Control and Automation of Wind Energy Systems

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Wind turbines (WT) or several WTs combined in a wind power plant (WPP) are complex systems whose operation requires extensive automation of both the overall system and the subsystems. In this context, wind energy systems (WES) are expected to at least meet the requirements of conventional power plants in terms of reliability, efficiency and operational control system. In contrast to conventional power plants, the supply of energy cannot be influenced but varies strongly and quickly due to the wind speed. For the automatic and safe operation and the large automatic adaptation of the operation of WES to different operating conditions, a complex automation technology is therefore required, which distributes the tasks to different subsystems.

Modern WES feed into the medium or high voltage level of the electrical grid via transformers. In order to optimise the power fed in and limit it to the rated power, WT are used with and without gearboxes with full or partial converters with variable speed and variable blade angles. The automation of WES includes measurement, control, regulation and monitoring of the main parameters within the WT as well as WT and WPP operation control system. It includes remote monitoring and visualisation as well as information and communication technology integrated into other systems, in particular, into the higher level grid control systems. Automation consists of the technical equipment (hardware), the associated programs (software) and the necessary communication systems. Despite the different types of WT, their automation increasingly shows common features, in particular, because in future, WT will have to be integrated into higher level control systems in the same way, irrespective of the manufacturer.

The chapter deals with modern WES and the basic open- and closed-loop control circuits within the WT, the WT and WPP operation control system, the connection of the WT to higher level systems and the so-called SCADA systems. It provides an

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overview of the essential aspects for the automation of WES, comparable discussions can be found in [4, 6, 7, 10, 15].

1 Fundamental Relationships

The aim of WES automation is the safe and efficient operation of the WT, which is extensively independent of humans. To achieve this, various tasks must be fulfilled, which essentially comprise measurement, control, regulation, monitoring, guidance and visualisation. In English, these individual functions are summarised by the generic term ‘control’; in German, the term ‘Automatisieren’ is used.

To make the content readable, there are some symbols that are not used as usual in English-language publications. The main differences are the wind speed v, the voltage u or U and the torque M.

1.1 Classification of WT Automation

Several hundred physical inputs and outputs must be processed in order to operate a WT. Individual WPP can consist of more than one hundred individual WT and, in addition to the WPP, other generators, consumers and grid resources must also be monitored and coordinated in the grid control system. The large number of automation functions, the requirements for reaction speeds and the data volumes to be processed can only be mastered if the tasks are distributed and arranged in a hierarchy. In plant automation, this hierarchy is represented in the form of an automation pyramid.

Figure 1 shows a frequently used automation pyramid with three main levels, whereby the terms automation or control level have become established for the middle level.

The tasks and requirements for response time and data volumes specified in the figure can also be transferred to the automation of WES. Thus, the switching times of the inverters in the field level are in the µs range, the reaction times of the programmable logic controllers in the automation level are in the ms range and the required response times of the WTs to the requirements for power reduction from the grid control system are in the range of seconds. If only a few analog and digital inputs and outputs are processed by a device in the field level, the data series of all units connected to a supply area, recorded over several years, are stored and evaluated in the management level.

To divide the functions, the three main levels are often subdivided. The division into four to six levels is typical. A uniform naming of the levels has not become established. In Fig. 2, the main subsystems of the WES automation are arranged in six levels. The designations chosen in the following correspond to the main functions of the respective level.

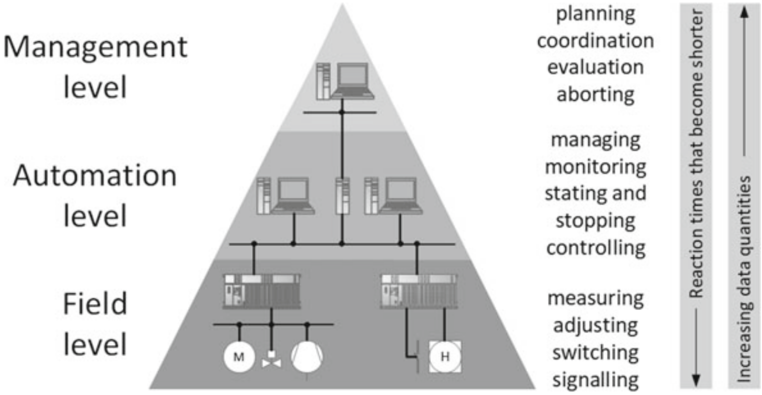

Fig. 1 Three-level model of plant automation with essential functions

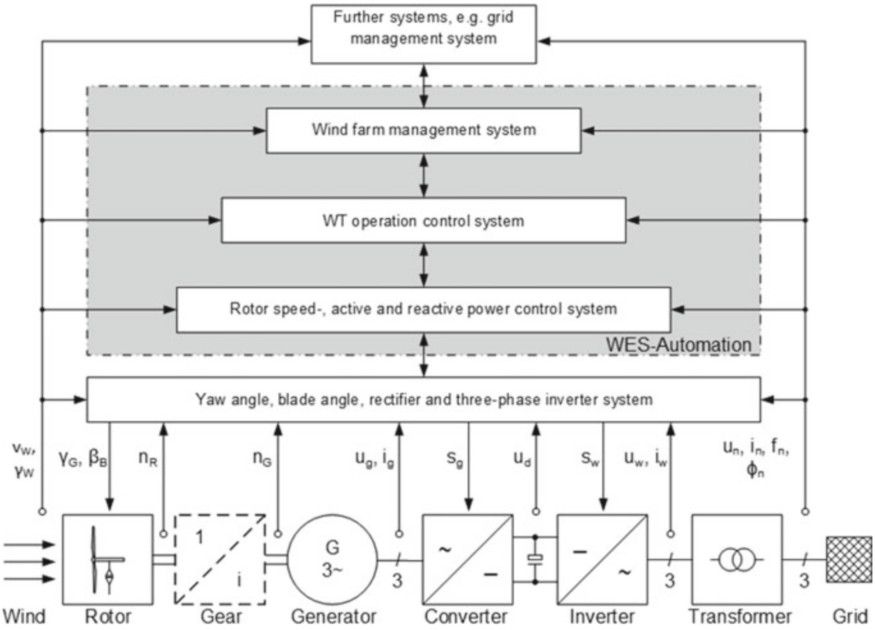

Fig. 2 Arrangement of WT automation in the automation hierarchy

- Sensor-actuator level: The lowest level shows the drive train of the WT with the input variables, wind speed v_W and wind direction γ_W. The characteristic output variables are the three-phase grid voltages u_n and grid currents i_n, the grid frequency f_n and the phase angle φ_n between current and voltage of the three-phase system. The rotor speed n_R is influenced by the variable yaw angle γ_G and the variable blade angles (pitch angles) $\beta = \beta_B$.

Different types of generators are used in WT, essentially the double-fed asynchronous machines (DASM), the separately excited synchronous machines (FSM), the permanently excited synchronous machines (PSM) and the asynchronous machines with squirrel-cage rotors (ASM). They are operated partly with and partly without gears and feed the generator power into the grid either completely or partly via a converter. The figure shows the drive train of a WT with a fully inverter-fed PSM with and without gears.

The mechanical power of the rotor P_R is transmitted via the drive train to the generator with the generator speed n_G. The generator power P_G is fed into the electrical grid via a transformer with the aid of a full converter. The full converter consists of the generator-side rectifier with the generator-side three-phase currents i_G and voltages u_G, the direct current (dc) link with the dc voltage u_d, and the grid-side inverter with the grid-side three-phase currents i_W and voltages u_W. The rectifiers and inverters are designed as six-pulse bridge circuits with IGBTs, each controlled by six control signals s_g on the rectifier side and s_W on the inverter side. With the aid of a transformer, the voltage on the inverter output side is adapted to the mains voltage of the medium- or high-voltage network.

- Adjustment level: The adjustment actuators of the individual drive systems are situated above the sensor-actuator level. The yaw angle actuator, often also called azimuth system, guides the alignment of the nacelle according to the wind direction. The pitch angle setting devices, often called pitch systems, set the pitch angles according to the desired setpoints or reference values. The generator-side electrical power P_G is influenced by the pulse-width-modulated control signals s_G of the pulse rectifier. The inverter-side active electrical power P_W and reactive power Q_W are influenced by the pulse-width-modulated control signals s_W of the pulse inverter. The DC link voltage u_d remains constant if the rectifier-side and inverter-side active powers are identical.
- Closed control loop level: The actual control to the setpoints of the active grid power P_n and reactive grid power Q_n as well as the limitation of the rotor speed takes place in the closed control loop level located above the actuation level. Depending on the operating mode of the WT, different controllers calculate the setpoints for the yaw and pitch angles as well as for the rectifier and the inverter.
- Operation control loop level: The control systems receive their setpoints from the higher level operation control system, which is located in the operation control loop level. Depending on the wind speed, the setpoints from a grid control system or a WPP control system and external specifications, the operational management controls the WT into the required operating state. In addition to specifying the setpoints for the controls, the operational management also controls the other actuators in the WT such as brakes, contactors, heating and ventilation systems or the firing systems and processes additional sensor signals such as temperature, humidity or oil pressure. The plant management system exchanges the information either directly or via a control system with the remote monitoring and control system of the manufacturer or operator as well as with the control system of the grid operator.

- Process control level: If several WTs are operated in a WPP, a WPP control and automation system is superordinate to the individual WT operation control system. The system allocated to the process control level distributes the required power reduction and reactive power fed into the individual WTs in accordance with the setpoints required by the grid operator and ensures the required participation in the short-circuit current in the grid. The WPP control system also ensures an orderly and continuous start-up and shutdown process of the WPP so that no power surges occur.
- Management or planning level: WT operation control or WPP control system receives their setpoints from the management level, also called planning level, and return the actual values of interest back to it. Both the grid control system and the billing systems or the higher level management systems of the plant operators, which are usually oriented towards business management, can be assigned to the top level.

1.2 System Properties of Energy Conversion in WTs

The control, operation and automation systems of the WT aim to optimise the energy conversion from the kinetic energy of the wind to the electrical energy of the grid and to operate the turbine safely in compliance with specified limit values.

Below the nominal wind speed of a WT v_{WN}, the power fed into the grid is maximised for this purpose and above this wind speed it is limited to the nominal power P_N, the nominal electrical power P_{nN} at the grid connection point (GCP). To comply with the grid connection conditions, the WES must limit the active power to the requirements and with rising grid frequency. The reactive power must be changed on demand in case of grid voltage fluctuations. In the event of temporary voltage dips, WES must support the grid by feeding in a specified reactive current.

In order to develop the basic open-loop and closed-loop control functions of a WT, the essential system characteristics of the energy conversion in WTs required for the description are first summarised. Despite the differences in the drive trains (with and without gearbox, high ratio, low ratio), the generator systems (ASM, DASM, FSM, PSM) and the pitch and azimuth drives (hydraulic, electric), the control has fundamental similarities.

Figure 3 shows the block diagram of the energy conversion, in which the subsystems are connected according to their quantities describing the power flow. The DC link, the grid-side inverter and the transformer are combined in one block. This diagram is used to describe the possibilities for influencing the power flow.

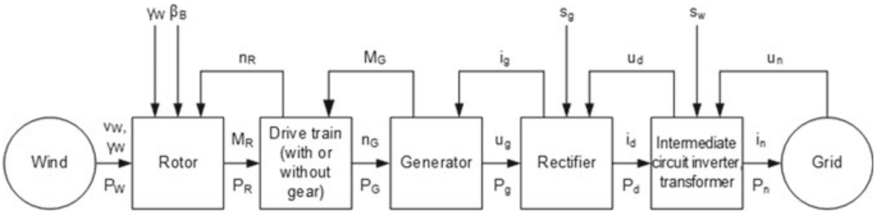

Fig. 3 Schematic representation of the power flow in WTs

1.3 *Energy Conversion at the Rotor*

Figure 4 shows, using the view of a WT (a), the sectional view of a blade (b) and the plan view (c), the orientation of v_W, n_R, characterising the energy conversion, the rotor diameter D, γ_G and β_B. A good summary of the dependence of the rotor power on these quantities can be found in [15]. At this point, the relationships that are crucial for control and automation are summarised.

In the sectional view, the circumferential speed of the blade u_B and the active speed v_u acting on the blade cross section are shown. The circumferential speed of the blade tip is denoted by u:

$$u = 2 \cdot \pi \cdot n_R \cdot D/2 \tag{1}$$

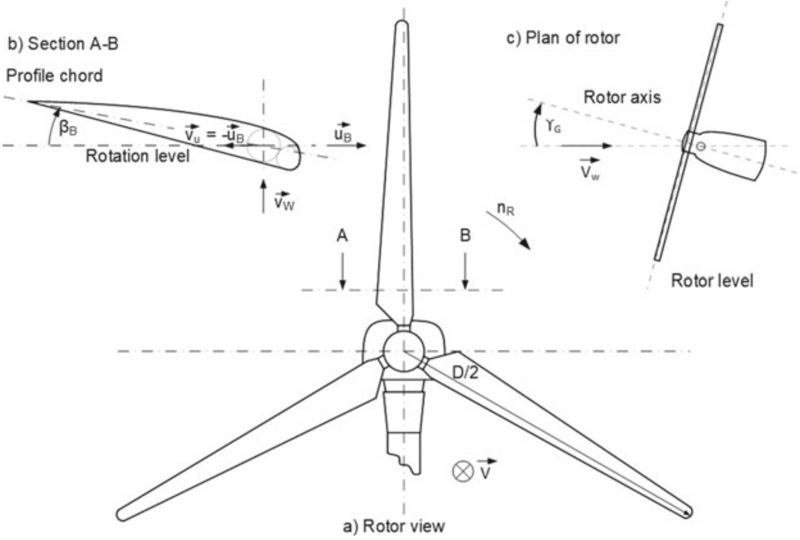

Fig. 4 Characteristic quantities of the rotor for the calculation of the rotor power

The kinetic energy of the undisturbed air flow is partially converted by the rotor into the mechanical energy of the rotor. The ratio of the mechanical power P_R to the power of the wind P_W is called rotor power coefficient or power coefficient c_{pR} for short:

$$c_{pR} = \frac{P_R}{P_W} = \frac{2 \cdot \pi \cdot n_R \cdot M_R}{1/2 \cdot \rho \cdot \left(\pi \cdot D^2/4\right) \cdot v_W^3} \tag{2}$$

where ρ is the air density and D is the diameter of the rotor. The power coefficient is determined by the number of blades N, the blade geometry, the pitch angles β_B, the yaw angle γ_G, the wind speed v_W and the rotor speed n_R:

$$c_{\mathrm{pR}} = f(N, \mathrm{bladegeometry}, \alpha_G, \beta_B, v_W, n_R) \tag{3}$$

The rotor power becomes maximum when the yaw angle, which indicates the deviation of the wind direction from the orientation of the rotor axis, is zero. As the yaw angle increases, the normal component of the rotor area related to the wind direction becomes smaller, so that the power decreases in first approximation proportional to the cosine of the yaw angle. WTs guide the nacelle according to the wind direction; the influence of the yaw angle on the rotor power is therefore not considered in the following explanations.

The ratio of the blade tip speed u to the wind speed v_W is called the high-speed ratio λ or TSP (tip-speed ratio) and is an essential parameter for performance control:

$$\lambda = \; u/v_W = (\pi \cdot D \cdot n_R)/v_W \tag{4}$$

For a given number of blades and blade geometry and with a constant yaw angle, the introduction of the tip-speed ratio enables the two-dimensional representation of the power coefficient, the rotor power or the rotor torque. It has been shown that for constant pitch angle, the variation of the power coefficient as a function of the high-speed number shows a maximum. For given blade geometries, the maps $c_{\mathrm{pR}} = f\ (\beta, \lambda)$ can be calculated or measured for implemented WTs.

For replication, the maps are replied by analytical functions, which lead to a satisfactory agreement with measured values by parameter adjustments. Based on the proposal in [1], the following form is used for Figs. 5 and 6:

$$\begin{aligned} c_{\mathrm{pR}} &= c_1 \cdot \left(c_2/\lambda_i - c_3 \cdot \beta - c_4 \cdot \beta^x - c_5\right) \cdot e^{-c_6/\lambda_i} \text{ with} \\ \frac{1}{\lambda_i} &= \frac{1}{\lambda + 0{,}08 \cdot \beta} - \frac{0{,}035}{\beta^3 + 1} \end{aligned} \tag{5}$$

The constants for the representations are: $c_1 = 0,6$, $c_2 = 116$, $c_3 = 0,4$, $c_4 = 0,001$, $c_5 = 5$, $c_6 = 20$, $x = 2$

The maximum rotor power coefficient occurs for very small pitch angles and is at an optimum tip-speed ratio of 8 for the curves shown. Below the rated wind speed,

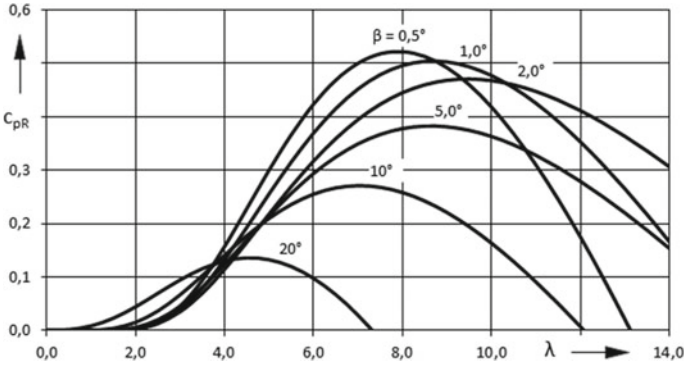

Fig. 5 Curve of the rotor power coefficient at constant pitch angle

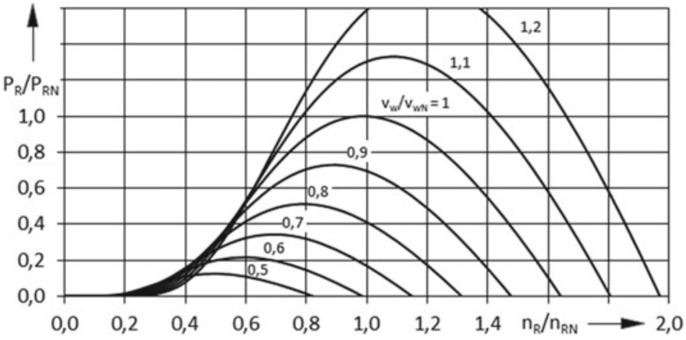

Fig. 6 Curve of the rotor power coefficient at constant wind speed

the rotational speed is adjusted to the changing wind speed in order to convert the maximum power of the wind into rotor power.

For power automation and limitation, it is of interest how the rotor power for the optimum pitch angle is related to the rotational speed of the rotor. The rotor power referenced to the nominal rotor power P_{RN} is surrendered by using the power coefficient in nominal operation c_{pRN} as follows:

$$\frac{P_R}{P_{\mathrm{RN}}} = \frac{c_{\mathrm{pR}}}{c_{\mathrm{pRN}}} \cdot \left(\frac{v_W}{v_{\mathrm{WN}}}\right)^3 = \frac{c_{\mathrm{pR}}}{c_{\mathrm{pRN}}} \cdot \left(\frac{n_R}{n_{\mathrm{RN}}} \cdot \frac{\lambda_N}{\lambda}\right)^3 \tag{6}$$

With the power equation and the setpoints characterised by the index N, we obtain the curves shown in Fig. 6 for $\beta = 0.5°$ and $\lambda_N = 8$ for different wind speeds.

The curves show that the optimum rotor speed increases proportionally with increasing wind speed. If the power above the nominal wind speed is limited to nominal power at constant rotor speed, the pitch angle must be increased.

1.4 Energy Conversion at the Drive Train

For the control of the WT, it is crucial how the rotor power P_R is converted into the generator power P_G. The drive train is a complex oscillatory system and can be described in a simplified manner by the two-mass model shown in Fig. 7. The characteristic properties are the mass moment of inertia of the rotor J_R; the stiffness of the shaft k_{shaft}; the damping constant d_{shaft}; the gear translation i, which is equal to one for gearless systems and the mass moment of inertia of the generator J_G. The gears are assumed to be frictionless and massless in this representation. The rotor torque can be determined from the rotor power using Eq. (2) from the rotor power:

$$M_R = c_{\text{pR}} \cdot \frac{1/2 \cdot \rho \cdot \left(\pi \cdot D^2/4\right) \cdot v_W^3}{2 \cdot \pi \cdot n_R} \tag{7}$$

With the introduction of the torque $\mathrm{M_K}$ applied to the generator coupling and the coupling torque M'_K applied to the rotor side, and using the ratio of the ideal gear drive $i = n'_R/n_G = M_K/M'_k$, the following equations for rotor and generator torque are obtained:

$$\begin{aligned} M_R =& J_R \cdot 2 \cdot \pi \cdot \frac{dn_R}{dt} + M'_K \text{ mit } M'_K = d_{\text{Welle}} \cdot 2 \cdot \pi \cdot (n_R - n_G \cdot i) \\ &+ k_{\text{Welle}} \cdot 2 \cdot \pi \cdot \int (n_R - n_G \cdot i)dt \end{aligned} \tag{8}$$

$$M_G = M_K - J_G \cdot 2 \cdot \pi \cdot \frac{dn_G}{dt} \text{ mit } M_K = i \cdot M'_K \tag{9}$$

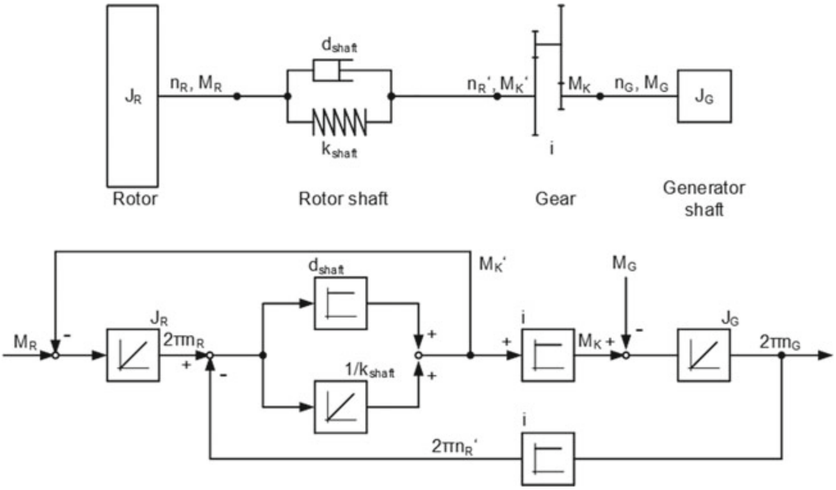

Fig. 7 Two-mass model of the drive train and associated block diagram

Accordingly, for the two-mass model, the block diagram of an oscillatory system is shown in Fig. 7. By large ramp-up times of the WT in the range of seconds and non-instantaneous change of the generator torque, it is achieved that the deviation between start and drive speed remains small. In this case, a rigid shaft can be assumed for simplification, for which only one speed has to be taken into account. For an ideally rigid shaft with $i = n_R/n_G$ the known acceleration equation is obtained as follows:

$$\frac{dn_G}{dt} = \frac{1}{i}\frac{dn_R}{dt} = \frac{(M_R/i - M_G)}{2 \cdot \pi \cdot (J_G + J_R/i^2)} \tag{10}$$

For vibration damping, so-called differential speed controllers are used, which use rotor and generator speed, as known from general drive technology [18].

1.5 Energy Conversion at the Generator-Converter System

The generator-converter system converts the mechanical power at the generator shaft into the electrical power of the grid via several subsystems. To dynamically influence the generator torque and the generator reactive power as well as the grid active power and grid reactive power, it is common to describe the three-phase, electrical quantities by complex time-varying space pointers. A comprehensible introduction can be found in [17].

Detailed descriptions for the individual generator systems can be found, among others, in [14, 16]. For the sake of simplicity, the following explanations refer to the symmetrical cylindrical rotor-SM with restriction to the fundamental frequency behaviour and the copper losses.

Figure 8 shows the simplified equivalent circuit of a PSM and the associated space vector in generator operation. With known rotor position and impressed space vector of the stator voltage $\underline{u}_g$ the angle δ_g to the space vector of the rotor current can be determined. The three stator string currents of the generator are detected and described by the space vector $\underline{i}_S = \underline{i}_g$. The space vector can be transformed to the stationary αβ-components $\underline{i}_{g\alpha\beta} = i_{g\alpha} + j\, i_{g\beta}$ and converted to the rotor-current-oriented dq-components $\underline{i}_{\mathrm{gdq}} = i_{\mathrm{gd}} + j\, i_{\mathrm{gq}}$ using the angle δ_g. The component i_{gd} points in the direction of the permanent magnetic current $\underline{\Psi}_{\mathrm{PM}}$ and the component i_{gq} is perpendicular to it.

The absolute value of the space vector of the induced voltage $\underline{u}_{\mathrm{gPM}}$ is obtained for a generator with the number of pole pairs p from the induction law:

$$u_{\mathrm{gPM}} = 2 \cdot \pi \cdot n_G \cdot p \cdot \Psi_{\mathrm{PM}} \tag{11}$$

The magnitude of the space vector is determined in such a way that in the stationary case it corresponds to the complex vector of the amplitude of the geometric sum of the string quantities, and it is therefore 2/3 of the geometric sum of the individual

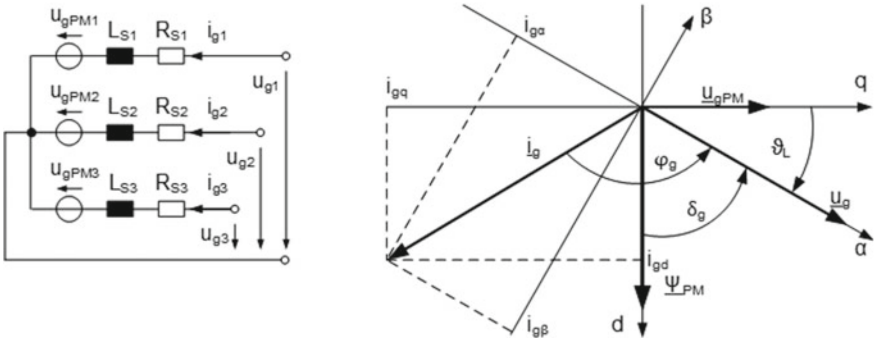

Fig. 8 Simplified equivalent circuit of the PSM and space vector in generator operation

currents. This results in active and reactive power as well as generator power and generator torque as follows:

$$P_g = \frac{3}{2}\left(u_{\mathrm{gd}} \cdot i_{\mathrm{gd}} + u_{\mathrm{gq}} \cdot i_{\mathrm{gq}}\right) \text{ and } Q_g = \frac{3}{2}\left(u_{\mathrm{gq}} \cdot i_{\mathrm{gd}} - u_{\mathrm{gd}} \cdot i_{\mathrm{gq}}\right) \tag{12}$$

$$P_G = 2 \cdot \pi \cdot n_G \cdot M_G = \frac{3}{2} \cdot u_{\mathrm{gPM}} \cdot i_{\mathrm{gq}} \text{ and } M_G = \frac{3}{2} \cdot p \cdot \Psi_{\mathrm{PM}} \cdot i_{\mathrm{gq}} \tag{13}$$

Figure 8 makes clear that for the PSM the maximum power occurs at minimum current for $i_{\mathrm{gd}} = 0$. The space vector of the voltage u_g can be influenced by a variable current i_{gd} at constant moment.

The grid-side inverter can be treated in a similar way. For this purpose, the grid-side voltages are transformed to the inverter side. Figure 9 shows the simplified equivalent circuit of the grid referenced to the inverter side and the associated space vector in generator operation. With the aid of a phase-locked loop (PLL), the frequency and phase position of the grid voltage are detected and thus the space vector of the grid

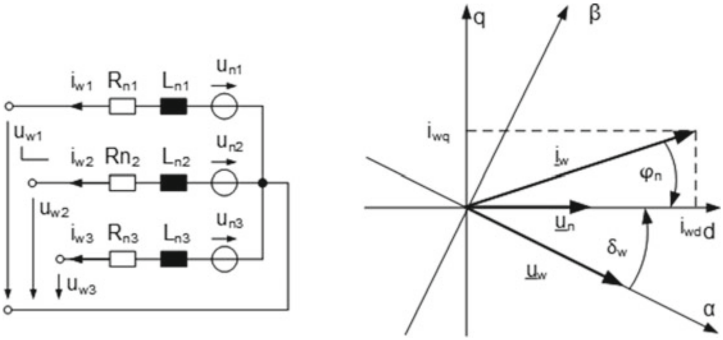

Fig. 9 Simplified equivalent circuit and space vector in generator operation

current is divided into the grid-voltage-oriented d-component and the perpendicular q-component.

If the grid component $i_{\mathrm{nd}} = i_{\mathrm{wd}}$ points in the direction of the space vector $\underline{u}_n$, then active and reactive power can be influenced in a simple manner with the aid of the current components:

$$P_n = \frac{3}{2}(u_n \cdot i_{\mathrm{wd}}) \text{ and } Q_n = \frac{3}{2}\left(u_n \cdot i_{\mathrm{wq}}\right) \tag{14}$$

Figure 10 shows the simplified structure of the generator-inverter system for a PSM with full inverter and grid variables transformed to the inverter side. The setpoints transferred by the control system are marked by an *.

Highly dynamic control of generator torque and voltage is possible when the current components are controlled to the setpoints i^*_{gq} and i^*_{gd} with the aid of a controller. The output of the current controller determines the voltage components to be set using pre-control values calculated using a simple generator model. The voltage components are converted into the required control signals of the six-pulse rectifier using pulse width modulation (PWM).

Also, for the grid-side inverter, the setpoints of P and Q can be impressed highly dynamically using the current setpoints i^*_{wd} and i^*_{wq}, the current controllers and the

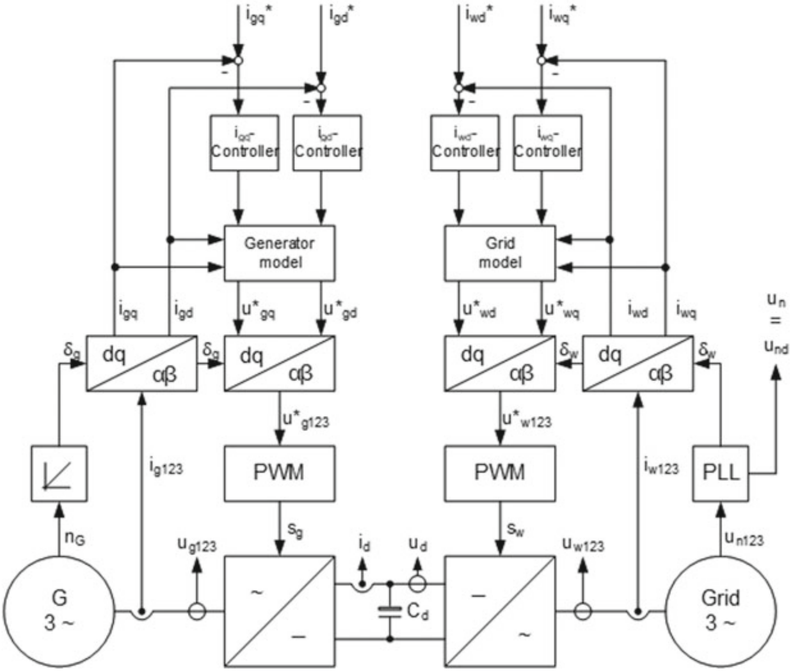

Fig. 10 Simplified structure of the generator-converter system for PSM

PWM of the six-pulse inverter. Here, the pre-control values are determined by the grid model.

The rectifier and inverter are connected by the DC voltage link. The voltage at C_d is determined for lossless assumed rectifier and inverter by integration over the difference of the instantaneous powers $p_g - p_w$ with $p_w = p_n$:

$$C_d \cdot \frac{du_d}{dt} = \frac{p_g}{u_d} - \frac{p_w}{u_d} \quad \text{mit} \quad u_d(t) = \sqrt{u_d(t=0)^2 + \frac{2}{C_d} \cdot \int_0^t (p_g(t^*) - p_w(t^*))dt^*} \tag{15}$$

If, in the stationary case, the effective generator power and the effective mains power are the same, the DC link voltage does not change.

1.6 Idealised Operating Characteristic Curves of WTs

Based on the system characteristics in the energy conversion of the rotor, four different operating ranges of a WT can be distinguished. These are described on the basis of the idealised sequences with the characteristic variables shown in Fig. 11.

The operating ranges have the following properties:

- Underload (I): Below the cut-in wind speed v_{cin}, the pitch angle is reduced with increasing wind speed so that the WT starts up. The WT does not yet feed into the grid and the rotational speed of the rotor increases.
- Partial load (II): In the range from v_{cin} to v_{wN}, the WT is operated at optimum fast speed by increasing the rotational rotor speed linearly at a constant pitch angle. The power fed into the grid increases cubically.
- Full load (III): Above the nominal wind speed up to the switch-off wind speed (cut-out wind speed v_{cout}), the grid power is limited to nominal power by increasing the

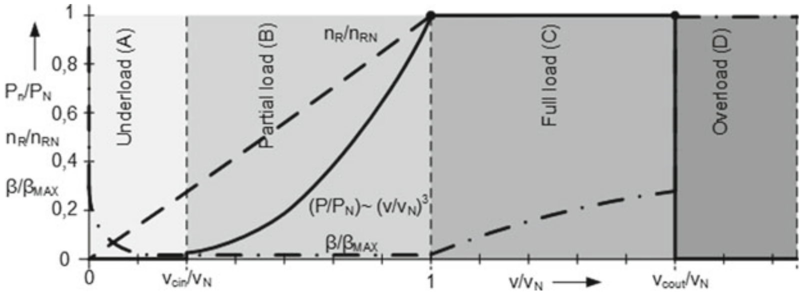

Fig. 11 Idealised operating characteristics of WTGs

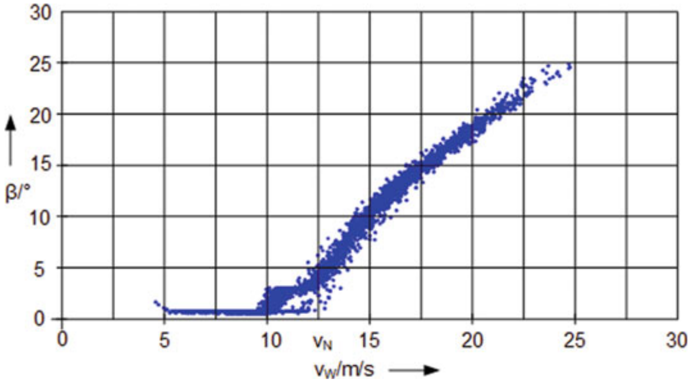

Fig. 12 Measured pitch angle of a WT

pitch angle and thus keeping the rotational rotor speed constant with increasing wind speed.

- Overload (IV): Above the switch-off wind speed, the pitch angle is increased so that the WT decelerates to zero speed. The WT no longer feeds power into the grid.

Throughout the entire operating range, the nacelle tracks the changing wind direction so that the yaw angle is always zero.

In fact, the occurring parameters of the WT deviate from the idealised curves. Short-term changes in wind speed, such as those occur in particular during wind gusts, lead to a change in power, which has an effect on the characteristics depending on the properties of the drive system and the control arrangements.

Figure 12 shows an example of the measured pitch angle of a WT with a cut-in wind speed of 4 m/s, a nominal wind speed of 12.5 m/s and a cut-out wind speed of 25 m/s. The deviations from the idealised characteristic curve at the transition from the partial load to the full load range can be clearly seen. The short-time average over one minute is shown.

The actual operating characteristics, the deviations from the idealised characteristics and the fluctuation range depend essentially on the control systems used and the controller parameterisation.

2 Control Systems of the WT

The control systems used aim to minimise both the dynamic and static deviations of the characteristic variables compared to the idealised curves while complying with the specified limit values of the WT. For this purpose, the control devices of the WT change the yaw angle, the pitch angle, the generator power or the generator torque as well as the active and reactive power fed into the grid.

2.1 Yaw Angle Control

The alignment of the rotor hub actively follows the wind direction. For this purpose, the entire nacelle is adjusted via several frequency converter-controlled geared motors (azimuth drives) and a gear rim attached to the tower. Brakes on the tower ring ensure that the nacelle is fixed when the motors are not driving it. The cut-in times, speeds and direction of rotation of the azimuth drives are controlled and regulated so that, on the one hand, the yaw angle remains low in fluctuating wind directions and, on the other hand, the number of adjustment processes does not become too large.

Figure 13 shows the block diagram of a yaw angle control that optimises the behaviour using parameter adjustment for different wind speed ranges. For tracking, the wind direction Υ_{W} is acquired and compared with the orientation of the rotor hub or rotor shaft Υ_R.

If the yaw angle $\Upsilon_G = \Upsilon_W - \Upsilon_R$ exceeds a minimum limit value (a few degrees) over a longer period of time, the brakes are opened and the nacelle alignment is regulated. The time for which the deviation must be present decreases with increasing wind speed and with increasing yaw angle. Gain and integration time constant of the PI yaw angle controller are adjusted depending on the wind speed.

At very low wind speeds ($v_W << v_{\mathrm{cin}}$) the nacelle is not tracked. As the wind speed increases, the speed of the azimuth gears increases with increasing yaw angle. The speed is limited so that the nacelle rotates slowly. Typical maximum speeds are well below one rotation per minute (rpm).

A possibility of parameter adjustment by defining different operating ranges depending on the wind speed and the yaw angle is described in [6]. Due to the fuzzy formulation of the control behaviour, the use of fuzzy controllers is also proposed.

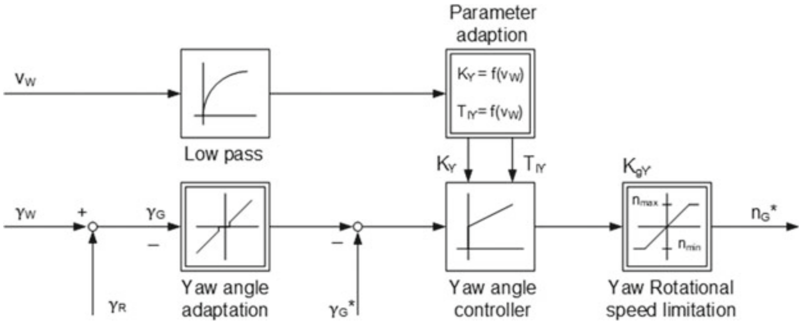

Fig. 13 Block diagram of the yaw angle automation

2.2 *Pitch Angle Control*

Power and speed limitation in the full load range is achieved by pitch angle automation using electric or hydraulic actuators. The three independent actuators mounted in the hub increase the pitch angle above the rated wind speed in order to keep the rotor power constant with increasing wind power.

In order not to have to react to the fast wind speeds, which can only be determined imprecisely, the deviation of the rotor speed from the nominal rotor speed is used as input of the pitch angle adjustment. In the case of positive deviations, the pitch angle is increased by the PI controller.

The behaviour of the line is non-linear. For small deviations of the wind speed from the nominal wind speed, a large pitch angle change is required to keep the power and thus the speed constant. For large wind speeds, a small pitch angle change is sufficient to limit power and speed. Known controls therefore use a PI pitch angle controller with adjustment of the gain factor (gain scheduling). In this case, the gain factor decreases with increasing pitch angle, so that even at high wind speeds, the control deviations of the speed do not become too large or the closed control loop may even become unstable.

Figure 14 shows a possible pitch angle control structure in which both the pitch angle setpoint and the pitch angle speed are passed to the azimuth drives. Commonly used electric servo-drives then internally use a cascade automation consisting of a superimposed angle control, a speed control and a subordinate torque or current control. Detailed descriptions of the design can be found, among others, in [5, 9].

The speed limitation is designed in such a way that even for an emergency stop the maximum pitch angle of almost 90° is reached in less than 10 s, this means angular velocities of several °/s. This means that the blade angle controller is much slower compared to torque or power control, so that noticeable changes in speed occur with dynamic wind speed changes.

In order to achieve a continuous transition from variable-speed to constant-speed operation, the pitch angle control starts before the rated wind speed and the rated rotor speed are reached. Increasing the gains and decreasing the integration time can

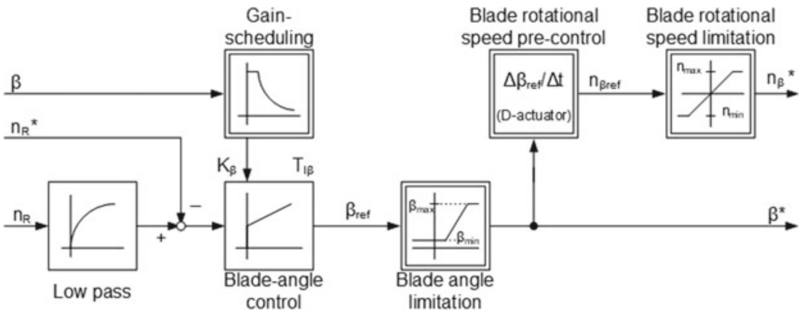

Fig. 14 Pitch angle control with parameter adjustment

reduce the maximum speed deviation. However, such a controller setting leads to a large actuating activity of the pitch angle control, especially during the transition from the variable-speed to the constant-speed range of the WT, which can have the effect of an increased noise level in this wind speed range. The design is therefore often adjusted during test operation. Here, the use of fuzzy controllers is suggested due to the fuzzy formulation of the control behaviour, too.

2.3 Active Power Control

Active power control and limitation is also carried out without direct evaluation of the wind speed measurement. Since the optimum power is achieved in the partial load range at optimum fast speed, the rotational rotor speed is also used for active power control. In partial load mode, it adjusts itself freely according to the difference between drive and generator power.

Control to the maximum achievable power is achieved by specifying the target power P_n^* as a function of the rotor speed via a characteristic curve and setting it by the inverter. If the power specified from the active power characteristic curve is less than the power contained in the wind, the rotor speeds up. If the power specified from the active power characteristic curve is greater than the power contained in the wind for the current wind speed, then the rotor will slow down. In the stationary case, the maximum power coefficient and the optimum rotor speed result for each wind speed in the partial load range.

In Fig. 15, the schematised nominal curve of the power characteristic is plotted in the characteristic diagram of the rotor power coefficient. The cubic curve for low speeds and the constant power for high powers can be seen. The characteristic curves with the specification of power limits by the energy supplier, in this case the typically used 60° and 30° limits, are entered in dashed dot lines.

If the power contained in the wind increases above the limiting characteristics, the increase in rotational speed causes the pitch angle control to kick in, limiting the

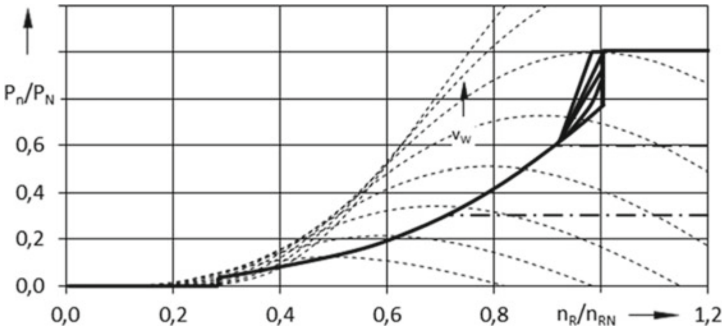

Fig. 15 Schematic setpoint curves of the power

power. Modifications of the characteristic curve are used to optimise the transition between variable and constant speeds, and a detailed description can be found in [3].

In the stationary case and neglecting the losses in the generator-inverter system, the DC link voltage is constant, generator power and active grid power are the same. The generator power or the generator torque can therefore be controlled both directly and via the mains active power if a controller for the DC link voltage ensures that this remains almost constant. Thus, there are two possibilities for active power control:

(a) Control of the grid-side inverter to the maximum achievable power and control of the active power of the rotor-side rectifier so that the DC link voltage remains almost constant.
(b) Control of the rotor-side rectifier to the maximum achievable power and control of the mains active power so that the DC link voltage remains almost constant.

Figure 16 shows the solution for variant (a). Based on the rotor speed, the setpoint value of the active power is specified. According to the deviation between the setpoint and actual value of the grid power P_n, the active power-forming current setpoint i^*_{wd} of the inverter is changed with the aid of a PI controller.

In addition, the active power reductions due to the grid operator's specifications have been added to the figure [21] (BDEW) [2, 19]. On the one hand, this is the gradual reduction of the active power related to the nominal power on demand by means of a control signal to protect against overload of individual grid sections of the transmission grid. On the other hand, it is the continuous reduction of the power available at the time of the request if the grid frequency is too high.

The control of the generator-side currents is shown in Fig. 17. The moment-forming current setpoint i^*_{gd} of the generator-side rectifier is specified in such a way that the DC link voltage remains constant. If the DC link voltage exceeds an upper limit, then the moment-forming current is reduced. If the DC link voltage falls below a lower limit value, then it is increased. The rotor-oriented current i^*_{gd} is either controlled to zero or used to control the optimum stator voltage $u_S = u_g$. If the voltage is too low, the rotor-oriented current is increased accordingly.

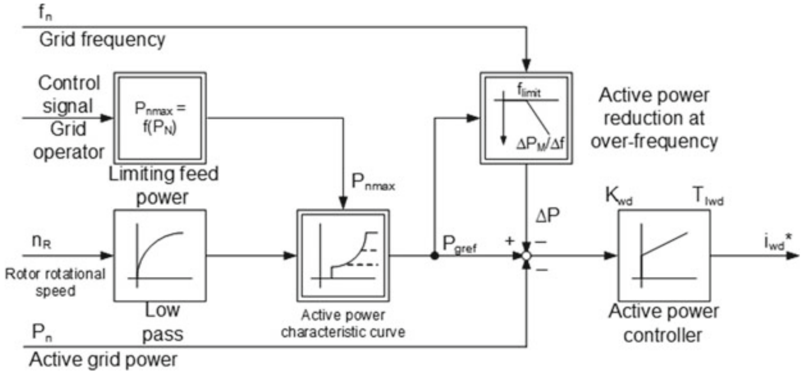

Fig. 16 Active power control by means of the grid-side inverter

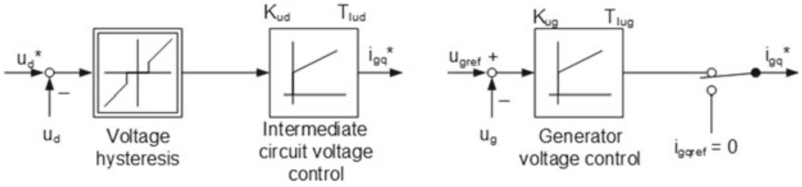

Fig. 17 Control of the generator-side currents

In Sect. 1.4, it is shown that the rotor speed can fluctuate around an average value due to the flexible drive shaft. In [16], it is proposed to damp the oscillations of the rotor speed by prescribing the setpoint of the DC link voltage as a function of the rotational rotor speed deviation in order to impress a moment-forming current which actively damps the oscillations. The voltage hysteresis must then be omitted.

2.4 Reactive Power Control

The grid feed of the WTs is conventionally operated in such a way that the reactive power at the connection node is zero. This means that the active power is fed into the grid at the minimum required grid current. For efficient and safe grid operation, WTs must contribute to voltage regulation both in quasi-stationary operation and dynamically by feeding inductive or capacitive reactive power into the grid. To increase the voltage in the connection node, a capacitive reactive current is usually impressed; the corresponding grid connection guidelines speak of overexcited operation. For voltage reduction, an inductive reactive current is impressed in so-called under-excited operation.

In Fig. 18, a block diagram is shown which enables reactive power control by impressing the reactive power-forming current component $i^*_{\mathrm{wd}} = i^*_{\mathrm{nd}}$. In order to consider specifications of the grid operator, the block diagram shows a quasi-stationary and a dynamic reactive power feed according to the regulations in BDEW [2, 21].

The specification for the quasi-stationary reactive power feed can be carried out in different ways: the grid operator can directly specify the reactive power to be fed in or the power factor cosϕ via a control signal. Alternatively, the reactive power can be fed in continuously as a function of the deviation between the actual voltage value and the setpoint value. To limit the required over-dimensioning of the grid-side inverter, the grid operator specifies required limit curves for the reactive power.

When significant dynamic voltage deviations occur, especially in the case of voltage drops due to grid faults, WTs must automatically inject a reactive current to support the voltage. For this purpose, the voltage before the fault is taken as a setpoint and compared with the current grid voltage. Depending on the deviation and a variable amplification factor, the reactive current is corrected accordingly.

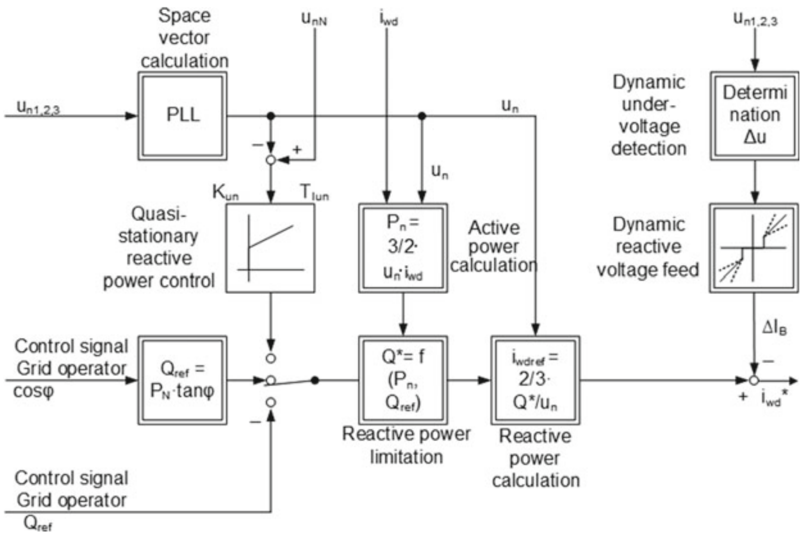

Fig. 18 Quasi-stationary and dynamic control of the mains reactive power

2.5 Summary of the Control Behaviour and Extended Operating Ranges of the WT

The behaviour of the control systems within the WT can be summarised as follows for independent operation without specifications from a grid operator:

- In the entire wind speed range, the nacelle is guided by the azimuth drives according to the wind direction.
- In the entire power range, the generator is operated with optimum current and the grid-side inverter is operated in such a way that no reactive power is fed into the grid.
- The DC link voltage control ensures that the active power of the generator-side rectifier is identical to that of the grid-side inverter in the stationary case.
- Below the rated wind speed, the power is maximised by setting the active power as a function of the rotational rotor speed. The blade adjustment remains constant at its optimum value.
- Above the rated wind speed, the rotational speed and power are kept constant by the pitch angle control.

Speed, blade pitch and power influence each other. Modern WTs have further significant transition areas in addition to the four Fig. 11 marked operating ranges, modern WTs have further significant transition ranges. Figure 19 shows the typical curves depending on the wind speed.

For a continuous transition of the system variables from partial to full load, the control characteristic of the power causes the rotational rotor speed to no longer

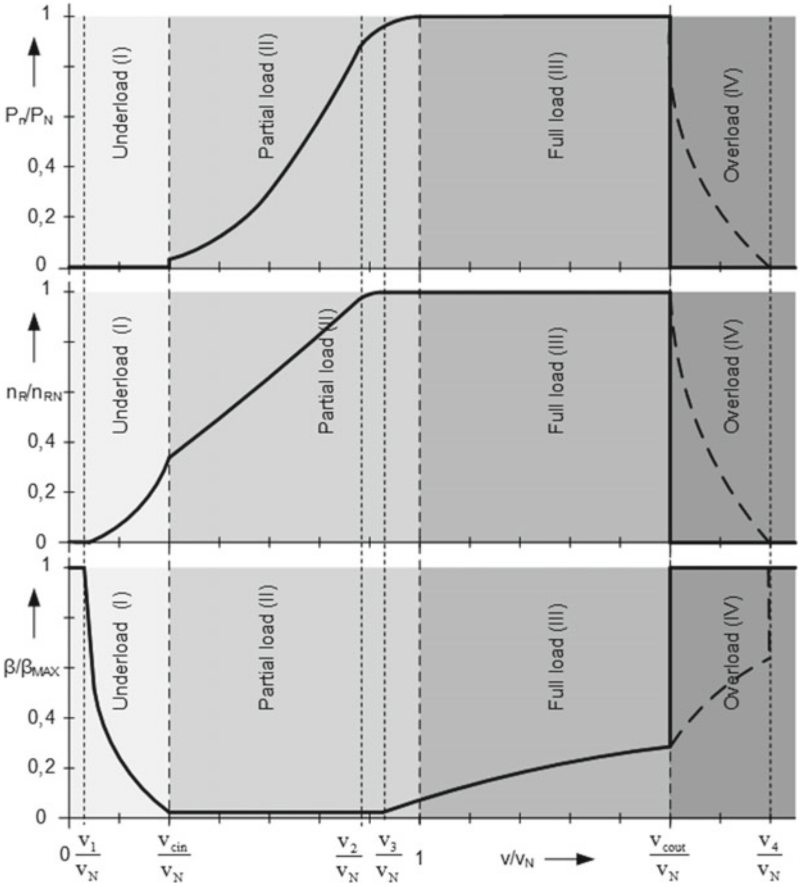

Fig. 19 Extended operating ranges of a WT with operating characteristic curves

increase in proportion to the wind speed even below the nominal wind speed. From v_2 onwards, the WT is therefore no longer operated at the optimum high-speed speed. Blade adjustment control starts at v_3, even if the rated power is not yet fully reached. Thus, the rotor power coefficient decreases additionally. A WT therefore reaches the optimum power coefficient below v_N; when the nominal wind speed is reached, the power coefficient has already dropped noticeably.

3 Operation Control Systems for WTs

The technical operation control system is used to enable the automatic, efficient and safe operation of the WT. It processes the input signals from the WT as well as the signals from the operating equipment and other higher level systems such as the management system. From these input signals, the operation control system determines the output signals for the WT, for the display devices and the higher level systems. The main tasks of the operation control system include the following:

- the control of the operating sequence and requirements for the setpoints for the WT control systems;
- monitoring critical variables and activating appropriate security measures;
- the collection, storage and exchange of relevant information with higher level systems.

According to these main tasks, the technical operation control system can be divided into three subsystems.

3.1 Control of the Operating Sequence of WTs

With the help of the operating sequence control, the operating state is determined and the transition between the operating states is coordinated. It depends on the selected operating mode (automatic, manual) and the place of operation (remote, local).

In automatic mode, the WT can only be switched on and off; all other functions are specified by the control system. In manual mode, which is required for commissioning, testing, maintenance or service, the change of operating states and the activation of output signals for the WT can also be influenced manually. As a rule, WTs are remotely controlled and monitored via control systems (remote control). Only in manual mode can the WT be controlled on site with the aid of operating equipment (local control). In this case, local control has priority over remote control.

The automatic operating sequence can be displayed with the aid of a sequence chain, whereby a simplified distinction is made between the following essential operating states of the WT:

- Initialise and test the system.
- Start-up of the system without grid feed.
- Operation of the plant in partial and full load mode.
- Shutdown of the plant under normal conditions.
- Quick stop of the system in the event of a fault.

The sequence is clear from the basic structure of Fig. 20. The change from one state to the other takes place depending on the transition condition, which is indicated at the crossbar on the connection.

The five operating states shown and the transitions are described in Fig. 21 taking into account the extended operating ranges from Fig. 19 in detail. The following tasks are to be performed in the steps which are described in detail:

- Initialise: After the system is switched on, all sub-controls initialise and communication between the subsystems and to the higher level controls is established.

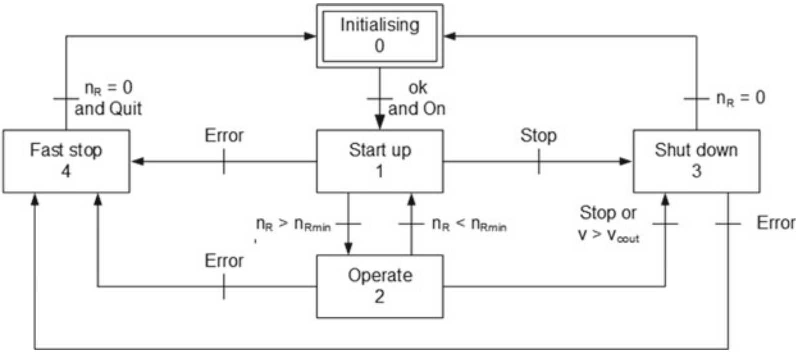

Fig. 20 Simplified basic structure of the sequence control for a WT

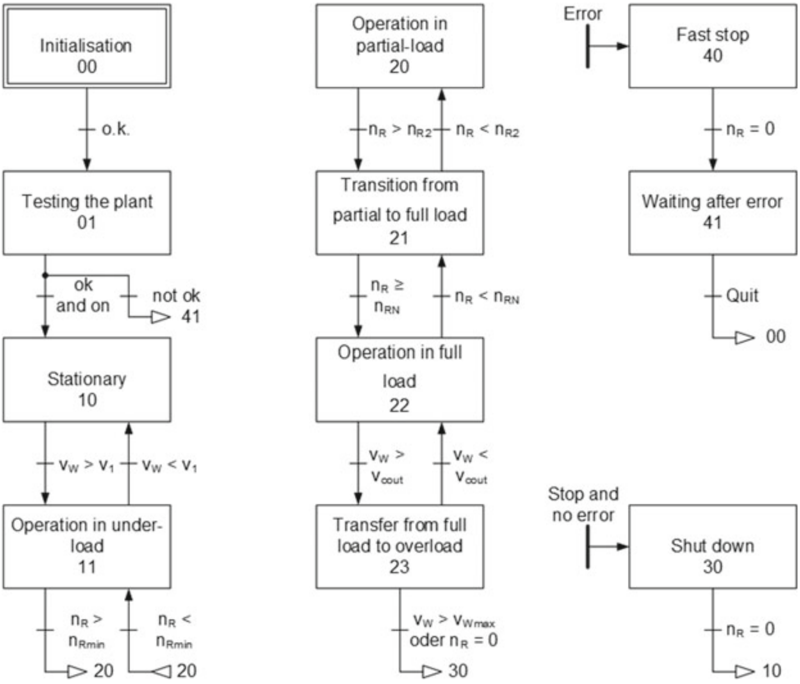

Fig. 21 Sequence control for WTs with extended operating ranges

After the initialisation phase, all status signals and measured values are logged and stored.

- Testing the system: After initialisation, the essential actuators and sensors are tested. Brakes are released and closed again, pitch and yaw drives and their encoders as well as the rotor and generator rotation encoders are tested by a short test run. The ambient conditions such as temperature and humidity, wind speed and direction as well as the numerous attached vibration and force sensors as well as the current and voltage sensors are checked for compliance with their limit values before the system enters the ready-to-operate waiting state with a stationary rotor.

- Standstill: As long as the wind speed remains lower than the minimum limit value v_1, the WT waits with stationary rotor and the pitch and azimuth drives are not activated. Only when the wind speed exceeds this value the WT switches to the start-up state.
- Operation in underload: For start-up, the turbine is aligned according to the wind direction with the brakes released. The pitch angle is slowly reduced so that the rotor starts to rotate. After exceeding a minimum required rotational rotor speed, the generator-side rectifier builds up torque and the WT starts to feed power into the grid via the converter.
- Operation at partial load: In the partial load range, the active power is maximised by adjusting the rotational speed with an optimum pitch angle. If the wind speed increases to such an extent that the rotor exceeds the characteristic value n_{R2}, the WT switches to the transition range between partial and full load.
- Transition from partial to full load: In this range, the rotor speed and pitch angle are changed. The rotational rotor speed still increases slightly due to the specified power characteristic curve; the power fed into the grid has not yet reached the rated power.
- Operation at full load: Above the rated wind speed, the WT feeds the rated power into the grid. By controlling the pitch angle, the power and rotational speed are kept constant.
- Transition from full load to overload: After exceeding the limit wind speed v_{cout}, the power of the system is continuously reduced to zero (storm control). For this purpose, both the reference power and the reference rotational rotor speed become smaller as a function of the wind speed, so that the pitch angle is increased.
- Transition from full load to overload: For turbines with so-called storm control, the speed and torque are continuously reduced as the wind speed increases. Reference speed and reference power decrease continuously so that the pitch angle increases with a much larger gradient than in full load operation. If the turbine still does not come to a standstill even when a maximum permissible operating wind speed $v_{W\mathrm{max}}$ is exceeded, the WT automatically switches to shutdown mode.
- Shutdown: After exceeding the maximum operating wind speed or on request by a stop signal, the system moves down to zero speed controlled by a ramped, slow increase of the pitch angle. The brakes are then applied again. In the event of a request via the stop signal, the system always switches from the usual operating states to shutdown mode.
- Fast stop: In the event of a fault such as mains voltage failure or very high gust wind speeds, the turbine moves to zero speed in a controlled manner by increasing the pitch angle very quickly. For safety reasons, the rotor brake also engages if the speed is not yet zero after a certain time. From other operating states, the system always switches to fast stop mode if a fault occurs.

- Waiting after error: Automatic restart after a safety-critical error is not possible. A WT that has been slowed down by a quick stop due to a fault can only be restarted, when the cause of the fault has been clarified, is no longer present and can thus be acknowledged.

From the tasks listed here, the output signals for the actuators and the display devices can be derived for each step.

3.2 Safety Systems

In addition to controlling the normal operating sequence, safe operation of the WT must be ensured. The technical operation control system must monitor the operation of the plant and avoid malfunctions, detect faults and changes in the plant at an early stage and automatically initiate safety measures and maintenance work.

Like other installations, WTs must meet basic safety requirements. A good overview of general requirements for the prevention and control of failures as well as technical and organisational requirements for the operation of plants with programmable control systems can be found in [12]. In [10], the basic characteristics of safety systems for WTs are described.

For safe operation, a safety system is superimposed on the technical operation control. So-called failsafe control and switching components are used and additional safety systems are installed that detect the signals independently of the control system and take immediate safety measures.

The control of the operating sequence intervenes at an early stage if limit values, faults or malfunctions are exceeded in order to enable safe operation of the turbine. Even in the event of extraordinary wind speeds, ambient conditions such as the outside temperature, grid supply conditions or unforeseen failure of individual components, for example due to lightning, the WT will be transferred to a safe state.

The following events first lead to a power reduction, before the exceeding of the limit value triggers a quick stop:

- Exceeding threshold values for rotational rotor speed, for forces, torques and vibration amplitudes of tower, blade or drive train.
- Exceeding threshold values for the generator current, for the DC link voltage and for the mains current.
- Exceeding the thermal limits in the nacelle, generator or inverter or the limits of other climatic variables such as humidity.

The following events lead to an immediate quick stop by the blade displacement and the subsequent closing of the rotor brake:

- Failure of the measuring systems for rotational speed, wind speed, current and voltage.
- Failure of individual actuators such as yaw or azimuth drives.

- Failure of the communication systems within the WT between the control system and the actuators.
- Exceeding of mains voltage limits or falling below the limit curves for the permissible mains undervoltage.
- Exceeding the maximum or falling below the minimum mains frequency limit.

In addition, the operating condition of critical technical equipment of the WT is recorded by so-called condition monitoring systems (CMS). These systems automatically initiate the necessary measures, maintenance work or replacement of the equipment at an early stage before damage occurs.

4 WPP Control and Automation Systems

WPPs or wind farms are characterised by the fact that a large number of WTs, distributed over a wide area, are connected to the public grid via a grid connection point (NAP). The connected load of such WPPs exceeds 100 MW and they are often connected directly to the transmission grid.

The WTs in such a WPP often have different outputs. For example, in large WPPs, selected WTs are completely shutdown due to routine maintenance, while in others the power fed in is not identical due to the different wind speed distribution in the WPP. The wind speed of the WT that the wind hits first is much higher than the WT that is on the downwind side of the WPP. In newer large WPPs, the installed capacity of the WPP is greater than the rated connected load, so that it can be fed into the grid even if individual WTs are out of service for maintenance and the wind speed is sufficient.

The individual control of a WT to comply with the grid connection guidelines is now no longer practical. WPP control systems are therefore used which are superordinate to the WT control systems and specify individual setpoints. In detail, these WT control and automation systems have the following tasks:

- controlled increase of power at switch-on with limited dP/dt (switch-on control with presetting of rise time);
- controlled reduction of the power when switched-off with limited dP/dt (switch-off control with presetting of the ramp-down time);
- specification of reserve services;
- compliance with the active power limit specified by the grid operator and quasi-stationary frequency support at the NAP as well as
- compliance with the reactive power specified by the grid operator, quasi-stationary voltage stabilisation and dynamic voltage stabilisation in the event of voltage collapse due to reactive current injection at the NAP.

In Sect. 2, the control systems for individual WTs are described. When used in large WPPs, the tasks of maintaining the grid connection conditions are implemented by a WPP control system. Already in [8, 20] proposals for this were made, which

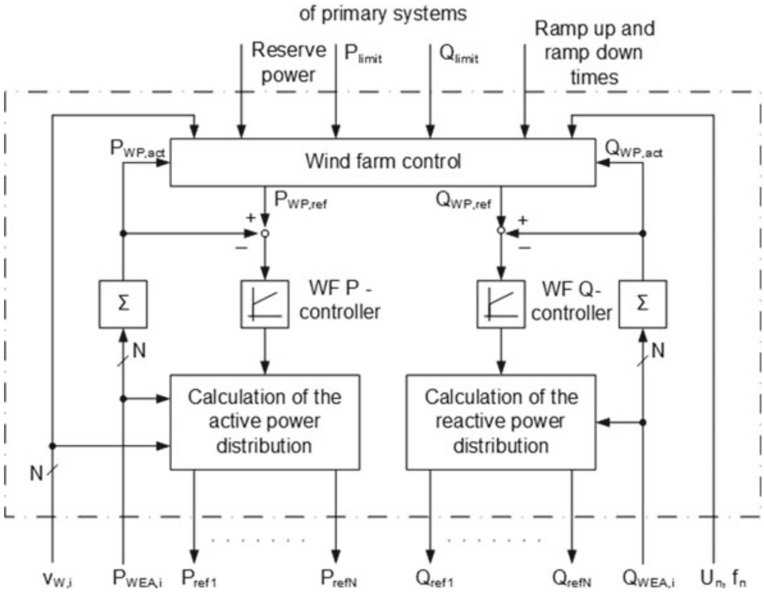

Fig. 22 WPP control system

are now gradually being introduced in new WPP control systems. Figure 22 shows a WPP control system which coordinates the tasks for active and reactive power injection according to the requirements of the grid operator.

The blocks for the distribution of active and reactive power to the individual WTs can be seen. The distribution is optimised by taking into account the WT operating states, the wind speeds and the current actual values of active and reactive power.

Dynamic voltage stabilisation in the event of a voltage drop due to reactive current injection is only possible if the setpoints are transferred quickly and the WTs react correspondingly fast. It may be necessary to add additional units solely for reactive current injection into WPP.

5 Remote Control and Monitoring

Both the data of the technical operation control system and the data of the operating condition monitoring are recorded, processed, displayed, evaluated and stored in modern remote control, maintenance and monitoring systems of WTs. These remote-control systems are abbreviated with the term SCADA for 'supervisory control and data acquisition'. In contrast to operational control system, control and automation, the SCADA system does not intervene directly or in real time in the energy conversion process of the WT.

SCADA systems control not only the individual WT but often all WTs supplied by one manufacturer to different operators or all WTs monitored by one operator from different manufacturers. In addition, the SCADA system also makes selected data available for other applications. For example, selected data is made available to the shareholders for information purposes or the operating companies can integrate selected data into their business data processing systems (billing systems).

The technical tasks of SCADA systems for WT and WPP can be classified as follows:

(a) Control tasks:

- Communication and identification of the WTs: The SCADA system establishes the connection to the WPP and WTs and identifies the location, type and other required plant information.
- Access and types of operating control: The SCADA system controls access to the plant and data depending on usage rights and access controls. It coordinates the switching of local and remote control, the switching of manual mode to automatic mode and the required interlocks.
- Functional testing and parameterisation: With the help of the SCADA system, various actuators can be tested for their function in manual mode. Essential system properties can be re-parameterised via the SCADA system.
- Alarming: The SCADA system automatically triggers warnings, alarms and, if necessary, service calls and spare part procurements via various channels such as email, fax or SMS.

(b) Data collection, analysis and archiving tasks:

- Data acquisition: The SCADA system reads in and stores the relevant measured values of the WT such as wind speed, wind direction, rotational speed, power, current, voltage, frequency, power factor, temperature, humidity, pressure in defined cycles. Operating states, system interventions, maintenance activities are also recorded in this way.
- Data analysis: The SCADA system evaluates the data and determines characteristic parameters such as average values, minimum and maximum values, standard deviations, wind speed distributions, power distributions, production and availability statistics and compiles the information for reporting or event logs.
- Archiving: The SCADA system stores and backs up the data.

(c) Display and operating tasks:

- Display: The SCADA system clearly displays location, time, operating conditions and alarms. It displays wind speed and direction, rotational rotor speed and other WT parameters such as power and energy.
- Visualisation: The SCADA system provides an overview image of WPPs, WTs and WT components in a hierarchical arrangement. It can display significant time histories as time series.

- Operation: The SCADA system offers standard operating options such as start, stop, reset and operating mode selection. Via password-protected login/logout functions, it enables user management and access control.

To fulfil the tasks, the remote-control and monitoring system consists at least of the man-machine interface in the control room (workstation terminal), the actual computer for processing, sending and receiving the data, the data storage, the communication infrastructure and the systems arranged locally in the WT and WPP for interaction with the control room. Different solutions for integration into the communication and automation infrastructure with different communication protocols and data formats are used.

6 Communication Systems for WES

Different communication systems are used in WES and for the exchange of information with the higher level systems, which are essentially determined by the transmission rate, the number of inputs and outputs, the required response times, the distances between the systems and the requirements for the security of the transmission. With the entering of international standards for 'Communication for the monitoring and control of wind turbines' [11] and for 'Communication networks and systems for automation in electrical power supply' [13], the communication structures and protocols for WES are becoming standardised.

Figure 23 shows a typical WT and WPP communication structure and the integration into a grid control system, into the WES remote monitoring and operation as well as further monitoring and diagnostic systems.

Within the WT, the sensors, actuators, WT control and automation exchange the required information via different decentralised communication systems. The different WTs in a WPP are connected to the WES control system via a local WPP bus system, which must meet the real-time characteristics for the time-critical processes. Fibre optic cables are used to achieve high transmission speeds over long transmission distances. External communication then takes place via the TCP-IP network using the standardised protocols and data formats.

In order to be able to integrate the specific information of WTs from different manufacturers into the higher level systems and to be able to control the WTs independently of the manufacturer, both the information exchange process and the representation of the WT information are standardised. Figure 24 shows the WT communication model (a) and the information model of a WT (b) based on [11].

The communication is based on the generally accepted client-server relationship. The WT components exchange the information with the WT information model of a server, which provides it for different clients. Different applications such as a SCADA system can use this data if the client has the appropriate rights. The actual data exchange between client and server takes place via uniform information

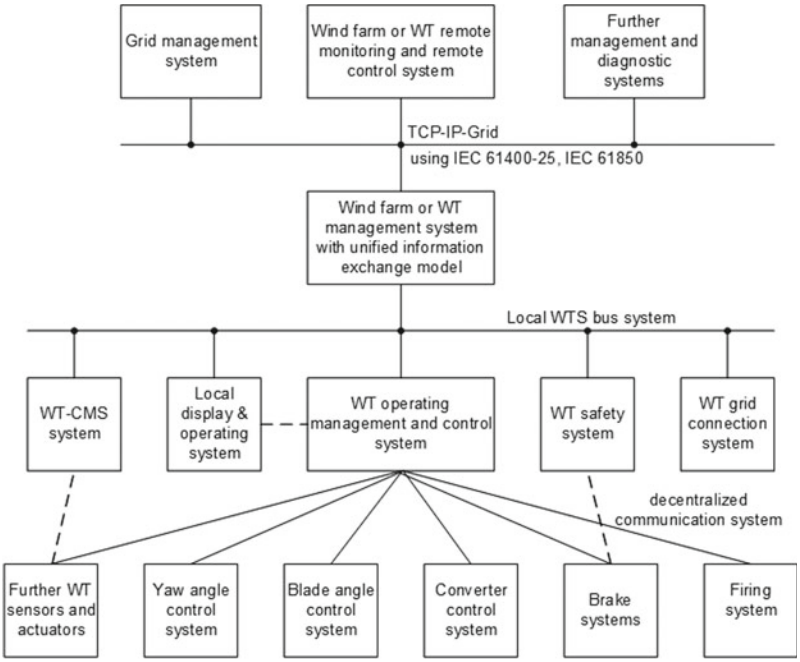

Fig. 23 Schematised WT and WPP communication structure

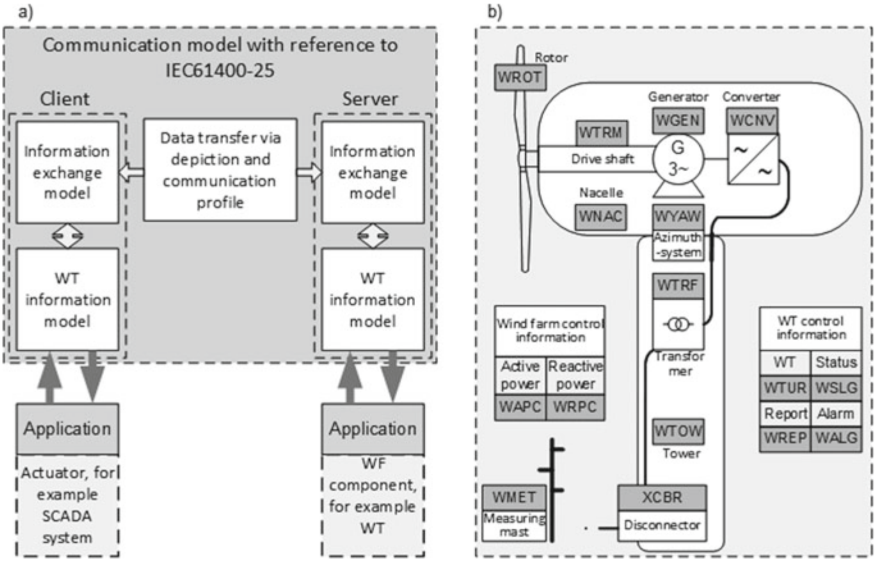

Fig. 24 Unified WT communication model (**a**) and information model (**b**)

exchange models for loading, setting, reporting, controlling or logging and by data transfer using uniform communication profiles for reading and writing.

The WT information model provides the content required for the information exchange between client and server. For this purpose, the components of the real WT write into the unified model of a virtual WT with unified mappings, labels, data types, resolutions and functionalities of the information. Figure 24b shows the main components of the virtual WT. The model is hierarchically organised and includes the information for the drive train with rotor, the power transmission (drive shaft), the generator, the converter and transformer as well as the information of the nacelle, the tower and the azimuth system. In addition, the information on the WT and WPP control system as well as data of the assigned meteorological measuring systems are also described. In Fig. 24b the names of the logical nodes for the components are entered in accordance with [11]. It can be seen that the information of the disconnector already belongs to the group of loops and is therefore coded differently.

With the help of this uniform communication and information model, it is now possible to fulfil different services such as control with the help of a grid management system, the evaluation of data with the help of a condition monitoring system or billing for business management tasks.

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