Chapter 2
Systems and Equipment of Wind Power Plants

As already mentioned in the previous chapter, wind power plants can be classified according to various aspects and criteria. One of the criteria, for example, is the design of the wind turbine according to which the wind power plants can be divided into plants with horizontal or vertical axis of rotation. Another aspect can be the method of swivelling the wind turbine or blades—accordingly, the wind power plants are divided into active or passive pitch control. However, more often we meet with the division of wind turbines according to their capacity of the wind power plant generator because this capacity subsequently determines the type of generator, actual adaptation of the wind power plant control system and power flow, including current type and the respective voltage levels to which the wind power plant output is brought. According to this major capacity viewpoint, the community dealing with the operation of wind power plants currently divides them as follows:

- micro wind power plants (up to 1 kV·A),
- small wind power plants (about 1–30 kV·A),
- medium wind power plants (30–300 kV·A),
- large wind power plants (300 kV·A and above).

Of course, the mentioned output power levels are just indicative and their determination is very subjective; nevertheless, if we perform a search of the currently operated wind power plants in the EU, we would come to a similar division. Capacity values are deliberately expressed in units of apparent output power, with regard to the possible regulation of active as well as reactive power using appropriate types of generators and modern control systems.

The following chapters will analyse the operating states of individual representatives of the output power levels of wind power plants using the results from long-term experimental measurements carried out by the expert group at the VSB-Technical University of Ostrava.

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2.1 Micro and Small Wind Power Plants

According to the generated output power, the micro and small wind power plants are defined among small power sources scattered in different locations. When thinking of the implementation of such plants, it is necessary to consider the economic and technical aspects. Electric energy generated in this way can be consumed by the producer alone—e.g., for lighting, heating of buildings, for water heating. Regarding larger installations, it is also possible to supply the produced electricity into the public supply external grid on the basis of a contract with the distribution company. The use of small wind power plant is preferred for power generation in areas without electrical connection from the distribution external grid (e.g., recreational facilities). In most cases, the small wind power plants are designed with the passive swivelling system which is realized in the form of a wind rudder, and with the horizontal rotation axis of the wind turbine and the height of the mast for placing the wind turbine up to about 10 m above the ground (Fig. 2.1).

Energy of the wind flow is transferred from the shaft of the wind turbine to the shaft of the generator using a gear unit with fixed conversion ratio (Fig. 2.2). In older types of small wind power plants, the electrical output is subsequently brought from the plant nacelle through a current-collection gear and ring head. In more modern small power plants, the electrical output is brought out directly through a cable line with electronic anti-twist control.



Fig. 2.1 Example of low low-capacity wind power plant

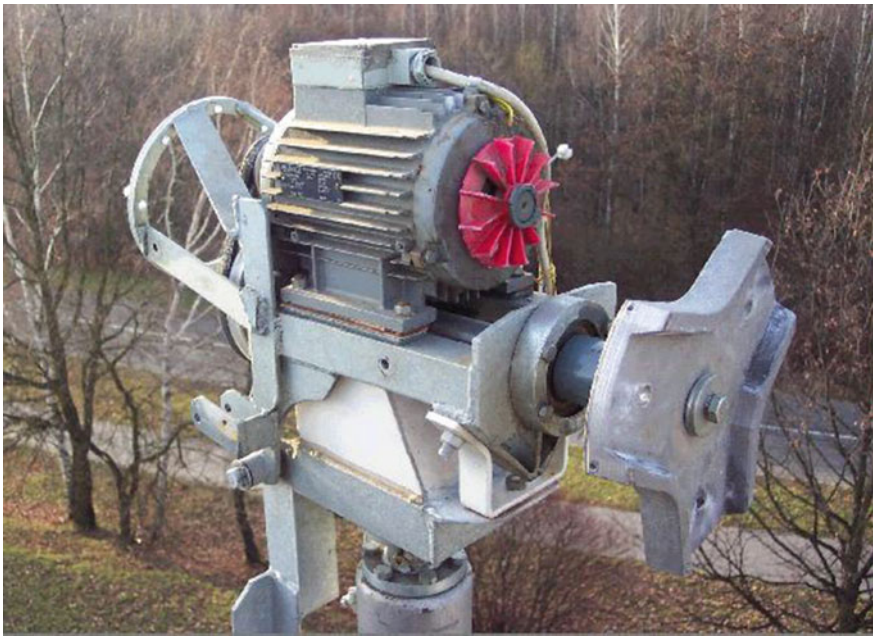


Fig. 2.2 A detail of the generator and gear mechanism placement

The control systems are relatively simple and can be divided by the type of operating the small wind power plant into the system for a autonomous mode (off-grid mode) without connection to the external grid and system for parallel generator cooperation with the external grid into which the generator output is brought. In the first case, the generator output power is directly brought into the load or is converted using the conversion elements to the desired voltage level, type of voltage and current (AC or DC), whereas the load may be constituted by general impedance, or the energy from the wind power plant can be directly accumulated in a storage facility. The control system thus only monitors the voltage limits for the connected load and overload current limits. The autonomous mode small wind power plants will be discussed in the following subchapters. In the second case, when the generator output is brought out to the distribution external grid, the control system mostly monitors the generator speed (n in Fig. 2.3) and provides connection of the generator with oversynchronous speed, reduces the current surge at the moment of connection, and switches the compensation device for compensating the power factor (C in Fig. 2.3) at the connection point. In modern small power plants, the wind speed is also measured and the plant is electronically or mechanically braked when the wind speed exceeds the limit at which the wind turbine could be mechanically damaged (v in Fig. 2.3).

In these plants, it is possible to use asynchronous or synchronous generators, less often dynamos as well as synchronous generators with permanent magnets (in

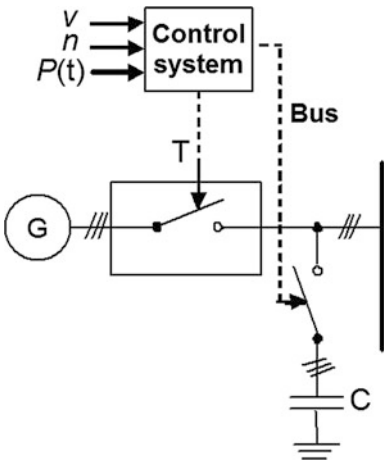


Fig. 2.3 Control system of low-capacity wind power plant

recent years). Static frequency converter is usually inserted between the asynchronous or synchronous generator and the external grid in order to better use wind energy. In such a system, the voltage is first rectified and then adjusted to the desired frequency. With regard to the simple design and the resulting operational reliability, the low-capacity power wind power plants commonly use induction machines.

From the design point of view, there is no difference between the induction motor and the induction generator; it is therefore normal that wind power plants (WPPs) are equipped with serially produced induction motors operating in generator mode. Installed wind power plants equipped with mass-produced induction motors reach low values of power factor; at rated power, the machine is therefore highly current-overloaded.

The following chapter presents an analysis of this operating state. The analysis is based on changes in electric power flow, i.e., the replacement of the motor electrical input and mechanical output by the mechanical input and electrical output of the generator.

Induction motor output P_{OUT} is the mechanical output P_{H} on the machine shaft according to the following relation (2.1).

$$P_{\mathrm{H}} = \omega \cdot M = \frac{\pi \cdot n \cdot M}{30} \tag{2.1}$$

where P_{H} is the mechanical output of the motor, ω is the angular velocity of the shaft and M is the torque on the shaft. Motor input is given by the electrical input P_{EL} on machine terminals according to the following relation (2.2)

$$P_{\mathrm{EL}} = 3 \cdot U \cdot I \cdot \cos \varphi \tag{2.2}$$

where P_{EL} is the motor input, U is the voltage, I is the current and cos φ is the power factor. Machine losses P_Z are given by the difference between the machine input P_{INP} and output P_{OUT} according to the relation below (2.3).

$$P_Z = P_{\mathrm{INP}} - P_{\mathrm{OUT}} \tag{2.3}$$

Total losses in the machine are not concentrated but unevenly distributed across individual parts, such as electrical losses in the winding, magnetic losses in iron, losses due to magnetic leakage, mechanical losses in the bearings, windage losses, etc.

The output of induction generator P_{OUT} means the electrical output P_{EL} on the machine terminals according to relation (2.2); the input P_{INP} means the mechanical output P_{H} according to relation (2.1). This change in the energy flow changes the way of recovering losses as well as their value. The change in the power flow is also reflected in the change of replacement machine diagram. Figure 2.4 shows an equivalent diagram of (a) the induction motor and (b) the induction generator. A fundamental change is reflected in the magnitude of the inner induced voltage U_i.

For induction motors, the magnitude of induced voltage is calculated according to the formula (2.4):

$$U_i = U_1 - Z_1 \cdot I_1 \tag{2.4}$$

and the induced voltage of the generator is calculated according to the following formula:

$$U_i = U_1 + Z_1 \cdot I_1 \tag{2.5}$$

where U_1 is the machine terminal voltage and $Z_1 I_1$ is the voltage drop across the stator winding. Therefore, if we operate the induction generator at the identical terminal voltage as the induction motor, then the magnitude of the internal induced voltage of the machine is greater by the double of the voltage drop across the stator winding. This is particularly reflected in the increased magnetic flux of the machine, higher induction in the air gap, the increase in total losses and, therefore, in the

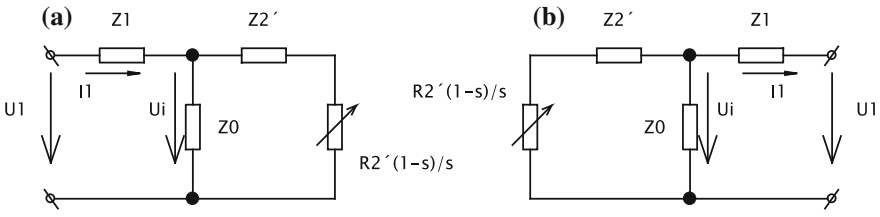


Fig. 2.4 Equivalent diagram of **a** the induction motor, **b** the induction generator

danger of overheating and reduced machine power factor. Reduced power factor of the machine leads to lower quality of the supplied electricity and the increased losses mean lower maximum machine utilization. A machine operated in this way is able to supply 50–70 % of the rated power to the external grid.

In practice, it is much better to use an induction machine designed for a higher voltage than the rated voltage of the external grid to which the generator is connected, or at least use a machine designed for D-connection operation in Y-connection operation.

To operate an induction machine as a generator, at least the following conditions must be satisfied:

- its speed must be oversynchronous,
- a source of reactive power must be at disposal.

Depending on operating conditions, the source of inductive reactive power may be, for example, a capacitor battery in case of independently working induction generator, or the generator can take inductive reactive power from the external grid into which the active power of the generator is supplied.

The generator reactive power can be determined from the following relation:

$$Q = m_1 X_{1\sigma} I_1^2 + m_1 U_i I_0 \cos \partial + m_1 U_i I_2 \sin \psi_2 \tag{2.6}$$

containing the following reactive inputs:

$m_1 X_{1\sigma} I_1^2$ on the stray magnetic field of the stator
$m_1 U_1 I_0 \cos \partial$ on magnetizing the magnetic circuit of the machine
$m_1 U_1 I_2 \sin \psi_2$ on the stray field of the rotor.

The minimum capacitance value of the capacitor battery can be determined from no-load (no-load) measurements. Because the power factor of no-load machine achieves very low values and high-output rolled capacitors are produced with tolerances ±20 %, the no-load current can be regarded as magnetizing. Then, the entire measurement can be simplified. The induction machine is connected to the external grid and the monitored variable is only the no-load current. The machine must be disconnected from the drive. Furthermore, this is based on the assumption of equality of the machine reactance and equality of the capacitor battery reactance.

$$x_C = x_L \tag{2.7}$$

According to the above described simplification, the current I_0 can be considered as magnetizing; therefore, the magnitude of the required capacitive reactance will be:

$$x_C = \frac{U_{1f}}{I_0} \tag{2.8}$$

where U_{1f} is the phase voltage of the generator; the value of the capacitance sought then will be

$$C = \frac{1}{2 \cdot \pi \cdot f \cdot X_C} \tag{2.9}$$

If a capacitor battery with this capacitance is connected to the generator, then the terminal voltage at speeds approaching synchronous speed (no-load speed) will be U_{1f}, at frequency f.

2.1.1 Start of the Excited Generator

If the capacitor battery is connected to the generator, then the voltage increases proportionally to the speed, as evident from the measured excitation characteristic of low-output generator in Fig. 2.5.

After starting up the generator (at low speeds), a voltage caused by remanent magnetism appears at the terminals. This remanent voltage varies in the range of 5–10 % of nominal voltage. The speed increases and a step voltage change is observed at a certain speed value (breakthrough speed—see Fig. 2.5). This voltage becomes stabilized at value U_0. Voltage U_0 and excitation speed are given by capacitance of the capacitors and reactances of the machine. Figure 2.5 shows the voltage magnitude depending on the machine speed whereas the parameter is the capacitance of the capacitor battery. The current flowing through the capacitors and the stator winding of the machine is shifted behind voltage by 90°; therefore, it is a reactive current ensuring the formation of the machine magnetic field.

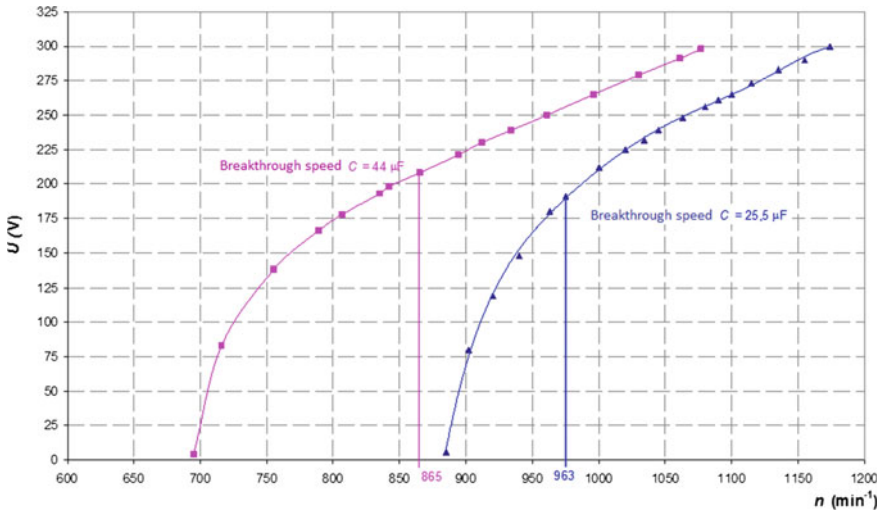


Fig. 2.5 Exciting characteristic of induction generator; C = 25 µF (*blue*), C = 44 µF (*pink*) (color figure online)

Excited generator is loaded by no-load losses and losses in the capacitors. This load causes a slip (we measured about 2 % at a 6 poles machine with output of 1.1 kW; this means that the generator frequency for the calculated capacitance of the capacitor battery was 50 Hz at 1020 min^{-1})—at this speed, therefore, the excited voltage corresponds to the external grid rated voltage.

2.1.2 *Connecting of the Induction Generator to the Distribution External Grid*

In the case of differences between instantaneous values of voltage, frequency and phase shift of the external grid and the generator, the actual connection to the external grid is accompanied by a current surge with magnitude being 10 times greater than the rated current and an overvoltage peak of large steepness and amplitude (see Fig. 2.6).

This current surge can be reduced by connecting the induction generator to the external grid via resistors connected in series to the generator winding. After a defined time delay, these resistors are bypassed. In this case, therefore, there are two smaller current surges. It has been measured that amplitudes of these current surges are less than half of the rated current if the resistance values are optimal.

Connection of the induction generator to the external grid through resistors is shown in Fig. 2.7. The optimal resistance value for the induction generator (P_n = 1.1 kW, U_n = 400 V, I_n = 3 A, cos φ = 0.75, 6p) was determined by

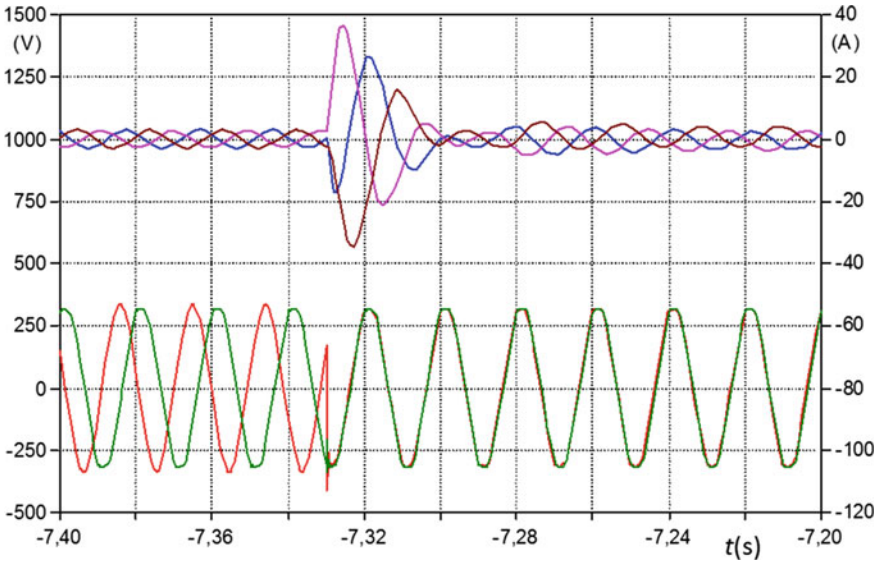


Fig. 2.6 Voltage curve when connecting the induction generator to the external grid. Generator voltage U_g (*red*) (V), external grid voltage U_s (*green*) (V), phase currents I_1 (*blue*), I_2 (*pink*), I_3 (*brown*) (A) (color figure online)

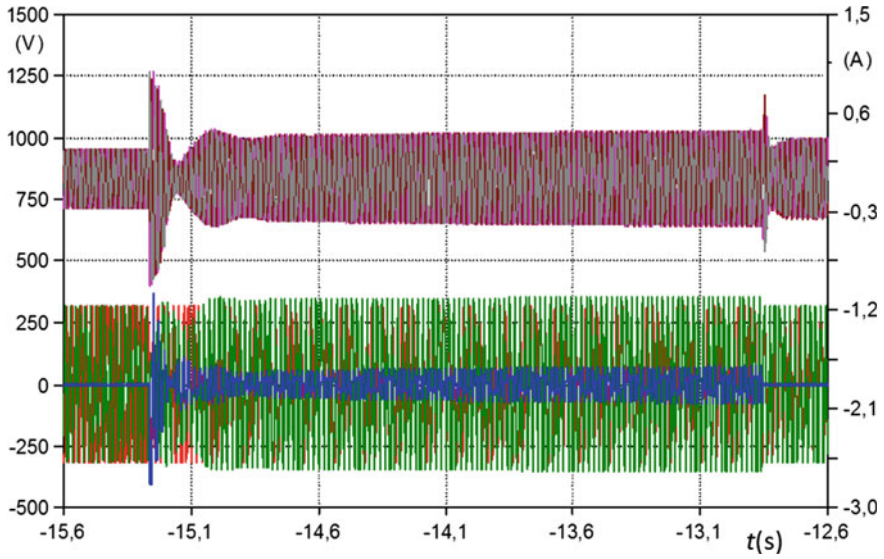


Fig. 2.7 Connecting the induction generator to the external grid in an optimal way—via 50 Ω resistors. External grid voltage U_s (*red*) (V), generator voltage U_g (*green*) (V), voltage across the resistor U_r (V), phase currents I_1 (*blue*), I_2 (*pink*), I_3 (*brown*) (A) (color figure online)

measurements as 50 Ω at a speed of 1022 min^{-1} [1–3]. Before connection, magnetizing current from the capacitor battery flows through the winding. The connection was carried out at the moment when the generator voltage was in phase opposition with regard to the external grid voltage. The connection to the external grid via resistors resulted in a current surge whose magnitude was 0.23-multiple of the machine rated current. Generator voltage was phase-delayed behind the external grid voltage. After about 2 s, the resistors were bypassed and the voltage across them dropped to zero. Generator voltage adapted to the external grid voltage. Magnitude of the respective current surge was 0.18-multiple of the rated current. Similarly, the current surge can be limited using soft start.

2.1.3 Connecting the Non-excited Generator to the External Grid

Connection of non-excited generators to the external grid is also accompanied by transients. However, the amplitude of the current surge is smaller than in the case of excited generator. This is because the worst case for this method of connecting the generator to the external grid can occur at the moment when the voltage on the generator is zero and the external grid voltage is maximal (see Fig. 2.8).

In the case of excited generator, the current surge is largest when the generator voltage is in the opposite phase (antiphase).

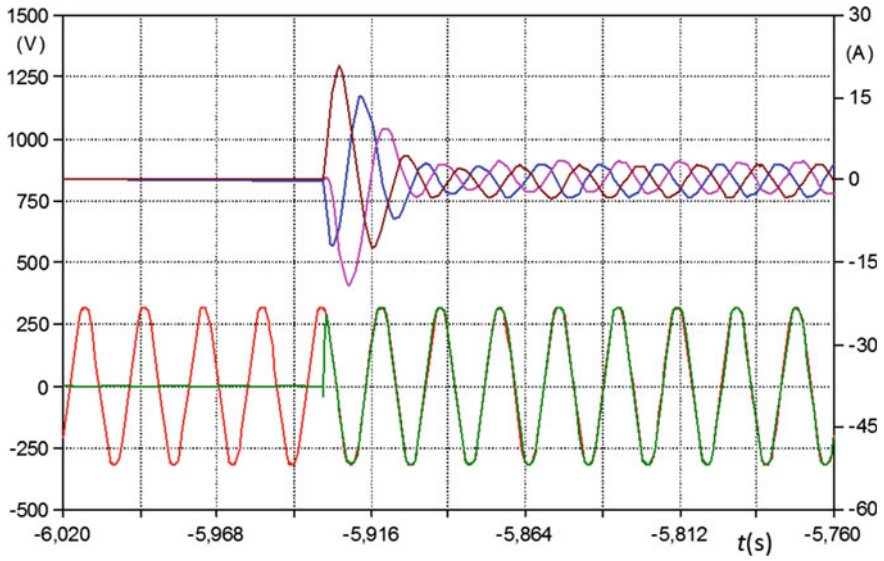


Fig. 2.8 Connecting the non-excited generator to the external grid External grid voltage U_s (*red*) (V), generator voltage U_g (*green*) (V), phase currents I_1 (*blue*), I_2 (*pink*), I_3 (*brown*) (A) (color figure online)

As in the previous case, the current surge can be limited by appropriately chosen resistance. When the non-excited generator was connected to the external grid via resistors, the current surges reached 0.4–0.55-multiple of the rated current of the machine at speed of 1022 min^{-1} [4].

In cases of connecting the generator to the external grid via resistors connected in series to its winding, no overvoltage was observed.

2.1.4 *Instantaneous Disconnection of the Generator from the External Grid*

Instantaneous disconnection from the external grid is associated with overvoltage that occurs due to sudden change of the generator power factor. All current becomes magnetizing and the total energy of the generator only covers its no-load losses and losses of the capacitor battery. The generator torque decreases and speed increases at constant output of the driving device.

The terminal voltage of the non-loaded generator increases with increasing speed (see Fig. 2.9) according to the excitation characteristic (see Fig. 2.5). When disconnecting the generator, it is therefore necessary to limit mechanical energy in the rotor in order to avoid damage to the machine insulation.

Overvoltage magnitude is proportional to the speed. If the generator is disconnected at the moment when it is not excited from the capacitor battery (not

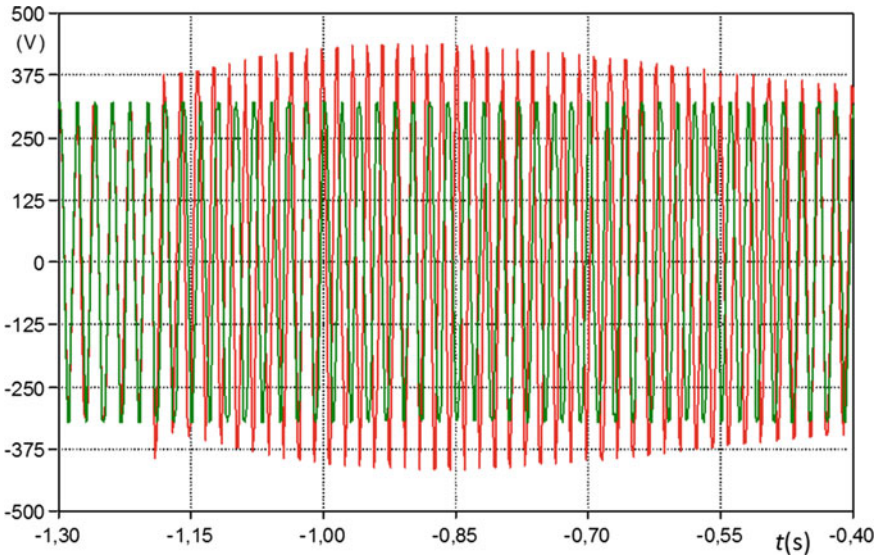


Fig. 2.9 Disconnecting the generator from the external grid. Generator voltage U_g (*red*) (V), external grid voltage U_s (*green*) (V) (color figure online)

connected in the circuit) but from the external grid, no overvoltage arises and the generator current ceases in a few periods.

2.1.5 Connecting Capacitors to the Running Generator

At the moment of connecting the capacitor battery to the running induction generator, the capacitor battery current excites the generator. Steady-state values of measured electric variables are presented in Table 2.1 and the course of connecting the capacitor battery to the running induction generator is shown in Fig. 2.10.

As evidenced by Table 2.1, increasing capacitance of the capacitor battery is associated with increasing current and voltage as well as with sharply rising machine losses.

Table 2.1 Steady-state values of electric variables at connecting the capacitor battery to the running induction generator

Capacitance	n (min^{-1})	I_0 (A)	U_0 (V)	f (Hz)	M (N m)	P_0 (W)
D 44 μF	1000	3.27	268.7	47.94	3.9	408
Y 25 μF	1000	1.43	181.6	48.26	1.1	115
D 44 μF	1022	3.77	292	50.55	4.5	482
Y 25 μF	1022	1.87	223	50.87	1.5	160
D 44 μF	1058	4.04	304.3	52.09	5.7	631
Y 25 μF	1058	2.07	239.32	52.57	1.8	199

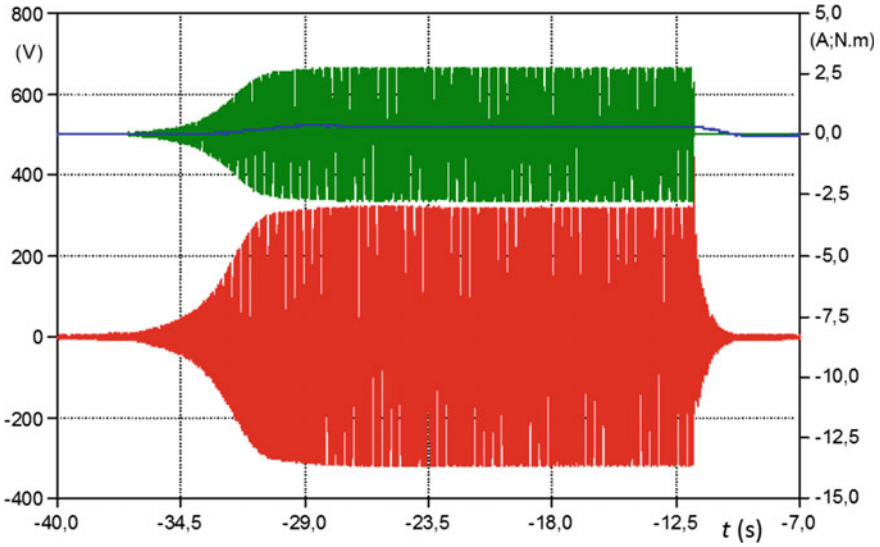


Fig. 2.10 Connecting the capacitor battery. Generator voltage U_g (*red*) (V), capacitor current I_c (*green*) (A), moment M (*blue*) (N·m) (color figure online)

2.1.6 Load Changes

If the generator at oversynchronous speed is connected to the external grid which has incomparably higher short-circuit power in comparison with the induction generator, it supplies active energy to this external grid. Increasing the torque on the shaft results in increased speed and thereby increased current of the generator; conversely, at the moment when its speed decreases below synchronous speed, the induction machine breaks into motor operation, as evidenced by Fig. 2.11.

2.1.7 The Effect of Terminal Voltage Changes During Cooperation with the External Grid

In operation condition, the distribution external grid voltage sometimes differs from its rated value, which may have a serious impact on the operation of induction generator in parallel cooperation with this external grid. Induction generator can operate in parallel with the distribution external grid whose rated voltage can fluctuate within ±5 % (according to standard EN 341610). Changes in the terminal voltage of the induction generator are associated with changes in the moment (torque) characteristic of the induction generator according to the following relation:

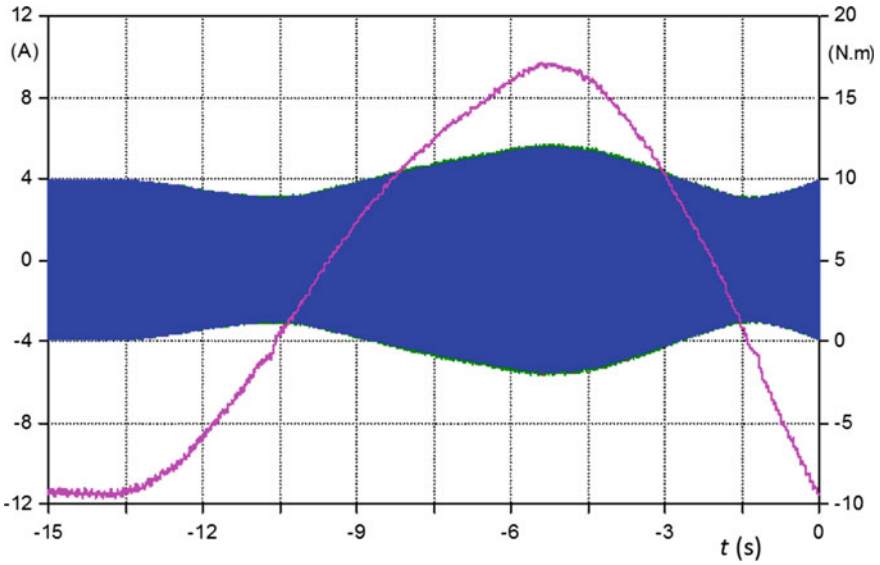


Fig. 2.11 Continuous speed change. Phase current I_1 (*black*), I_2 (*red*), I_3 (*green*) (A), moment M (*blue*) (N·m) (color figure online)

$$M = \frac{m_1 R_2' U_1^2}{s\omega_1 \left[\left(R_1 + c_1 \frac{R_2'}{s} \right)^2 + \left(x_{1\sigma} + c_1 x_{2\sigma}' \right)^2 \right]} \tag{2.10}$$

The torque is dependent on the square of the terminal voltage. The torque characteristic of the induction generator thus changes, especially the gradient of its linear part within the slip range $\pm s_{\max}$. Changes in the terminal voltage of the induction generator lead to changes in the value of maximum torque. Assuming that the external grid voltage U_{1n} changes to αU_{1n} at constant torque on the shaft of the generator, where $\alpha = < > 1$, then the generator slip will be given the relation 2.11:

$$s' \approx \frac{s}{\alpha^2} \tag{2.11}$$

Changes in the slip are associated with changes in the frequency in the rotor winding

$$f_2 = s \cdot f_1 \tag{2.12}$$

Increased frequency results in an increase in the rotor winding reactance

$$x_{2\sigma} = \omega_2 \cdot L_{2\sigma} \tag{2.13}$$

and decrease of the reactive component of the generator current. Reduction of the reactive current component is associated with an increase in the machine power factor.

The behaviour of the induction generator with changes in the terminal voltage was verified by measurements using an induction machine with the following parameters: P_n = 1.1 kW, U_n = 400 V, I_n = 3 A, cos φ = 0.75, 6p, 930 min^{-1}. Measurements were carried out on this induction machine in generator operation, changes in the terminal voltage were realized through an autotransformer within the range of 65–110 % U_{1n}. The measurement results for the constant speed of 1040 min^{-1} are shown in Fig. 2.12 [5–7].

Declining terminal voltage results in the reduction of machine torque and its output. At constant torque, the current decreases according to the following relation:

$$I'_{1a} \approx \frac{I_{1a}}{\alpha} \tag{2.14}$$

As mentioned above, the terminal voltage drop is also accompanied by a decrease of the current reactive component, resulting in the increase of the power factor. For this reason, also the induction generator efficiency slightly increases. When operating the induction generator with reduced terminal voltage, the working area of the machine becomes limited in terms of maximum torque reduction.

2.1.8 *Induction Generator of the Wind Power Plant in the Autonomous Mode*

Separately working induction generator has a soft shunt load characteristic. When the load changes, the machine slip as well as frequency changes according to the relation below:

$$f = \frac{n \cdot p}{60 \cdot (1 - s)} \tag{2.15}$$

The change in frequency leads to changes in capacitance X_C and reactance X_L. Increasing load further reduces the terminal voltage and also changes the machine power flow. Therefore, the magnitude of the calculated capacity is minimal. For loading the generator, this capacity must be increased. As regards a practical use of the generator in the area of rated power, the resulting magnitude of the capacity may be even double.

After starting, the machine becomes excited and its terminals show voltage given by the speed and magnitude of the capacity connected to the generator. After energizing the generator, it is possible to start its loading. The terminal voltage drops with decreasing load impedance. After reaching the minimum voltage (30–50 % of U_N) when the capacitor battery is no longer able to excite the machine, the voltage and current drops to zero. Load characteristic shows the so-called "knee"; in this area, the generator supplies the load with output of maximum efficiency—see Fig. 2.13.

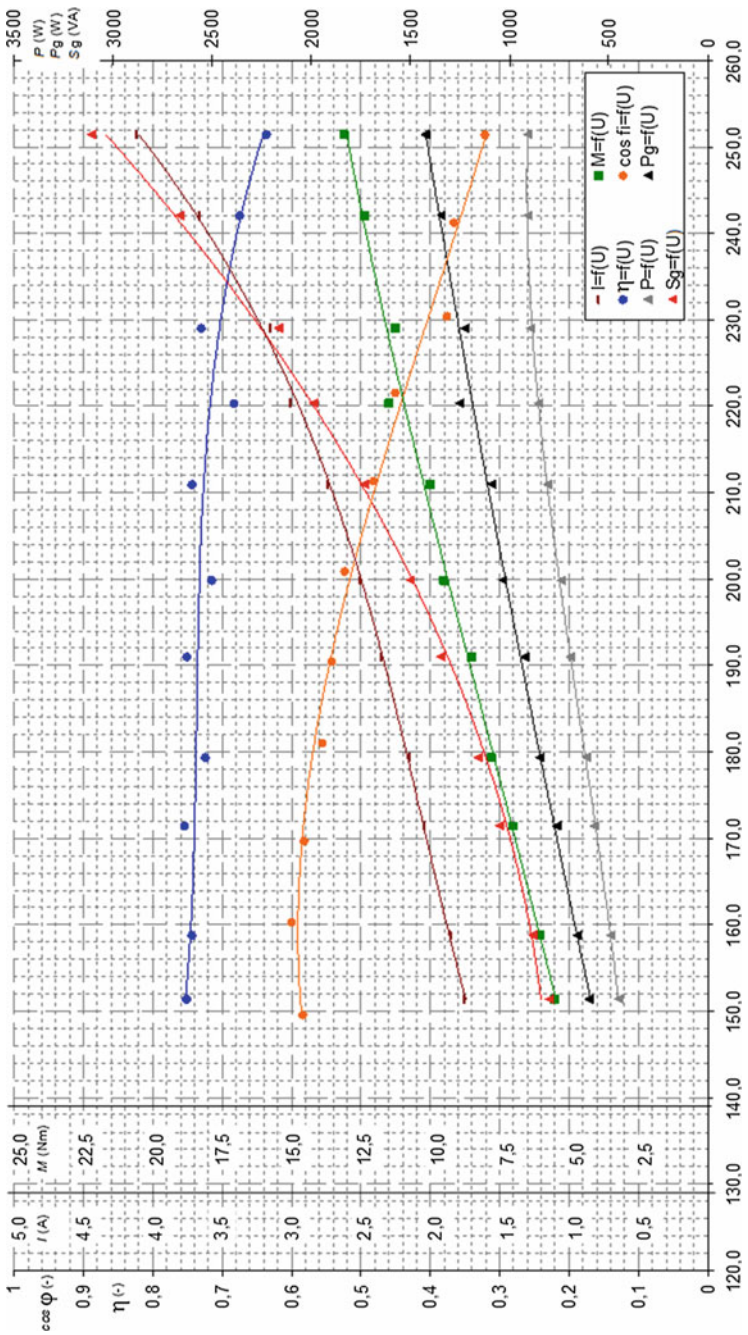


Fig. 2.12 Behaviour of the induction generator during terminal voltage changes

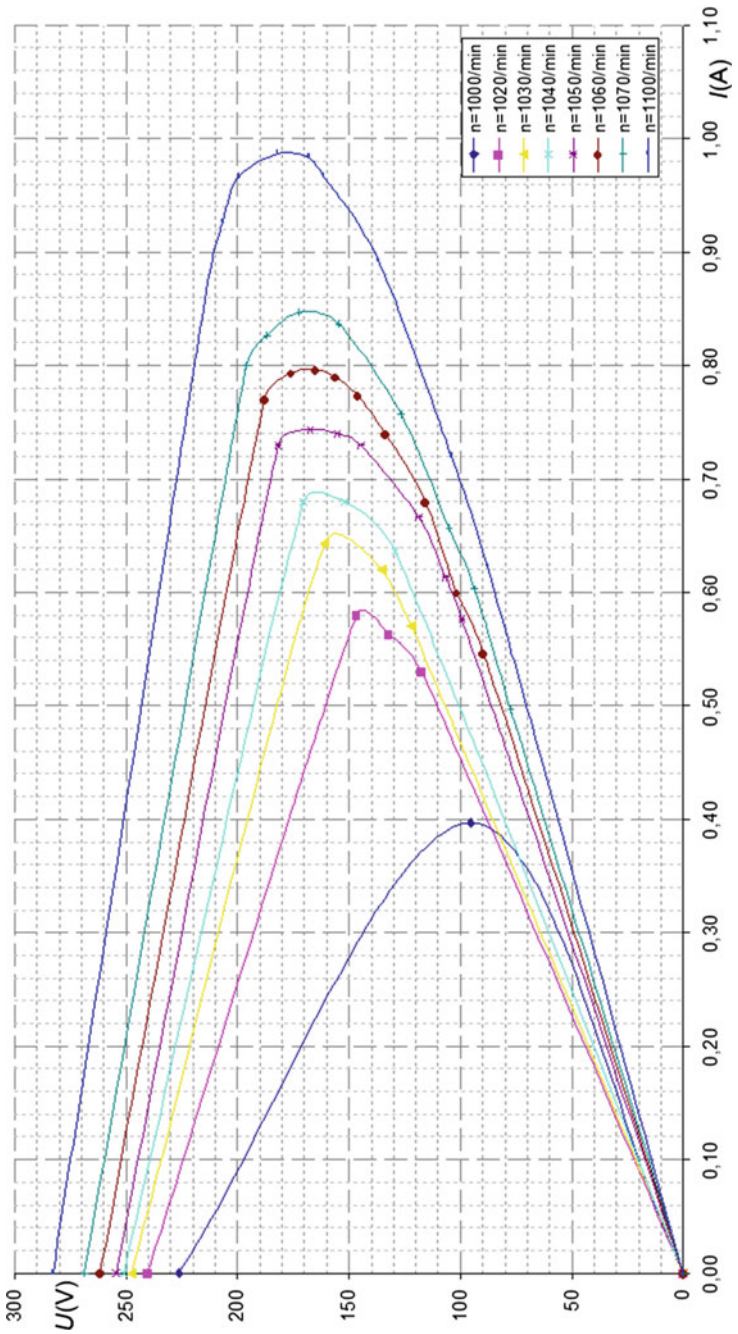


Fig. 2.13 Load characteristics of the separately working generator, for different speeds

Loading the generator with inductive load reduces the reactive energy supplied to the generator for excitation; the load characteristic is steeper and is therefore softer. Load characteristics for inductive loads are shown in Fig. 2.13. If the inductive power factor is compensated, the load characteristics are the same as for cases of loading with resistors. Increasing capacitive load, however, leads to considerable decreases in the machine efficiency (Fig. 2.14).

In the "knee" area of the shunt characteristic, the generator supplies the load with output of maximum efficiency, as shown in Fig. 2.15. This figure presents individual monitored variables (apparent generator output S_G, generator active input P_G, output on the resistive load P_R, generator current I_G, torque on the generator shaft M, efficiency η and power factor cos φ) depending on the terminal voltage U_R of the machine, at constant speed $n = 1070\ \text{min}^{-1}$. As shown in Fig. 2.15, the knee peak occurs at the terminal voltage $U_R = 190$ V. The maximum generator output is reached in the area before the knee of the load characteristic, at about $U_R = 210$ V. Optimum generator operation at constant shaft speed $n = 1070\ \text{min}^{-1}$ is achieved at the terminal voltage of 220–160 V when the efficiency of using the output on the shaft is maximal ($\eta = 68$ %) [7, 8].

2.2 Medium Wind Power Plants

Development of medium wind power plants was accelerated by the options of bringing the output from these plants into the external grid, i.e., mainly the medium-voltage system, with regard to their capacity. Therefore, these facilities included wind power plants and their control systems enabling parallel cooperation with the external grid whereas the respective output was brought out through a power transformer. Block connection of this power transformer and the wind generator then formed the so-called plant up to the transfer point, i.e., the place in which the output from this plant is transferred to the external grid.

From the viewpoint of the design of medium wind power plants, these were mostly systems with active vane swivelling (pitch) (Fig. 2.16) and generator placed in the nacelle (Fig. 2.17) which was located on the wind power plant tube at a height of about 30–50 m above the ground.

Entire equipment (Fig. 2.18) was placed in the base of the wind power plant tube, consisting of a simple control system, the compensation device and power outlet to a LV/MV transformer station through a low-voltage cable; the LV/MV transformer station is usually positioned close to the wind power plant and MV overhead lines.

The dominant element of the nacelle was "solely" the generator and hydraulic systems for swivelling the wind turbine and its vanes in order to optimally use the wind power, or (in older models) for swivelling the tips of vanes (blades) of the wind turbine during its braking (Fig. 2.19).

At the end of the last century, in terms of usability and return on investment, the installations in the Czech Republic were especially old refurbished machines

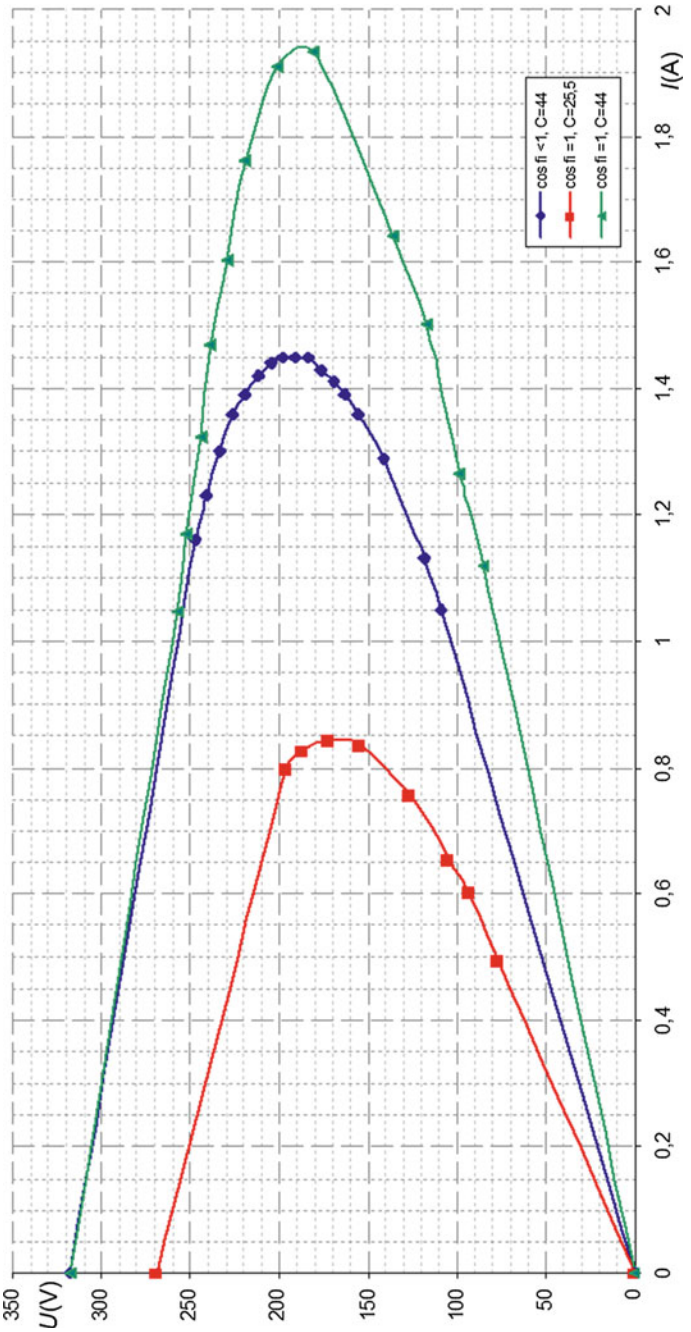


Fig. 2.14 Load characteristics for various connections, at constant speed

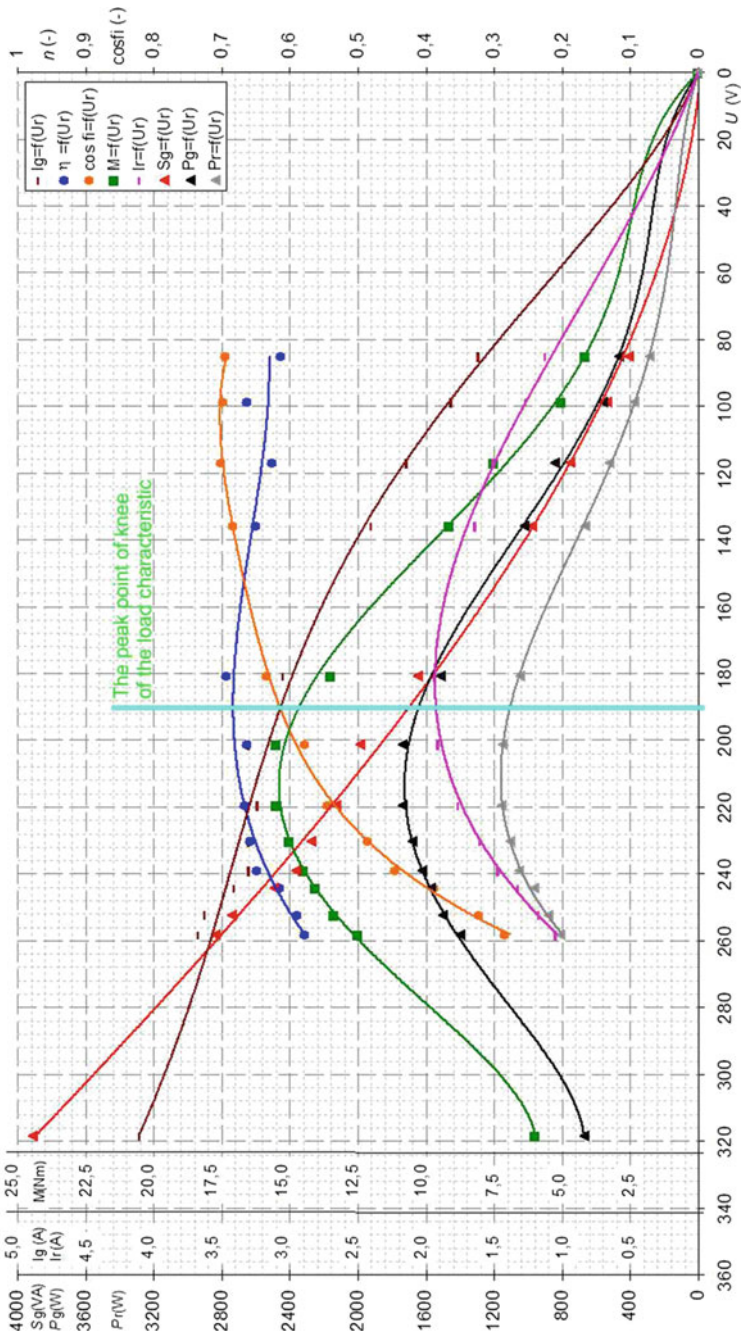


Fig. 2.15 Load characteristic of the induction generator at constant speed $n = 1070\ \text{min}^{-1}$ with attachable capacitor battery C2



Fig. 2.16 Active system of swivelling the vanes



Fig. 2.17 A generator placed in the nacelle of the wind motor

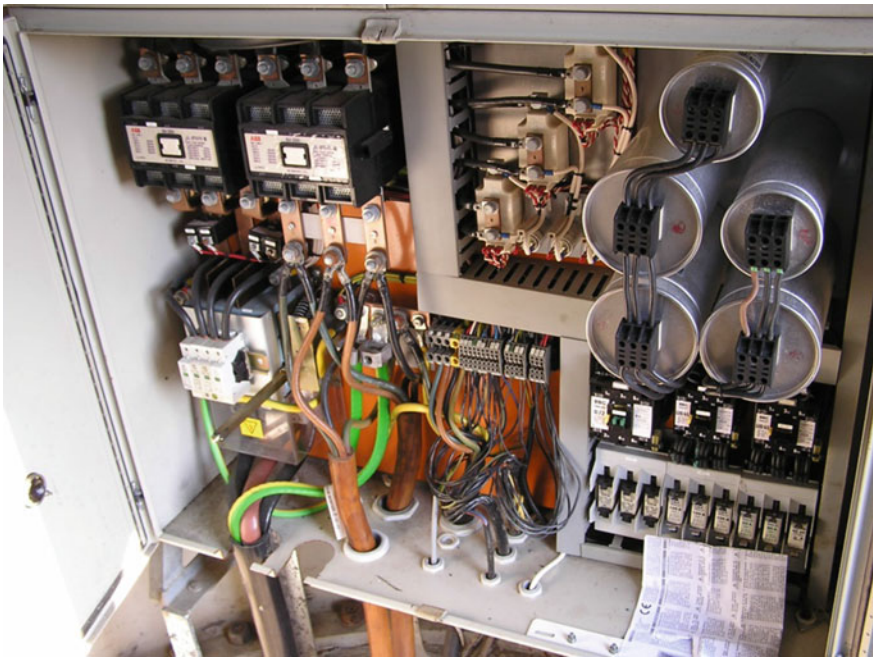


Fig. 2.18 Equipment of the medium wind power plant (a detail of the compensation device)

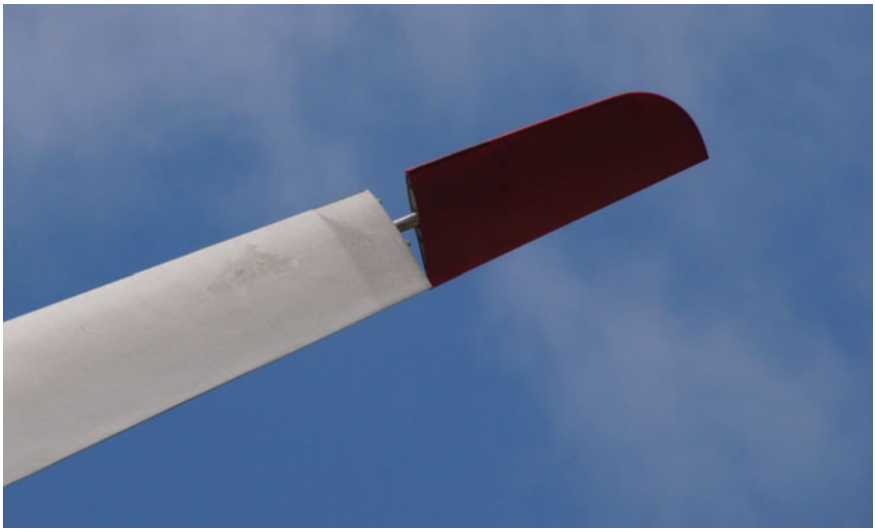


Fig. 2.19 Braking the wind turbine by deflecting tips of the blades

imported from Western Europe. They are used in areas with limited connectivity to the distribution external grid. Many times, they did not meet the conditions for connection to the external grid; their owners, therefore, gradually modernized the control algorithm and equipment of these wind power plants.

Common features of these power plants are firmly seated rotor blades with STAHL regulation; in order to block the power plant, the blade tips are extended and rotated so that the countermoment slacks up the rotor of the wind turbine. Then final braking is ensured by a hydraulic brake. For optimum conversion and the corresponding better use of wind energy, the medium power plants use a planetary gear that mostly propels an induction generator.

2.2.1 Generators of Medium Wind Power Plants

In addition to selecting a suitable site for the construction of wind power plants and optimum features of the wind turbine, the maximum use of wind energy is substantially influenced by the choice of the type and characteristics of the power generator. If looking into the catalogue of manufacturers of electric machines, we find that many machine parameters significantly vary with the magnitude of the machine output, speed, type, etc. When choosing the type and method of operation of any generators, we often have to decide whether we should use the drive with or without a gearbox, whether to choose a machine with more or less poles, etc. Besides the technical possibilities, investment costs and other conditions, we should take into account the efficiency, power factor and weight of the machine.

Apparent output power of electric machines is given by the so-called power equation:

$$S_i \approx D \cdot l \cdot n \cdot N_{S1} \cdot I_1 \cdot B_{\vartheta} \cdot k_V \cdot m \tag{2.16}$$

where: D and l are the internal diameter and length of the stator, respectively, n is the machine speed, B_{υ} is the induction in the air gap, I_1 is the stator current (it can be replaced by the product $\sigma_1 \cdot S_1$ where σ_1 is the load current and S_1 is the cross-section of stator winding conductors), k_V is the winding factor, k_B is the curve shape factor, N_{S1} is the number of conductors of one phase in series, and m is the number of phases).

The Eq. (2.16) shows the dependence of dimensions and hence the weight of the turbine on its output power. Therefore:

- To have a machine of the same output but with lower speed, we have to increase the amount of active iron; conversely, at the same volume, the output decreases with the increasing number of poles.
- The specific weight decreases with the output power.
- Multipole machines are massive (for the same output and lower speed, the turbine must have larger volume of the magnetic circuit).
- The better the winding (with higher k_v), the more we can reduce the magnetic circuit saturation or current density in the conductors at the same output.
- Energy indicators and thus the efficiency of the machine can be easily increased by increasing dimensions of the active parts of the machine, i.e., by increasing the volume of the magnetic circuit (through reducing its saturation) and increasing the cross-section of the winding conductors, while maintaining the rated power (this will reduce overall losses of the machine).
- contains a relationship indicating that the k-multiple increase in each dimension of the motor results in the increase of its efficiency η as follows:

$$\eta_k = \frac{k \cdot \eta_0}{1 + \eta_0(k-1)} \tag{2.17}$$

  where η_0 is efficiency of the motor with original dimensions. This is due to the fact that the machine output increase is proportional to k^4 while losses are proportional to k^3. The machine surface increases with k^2; therefore, the following should apply: the larger machine dimensions, the better thermal utilization of the machine.

The overall energy efficiency of machines in operation is affected mainly by the below-mentioned factors:

- Load magnitude.
- Time utilization.
- Number of starts.
- Magnitude of the machine rated voltage and deviations from the rated voltage.
- Harmonic content in voltage or current.
- Maintenance and repairs.

Medium wind power plants most often used induction generators primarily due to their simple design and the corresponding higher operating reliability, especially squirrel-cage induction generators.

Among other things, induction machines must have oversynchronous speed to work as generators. Furthermore, induction machines (motors as well as generators) need reactive power from the external grid (or other sources) to create the rotating magnetic field. Besides numerous advantages, this is a significant disadvantage of these machines. The required reactive energy for the motor will depend on:

- Design concept of the machine (the size of the air gap, the shape of the grooves, magnetizing current, stray, etc.).
- The number of poles.
- The type of the rotor used.
- Load magnitude.
- Terminal voltage.

Induction machines can have a rotor with squirrel-cage winding or wound rotor. Other used machines can switch the number of poles. Currently, often used induction generators are those with wound rotor. Their advantage is the possibility of dual feeding.

As seen from the relationship (2.16), induction machines with more poles, i.e., lower speed, must have greater capacity of the magnetic circuit at the same rated output. As the magnetic circuit saturation usually also remains the same, the excitation of the needed magnetic field will require greater reactive power. This means that machines of the same type size but with different number of poles will have a different power factor. The smaller the number of poles, the higher the power factor.

Compared to the slip-ring rotor, the machines with squirrel-cage rotor have higher power factor. This results from the magnitude of stray flux which is smaller in the cage rotor.

Magnitude of the reactive energy under load is determined from the relationship

$$Q_M = Q_o + Q_Z \tag{2.18}$$

where

$$Q_0 = I_0 \cdot U_N \cdot \sin \varphi_0 \tag{2.19}$$

is the no-load reactive input—independent of load, and

$$Q_Z = m \cdot X_\sigma \cdot I_2^2 \tag{2.20}$$

is the magnitude of the reactive input varying with load magnitude (X_σ is the total leakage reactance of the stator and rotor winding, and I_2' is the converted value of the rotor current to the stator).

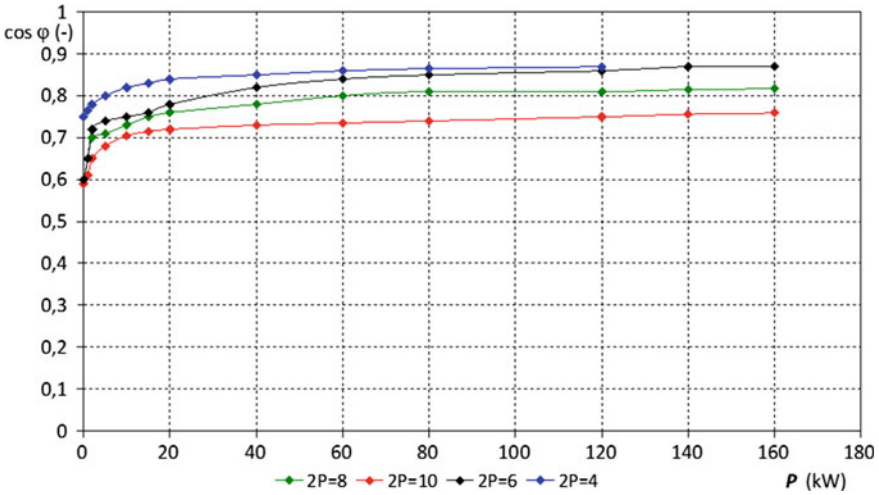


Fig. 2.20 Dependence of the power factor on the active output of asynchronous machine

The power factor of induction machine is significantly reduced with decreasing the load as the magnetizing current component becomes more significant. Figure 2.20 shows that the power factor increases with the machine output and decreases with the number of poles.

When assessing the consumption of electricity, we must also consider active losses caused by the reactive component of the current. The lower the power factor of the motor (at constant load), the higher the losses and thus lower drive efficiency. Furthermore, it holds that:

(a) The reactive power is consumed to excite the magnetic field. The size of the air gap in relation to the rated output of the machine is reduced and the consumption of reactive power in large machines is therefore less.
(b) At the same rated power, multi-pole machines have greater weight; the generation of the magnetic field of the same magnitude therefore requires greater reactive power.
(c) Variations in voltage cause a change in reactive power.
(d) Power factor of the machine decreases when the load is less than rated. This also reduces its effectiveness. Furthermore, it is equally important that losses in the supply external grid increase as well.

When selecting the induction generator, particularly for outputs up to 100 kW, we usually choose an available induction motor. In this respect, it is necessary to realize a few basic facts:

- The induction motor operating in the generator mode will have different output because the nominal motor output is the output on the shaft; in generators, it is the output on machine terminals,

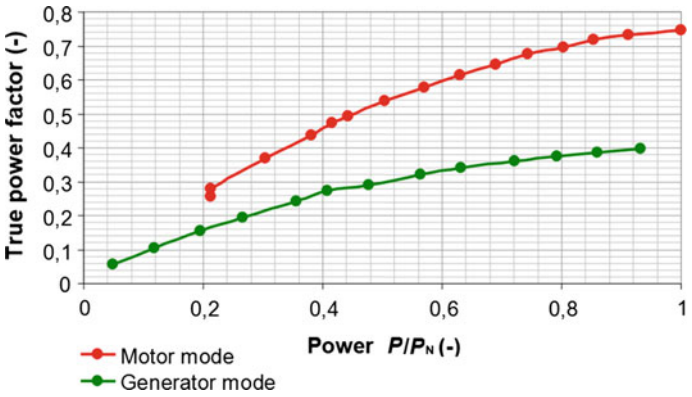


Fig. 2.21 The course of true power factor in induction machine 50 kW

- in generator operation, the machine will have a lower power factor because the internal induced voltage must compensate for voltage drop across the impedance of the stator to reach the rated voltage,
- efficiency in generator operation with maintaining the rated output on the shaft may be even higher because the mechanical losses are covered by the drive device.

These facts are evident from Fig. 2.21 which also shows the course of power factor subtracted by a circle diagram for 50 kW motor.

In machines with higher outputs, the difference for the motor area and generator area is not so large, as shown in Fig. 2.22 for 150 kW motor. Efficiency curves of the same machines are presented in Fig. 2.23 (Fig. 2.24).

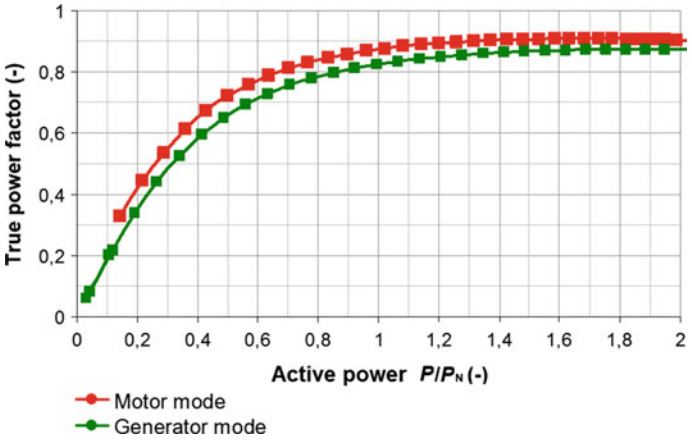


Fig. 2.22 The course of true power factor in induction machine 150 kW

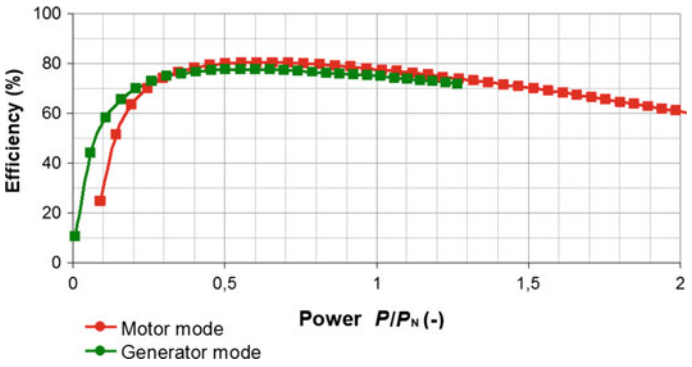


Fig. 2.23 Efficiency curve of induction machine 50 kW

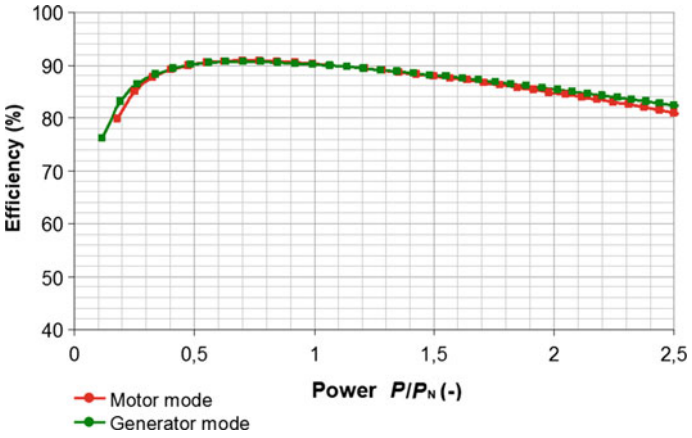


Fig. 2.24 Efficiency curve of induction machine 150 kW

The power factor differs in machines with different number of poles and different output within the same type range as already graphically shown in Fig. 2.20.

It is widely envisaged that the efficiency of the synchronous machines is usually higher than in induction machines. Comparison in Fig. 2.25 shows that this is not valid in general. Even this may be a criterion in deciding what kind of generator will be used. The same applies to the weight of these kinds of machines as evidenced by Fig. 2.26 [10].

Initially, the medium wind power plants were fitted with induction generators with a single squirrel-cage. Subsequently, modern wind power plants were using pole-changing induction generators (employing the method of changing the number of poles) or generators having a stator with a greater number of separate windings, eventually a combination of both. The reason for the expansion of the later solution is very prosaic and relates to the principle of conversion of the wind energy into

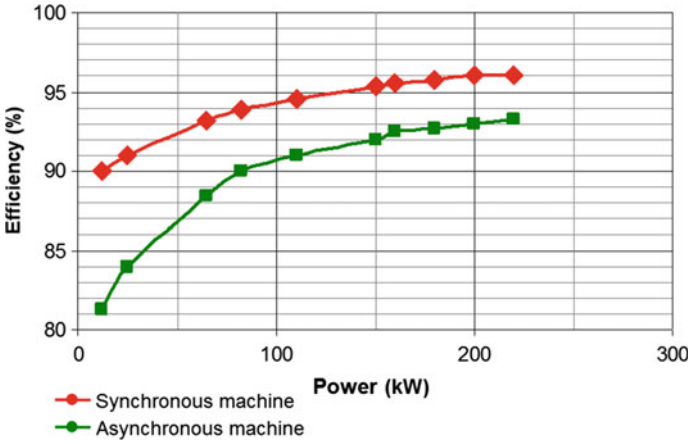


Fig. 2.25 Efficiency of synchronous and induction machines

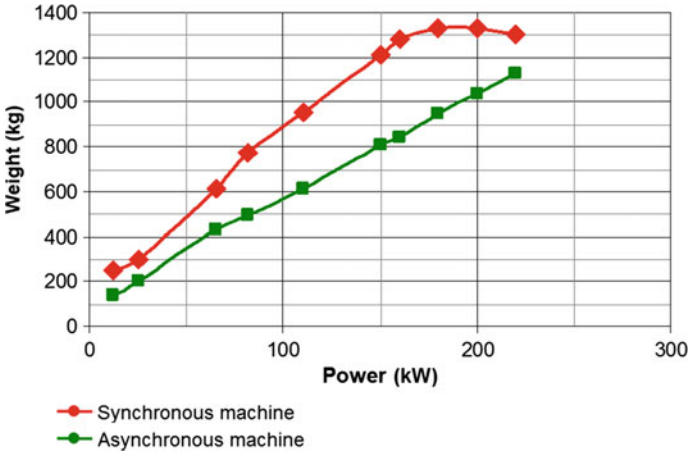


Fig. 2.26 Comparison of weights of synchronous and induction machines

electricity by wind power plants, which takes place according to the so-called power curve of the wind turbine, as already mentioned in previous chapters. Induction generators changing the number of poles better utilize wind flow energy for a wide range of wind velocities. At the start and lower torque and speed values on the wind motor shaft, they use the winding with higher number of poles; if the wind velocity and the corresponding mechanical output on the shaft of the wind turbine increases, the winding with lower number of poles is subsequently connected.

The steps of changing the speed correspond to synchronous speed at different number of poles. The stator has either a number of separate windings with different

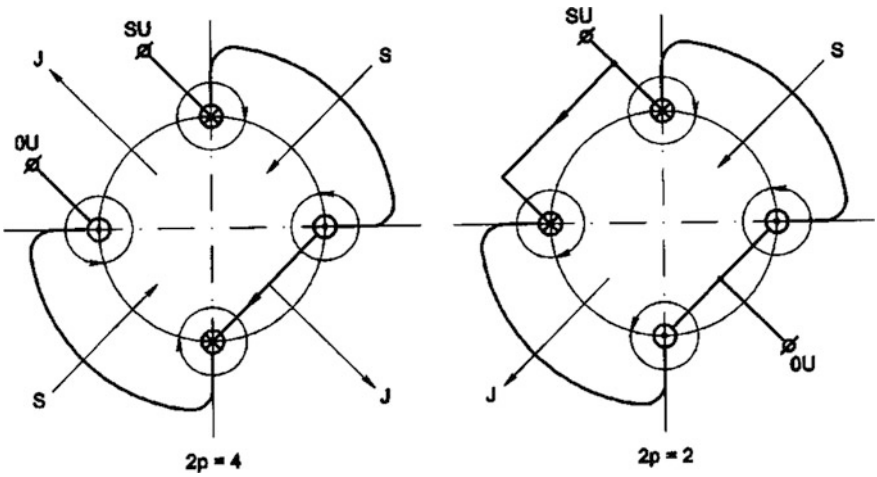


Fig. 2.27 The principle of Dahlander connection

number of poles or one switchable winding, or both methods are combined. Such a solution leads to an increase in the machine size and weight but provides the possibility of any speed ratio, e.g., 1/3 as well as 1/12 [8, 9].

When changing the number of poles, the windings must meet many requirements. The machine must mainly have the same sense of rotation within the entire speed range; the machine rated output power output must be determined for each speed, etc.

Creating a switchable winding meeting all the requirements is not easy and the solutions are usually patented. For switching a motor with one winding in ratio 1/2, the most frequently used system is the so-called Dahlander connection. Its principle is shown in Fig. 2.27.

In one phase, two coils of 4 poles winding are connected in series with brought-out neutral point. If both coils are connected in series, they form a 4 poles magnetic field. When connected in parallel, the magnetic field between the coils ceases and 2 poles magnetic field is formed. For 2 poles, the winding is less utilized because the winding step is reduced to 1/2 of the pole pitch (Figs. 2.28 and 2.29).

Induction motors usually use two ways of changing the number of poles:

- Wye (Y)—double wye switching.
- Delta (D)—double wye (YY) switching.

Y—YY Switching

Output power at Y connection is

$$P_y = 3\,\frac{U_N}{\sqrt{3}} I_f \eta_y \cos\varphi_y \tag{2.21}$$

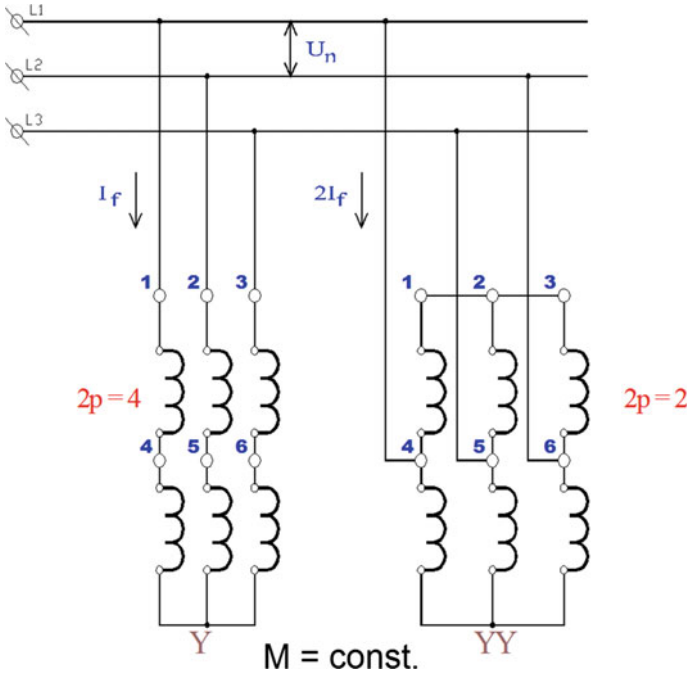


Fig. 2.28 Dahlander connection, wye—double star switching (Y–YY)

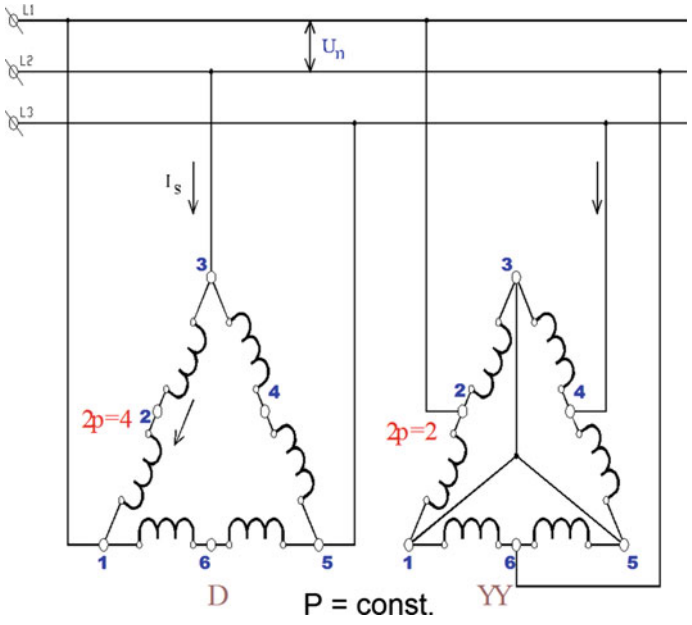


Fig. 2.29 Dahlander connection, delta—double star switching (D–YY)

where P is the active output, U_N is the rated voltage of the machine, I is the winding current, η efficiency and cos φ is the power factor of the machine.

At YY connection:

$$P_{yy} = 3 \cdot \frac{U_n}{\sqrt{3}} \cdot 2 \cdot I_f \cdot \eta_{yy} \cdot \cos \varphi_{yy} \tag{2.22}$$

For approximate assumption that the power factors and efficiencies are the same ($\eta_y \cdot \cos \varphi_y = \eta_{yy} \cdot \cos \varphi_{yy}$), it holds that

$$P_{yy} = 2 \cdot P_y \tag{2.23}$$

Because the turbine moment (torque) $T \approx \frac{P}{n}$ and because $n_{yy} = 2n_y$, the moment will be the same in both cases, i.e., $T_{yy} = T_y$.

D—YY switching

Phase voltage at the delta connection will be $U_{fd} = U_n$,

$$P_y = 3 \cdot \frac{U_n}{\sqrt{3}} \cdot I_s \cdot \eta_y \cdot \cos \varphi_y \tag{2.24}$$

At YY connection:

$$P_{yy} = 3 \cdot \frac{U_n}{\sqrt{3}} \cdot 2 \cdot \frac{I_s}{\sqrt{3}} \cdot \eta_{yy} \cdot \cos \varphi_{yy} \tag{2.25}$$

Again, assuming the same power factors and efficiencies, the following applies

$$P_{yy} = \frac{2}{\sqrt{3}} P_d = 1.16 P_d \tag{2.26}$$

The output is therefore constant (almost); Torque T_d then will approximately $2T_{yy}$. Machine output or torque at certain speed is given by load torque of the driven machine. Therefore, the term "switching at constant output or moment" characterizes the fact that the motor can operate with the respective output or torque without the danger of thermal overload.

However, when changing the number of poles, there are switching transients causing the emergence of switching surges (overvoltages). Switching overvoltages strain the winding insulation; it is therefore essential to choose an appropriate control system to limit these surges. Obviously, the magnitude of these surges is affected by the moment of the transient inception, the magnitude of the instantaneous generator load (RLC parameters of the generator) and the moment at which individual contacts are closed. Figure 2.30 shows the voltage of the Y and YY winding terminals during one switching cycle of the test induction machine 0.65/2.5 kW, 700/1400 min^{-1}. At 0–Y–YY–Y–0 switching cycle, the largest overvoltage was measured when disconnecting the wye connection [see Fig. 2.30,

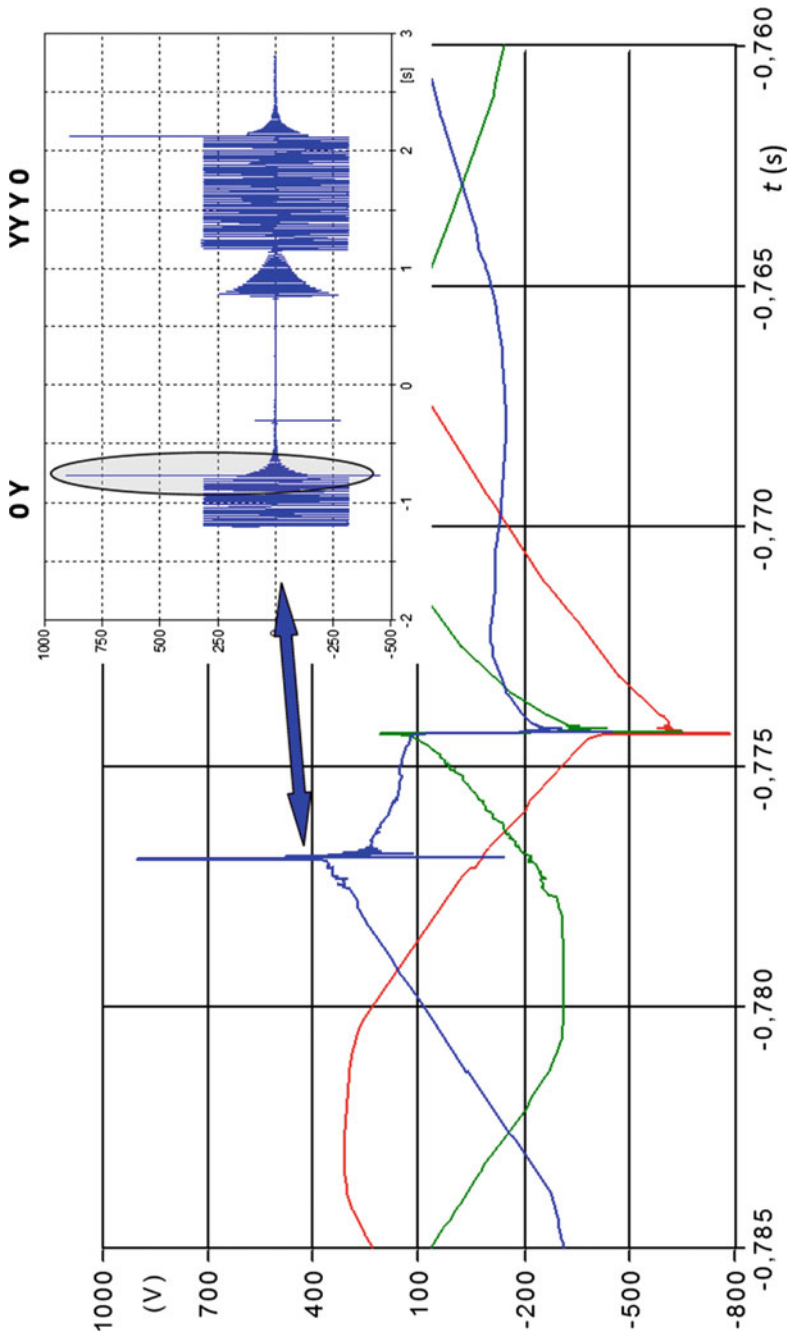


Fig. 2.30 Overvoltage formation when switching the number of poles

voltages U_1, U_2, U_3 (V)]. Magnitude of the first amplitude of the transient is 900 V for time of 20 μs; steepness of the voltage rise is therefore 45 kV m s^{-1}.

Magnitude of overvoltage amplitudes is limited due to increasing load of the generator. With a suitable control system, these peaks can be reduced. The mentioned conclusion was confirmed by practical measurements in the wind power plant; this wind power plant uses an induction generator changing the number of poles to 6/8 and measurements did not find overvoltage peaks in the range presented in Fig. 2.30.

Figure 2.31 shows the already mentioned output curve of the wind power plant, which is the main characteristic of each wind power plant, necessary for determining the overall efficiency of the wind power plant operation, e.g., through utilization ratio as defined in the preceding chapters, as well as for determining its appropriate location. Figure 2.31 explains the process of changing the number of poles: 8 poles active winding is used for the area specified by speeds of 4–6 m s^{-1} (the so-called starting phase) while 6 poles active winding is used for the area defined by speeds of 6 m s^{-1} and above (the so-called operational phase). The output curve was constructed for a wind power plant with double squirrel cage induction generator, rated output of 150/30 kW, with the corresponding system for changing the number of poles to 8/6 and speed of 758/1012 min^{-1}.

A simplified block diagram of the control system of this wind power plant equipped with the induction generator with a double squirrel cage and the system

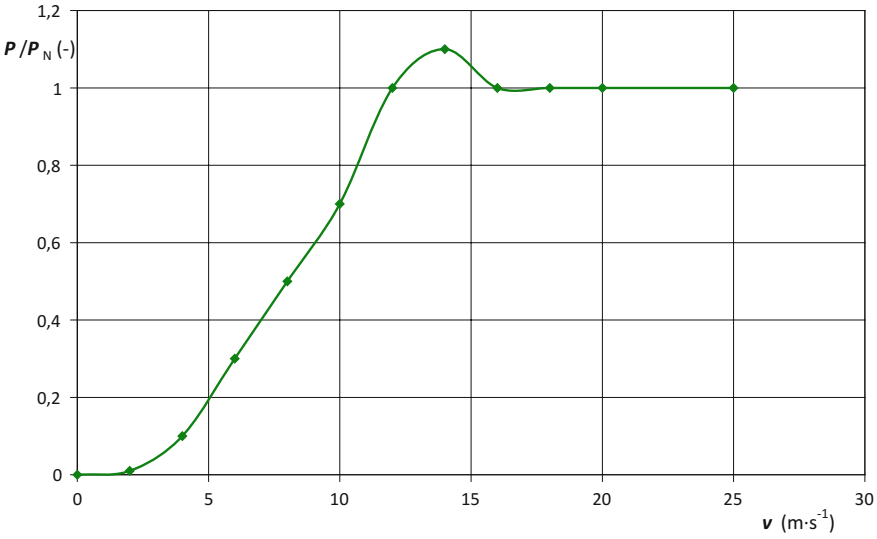


Fig. 2.31 Output curve of the WPP fitted with induction generator 150/30 kW with short-circuit armature and the system for changing the number of poles

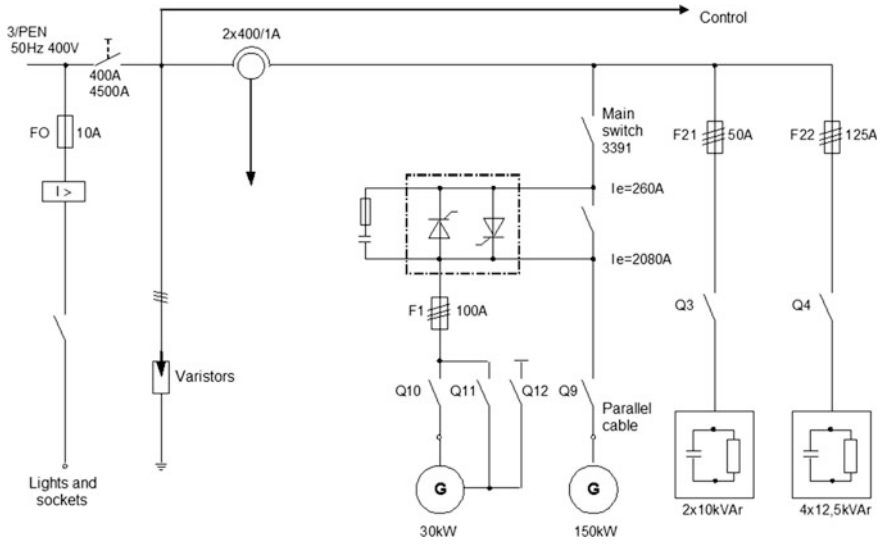


Fig. 2.32 Simplified block diagram of the control system of WPP equipped with the squirrel-cage induction generator and the system for changing the number of poles

for changing the number of poles is shown in Fig. 2.32. The algorithm for connecting and operating the analyzed wind power plant is very simple.

The control system monitors the wind speed; if the speed exceeds the first level W1, the WPP is unbraked and the vanes of the wind turbine are swivelled in breakaway angle. Faster rotation of the aggregate is ensured by operation in the machine motor range.

Upon exceeding the second wind speed level W2, the system breaks into standby mode; the motor drive is disconnected when the wind speed excess persists. After reaching the synchronous speed for the respective winding, the WPP is connected to the parent electricity external grid via a soft starter (motor controller) whereas the connected stator winding is that with a higher number of poles.

The soft starter limits the current surge and torque on the shaft of the WPP generator which subsequently reduces mechanical shocks as well as voltage drops in the power system at the connection point. Through controlling the phase angle of the thyristor in antiparallel connection, the voltage on the generator terminals is reduced to the set initial value and smoothly increases to full voltage value within the set interval using a ramp function. Comparison of the direct connection of the wind turbine to the external grid and the connection via the soft starter is presented in Figs. 2.33 and 2.34.

If the wind speed (i.e., WPP speed) falls below a specified level, the WPP is disconnected and waits until the condition for exceeding the limit W2 is met again. If the limit W2 excess persists for a set period (usually about 5 s), the winding with a lower number of poles is connected directly outside of the soft starter.

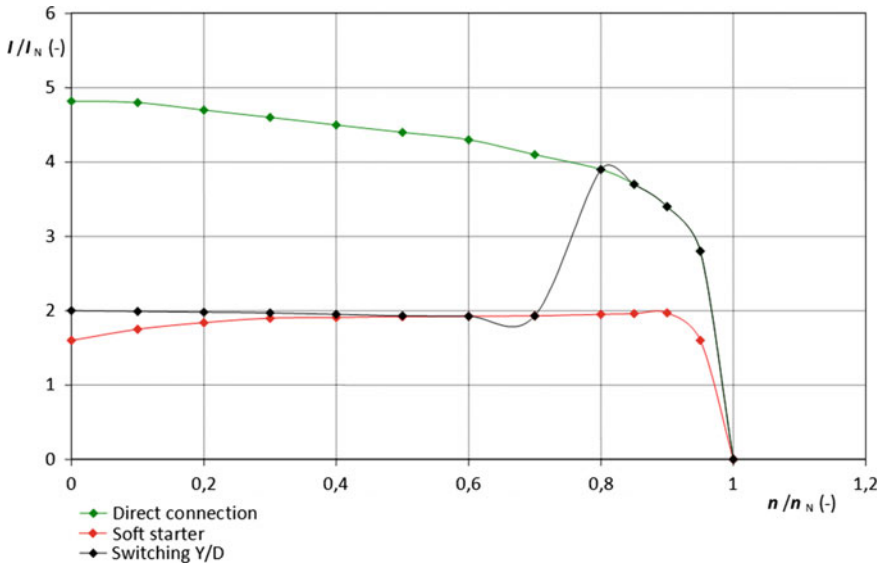


Fig. 2.33 The course of current effective values

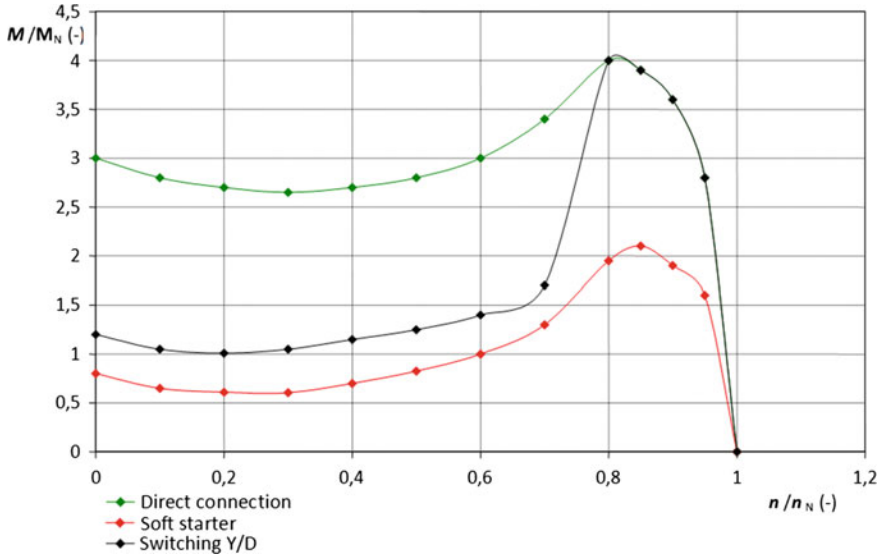


Fig. 2.34 The machine torque characteristic

Once the generator operates in parallel with the distribution external grid, the WPP system involves a compensation unit to compensate for the low power factor of the generator. Courses of electrical quantities when connecting the wind power plant to the distribution external grid are shown in detail in Figs. 2.35 and 2.36.

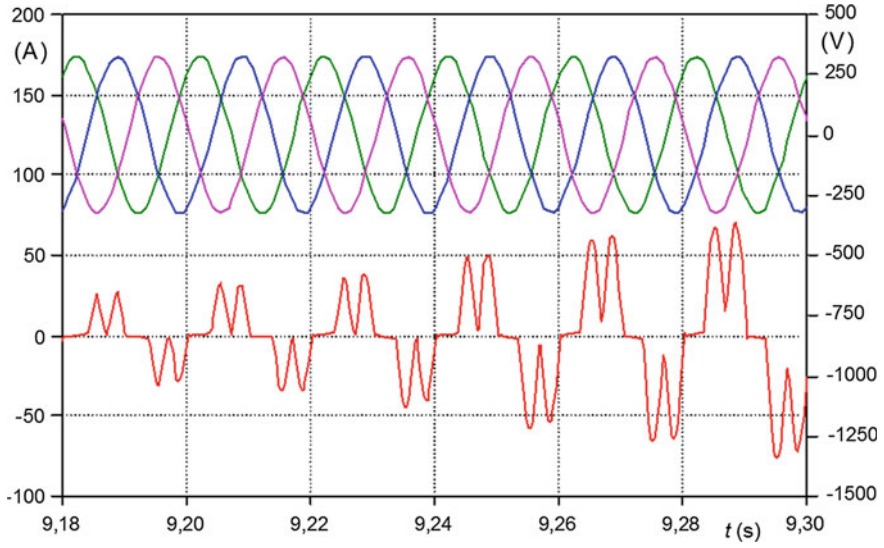


Fig. 2.35 The cycle of connecting the generator to the external grid, soft start detail, course of voltages U_1 (*green*), U_2 (*blue*), U_3 (*pink*) (V) (*right axis*) and current I_1 (*red*) (A) (*left axis*) (color figure online)

In area 1, the wind turbine is run by the generator which operates in the motor mode and is connected to the external grid via soft-start. When the wind turbine rotates, the generator is disconnected from the external grid; if the aggregate speed rises above the synchronous speed, the device is reconnected to the external grid using the soft-start, as seen from area 2—see Fig. 2.36.

Although using the soft start, there are transient phenomena associated with the current and torque strain of the device, which is reflected especially voltage fluctuations at the connection point, etc.

After determining the appropriate generator, the other basic factors include the way of connection to the distribution external grid and the selection of measuring and control equipment. The way of connecting the wind power plant to the external grid (external grid) is provided by the competent operator of the external grid on the basis of the given external grid conditions, power and the method of wind power plant operation mode. It is important to choose an appropriate switching device. During switching, there can be short-term changes in voltage; for wind power plants with the connection point in the low-voltage external grid the allowable tolerance is ≤ 3 % of the rated voltage unless the switching occurs more frequently than once every 1.5 min. In wind power plants with induction generators, short-term declines may occur during the connection at approximately asynchronous speed due to internal transients. Such a decline may reach a double of otherwise allowable value (approximately 6 % for low-voltage external grid) unless in interval longer than 2 periods. For wind power plants, it is necessary to

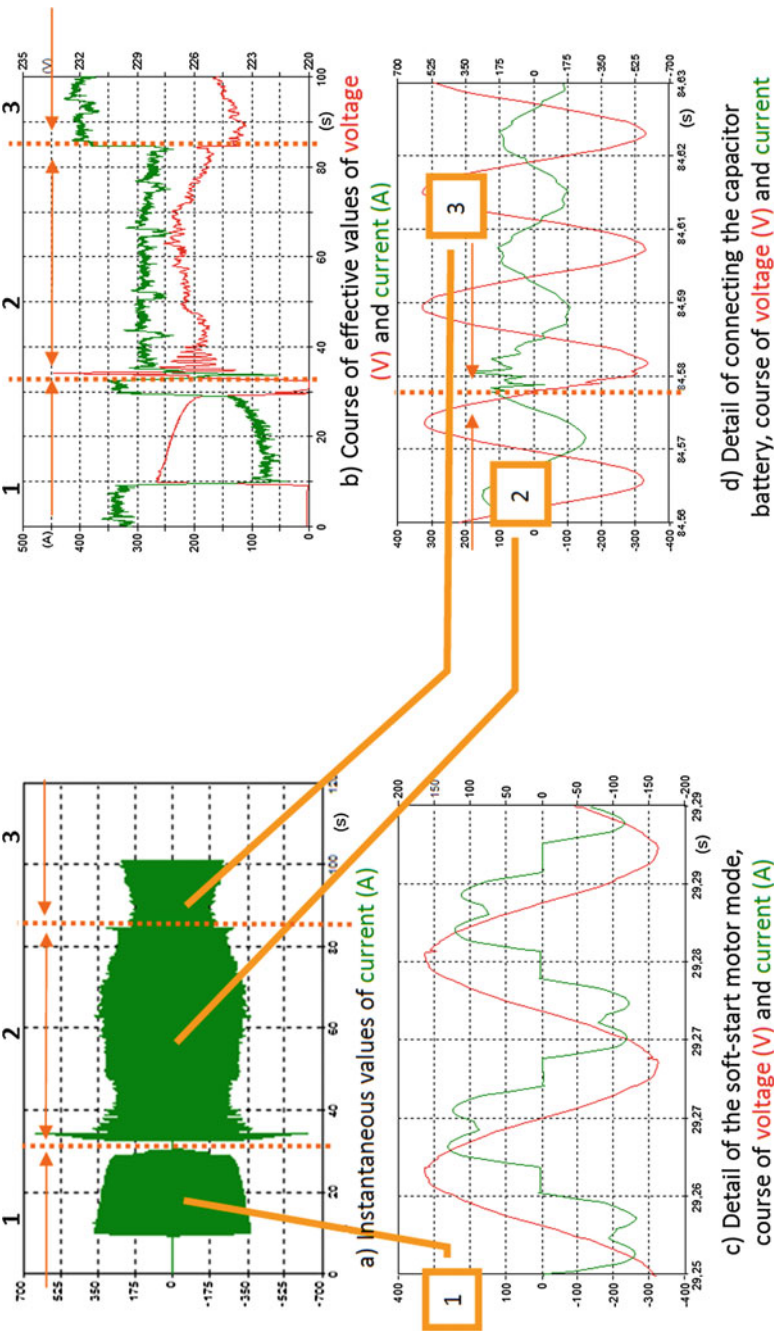


Fig. 2.36 The process of connecting the wind power plant to the external grid

consider a special switching factor dependent on the control system conditions, which is used to evaluate their switching and which also respects the mentioned ultra-short transients.

Figure 2.36b shows the mentioned voltage drop at the time of connecting the wind power plant to the value of about 221 V—this is associated with a percentage change of 4.3 % which is not in accordance with the prescribed value for low-voltage connections. At the moment of direct connection (process 2) at approximately synchronous speed, there is again a short-term decline of about 4.2 % which meets the limit of 6 % for WPPs; nevertheless, the decline is outside of the range of 2 periods.

For switching, i.e., connecting the wind power plant to the external grid, the so-called current surge factor is defined. This factor is given by the ratio of the inrush current surge to the rated current of the generator and is equal to 4 for induction generators connected with 95–105 % of synchronous speed.

Reactive power control applies to sources of 5 MW and above. These sources must be equipped for some of the following modes of reactive power control: maintaining the specified power factor, maintaining the desired value of reactive power (take-off/supply) within the operating machine diagram, maintaining the voltage in the transfer point (block connection of a generator and the block transformer). The generator must be able to supply power in the range of power factors of 0.85 (supply of the reactive power of inductive nature) to 0.95 (generator running in an underexcited state) at the permitted range of voltage on the generator terminals and at frequency in the range of 48.5–50.5 Hz. In the compensating device of sources, it is necessary to consider the manner of production operation and the resulting reverse effects on the system voltage. When the drive of wind power plants heavily fluctuates, the reactive power compensation must be automatically and sufficiently quickly regulated.

Figure 2.37a shows the course of power factor at the switching process of connecting the wind power plant to the external grid. The figure clearly presents the variance of a power factor, from 0.56 for the inductive character to 0.98 for the capacitive character. For 2-step compensation device connected to the analyzed wind power plant according to the block diagram in Fig. 2.32, it is clear that the compensation is insufficient, mainly in the area of motor starting. Inadequacy of the compensation is also enhanced by the difference in output ratios when operating the pole-changing generator (changing the number of poles to 6/8) which corresponds to the rated power of 150/30 kW. The course of connecting the capacitor battery is shown in detail in Fig. 2.37b.

Figure 2.37 demonstrates the distortion due to parallel resonance between the stray reactance of the transformer, the reactance of the generator and the sum of all external grid capacitances including the compensating device, which is evident from the course of currents. Connection of the capacitor battery is also accompanied by the formation of overvoltage (up to 1.5)—see Fig. 2.37.

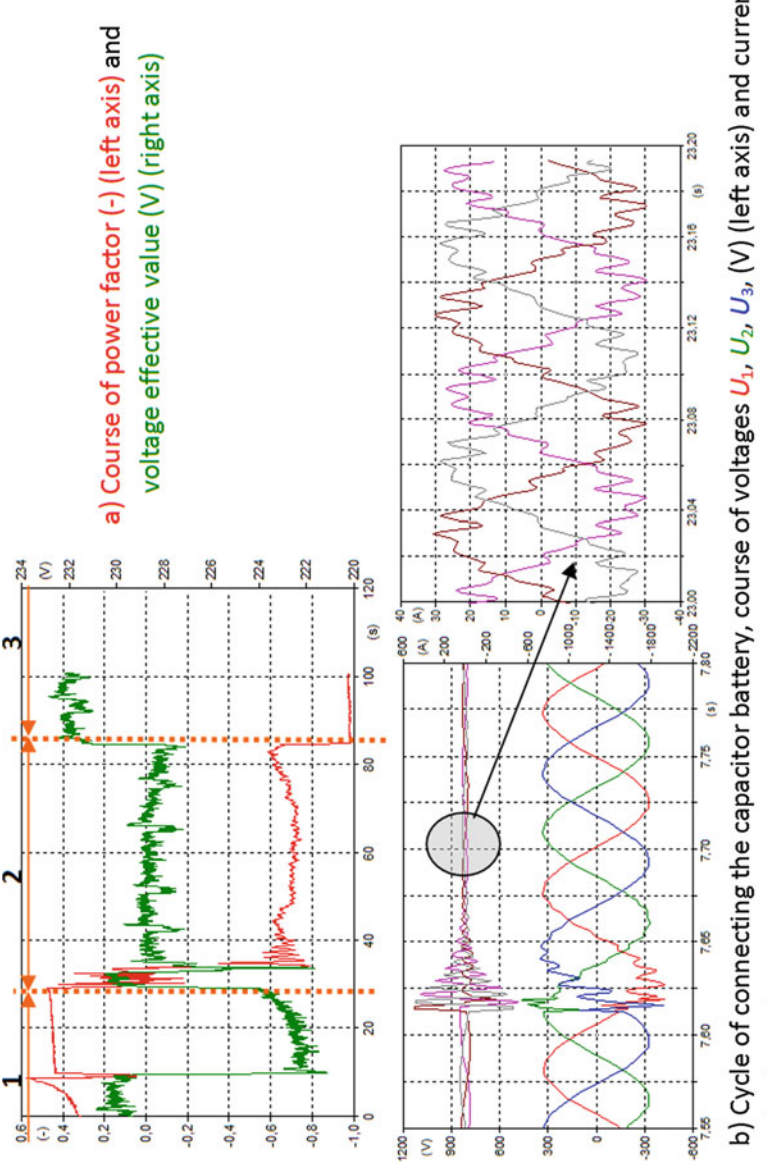


Fig. 2.37 Analysis of the process of connecting the wind power plant to the external grid—detail the compensation device connection

2.3 Large Wind Power Plants

In recent years of the development of wind power plants (WPPs) in the Czech Republic, the investors therefore mainly preferred construction of high-capacity wind power plants (large wind power plants); with regard to a substantial increase in the height of the wind power plant tube, the priority for their construction was not high altitude as they can also be used in lowland sites. In the case of building modern high-capacity power plants, mainly the following fundamental trends of development were respected:

- increase in the WPP unit output associated with the increased size of the wind turbine rotor,
- increase in the WPP tube height,
- improvement in the quality of WPP technology and the consequent reduction in fault rate, noise and other negative impacts,
- reduction in the unit costs of WPP construction and operation, etc.

Unlike medium and low-capacity WPPs, the high-capacity WPPs use of wind turbines with swivelling propeller blades, i.e., the pitch type regulation, which allows adjustment of the blades according to the current wind speed through their swivelling. A further substantial difference from the medium and low-capacity WPPs is the location of the transformer (typically with the ratio of transformation of 0.69/22 kV) directly in the WPP nacelle where it also balances the relatively large masses of the turbine, generator and semiconductor technology. A typical arrangement for high-capacity WPPs, together with a basic description, is presented in Fig. 2.38.

The wind turbine blades are usually made of plastics reinforced with glass fibres whereas the reinforcement can also be made using carbon fibres or laminates. Some blades are fitted with technologies for protection against lightning strikes. In cold areas, the blades are equipped with a heating device to prevent icing. Angle of the blades is controlled by a control system and is usually adjusted by a hydraulic system or electric motors. The pitch type regulation also allows for a more even start of the turbine when the wind speed rises (Table 2.2).

To achieve an optimal gear ratio, the high-capacity WPPs are fitted with a planetary gearbox with variable transmission ratio. The planetary gear consists of a sun gear (central gear), satellites, the satellite carrier and the ring gear. The sun gear, ring gear and the satellite carrier have a common axis. The satellites are placed on the carrier and are engaged in the central as well as ring gear. The basic advantages of the planetary gearbox include:

- smaller dimensions compared to conventional gearboxes,
- simpler shifting due to gears in constant engagement,
- longer lifespan of gears than in conventional gear units,

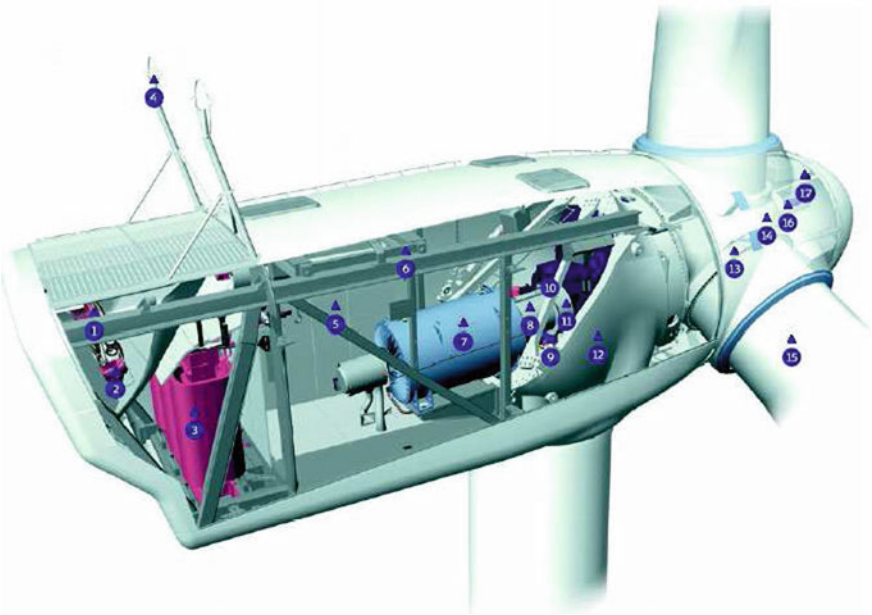


Fig. 2.38 Structural division in the nacelle of a large WPP (VESTAS V90)

Table 2.2 Components of large wind power plants

1	Oil cooler	10	Gear unit (gearbox)
2	Cooler of water for the generator	11	Mechanical clutch
3	Transformer	12	Machine frame
4	Ultrasonic wind sensor	13	Bearing of the rotor blades
5	Inverter control panel	14	Rotor head
6	Service crain	15	Turbine blade
7	Generator	16	Cylinder for adjusting the angle of inclination
8	Composite clutch	17	Controller for adjusting the angle of inclination
9	System for swivelling the nacelle		

- easy achievement of large gear ratios with respect to the dimensions,
- torque reaction only, symmetric distribution of the load, more gear combinations.

Its drawbacks may include higher bearing loads, more complex design and higher cost compared to conventional transmissions. The operating principle is illustratively shown in Fig. 2.39.

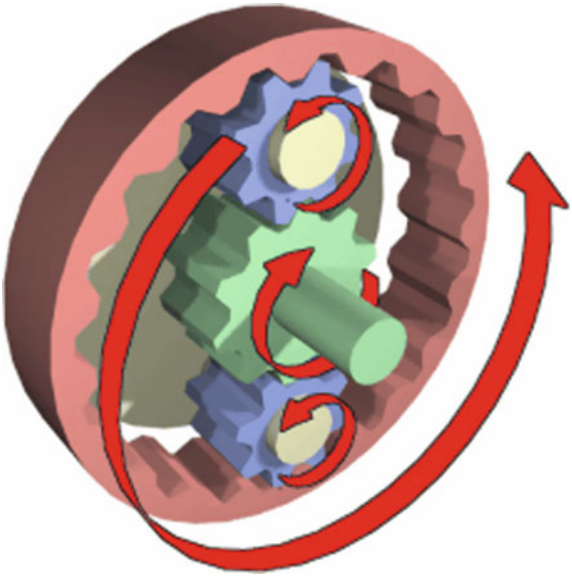


Fig. 2.39 The operating principle of planetary gearboxes

2.3.1 Control Systems for High-Capacity Wind Power Plants

High-capacity WPPs, i.e., wind power plants with their capacities in the range of hundreds of kV·A up to units or tens of MV·A, are characterized by bringing the output on the generator terminals to the external grid through power electronics which helps to optimize the plant operation including the connection process, regulation for maximum wind energy utilization within a wide range of wind speeds and provision of qualitative elements of the electric energy. After various prototype solutions, the control systems for high-capacity wind power plants have settled on two essential solutions that differ from each other by the type of generator used and the method of connecting the power electronics-converter through which the output from wind power plants is brought into the external grid.

2.3.2 WPP Control System Cooperating with Frequency Converters

Currently, the high-capacity (usually 850 kW) wind power plants mostly use control systems with induction generators with wound rotors utilizing cooperation with a frequency converter with recuperative unit. It is a system in the so-called "cascade connection". When works the WPP control system with frequency

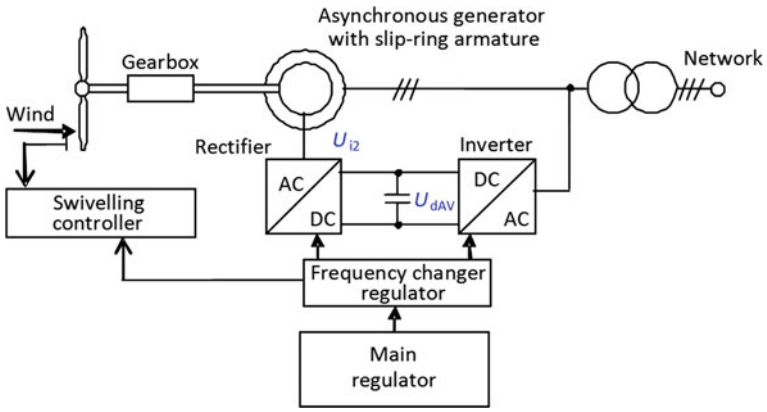


Fig. 2.40 The system of wind power plant with frequency converter in the cascade connection

converter, it is possible to better use the wind energy flow and ensure a more stable supply of electricity to the external grid.

If the system works in cascade, the generator stator is directly connected to the electricity supply system (through a low voltage/medium voltage transformer) and the wound rotor of the generator is powered from the frequency converter.

It is a special connection of indirect frequency converter consisting of two thyristor bridges. The converter is connected between the rotor of the slip-ring induction motor with a slip frequency and the external grid (Fig. 2.40).

The control principle is as follows: Voltage u_{i2} is induced in the rotor of induction machine and the control voltage is brought against from the converter. This control voltage is actually the voltage of the DC intermediate circuit, $U_{d\mathrm{AV}}$, that is set using the control angles of the inverter consisting of a 3 phase thyristor bridge operating in an inverter mode. When the control voltage is changed, u_{i2} changes in the same way; e.g., if increased, u_{i2} grows—therefore, the slip must increase and the speed falls accordingly. If the control voltage is zero, i.e., for the control the angle $\alpha = 90°$, the speed is approximately synchronous. Speed control through the slip when using control voltage is also utilized in classical loss control by rotor resistors where its function is represented by voltage drop across these resistors. This drop, however, is dependent on the load and the torque characteristic therefore becomes softer. In the cascade control, the control voltage is independent of the load and torque characteristics are the same as in the frequency control [11].

To determine the power balance when operating the system in subsynchronous cascade, it is possible to rely on general relations for output ratios of induction machines.

The following holds for the machine moment (torque):

$$M = \frac{P}{\omega} = \frac{P_\delta(1-s)}{\omega_1(1-s)} = \frac{P_\delta}{\omega_1} \tag{2.27}$$

where P_δ is the output in the air gap, ω is the angular velocity of the rotor and ω_1 is the angular velocity of the stator field, i.e., synchronous angular speed.

On small slips, almost entire P_δ is consumed for the mechanical output according to the following relation

$$P = P_\delta(1 - s) \tag{2.28}$$

Oh higher slips, however, the remaining, the so-called slip output $s \cdot P_\delta$, is redundant. The synchronous cascade transfers it back to the external grid; under resistance control, it is converted into heat output, i.e., power dissipation.

The cascade is therefore advantageous, both in terms of control and economy.

2.3.3 Switching the Wind Power Plant in the External Grid

Operation of the WPP control system in cooperation with the frequency converter is mostly ensured by multiprocessors. The control system evaluates the wind velocity and wind turbine speed; the torque characteristic of the machine is adapted accordingly. The course of voltage and current on the generator rotor is therefore controlled in order to maximally utilize the wind energy assuming minimal negative impacts on the external grid. The output power controlled by the frequency converter is fractional compared to the generator output; therefore, its effects on the distribution external grid can be negligible. The control system also ensures connecting to the external grid with minimal current surges in generator operation and without significant overvoltage events.

Figure 2.41 shows a detail of the connection of a WPP system with induction generator with wound rotor in the so-called cascade connection (2 MW, 690 V, D connection). Figure 2.41 demonstrates the optimization of the WPP connection to the external grid without high-frequency transients, with current surges corresponding maximally to 1/3 of the rated current of the generator. In modern WPPs, these current surges are further limited by switching the Y–D stator winding.

Special rotor winding is energized through rings from the four-quadrant frequency converter. A choke and sinusoidal filter are placed between the converter and the rotor winding in order to smooth the voltage and current waveforms.

For switching, i.e., for connecting the wind power plant to the external grid, the so-called current surge factor is defined by [5]. This factor is given by the ratio of the inrush current surge to the rated current of the generator is equal to 4 for induction generators connected with 95–105 % of synchronous speed.

A priority for the operator of the external grid is maximum elimination of adverse effects of the WPP operation on the external grid. These effects are primarily caused by the way of connecting the wind power plant generator to the external grid, parameters of the external grid connection point (short-circuit capacity) and the choice of the measuring and control equipment. The way of

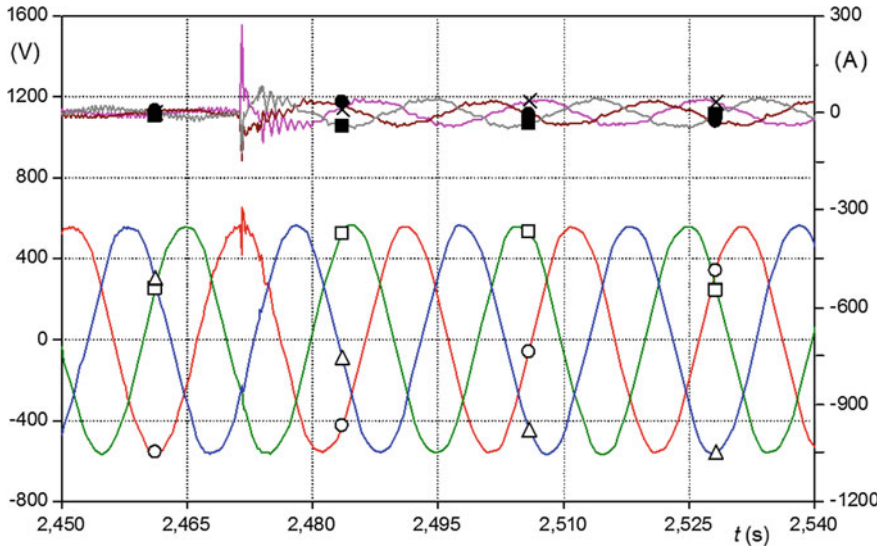


Fig. 2.41 A detail of the connection of the system with induction generator with wound rotor in the cascade connection, the course of phase voltage U_1 (*red*), U_2 (*green*), U_3 (*blue*) (V) (*left axis*) and stator winding currents I_1 (*pink*), I_2 (*brown*), I_3 (*grey*) (A) (*right axis*) (color figure online)

connection to the distribution external grid is provided by the competent operator of the external grid on the basis of the given external grid conditions, power and the method of production operation. It is important to choose an appropriate switching device. During switching, there can be short-term changes in voltage; according to [5], for power plants with the connection point in the LV external grid, the allowable tolerance is ≤ 3 % of the rated voltage unless the switching occurs more frequently than once every 90 s. In wind power plants with induction generators, short-term declines may occur during the connection due to internal transients. Such a decline may reach a double of otherwise allowable value (approximately 6 % for low voltage) unless lasting longer than 2 periods [5]. For wind power plants, it is necessary to consider a special switching factor dependent on the system conditions, which is used to evaluate their switching and which also respects the mentioned ultra-short transients.

For comparison, Fig. 2.42 shows the course of instantaneous values of the phase voltage at the connection point for the WPP for the system with squirrel-cage induction generator (150 kW, 400 V, D connection) and the system with induction generator with the wound rotor in the cascade connection (2 MW, 690 V, D connection) at the moment of connecting the WPP to the power supply system (time 12 ms in Fig. 2.42). Figure 2.42 again clearly demonstrates the following: if the process of connecting the WPP to the external grid is optimized using the control by recuperative frequency converter (U_{1f} in Fig. 2.42), there is no significant transient affecting the steady course of the system voltage. If the wind power

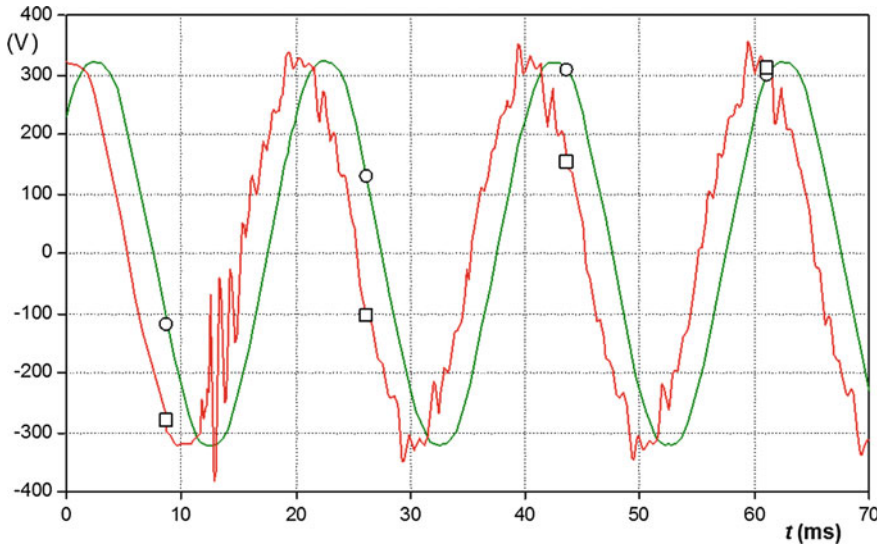


Fig. 2.42 The course of instantaneous values of phase voltage at the WPP connection point for the system with squirrel-cage induction generator (*red*) and the system with induction generator with wound rotor in the cascade connection (*green*) (color figure online)

plant is connected to the external grid via a thyristor starter, the current surge is limited but overvoltage may be present (U_{1f} in Fig. 2.42) [12].

2.3.4 *Comparison of Different Systems of Wind Power Plants*

Using the results of experimental measurements on wind power plants with various capacities and control systems, we analyzed switching processes in three systems used in WPPs with rated capacity of about 1.5 MV·A for a synchronous machine, and 1.4 in the range of 1–1.6 MW for an induction machine.

Particularly, the following systems were involved:

- Control system with a synchronous generator with separate excitation and direct connection to the external grid.
- System with an squirrel-cage induction generator and direct connection to the distribution external grid.
- Control system with an induction generator with wound rotor and frequency converter in the cascade connection.
- Analysis of reverse effects of switching processes was carried out for the same conditions of the actual load setup, the same power system topology and identical conditions of the mechanical input on the shafts of individual generators.

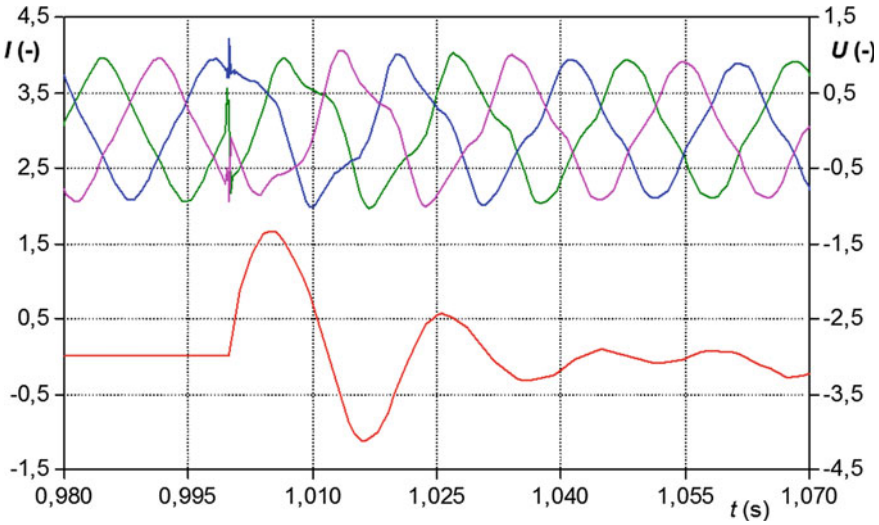


Fig. 2.43 The course of instantaneous voltage values at the connection point U_1 (*blue*), U_2 (*green*), U_3 (*pink*) (–) and one phase current I_1 (*red*) (–); a detail of the WPP connection—synchronous generator (color figure online)

Specifically, the switching processes were evaluated according to the following parameters:

- relative current surge at the moment of connection I/I_N,
- relative voltage change at the connection point at the moment of connection U/U_N,
- THD voltage at the moment of connection and in the steady-state of the generator operation of the analyzed machine.

Figure 2.43 shows a detail of the connection of the WPP with synchronous generator and the system of direct connection to the distribution external grid. At the moment of connection, we simulated the conditions for connecting the synchronous generator excited to the rated value at the connection point and the difference in frequencies up to about 15 % of the system frequency while respecting the direction of rotation and the phase sequence. The figure demonstrates the current surge with the relative value of 1.58, subsequently causing a percentage change in voltage at the connection point up to the relative value of 1.02. The resulting values are always relative to the rated current of the given generator and the rated voltage value at the connection point of the WPP. The figure also shows the voltage waveform distortion; this distortion disappears in the steady state and THD settles at the value of 1.1 %.

Connection of an squirrel-cage induction generator and the system of direct connection to the distribution external grid is shown in Fig. 2.44. The induction

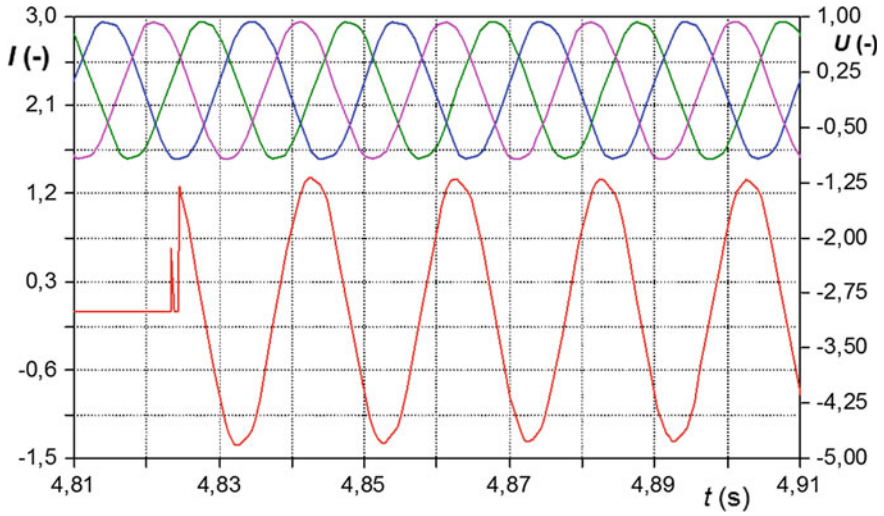


Fig. 2.44 The course of instantaneous voltage values at the connection point U_1 (*blue*), U_2 (*green*), U_3 (*pink*) (–) and one phase current I_1 (*red*) (–); a detail of the WPP connection—induction generator (color figure online)

generator was connected as non-excited; for the graphic demonstration, we have chosen the state of connection at generator speed approaching the synchronous speed (−2 %). This resulted in a current surge with amplitude having a relative value of 1.2 (Fig. 2.45).

At the moment of connecting the compensation, we observe a similar surge, but reactive in its nature, and the corresponding voltage waveform distortion at the connection point with amplitude of about 1.2 which disappears after about 2 waveform periods.

Figures 2.46 and 2.47 show the voltage and current waveforms for the last analyzed system, i.e., the system with induction generator with a wound rotor and frequency converter in the cascade connection. It is the most commonly used system in the Europe; in terms of the observed parameters, it exhibits lower values of the current surge and percentage changes in voltage as evidenced by Fig. 2.46 where the resultant value of the current surge does not exceed 50 % of the rated current. Figure 2.46 further demonstrates the course of voltage at the connection point and the course of one current phase in the steady state of the generator operation (Table 2.3).

Furthermore, a comprehensive evaluation of the systems was performed on the basis of:

- the results obtained from experimental measurements of the team of authors,
- the analysis of the database of faults for selected types of control systems (criterion—reliability),
- offering sheets (criterion—price).

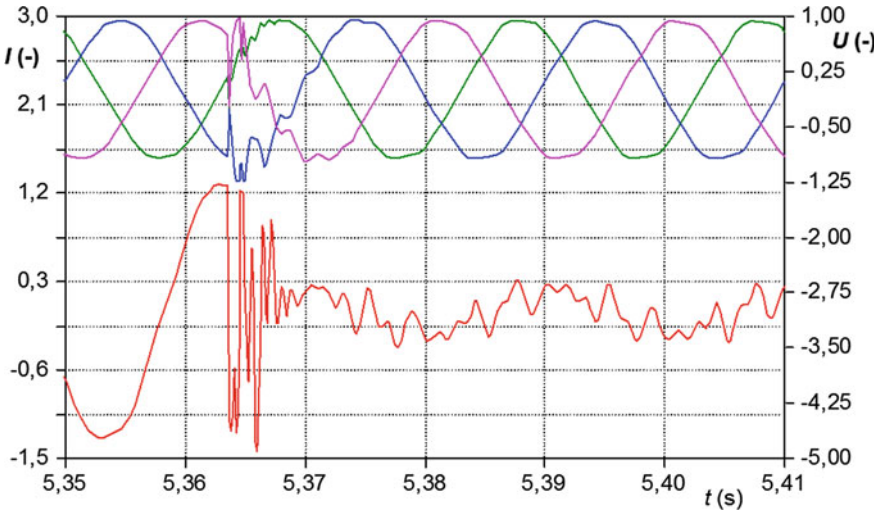


Fig. 2.45 The course of instantaneous voltage values at the connection point U_1 (*blue*), U_2 (*green*), U_3 (*pink*) (–) and one phase current I_1 (*red*) (–); a detail of the WPP compensation connection—induction generator (color figure online)

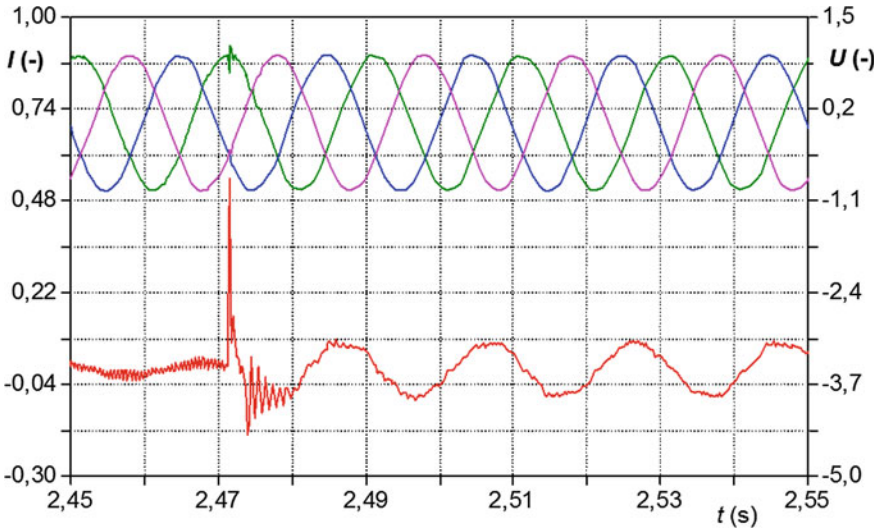


Fig. 2.46 The course of instantaneous voltage values at the connection point U_1 (*blue*), U_2 (*green*), U_3 (*pink*) (–) and one phase current I_1 (*red*) (–); a detail of the WPP connection—induction generator with frequency converter in the cascade connection (color figure online)

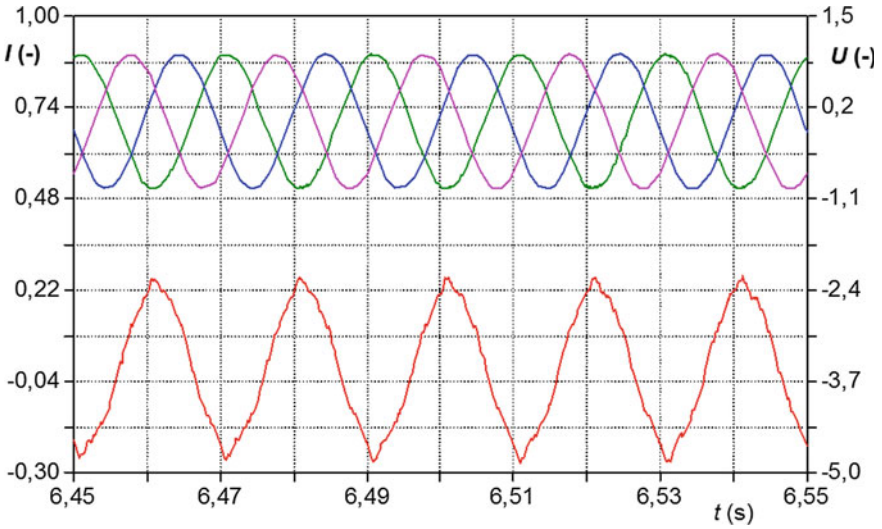


Fig. 2.47 The course of instantaneous voltage values at the connection point U_1 (*blue*), U_2 (*green*), U_3 (*pink*) (–) and one phase current I_1 (*red*) (–); a detail of the WPP operation in the generator mode—induction generator with frequency converter in the cascade connection (color figure online)

Table 2.3 The final evaluation of the WPP control systems

Source	Connection status	I/I_N	U/U_N	THD
SG	Optimal	1.12	1.03	1.1
	Speed +1 %	1.46	1.02	1.1
	Voltage +1 %	1.12	1.02	1.1
	Voltage −1 %	1.07	1.02	1.1
	Dephasing 5°	1.17	1.02	1.1
	Dephasing 15°	1.58	1.02	1.1
	Dephasing 30°	2.37	1.02	1.1
	Dephasing 45°	2.39	1.02	1.1
	Output outage 50 %	0.63	1.01	1.1
	Optimal	1.2	0.95	1.8
ASG	Speed +10 %	2.5	0.90	1.8
	Speed −10 %	2.5	0.90	1.8
ASG + FR-ME	Independent	By setting (<1)	RMS—no effect (<1)	3.2

The resulting evaluation is shown in Table 2.4 where the scores of 1 and 5 correspond to the best and the worst rating, respectively.

For an optimum process of connecting to the external grid, the synchronous generator with separate excitation and direct connection needs a phasing device ensuring the synchronization of waveforms of the machine output voltage and the voltage at the connection point. However, even in the case of optimum connecting

Table 2.4 Overall evaluation of the WPP control systems

	Synchronous generator with separate excitation	Induction generator with direct connection	Induction generator in the cascade connection with frequency converter
Steady-state THD voltage	2	2[a]	3
Current surge at the moment of connection	3[b]	3	1
Voltage change at the moment of connection	3	2[c]	1
Utilization of torque on the wind turbine shaft for the given wind velocity	4	4	1
Possibility of regulating the reactive power	1	5	1
Price	3	1	2
System reliability	3	1	3

1—best, *5*—worst

[a]Valid for a steady state after connecting the compensation battery

[b]Valid in the case of ensuring optimal phasing conditions

[c]Valid in the case of connecting a non-excited machine (without the capacitor battery)

process, there is a current surge having mainly active character—with regard to the accuracy of measuring the phase shift of voltage signals and the corresponding change in the frequency of connected source systems (score 3). The dynamic current surge then causes a short-term voltage drop about 2 periods of the voltage signal (score 3). The quality of the supplied power and the corresponding THD value of the voltage signal is primarily derived from using semiconductor elements in the control system of the WPP with the induction machine and also from the value of the harmonic modulation of the excitation system (score 2). In the case of a synchronous machine with separate excitation, it is possible to control the reactive power in both quadrants of the Gaussian plane; therefore, the inductive reactive power can be supplied and also consumed (score 1). In the case of a synchronous generator with a direct connection through the synchronization unit, it is difficult to utilize the wind speed in its wide range; the generator is connected at the speed near synchronous speeds and the wind energy is not utilized optimally, even when assuming that the wind turbine is fitted with the planetary gearbox (score 4 and the planetary gear and score 5 for a transmission with a constant speed ratio). With reference to the necessity of the excitation system and the corresponding control system, this system can be included among the less reliable systems in comparison with induction generators, for example (score 3). The requirement for excitation system in a relatively high price (Grade 3). The requirement for excitation system is also reflected in a relatively high price (score 3).

When connecting a non-excited squirrel-cage induction generator to the external grid, we observe a current surge of mainly active character because this system is usually connected at subsynchronous speed (score 3). If considering the connection

process for an induction machine in non-excited state, there is usually no voltage drop at the connection point (score 2). The quality of electricity is determined by the machine design and the characteristic of the compensating device. If the compensation device is designed optimally for the entire range of machine speeds, there is no significant distortion of the output current and the corresponding distortion of the output voltage (score 2). Although it is possible to use a pole-changing induction machine or machine with double winding, the machine does not utilize the wide speed range optimally (score 4). From the design point of view, the squirrel-cage induction machine represents the simplest system which is also reflected in the price (score 1) and the overall reliability (score 1).

Systems with an induction generator with wound rotor in cascade connection with a frequency converter are the most widely used WPP control systems in the Europe. Using the frequency converter and control system optimizes the process of connection without current surges (score 1) and consequent voltage changes (score 1). The frequency converter control system subsequently adapts the torque characteristic of induction machines for the entire range of wind velocities; the system is therefore capable of supplying electricity continuously within the entire range of available wind speeds and torque on the shaft of the wind motor (score 1). However, the frequency converter affects the overall quality of supplied electricity; the values of current (as well as voltage) distortion factor may be higher, especially in the lower output range (score 3). When considering the cooperation between induction machines with wound armature and frequency converter in the cascade connection, the converter output is designed only for approximately 30 % of the overall machine output; this also affects the total price which is comparable with the price of synchronous generators (score 3).

2.4 Reactive Power Regulation

At present, the most widely used systems are those with frequency converter, operating in the cascade connection with the frequency converter. Nevertheless, the power factor regulation is another problem associated with bringing the output of WPPs with induction generator to the external grid. As results from the principle of induction machine operation, the power factor is not constant. This machine needs reactive energy for its magnetization and therefore acts as a consumer of inductive reactive power. The inductive current component, taken by induction machines from the distribution external grid, is proportional to the rotor field frequency and the slip value. However, if the induction machine output is brought to the external grid via a frequency converter with a recuperation unit with voltage or current DC bus, the power factor/true power factor value at the outlet from the WPP can be regulated within the desired range using the reactive power control, through the elements in the voltage intermediate circuit, and such a system (induction machine + frequency converter) can thus operate in all four quadrants of the PQ diagram (active power P vs reactive inductive power Q).

Generally, according to [5], the electrical power sources are subject to the following set rules for any of the below-mentioned modes of reactive power control:

- maintaining the specified power factor,
- maintaining the set value of reactive power (take-off/supply) within the operating machine diagram,
- maintaining voltage at the transfer point (generator outlet, behind the block transformer).

The generator must be able to supply power in the power factor range of 0.85 (the supply of reactive power of inductive character) up to 0.95 (the supply of reactive power of capacitive character) at the allowed range of voltage on the generator terminals and at the frequency range of 48.5–50.5 Hz. Regarding the compensating device of sources, it is necessary to consider the manner of production operation and the resulting reverse effects on the external grid voltage. In case of heavily fluctuating outputs of WPP drives, the reactive power compensation must be regulated automatically and sufficiently quickly. As already mentioned in the introductory part of the text, the lack of compensation at fluctuating power is a disadvantage mainly in systems utilizing squirrel-cage induction generators designed as step-switched. The mentioned disadvantage is solved by using frequency converters allowing 4-quadrant operation; power factor of the control system is then usually in the range of 0.96 (inductive character) up to 0.98 (capacitive character). In machines fed by frequency converters with vector-oriented control, it is therefore possible to achieve an optimum magnetic flux control and reductions in the required reactive energy.

Figure 2.48 shows a PQ diagram of the system of WPP with frequency converter (2 MW, 690 V, D connection). Figure 2.48 clearly demonstrates the following: when using the system with frequency converter in the cascade connection, it is possible to regulate the supply of active power with constant power factor in the mode of supplying reactive power of inductive nature (red curve in Fig. 2.48) or reactive power of capacitive nature (green curve in Fig. 2.48). Based on an agreement with the operator of the external grid to which the WPP is connected, the WPP control system defines the operation area according to the PQ diagram.

2.4.1 Selected Reverse Effects on the External Grid

The next chapter analyzes the selected qualitative parameters of electricity supply for the control system of a WPP using an induction generator (2 MW, 690 V, D connection) with wound rotor in the cascade connection with a voltage-type frequency converter according to the block diagram in Fig. 2.40.

As mentioned above, it can be expected that the operation of a wind power plant will affect the parameters of the external grid. Interaction between the external grid and the analyzed WPP is defined in the so-called connection point.

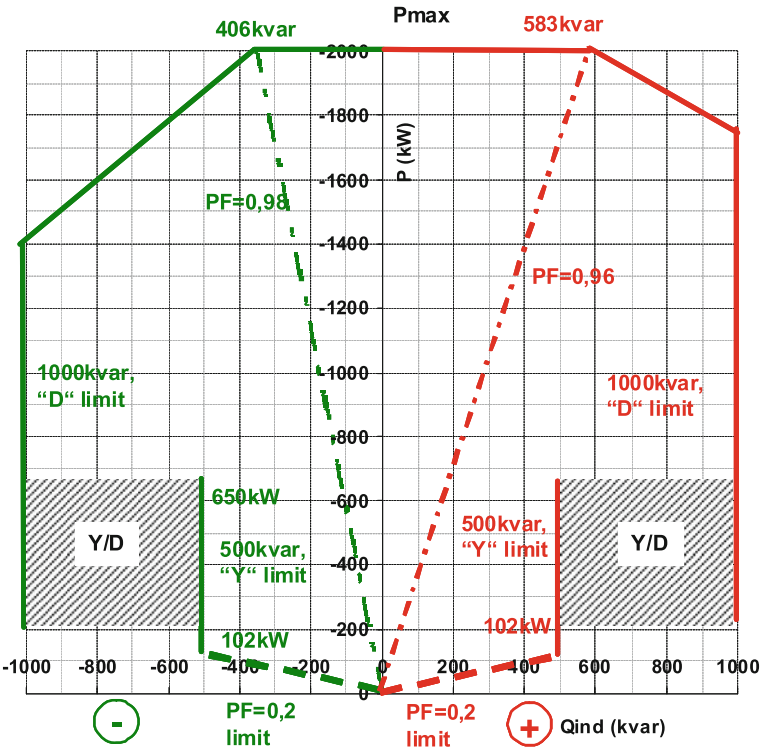


Fig. 2.48 Operating diagram of the system with frequency converter in the cascade connection (2 MW, 690 V, D connection)

For the operator of the distribution external grid, the priority is to ensure a stable supply of electricity, preferably with constant system parameters.

In terms of quality of the supplied energy, it is necessary to particularly monitor:

1. Changes in voltage.
2. Flicker—voltage fluctuations.
3. Effects on the devices of mass remote control.

Changes in Voltage

Annex no. 4 [5] stipulates that the changes in voltage caused by the power supply from connected sources, i.e., wind power plants in our case, must not exceed 2 % of the nominal voltage U_N for WPPs connected to the medium-voltage external grid.

$$\Delta u_{vn} \leq 2\,\% \tag{2.29}$$

In our case, the wind power plants are connected to 22 kV external grid, i.e., the phase voltage is about 12.7 kV; the maximum allowable increase in voltage is then about 254 V. As shown graphically in Fig. 2.49, the voltage change ΔU copies the

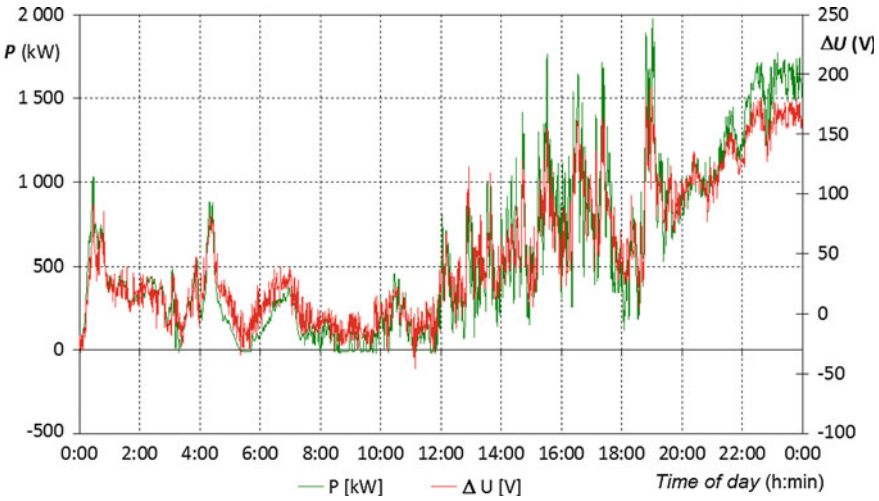


Fig. 2.49 Effect of power supplied from WPPs on changes in voltage at the connection point

change in power supplied. At the maximum supplied power (2 MW), at the time around 19:12, the voltage increased maximally by 200 V, which meets the condition defined by the rules for operating distribution external grids [13, 14].

Flicker—Voltage Fluctuations

Flicker is defined as a fluctuation in the light flux of light sources due to periodic voltage drops in the area of subharmonic frequencies, perceptible by human eye. These voltage variations are generally caused by changes of load in consumers or changes in power generation.

If analyzing the theoretical possibility of flicker which accompanies the operation of wind power plants, we may identify two basic causes of its origin: the influence of wind gusts and the influence of the wind power plant tube.

At short-term deviations of the wind velocity from its mean value, the influence of wind gusts is eliminated by the inherent inertia of rotating parts of the wind power plant; the influence of stronger gusts is more or less eliminated by the turbine power control.

Effect of the tower (mast) can be suppressed much harder. The tower represents an obstacle for wind flow and slows it down. At the moment when the turbine blade coincides with the tower, the turbine output is also naturally reduced. This is also one of the reasons why large wind power plants are always built with the turbine located before the tower (upwind placement). In the construction with the turbine located behind the tower (downwind placement), the blade would get to a complete wind shadow of the tower. Due to such resulting periodic power drop, both active and reactive, the following voltage drop arises across the external grid impedance:

$$\Delta U = \frac{\Delta PR + \Delta QX}{\sqrt{3}U_N} \tag{2.30}$$

where ΔU is the voltage drop across the external grid impedance (V); ΔP, ΔQ are active and reactive variations in the WPP output (W, var); R, X are external grid resistance and reactance (Ω); and U_N is the external grid rated voltage (V).

The relation (2.30) clearly indicates that changes in voltage causing the flicker do not virtually exist in external grids with significantly inductive character. Changes in active power, which tend to be greater than the changes in reactive power, are negligible at low-resistance external grids [15].

When respecting the external grid short-circuit power at the common feed point, it is possible to obtain the below-mentioned relationship for the proportional voltage drop:

$$\frac{\Delta U}{U_N} = \frac{\Delta S}{S_k''}\cos\left(\psi + \varphi_f\right) \tag{2.31}$$

where $\psi = arctg\frac{X}{R}\,\psi$ is the angle of external grid impedance, $\varphi_f = arctg\frac{\Delta Q}{\Delta P}$ is the relevant flicker angle, S_{kV} is the external grid short-circuit power at the common feed point.

However, the voltage drop caused by flicker is not directly used as a parameter determining the flicker; for this purpose, we use the quantity called the flicker emission or the level of flicker perception. We distinguish between the short-term flicker emission P_{st}, measured or counted in a time interval of 10 min, and the long-term flicker emission P_{lt} determined for the interval of 2 h. The flicker emission is proportional to the relative voltage drop:

$$P_{\mathrm{st,lt}} = \mathrm{d}u = \frac{\Delta u}{U_N} \tag{2.32}$$

Generally, the more blades of the wind turbine, the less the flicker emission. In most cases, the systems with frequency converter have less emissions than the systems with induction generator connected directly [16].

Magnitude of Voltage Drops

The total torque of the turbine is given by the sum of partial moments per individual blades; a third or half of the total torque falls on one blade in the case of 3-blade or 2-blade turbine, respectively. At the moments when the blade occurs in the area of the tower influence, the generator connected to the 3-blade turbine loses a third of its active output provided that the speed is constant. If connected to the 2-blade turbine, it loses a half of its output. If knowing also the change in reactive power, we can use the above relation (2.32) to calculate the relative voltage drops at the common feed point of the local external grid. Except the magnitude of the voltage drops, it is also essential to know the time of their duration and their frequency.

The latter two parameters are independent of the external grid and the generator; they are determined only by the equipment design.

Frequency of Voltage Drops

Repetition frequency of voltage drops in the external grid is derived from the turbine speed and number of blades. The frequency of blade passages along the tower is given by the following relation

$$f_f = a \cdot \frac{n_t}{60} \tag{2.33}$$

where f_f is the frequency of the voltage drop (Hz), a is the number of turbine blades, and n_t is the turbine speed (min^{-1}).

Therefore, it is a simple linear relationship where we additionally assume a direct proportionality between the changes in voltage and luminous flux of the light sources.

Human eye is capable of perceiving changes in the luminous flux from the frequency of 0.5 Hz up to 25 Hz and is most sensitive to frequencies around 9 Hz; with respect to the flicker phenomenon, the working speed of the wind turbine should therefore avoid this frequency band. However, this is impossible. The speeds of wind turbines typically achieve 30–50 revolutions per minute and this is reflected in the frequency of external grid voltage drops of 2–3 Hz.

Any design efforts may therefore result only in minimizing the emergence of flicker as the consequence of WPP operation but they can never completely remove it for physical reasons.

Duration of Voltage Drops

If the frequency of voltage drops is given only by the turbine design, their duration is also directly influenced by the size (diameter) of the tower—see Fig. 2.50.

If the turbine is characterized by its radius R, then the tower can be characterized by its radius r. Because of the conical shape of towers, the simplified calculation uses a mean diameter or mean radius. The time t, for which the blade passes along the tower, is determined by the circumferential speed of the blade tip v_R and the tower diameter $2r$. The circumferential speed is given by the following relation

$$v_R = \omega \cdot R \tag{2.34}$$

where R is the turbine radius, $\omega = \frac{2 \cdot \pi \cdot n_t}{60}$ is the angular velocity, and n_t is the turbine speed (min^{-1}).

The distance, that the blade must overcome, equals to the tower diameter. The time required is therefore given as

$$t = \frac{1}{\omega} \cdot \frac{2r}{R} \tag{2.35}$$

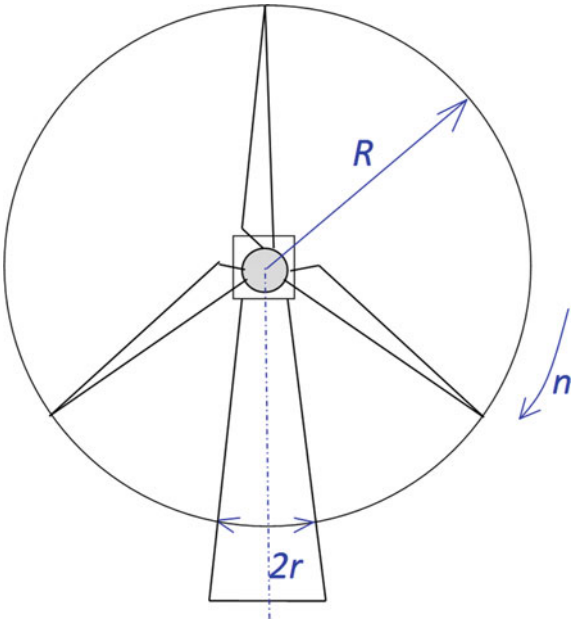


Fig. 2.50 A scheme for determining the duration of voltage drops

The ratio $R/2r$ (or its reciprocal value) is a characteristic number which, together with the turbine speed, ultimately determines the duration of voltage drops in the external grid caused by the wind power plant.

With the turbine radius $R = 40$ m and the average tower diameter of 3 m, which corresponds to the real situation, the voltage drop takes a full period of the external grid frequency, i.e., 0.02 s.

The flicker emergence is therefore given by three variables—the magnitude, frequency and duration of voltage drops; however, it is impossible to clearly determine which of them has greater impact. It is true that restrictions of any of these variables are positively reflected in the flicker reduction. Therefore, it is possible to establish the following general principles:

- Wind power plants should not be connected to local distribution external grids with low surge short-circuit output.
- Wind power plants with induction generators connected directly to the external grid should be connected in places where the value of the external grid impedance angle is close to 70°.
- Operating turbine speed should be lower rather than higher. The higher the turbine speed, the more sensitive reaction of human eyes.
- The ratio of the turbine radius to the mean tower radius $R/2r$ should be maximized.

However, the voltage drop caused by flicker is not directly used as a parameter determining the flicker; for this purpose, we use the quantity called the flicker

emission or the level of flicker perception. We distinguish between the short-term flicker emission P_{st}, measured or counted in a time interval of 10 min, and the long-term flicker emission P_{lt} determined for the interval of 2 h.

Generally, the more blades of the wind turbine, the less flicker emission. In most cases, the systems with frequency converters exhibit less emissions than systems with induction generators connected directly.

The rules for operating the external grid again define the maximum permissible values of the long-term level of flicker perception P_{lt}: it must not exceed the level of 0.46.

This value (0.46) indicates the contribution to the total P_{lt} caused by the source, i.e., the wind power plant. Figure 2.51 shows an example of the analysis of the wind power plant contribution to the increase in the value of long-term flicker perception at the connection point. 95 % value, $P_{lt} = 0.587$ (average of three phases: 0.581, 0.604, 0.577), was detected for the connection point. Given the fact that the standard specifies the permissible value, $P_{lt} = 1$, we can conclude that the connection point meets the requirements of the standard.

As demonstrated by the performed measurement whose results are shown in the graph in Fig. 2.51, it is impossible to prove the influence of the magnitude of the power supplied on the level of flicker perception P_{lt}. In Fig. 2.51, we can see the course of P_{lt} during the period of one week where P_{lt} values range from 0.338 to 0.631.

With respect to the permitted value ($P_{lt} = 1$) and the highest found 95 % value ($P_{lt} = 0.604$), it can be concluded that the wind power plant does not exceed the allowable contribution of 0.46 of the total P_{lt} value, and that our found value of 0.604 should be taken rather as a external grid background.

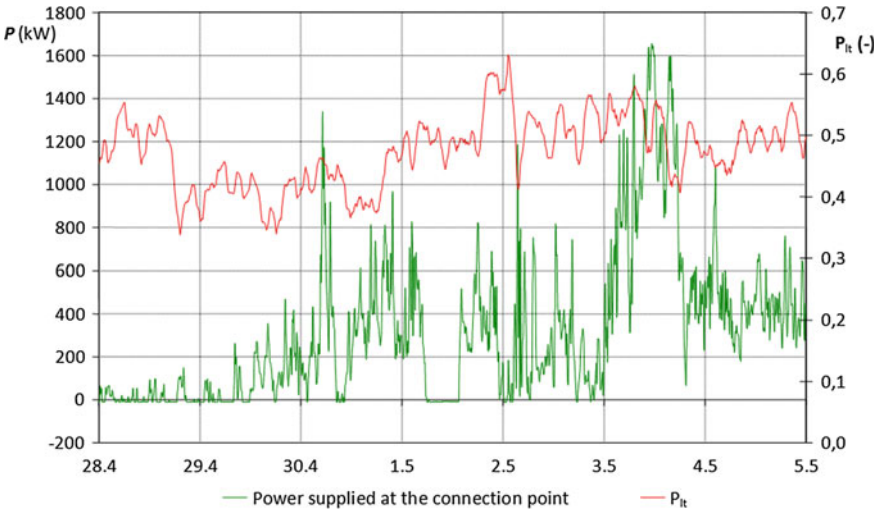


Fig. 2.51 Influence of the power supplied from the WPP on P_{lt}

Effects on the Devices of Centralized Telecontrol of Loads
Plants affect centralized telecontrol of loads (CTL) due to additional load of CTL transmitters:

- By the WPP equipment.
- Or by increased load of the part of the external grid into which the source supplies.

This influence can cause unacceptable changes in the levels of CTL signal at the common feed point. More detailed conditions and information about this reverse effect are available in [5].

2.4.2 *Influence of the WPP Operation on the Substation Supply Systems*

From previous chapters, it is clear that the WPP operation can affect the parameters of the external grid at the connection point and that this impact is primarily dependent on the ratio of the short-circuit power of the system into which the WPP capacity (output) is brought to the short-circuit power of the WPP generator, as well as on the WPP control system. If the high-capacity WPP output is brought to a external grid primarily with radial arrangement, whereas the WPP connection point is a position at the end of a branch, it is also necessary to respect the possibility of influencing the system parameters directly at the outlet from the substation of the given branch.

The following chapter analyses such a case. To identify the reverse effects of the connected wind power plants, we measured power balance of a distribution external grid branch to which two high-capacity WPPs are connected, each with an induction generator with wound rotor (2 MW, 690 V), working in the cascade connection with a frequency converter with recuperation. A simplified scheme of the connection of wind power plants is shown in Fig. 2.52.

Measuring point no. 1 was at the outlet of the monitored distribution external grid branch in a 110/22 kV substation. Measuring point no. 2 was in a distribution

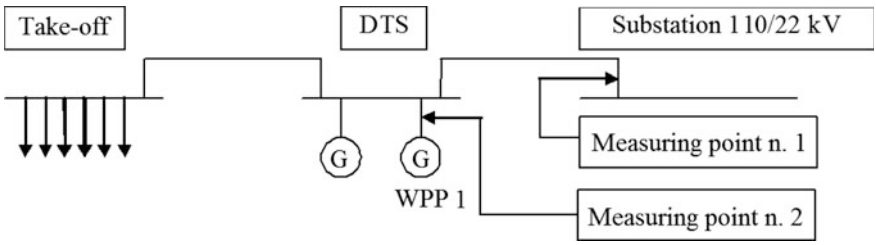


Fig. 2.52 A simplified scheme of the connection of wind power plants to a branch of the external grid

transformer station (DTS), i.e., at the connection point of the WPPs to the external grid. Measurements were carried out only for one wind power plant. Both instruments (meters) were time-synchronized; the electrical parameters were measured in all three phases.

When evaluating the measured data, the following three states of power balance were identified:

State 1—the connected wind power plants cover the consumption of customers connected to the monitored branch; in addition, the WPPs supply excess power to the distribution external grid through the parent 110/22 kV substation.
State 2—the connected wind power plants exactly cover the consumption of customers connected to the monitored branch (it is a balanced power balance, no active power is supplied to/from the parent substation).
State 3—the connected wind power plants do not cover the consumption of customers connected to the monitored branch; it is therefore necessary to supply the missing active power from the substation to which the monitored branch is connected.

If U_1 is the voltage at the connection point and U_2 is the voltage in the substation, the voltage deviation ΔU can be mathematically defined as the following difference

$$\Delta U = U_1 - U_2 \tag{2.36}$$

The dependence of the output supplied by the wind power plant on the voltage deviation ΔU can be seen in Fig. 2.53; if the WPP supplies power in the range of 0–100 kW (about 5 % of the installed capacity) to the external grid, the voltage in the substation is higher than at the connection point which is caused by voltage drop across the line. If the WPP supplies power higher than 100 kW, the voltage at the connection point increases to such a degree that the voltage deviation ΔU is getting from negative values, and the voltage U_1 at the connection point of WPPs therefore gradually increases with increasing power supply. This increase has a linear character. Deviations from the linear trend of growth are most likely caused by a small number of measured values for the monitored magnitude of the power supplied.

The evaluation of the measured data further shows that the operation of the wind power plant does not appreciably affect the long-term level of flicker perception, both at the connection point and in the parent substation. For each phase, the 95 % values of P_{lt} interval are shown in Table 2.5 [13].

The graph in Fig. 2.54 compares the courses of P_{lt} during the monitored period; the course of P_{lt} in the parent substation—in green, the course of P_{lt} at the connection point—in red. As evidenced by the graph, P_{lt} in the parent substation is higher which confirms the correctness of reasoning that the WPP contribution to the total P_{lt} value is almost negligible compared to the external grid background.

When analyzing the voltage total harmonic distortion (THDu), we also did not find any correlation with changes in the output supplied from the WPP and the total

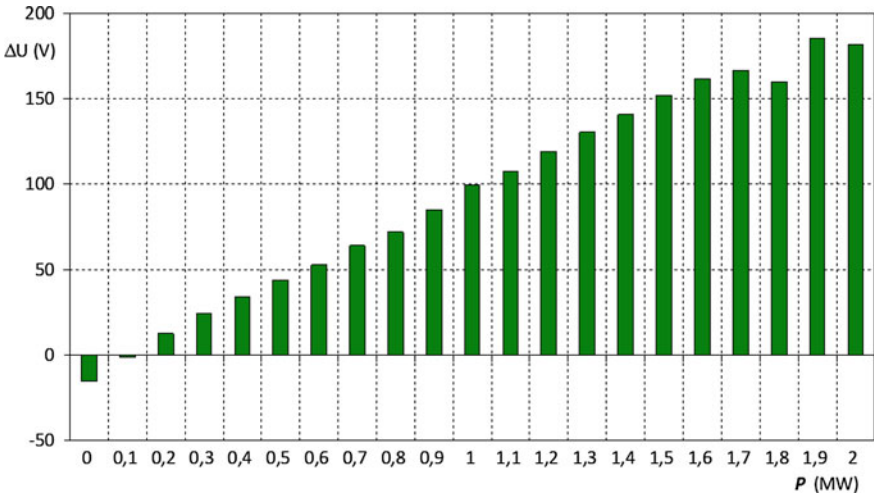


Fig. 2.53 Dependence of the voltage deviation on the output

Table 2.5 P_{lt} values for individual phases at the WPP connection point and in the parent substation

	Phase 1	Phase 2	Phase 3
Connection point (1)	0.581	0.604	0.577
Parent substation (2)	0.603	0.631	0.598

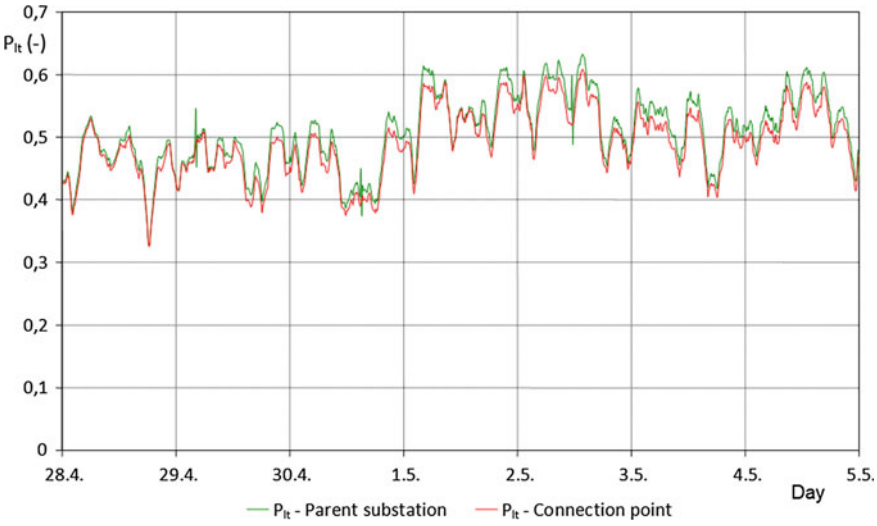


Fig. 2.54 Comparison of P_{lt} in the parent substation and at the WPP connection point

harmonic distortion factor varied around the value of 0.6 % with occasional deviations up to 1.8 % at the WPP connection point. The measured average value of the voltage total harmonic distortion (THDu) in the parent substation reached 0.7 % with occasional increases up to 2.2 %. Nevertheless, no timing between THDu increases at the connection point of wind power plants and in the parent substation has been proven.

References

1. Mišák S, Nevřala J (2008) Operation of small wind power plants with induction generators. Adv Electr Electron Eng 7:179–183
2. Mišák S, Nevřala J (2008) Asynchronní generátor v malé větrné elektrárně—část 1. Časopis pre elektroniku a energetiku 2:25–26
3. Mišák S, Nevřala J (2008) Asynchronní generátor v malé větrné elektrárně—část 2. Časopis pre elektroniku a energetiku 3:25–26
4. Mišák S, Chmelík K (2009) Generator for wind power plant of small and medium power. EPE 2009
5. System operation code (2010)
6. Mišák S (2010) Vybrané typy zdrojů elektrické energie. VŠB—TUO. Ostrava
7. Mišák S, Chmelík K (2007) Analýza provozu větrných elektráren s asynchronními generátory. Časopis pre elektrotechniku a energetiku 3:38–43
8. Mišák S, Chmelík K (2007) Analysis of wind power plant running with induction generators. Branzoly Odrodem Badawczo-Rozwojowy Maszyn Elektrycznych KOMEL, Katowice
9. Kačor P, Mišák S (2010) Zvýšení účinnosti synchronního generátoru s permanentními magnety pro větrnou elektrárnu. EPE 2010
10. Mlčák T, Mišák S (2010) Vyhodnocení provozních účinností větrné elektrárny. EPE 2010
11. Mišák S, Prokop L, Sikora T (2008) Provoz větných elektráren s frekvenčními měniči. ELEKTRO 10:4–6
12. Mišák S, Prokop L, Sikora T, Krejčí P (2008) Větrné elektrárny s asynchronními generátory v sítích VN. Elektrorevue 47:1–11
13. Mišák S, Prokop L, Sikora T, Krejčí P (2008) Zpětné vlivy provozu větrných elektráren na distribuční síť. Energetika
14. Mišák S, Prokop L (2009) Problem of wind power plant turbineering in the Czech Republic. POWERENG 2009
15. Mišák S, Chmelík K (2009) Characteristics parameters and operational states of generators for wind power plants. ISEM 2009
16. Mišák S, Nevřala J (2007) Using frequency converter at wind-power plants with induction generator. EPE 2007. Ostrava

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