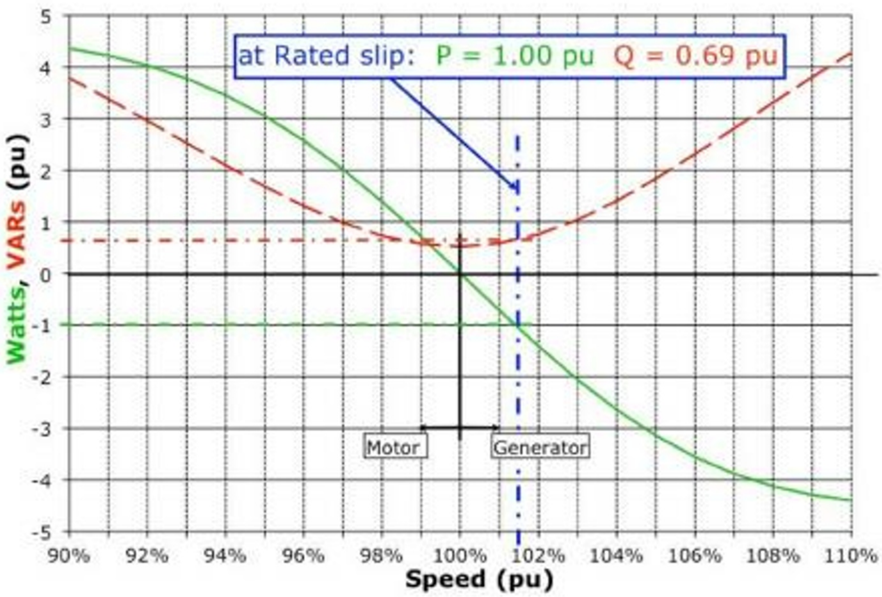


Fig. 5. Graph of the dependence of the active and reactive power of an asynchronous generator on rotor slip.

Self-excited asynchronous generators can also be used in a controlled electric drive (for example, with regenerative braking).

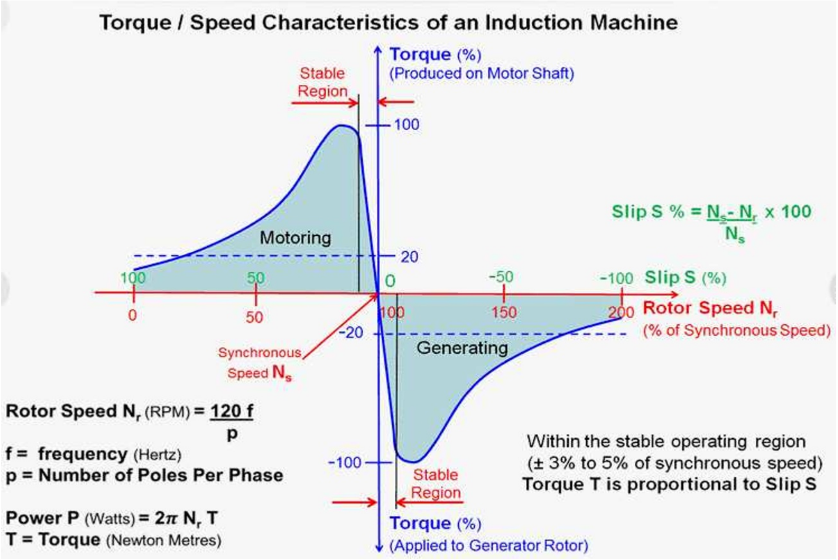


Fig. 6. Analysis of the steady-state operating range of an asynchronous generator.

An asynchronous machine is used as a generator on test benches for diesel engines of cars and tractors. In this case, when the engine is cold, the asynchronous machine operates as an electric motor, warms it up, and then switches to generator mode. In this case, the asynchronous generator creates braking torque and serves as a load for car and tractor engines.

Asynchronous tachogenerators with a hollow or squirrel-cage rotor are used as a source of high-frequency electrical energy for hand-held electrical appliances, in automatic control systems, in servo electric drives and in computing devices.

4 Conclusion

- Because they can recover energy through relatively simple control, induction generators are useful in applications such as mini hydro power plants, wind turbines, or when the pressure of high pressure gas streams is reduced to a lower one.
- Once started, an induction generator can use a capacitor bank to generate reactive field current, but the voltage and frequency of the isolated power system are not self-regulating and are easily destabilized.
- Asynchronous generators are often used in wind turbines and some micro-hydraulic installations due to their ability to produce useful power at different rotor speeds. Induction generators are mechanically and electrically simpler than other types of generators. They are also more durable and do not require brushes or collectors.
- Asynchronous generators are particularly suitable for wind farms because speed is always a variable factor. Unlike synchronous motors, asynchronous generators are load dependent and cannot be used alone to regulate the network frequency.
- Asynchronous generators are distinguished by high reliability and ease of maintenance; they are easily switched on for parallel operation even with relatively large mismatches of angular velocities. The shape of the AG voltage curve is closer to sinusoidal than that of synchronous generators when operating at the same load.

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