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Control Methods for Variable Speed Wind Energy Converters

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1. Introduction

By the utilization of wind energy, wind energy converters are preferably designed to provide electrical energy. The electrical energy is, in most cases, fed into the electrical grid. The kinetic energy of flowing air masses is converted into rotational mechanical energy with the help of uplift or air resistance effects at wind rotors. This energy is transmitted through a drive shaft and, in most cases, additionally through a gear box, to feed the generator. The generator transforms the mechanical energy into electrical energy. Depending on the generator system, the energy is then, either directly or through a power electronic device, fed into the electrical grid.

For the efficiency of the wind energy utilization and the durability of the energy conversion chain of the wind energy converter, it is of essential significance that the stationary and dynamical operation behavior of each component are adjusted to each other and to optimize the operational behavior of the whole energy conversion chain. In the first instance, the stationary and dynamical operation behavior of the wind energy converter must, on the one hand, meet the demand of the wind energy conversion process (aerodynamic process) and, on the other hand, the demand of the electrical supply network. Above that, from the system side of view, basic conditions concerning the operational behavior of the energy conversion chain have to be considered.

The basic requirement to meet the above mentioned demands on the operational behavior can be realized by the basic set up, e. g. the variable speed operation, of the energy conversion chain. The optimal operational behavior can be finally set with the help of the control and of the operation management. Depending on the structure and the operating characteristic of the energy conversion chain of wind energy converters, the type and structure of the control unit and of the operation management varies.

In the frame of this chapter, the theoretical fundamentals of wind energy converter controls will be presented and explained. Among others the approach to lay out a mathematical model of the energy conversion chain of wind energy converters, which reproduces the stationary and dynamical behavior, will be described. Furthermore, the basic structure of the control and the operation management will be presented and explained, whereat a differentiation between the task of the control and operation management will take place.

For the control, different conventional methods will be described. For this purpose the controller design and layout, based on control technique methods, will be presented. Additionally, newly studied control methods will be presented. They will be compared to

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the conventional control methods. For comparing the efficiency of the wind energy conversion, the fluctuation of the delivered electrical power and therefore the system perturbation, and the load spectrum in the energy conversion chain will serve as criteria.

2. Energy conversion chain of wind energy converters

The operating behaviour of the energy conversion chain of wind energy converters is significantly influenced by the wind rotor and the mechanical-electrical energy converter system, which generally comprises of a generator and the connection system to the electrical grid. Two basic categories can be distinguished; "Constant speed systems," where an asynchronous machine is coupled to the electrical grid, can be compared with "variable speed systems," which feature a decoupling of the generator frequency resp. speed from the grid frequency by means of a dc-link inverter. Nowadays, variable speed systems are realized preferably by a synchronous generator machine (see Figs. 1c and d) which is coupled to the electrical grid by a dc-link inverter, or by means of a doubly fed asynchronous machine (see Fig. 1b).

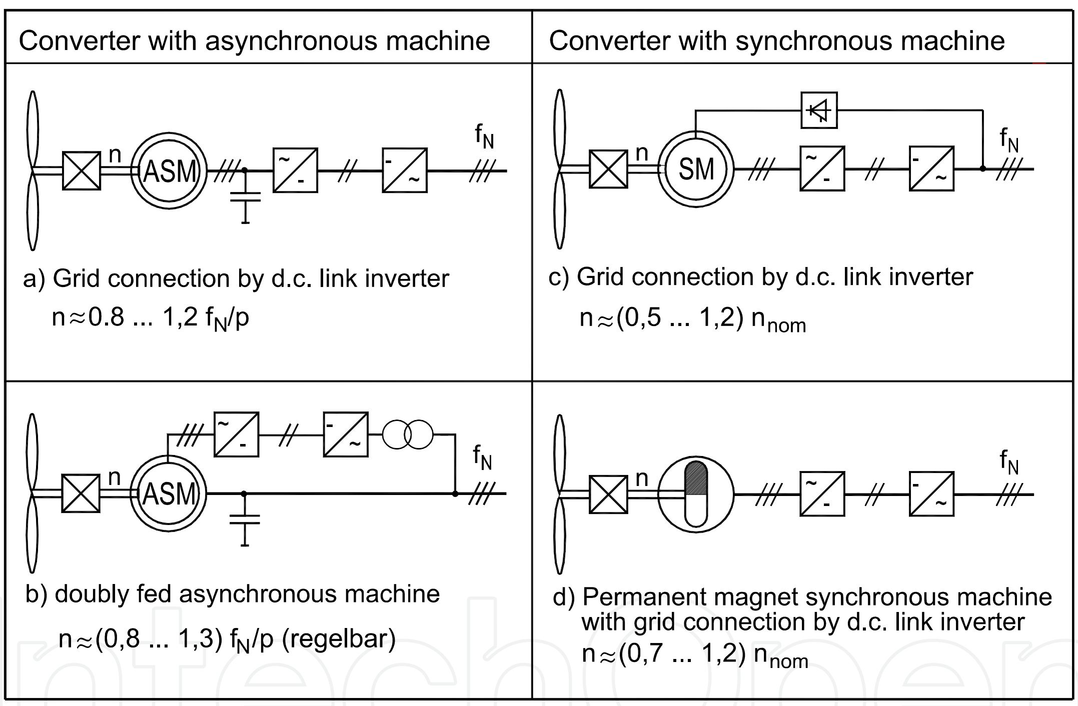

Fig. 1. Applied Generator Systems for variable speed wind energy converters

The necessity of variable speed operation can be attributed directly to the general requirements of the process of wind energy utilization. They can be formulated as follows:

- operation at maximum possible power coefficient c_p of the wind rotor,
- reduction of wind caused power fluctuations in the drive train of the wind energy converter and
- reduction of the resulting mains pollution.

By decoupling the generator speed and thus the wind rotor speed from the grid frequency, the speed of the wind rotor can be adjusted dynamically to the prevailing wind speed, so that the wind rotor is able to operate at the maximum power point (MPP) (see Fig. 2).
At the same time, variable speed wind energy converters offer the possibility to smoothen short-time wind caused power fluctuations by utilizing the rotating masses (e.g. the wind

rotor) as kinetic energy storage. When the wind speed increases, the rotor speed must be increased too so that the wind rotor operates at the MPP (see Fig. 2).
Part of the wind power is then stored in the rotor masses. When the speed is reduced at wind slacks, the kinetic energy stored in the rotor masses is transformed into electrical energy, so that alterations (fluctuations) of the supplied electrical power and thus of the torque in the drive train are reduced. This requires a suitably designed speed/power control and operation management.

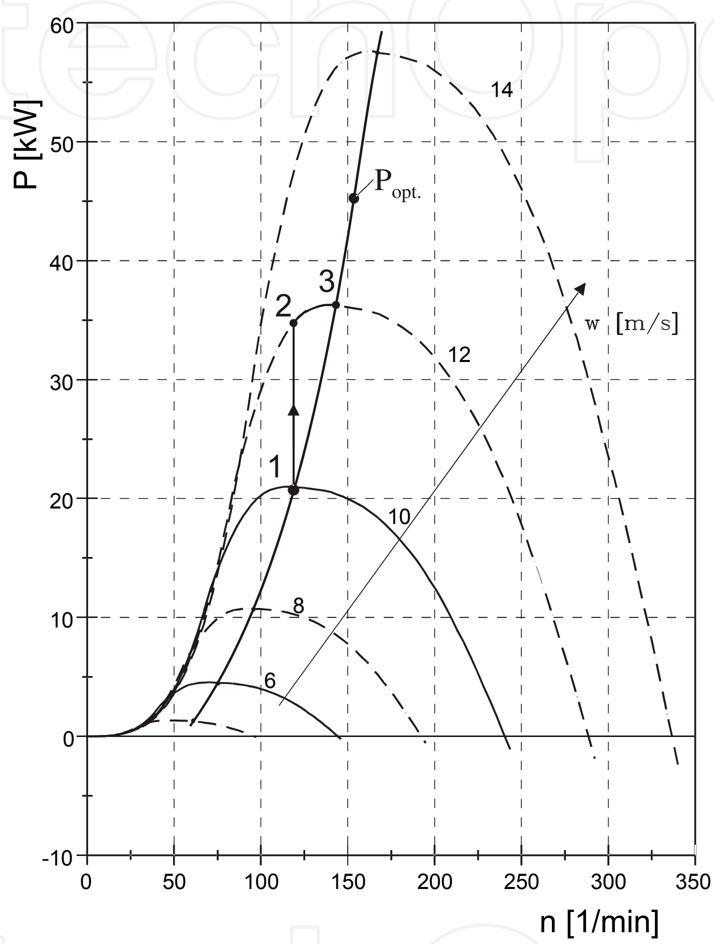

Fig. 2. Power map example of a wind rotor

Based on the requirement to achieve maximum energy yields, the primary control-engineering task is to provide a dynamical control of the respective optimal operating speed. At the same time, the wind caused power fluctuations at the wind rotor shall be smoothed by utilizing the storage effect of the rotating mass and thus avoids mains pollution in form of flicker effects. Furthermore, the power or torque fluctuations in the drive train are reduced. To minimize cumulated loads and thus enable an increase of the life of drive train components, the torsional vibrations, possibly caused by load peaks, must be damped as well.

3. Control path and basic control structure

The structure of a mechanical-electrical drive train of variable speed wind energy converters is generally suitable for a two-level type basic control structure. The inner control defines

the operating behavior of the electrical subsystem and provides a dynamical impression of the electrical counter-torque in accordance with the demand. The internal control has the task to dampen torsion vibrations in the drive train induced by load peaks. The process control (e.g. speed control) is realised in the second level. The process control shall improve the quality of the energy conversion process at the wind rotor by adjusting the optimal speed for the prevailing wind speed dynamically. At the same time, the set point torque value shall be regulated dynamically in such a way that wind caused power fluctuations in the drive train of the wind energy converter are smoothed.
Following considerations are exemplarily based on the drive train of a wind energy converter with synchronous generator. The generator is connected to the electrical grid by a dc-link inverter (Fig. 3).

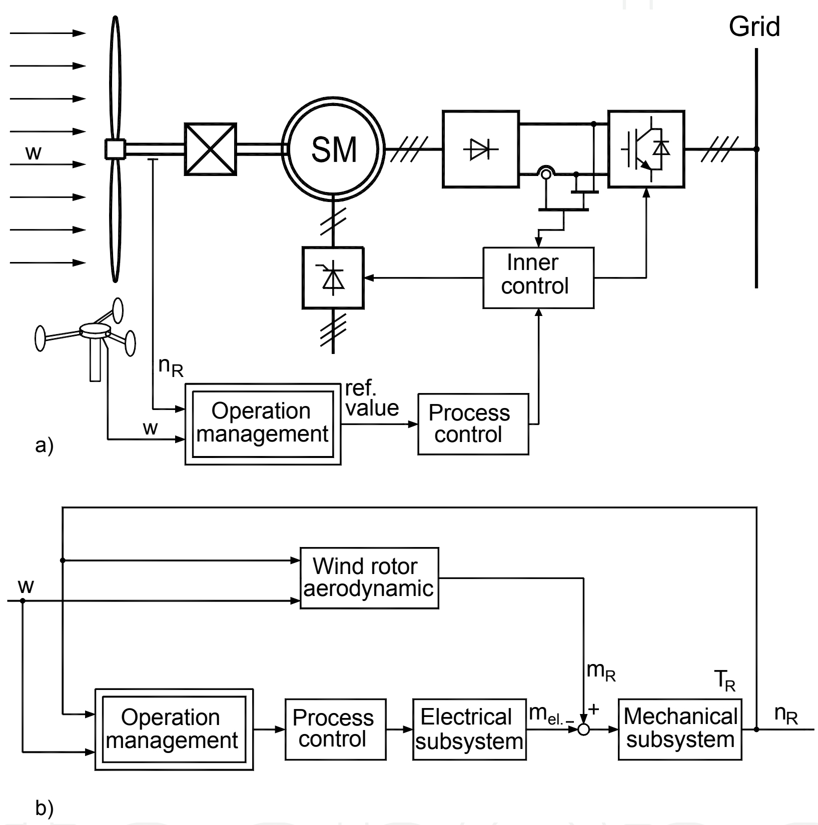

Fig. 3. Drive train structure of variable speed wind energy converter: a) function diagram; b) block diagram

The basic structure of the drive train can be split into a mechanical and an electrical subsystem as shown in Figs. 3 and 4. Based on the general differential equations of motion, the dynamic behavior of the mechanical subsystem is presented by the mathematical model of a two-mass spring system (see Fig. 4) simplified by the assumption that the mass of the shaft is small enough to be neglected. Besides others this simplification means that the mechanical subsystem of the drive train or its operating behavior respectively can be identified by a single dominant natural frequency.
For control-engineering purposes, this structure simplification of the mechanical subsystem, which is in real a multi-mass oscillator, has to be carried out according to Klöckner [4]. Contrary to other methods this method makes sure, that the reduction is carried out solely physically. The physical interpretability is retained and the remaining natural oscillation

frequencies are also exactly retained. The procedure according to Klöckner can be applied successively, until the subsystem is reduced to a two-mass oscillator. In the following, the first mass is identified by the rotor mass of the drive motor and the second mass by the rotating mass of the process machine for simplification purposes.

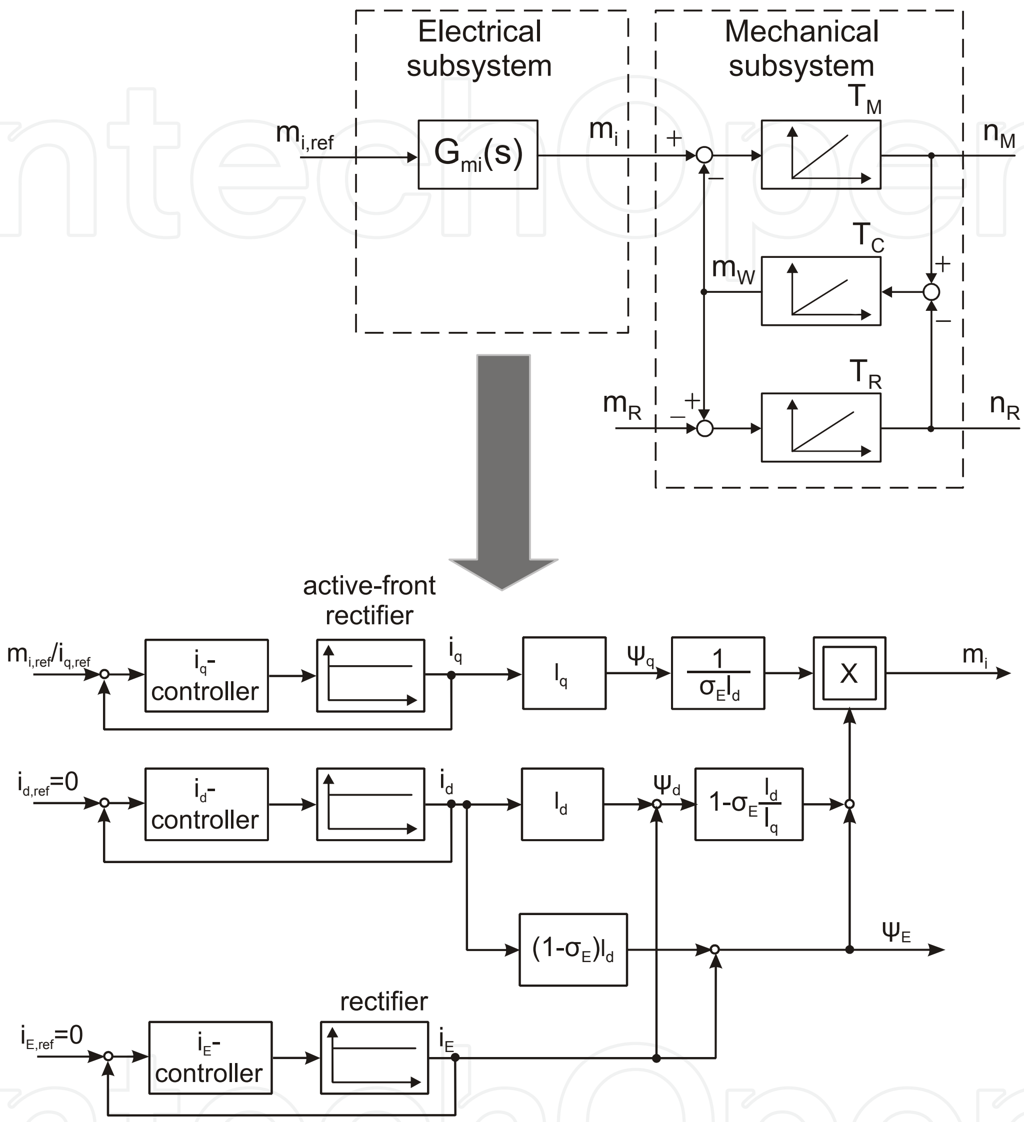

Fig. 4. Simplified mathematical model of the electro-mechanical drive train

The following simplified equation system provides the modelling basis:

$$
\begin{aligned}
M_i - M_W &= J_M \frac{d\omega_M}{dt}, \\
M_W &= C(\varphi_M - \varphi_R) = C\int(\omega_M - \omega_R)\,dt, \\
M_W - M_R &= J_R \frac{d\omega_R}{dt}.
\end{aligned} \tag{1}
$$

After normalization of the motor speed n_M, the load speed resp. rotor speed n_R, and the shaft torque m_W, the system is transformed into state space representation. Air gap torque m_i and rotor torque m_R are the input variables.

$$\begin{bmatrix} \dot{n}_M \\ \dot{m}_W \\ \dot{n}_R \end{bmatrix} = \begin{bmatrix} 0 & -\frac{M_{nom}}{2\pi n_{nom}} \cdot \frac{1}{J_M} & 0 \\ \frac{2\pi n_{nom}}{M_{nom}} \cdot C & 0 & -\frac{2\pi n_{nom}}{M_{nom}} \cdot C \\ 0 & \frac{M_{nom}}{2\pi n_{nom}} \cdot \frac{1}{J_R} & 0 \end{bmatrix} \cdot \begin{bmatrix} n_M \\ m_W \\ n_R \end{bmatrix} + \begin{bmatrix} \frac{M_{nom}}{2\pi n_{nom}} \cdot \frac{1}{J_M} & 0 \\ 0 & 0 \\ 0 & -\frac{M_{nom}}{2\pi n_{nom}} \cdot \frac{1}{J_R} \end{bmatrix} \cdot \begin{bmatrix} m_i \\ m_R \end{bmatrix} \tag{2}$$

By introduction of the relevant time constants, the mechanical quantities (mass inertia and spring stiffness) can be replaced. With the acceleration time T_M of the motor

$$T_M = \frac{2\pi n_{nom}}{M_{nom}} J_M , \tag{3}$$

the acceleration time T_R of the load mass resp. of the rotor (e.g. wind rotor)

$$T_R = \frac{2\pi n_{nom}}{M_{nom}} J_R \ , \tag{4}$$

the mass inertia ratio v

$$v = \frac{J_M}{J_R} = \frac{T_M}{T_R} \tag{5}$$

and the time constant T_C for spring stiffness C,

$$T_C = \frac{M_{nom}}{2\pi n_{nom}} \cdot \frac{1}{C} . \tag{6}$$

The following is applicable for the eigen angular frequency ω_{ef} of the mechanical subsystem resp. its relevant time constant T_{ef} [5], [6]:

$$\omega_{ef} = \frac{1}{T_{ef}} = \sqrt{C\left(\frac{1}{J_M} + \frac{1}{J_R}\right)} = \sqrt{(1+v)\frac{C}{J_M}} \tag{7}$$

The state space representation adopts the following form by introducing the time constant:

$$T_{ef} = \frac{1}{\omega_{ef}} = \sqrt{\frac{T_C T_M}{(1+v)}} . \tag{8}$$

From state space representation, the transfer function between air gap torque m_i resp. shaft torque m_w can be derived. After execution of the Laplace transformation

$$\begin{bmatrix} \dot{n}_M \\ \dot{m}_W \\ \dot{n}_R \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{T_M} & 0 \\ \frac{T_M}{(1+v)T_{ef}^2} & 0 & -\frac{T_M}{(1+v)T_{ef}^2} \\ 0 & \frac{1}{T_R} & 0 \end{bmatrix} \cdot \begin{bmatrix} n_M \\ m_W \\ n_R \end{bmatrix} + \begin{bmatrix} \frac{1}{T_M} & 0 \\ 0 & 0 \\ 0 & -\frac{1}{T_R} \end{bmatrix} \cdot \begin{bmatrix} m_i \\ m_R \end{bmatrix}, \tag{9}$$

following transfer function is obtained:

$$\begin{aligned} m_w(s) &= \frac{1}{v+1} \cdot \frac{1}{s^2 T_{ef}^2 + 1} \cdot m_i(s) + \underbrace{\frac{v}{v+1} \cdot \frac{1}{s^2 T_{ef}^2 + 1}}_{m_R^*} \cdot m_R(s) \\ m_w(s) &= \frac{1}{v+1} \cdot \frac{1}{s^2 T_{ef}^2 + 1} \cdot (m_i(s) + v m_R(s)) . \end{aligned} \tag{10}$$

The transfer function with a drive shaft torque m_w as output variable is the basis for examinations on the operating behaviour of the mechanical subsystem (see Fig. 4) with respect to the propagation of load peaks from the process and excitation of torsion vibrations. From the transfer function a direct correlation arises between load peak propagation in the drive train and the mass inertia ratio v. With increasing mass inertia ratio v at constant total mass inertia, higher torque peaks can be expected in the time response of the shaft torque. The same behaviour of the mechanical subsystem was visible in connection with the excitation affinity of torsion vibrations in the drive train.

Considerations about the operating behaviour of the mechanical subsystem are based on the assumption, that the air gap torque impression by the electrical subsystem is free of feedbacks to the mechanical subsystem.

The electrical subsystem which is part of the basic structure of the drive train consists of the electrical part of the electromechanical energy converter (motor resp. generator), the electrical grid and the frequency inverter with internal current control. In modern converters this is generally realized in compliance with the basic concept of field-oriented control, which features a decoupled control of the two orthogonal components of three-phase systems (Fig. 4). Flux- and torque building components are part of the dq-coordinate system constantly rotating with the rotary field. In the nominal speed range (constant flux), the operating behavior of the electrical subsystem is described by the transfer behavior (control behavior) of the control circuit for the torque-building current components i_q resp. the air gap moment M_i. Since overshoot is generally not allowed at reference jumps, the reference reaction of the control loop and thus the operating behavior of the electrical subsystem can be approached by a 1st order lag function (PT_1 element) (see Fig. 5). The substitution time constant T_{Str} of the approached transfer function for the electrical subsystem corresponds to the control rise time of the torque-generating current component's control loop.

4. Process control and operation management for variable speed wind energy converters

As mentioned before, the wind energy converter must be operated within a wide speed range in the course of the wind energy transformation process. This means that the often

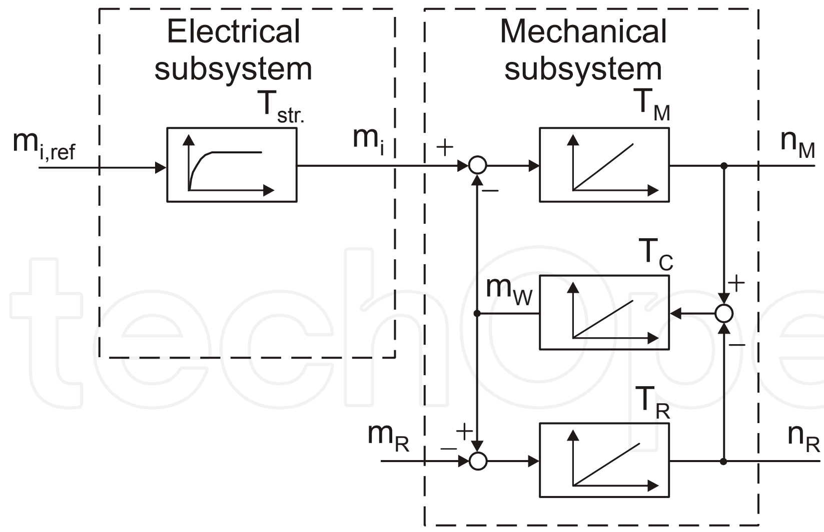

Fig. 5. Simplified mathematical model of the electromechanical drive train

applied linearization of the operating point is not permitted in this case. Another special characteristic of the process is, from a control-engineering point of view, that every change of the wind speed affects the disturbance effect of the non-linear transfer function of the wind rotor on the one hand, and requires an adjustment of the nominal value by displacing the "optimal working point" on the other.

Variable speed operation makes it possible to store part of the energy generated by the wind in the rotating mass for a short time period. At the same time, the speed shall be adjusted to the prevailing wind speed, so that the wind rotor is operated at maximum power coefficient. Task of the process control/operation management is, to provide a reference value for the dc-link current $I_{z,soll}$ resp. for the shaft torque at any operation state $x(n_R, w)$, given by the rotor speed n_R and the wind speed w, on the basis of which the internal regulation controls the electrical subsystem.

Besides the wind rotor and the mechanical-electrical energy transformation system, the operating behavior of the wind energy converter is determined by the power control and in the broadest sense by the operation management too. Power conversion at the wind rotor is described by the coefficient c_P, which reaches its maximum only at a certain tip-speed ratio. A maximum energy yield can therefore only be achieved by adjusting the rotor speed to the prevailing wind speed. At the same time variable speed operation allows to utilize the rotating masses as energy storage to smoothen short-time, wind caused power fluctuations.

To ensure an as high as possible energy yield, a quick adjustment to maximum power conversion at the wind rotor must be aimed for. On the other hand, this has negative effects on the frequency spectrum of the power output. From the aspect of operation at maximum power coefficient and low ripple of the yielded power P_{el}, different power control methods are compared in the following.

4.1 Optimal rotor speed control

The correlation between wind speed and optimal speed n_{opt} can be derived from the characteristic operation field resp. c_P-λ-characteristic of the wind rotor (see Fig. 6). For this purpose, the tip-speed ratio at which the power coefficient c_P becomes maximal must be determined from the c_P-λ-characteristic. On this basis, the optimal speed can be calculated on the assumption that the instantaneous wind speed can be measured at good accuracy.

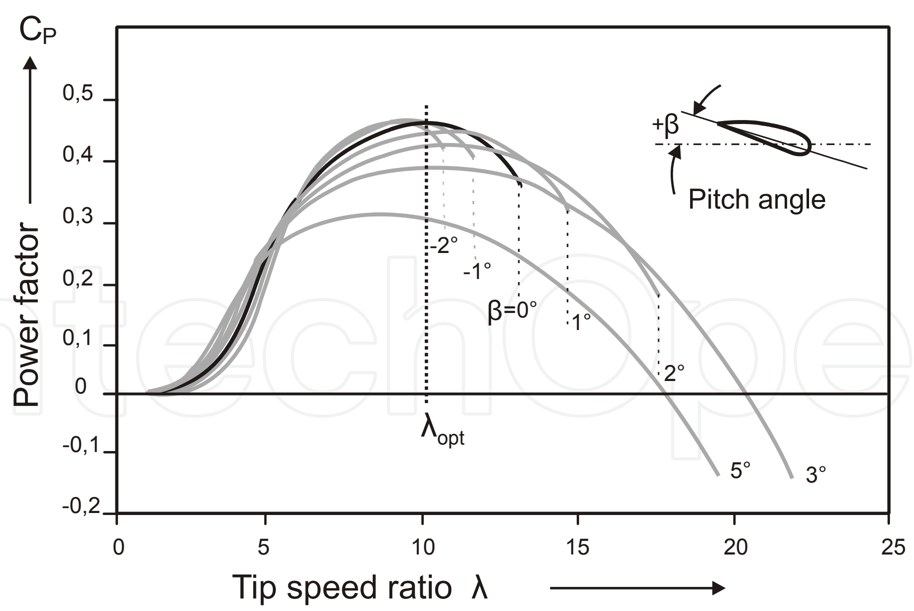

Fig. 6. Characteristic operation field of wind rotor

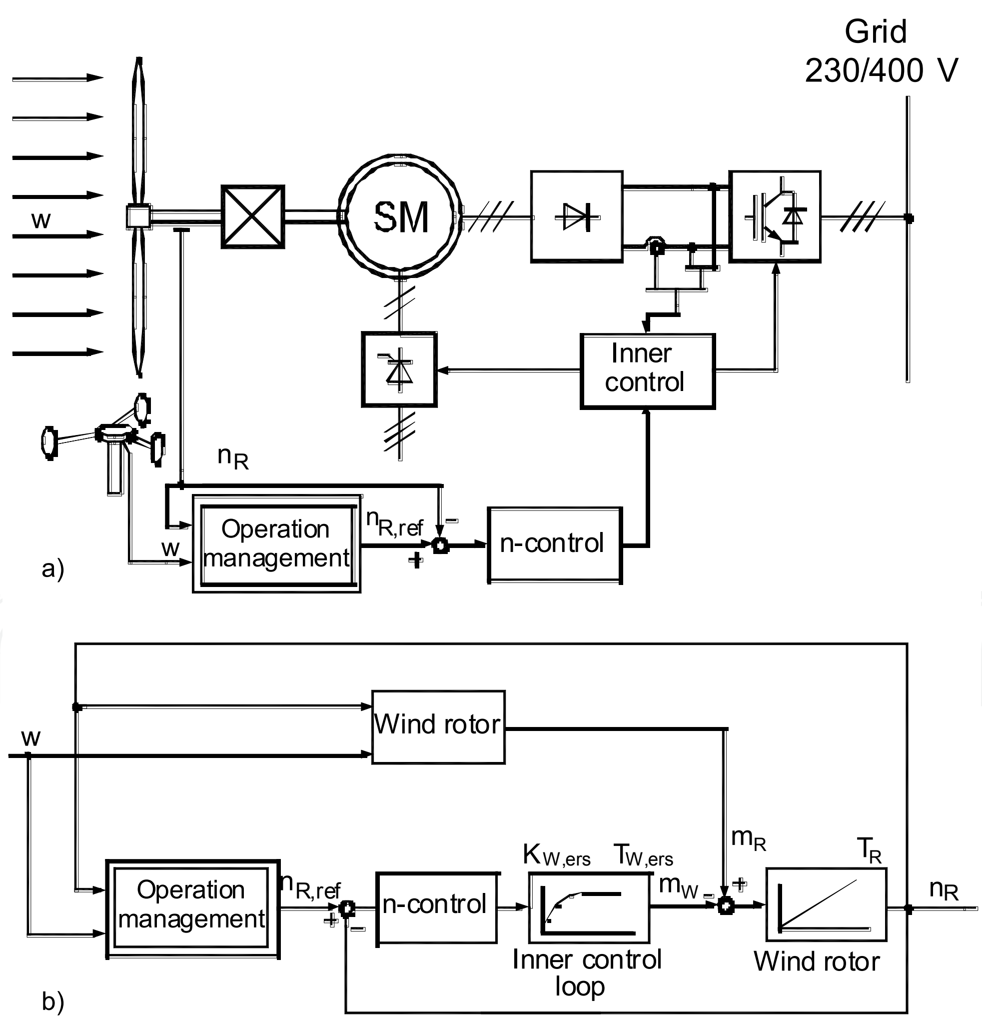

Fig. 7. Control of the optimal speed: a) principle of operation; b) block diagram of the controlled system

$$n_{R,opt} = \frac{1}{2\pi R_R} \lambda_{opt}\, w \tag{11}$$

with

R_R : the radius of the wind rotor,
λ_{opt} : the optimal tip-speed ratio,
$n_{R,opt}$: the optimal operating speed of the wind rotor, and
w : the prevailing wind speed.

Fig. 7 shows the function of the control procedure examined in this paper. When the wind speed w accelerates quickly, the actual value of the speed is not able to follow the nominal value n_{opt} due to the large mass inertia. The control difference at the input of the speed controller (n-controller) causes a step-type change of the power output since the speed controller attempts to accelerate the control procedure by relieving the load from the generator. At decelerating wind speed the reciprocal control procedure takes place.

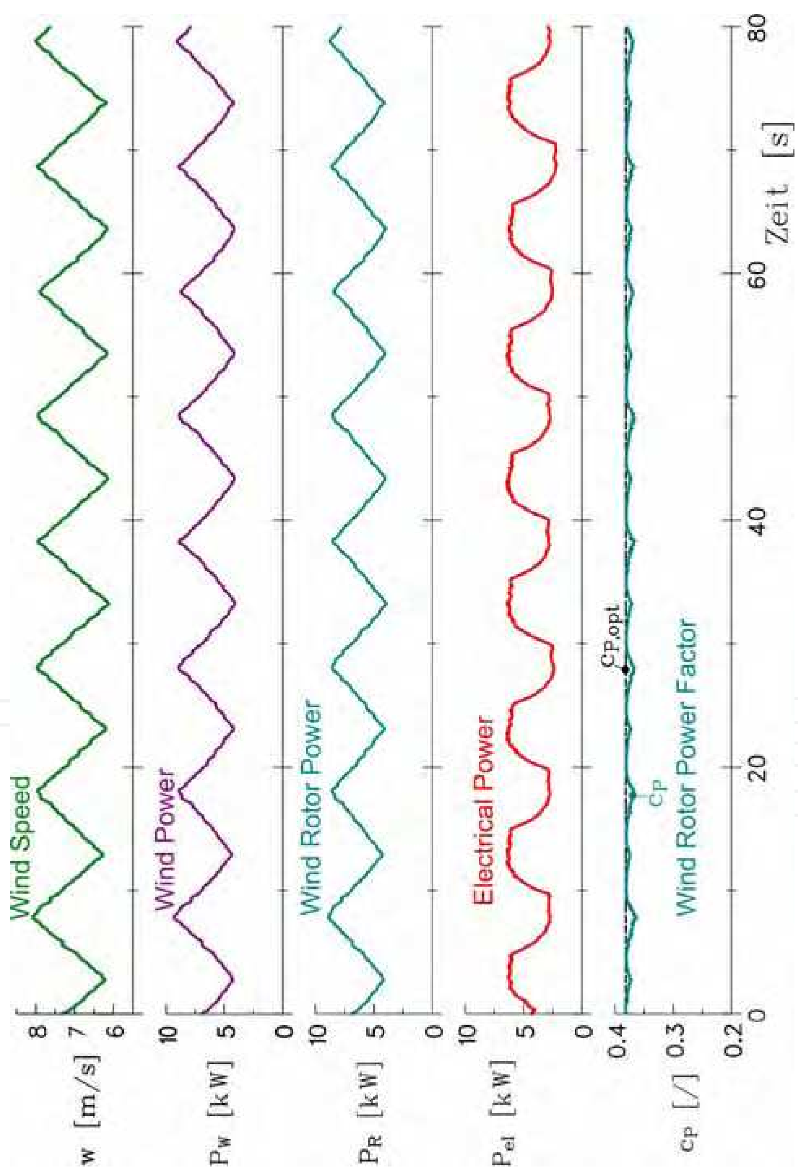

Fig. 8. Time response of parameters of the wind energy converter with speed control

In order to avoid fluctuations in the yielded power P_{el} caused by these control procedures, alterations in the course of the electrical generator counter-torque M_{el} during transition must be kept low. This can be achieved by admitting a limited speed difference between reference and actual values. A ramp function (T_{rp}), fulfilling the equation of movement of the simplified mechanical system, shall reflect the necessary time response of the reference value.

$$m_R - m_{el} = p\,T_R\,n_G \tag{12}$$

Examinations with the ramp-type time behaviour of the wind speed show relatively strong power fluctuations at low dynamical deviations of the c_P-value from the maximum value $c_{P,opt}$ = 0,388. This becomes obvious by the time response of the power coefficient (see Fig. 8). The control of the optimal speed features a good stationary behavior without continuous deviations. This is based on the condition that the wind speed can be recorded exactly and no alterations of the rotor characteristics occur.
Ice formation at the blades, deformation of the blades or alteration of the surface roughness influence the characteristics, so that the optimal tip-speed ratio is deferred to higher or lower values respectively.

4.2 Direct power control

Another possibility to adjust the rotor speed to the actually prevailing wind speed can be realized by presetting the reference value of the yielded power $P_{el,soll}$. This procedure determines the desired time response of the electrical power directly (see Fig. 9).
Based on wind and rotor speed, the operation management determines the tip-speed ratio for the actual operating point. Hereby, it can determine by means of the c_P-λ-characteristic, whether the plant is operating at maximum power, and, if applicable, adjust the power set point value $P_{el,soll}$ by a defined and steady transition. The calculation of the reference power value is carried out on the basis of the wind speed averaged over the time period Δt_v. The time period Δt_v and the kind of average determination have to be adapted to the desired power spectrum and the size of the wind rotor. Since the storage capacity of the rotating masses increases with their size, a wider time frame for averaging the yielded electrical power can then be selected.
A random extension of the time frame would only consider part of the demands on the operating behavior of the wind energy converter. The longer the considered time frame is, the farther away is the objective to adjust the optimal speed (resp. λ_{opt}, $c_{p,opt}$) quickly. On the other hand, the electrical power features an almost smoothed time behavior, which prevents the mechanical components from being damaged. Furthermore, in comparison to the speed control, this method enables a reduction of power fluctuations caused by speed control procedures (see Figs. 6 and 7), depending on the length of the time period.
For stationary operation, exact knowledge of the degree of efficiency over the whole speed range of the plant must be available besides exact recording of the wind speed, so that a stationary deviation of the power coefficient from the maximum value is avoided.

4.3 Self-adjusting maximum

Due to the fact that the air flow is affected by the wind rotor, an exact measuring of the wind speed by anemometers fitted to the wind energy converter is not possible and because of the inhomogeneous two-dimensional wind speed profile, measurements outside of the area influenced by the rotor are useless for the power control of a wind energy converter. A power control method which is able to adjust the operation point at a maximum c_P-value without the need to measure the wind speed is therefore of utmost importance for practical applications. Such a method is described in the following.

For this power control method, the power gradient is the decisive criterion whether an operation at maximum power coefficient is present or whether a speed adjustment is necessary. The operation management changes the reference speed value n_{opt} by Δn. After the speed reference value has been adjusted, the yielded power is measured and compared with the one prior to the control procedure. If the power alteration is positive, the speed is

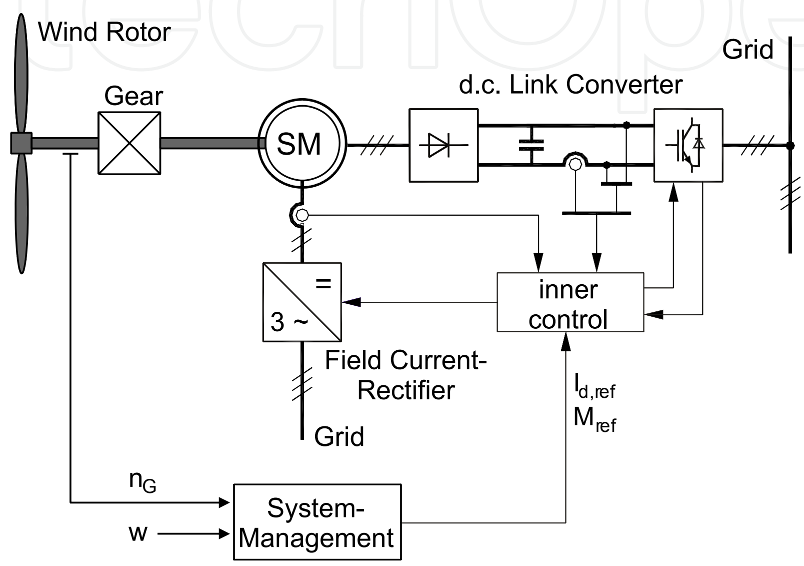

Fig. 9. Operating principle of average value power control

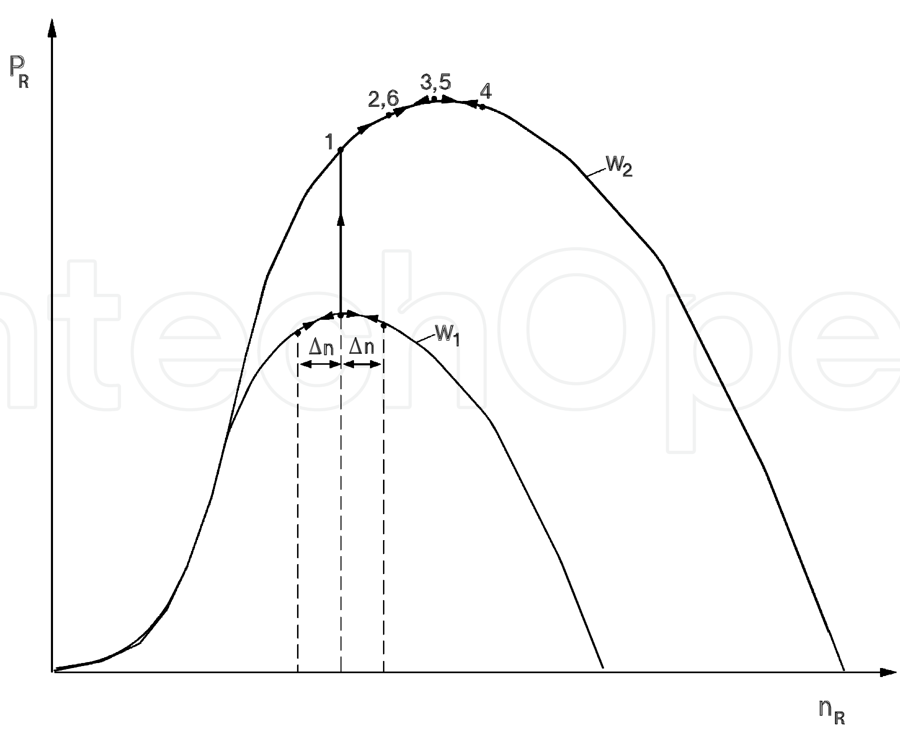

Fig. 10. Principle function of the search algorithm in the operation characteristic field of the wind rotor

changed by Δn in the same direction (Fig. 10). As long as the gradient of the power is positive, the same procedure is repeated. If a negative power gradient occurs, the prefix of the speed change is altered for the next step. The search procedure maintains the prefix of the speed change as long as the achieved power changes are positive.
In stationary operation, the speed oscillates around the optimal speed value of n_{opt}, in the most favourable case with an amplitude of $\Delta n/2$ resp. Δn. In order to minimize stationary offsets as well as power oscillations due to control procedures, the step width Δn of the search algorithm must be kept as small as possible. This has, however, the consequence of longer convergence periods, so that short-time wind fluctuations cannot be utilized optimally. The wind rotor is not able to yield 100 p.c. of the maximum possible power P_W due to the slow speed adjustment.

4.4 Speed-dependent torque control

A control procedure for power resp. speed control in the partial load operation range, which does not entail any unnecessary control procedures, is the "speed-controlled torque reference value setting" [8]. Based on the requirement for a constant tip-speed ratio λ - the ratio of the rotary speed of the rotor tip to the wind speed w - the torque M_R developed by the wind rotor at the then prevailing wind speed can be described as a function of the speed n_R.

$$M_R = \frac{P_R}{\omega_R} = \frac{\frac{1}{2} c_P \rho \pi R^2 w^3}{2\pi n_R} = 2\frac{c_P \rho \pi^3 R^5}{\lambda^3} \cdot n_R^2 , \quad \text{mit} \;\; \lambda = \frac{2\pi R n_R}{w} \tag{13}$$

$$M_R = K \cdot n_R^2$$

The procedure entails inaccuracies and alignment problems associated with the control:

- For a one-time adjustment of the control by

$$M_{el} = \eta_G \eta_{Getr} 2 \frac{c_P \rho \pi^3 R^5}{\lambda^3} \cdot n_R^2 , \tag{14}$$

  exact knowledge of the parameters is necessary, which are assumed to be constant for the whole speed and power range. This requires measuring investigations which are combined with high technical efforts.
- Alterations of the parameters resp. displacement of the optimal operation point due to increased roughness of the rotor blade surface, bending or twisting of the rotor blades cannot be taken into account.

4.5 Stochastic Dynamic Optimisation (StoDO)

Another approach to WEC control is the stochastic dynamic optimisation [2] with iterative adaptive wind speed probability distribution, given the general name of "iterative self-adapting system management" (ISSM) [3].
This procedure assesses informative values of the actual wind speed data on the short-term or medium-term wind power capability at a given location on the basis of the hitherto characteristics of the wind speed (resp. frequency distribution). Non-representative instantaneous values of the wind speed of minor importance can thereby be taken into

account for the calculation of the actual power reference value. Compared with known procedures, the new procedure shall avoid unnecessary control actions and thus power fluctuations due to short-time, for the location not representative alterations of the wind speed. At a short-term wind gust the control does not change the operation point of the plant, a readjustment of the system is omitted and the optimal operation point can be regained much quicker as soon as the wind gust abated. This promises a higher energy yield at optimally adjusted control. The extent of the increased energy yield is directly connected with the gust frequency at the plant location. The more gusts are to be expected, the higher is the additional yield by using the ISSM.

The steady operation at maximum possible power coefficient entails a dynamic adjustment of the rotor speed to the prevailing wind speed resp. after every wind speed change, which presumes a good reference-variable response of the control circuit (speed control circuit). In order to smooth the power fluctuations due to alterations in the wind speed, a control procedure optimized for the disturbance reaction is essential.

The mentioned two demands on the technical system (drive train of the wind energy converter) and the resulting control-engineering requirements disagree with respect to the dynamic behavior of the wind energy converter. It is therefore obvious to formulate the problem as an optimisation task.

As a criterion for the compliance with these aims, two indices are implemented [1]:

A deviation from the power average is indicated by

$$P-\text{Index} := \frac{1}{m}\sum_{i=1}^{m}\frac{\left|\bar{P}-P_i\right|}{\bar{P}} = \frac{1}{m}\sum_{i=1}^{m}\frac{\left|\bar{I}_d-I_{d,i}\right|}{\bar{I}_d}, \tag{15}$$

with an electrical power $P_i=U_dI_{d,i}$ at a measuring point of time i as well as the average electrical power:

$$\bar{P} = \frac{1}{m}\sum_{i=1}^{m}P_i \tag{16}$$

Here, I_d is the dc-link current and U_d the assumed constant dc-link voltage. The deviation from $c_{p,opt}$ is described by

$$c_p-\text{Index} := \frac{1}{m}\sum_{i=1}^{m}\frac{\left|c_{p,opt.}-c_{p,i}\right|}{c_{p,opt}} \tag{17}$$

with $c_{p,i}=c_p(\lambda_i)$. The $c_{p,opt}$-value describes the maximum degree of efficiency of the transformation of wind energy into mechanical energy for a specific rotor profile.

These indices reach smaller values, the more the respective aim is maintained. The weighted sum

$$M = g(P-\text{Index}) + (1-g)(c_p-\text{Index}) \tag{18}$$

must therefore be minimized, whereby g with $0<g<1$, is the weighting factor for both indices simultaneously.

The algorithm of the "stochastic optimization" [8] is taken as a basis to solve the herewith formulated optimisation task. This algorithm is used to model uncertain problem-relevant incidents in form of random variables, the exact value of which is indeed not yet known at the time of optimal determination, but their probability allocation is presumed as being real.

The optimisation task then comprises the determination of decision variables in such a way, that the expected value of a quality functional is minimized, under consideration of the usual problem conditions and probability allocations of the random variables. If the wind energy converter is taken as stochastic process, the stochastic optimization method is a very good approach to solve this problem.

A suitable mathematical representation resp. modelling has been carried out for this purpose. Fig. 11 shows a scheme of the wind energy converter as stochastic process together with the operation management which determines the reference value. State quantities of the process are wind velocity w and speed n_R, whereby only the speed is influenced by the plant itself. The wind speed is exposed to a stochastic alteration (disturbance) z. The dc-link current $I_{d,soll}$ serves as control variable (resp. reference variable), which is determined by the operation management on the basis of a control law evaluation. The control law is hereby not static but continuously updated, although considerably slower than the power set point value. Hereby statistical data about the measuring values of the wind velocity and the dc-link current (active power) are used which are continuously updated during operation. This has the effect that the control adjusts itself automatically to long-term and medium-term alterations of the wind conditions. The plant therefore adapts itself to the different wind conditions independently which arise in the cause of a day or even a year, e.g. by the effect of a sea-land breeze.

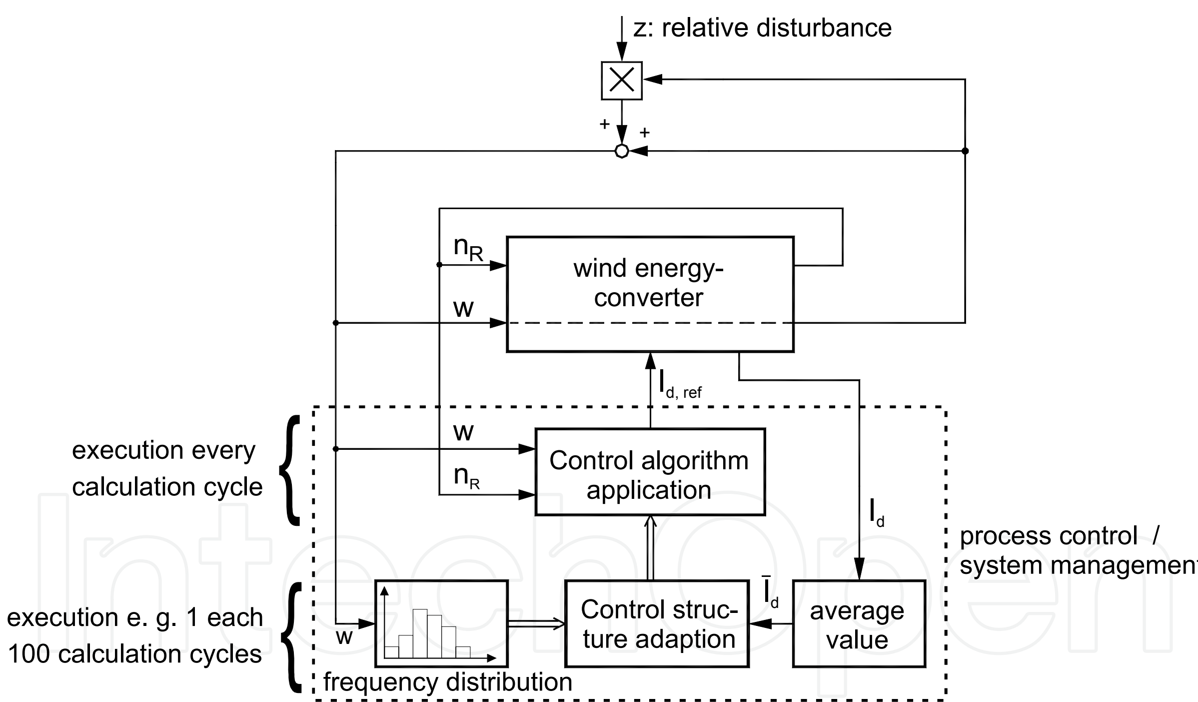

Fig. 11. Block diagram of an iterative self-adapting system management

To make sure that an implementation on a digital computer hardware is basically possible, a time-discrete modelling with a constant step width of $h:=t_{i+1} - t_i$ has been used as a basis.

The step width is defined by the sampling rate, which means by the time between two available measuring values for w and n_R. At the same time, the measuring values w, n_R and I_d are graded in amplitude-discrete manner and linearly interpolated, if applicable, so that a control law $I_{d,soll}(n_R,w)$ can be established in look-up table form. Optimal $I_{d,soll}$-values can be found by finite search. For simplification purposes, I_d is determined for (18) only on the basis of former current values, according to

$$\overline{I}_{d,i+1} := \alpha I_{d,mess} + (1-\alpha)\overline{I}_{d,i} \tag{19}$$

with an actual measuring value $I_{d,mess}$ and $0<\alpha<1$ which indicates how quickly I_d adapts itself to new measuring values.

$n_{R,i}$ and w_i are the state variables of the process. The transfer $(n_{R,i},w_i)$ -> $(n_{R,i+1},w_{i+1})$ is influenced by the stochastic disturbance of the wind z, the nominal value of the dc-link current $I_{d,soll}$ as control variable of the operation management as well as by resulting speed alterations of the wind energy converters. The disturbance variable z defines the relative change of the wind speed (see Fig. 11):

$$z_i = \frac{w_{i+1} - w_i}{w_i} \tag{20}$$

The transition probabilities for w_i -> w_{i+1} result from conditional probabilities $P(z\,|\,w)$, that means the probability of a disturbance z under the condition, that the last measured wind speed is w. If a measurement (z, w) is available, i.e. the last measured wind speed is w and the alteration of the actual wind speed z, the following is applicable:

$$P_{neu}(\tilde{z} \mid \tilde{w}) := \begin{cases} (1-\alpha)P_{alt}(\tilde{z} \mid \tilde{w}) + \alpha & \text{für} \quad (\tilde{z},\tilde{w}) = (z,w) \\ (1-\alpha)P_{alt}(\tilde{z} \mid \tilde{w}) & \text{für} \quad (\tilde{z},\tilde{w}) \neq (z,w) \end{cases}, \tag{21}$$

with α from (19).

By the terms of "Operations Research" [8] of which this algorithm is taken, deviations from the average current value and from the optimal power coefficient are defined as costs. From this the cost function can be determined, which indicates the contribution of a state (n_R,w) at a dc-link current I_d and a disturbance z in (18):

$$\varphi(n_R, w, I_d, z) = g\left|\frac{I_d - \overline{I}_d}{\overline{I}_d}\right| + (1-g)\left|\frac{c_p\left(2\pi R\dfrac{f(n_R,w,I_d)}{w+wz}\right) - c_{p,opt}}{c_{p,opt}}\right|. \tag{22}$$

Due to the stochastic disturbance, the cost function cannot be minimized at any time. The objective is indeed to keep the costs minimal within a time average, which means to minimize the expected value of the sum of the costs

$$\underset{z}{E}\left\{\sum_{\kappa=0}^{K-1}\varphi(n_R(\kappa), w(\kappa), I_{d,\kappa}, z(\kappa))\right\}, \tag{23}$$

whereby the expected value is calculated over all z, and K is the end time of the process. Here the system shall indeed not be transferred into an end state. Instead it shall operate arbitrarily long without any time limitation or a certain state to be reached. That means that the time horizon K is infinite [2].

In this case, the determination of a time-invariant control law is possible. It is a requirement for the convergence of the algorithm that the probability distribution of the disturbance variable is time-invariant. This can be assumed for the case under examination since convergence, that means a constant control law, is only aimed at in case of continuous frequency distribution. If the frequency distribution is changed, the algorithm converges to a new, adjusted control law. On this basis, the algorithm of the stochastic optimization has been specifically expanded by a new optimization algorithm for the application described here, which is called *stochatic dynamic optimization*.

The resulting infinite sum of the expected remaining costs in (23), e.g. the expected value of the costs incurred until the end state K= ∞ is reached at given nominal value $I_{d,soll}(\kappa)$, κ=k,...,K-1, can be dissolved by applying the principle optimality. The expected minimal remaining costs, that means the remaining costs to be expected at optimal control law are determined by

$$V\left(n_R(k),w(k),k\right)=\min_{I_{soll}(k)}\left\{\mathop{E}_{z(k)}\left[\begin{array}{l}\varphi\left(n_R(k),w(k),I_{d,soll}(k),z(k)\right)+\\ V\left(f\left(n_R(k),w(k),I_{d,soll}(k)\right),w(k),k+1\right)\end{array}\right]\right\}, \tag{24}$$

that means minimization is reduced to one single step.

This procedure is based on the principle to always reuse the stored values $V(n_R,w)$ independent of k, instead of $V(n_R,w,k)$, so that $V(n_R,w)$ is iteratively improved for all (n_R, w). This entails, however, an unlimited increase of $V(n_R, w)$, since always positive values are added to $V(n_R, w)$ in (24) and φ does not approach 0. Therefore, a weighted sum is introduced in (24):

$$V\left(n_R(k),w(k),k\right)=\min_{I_{soll}(k)}\left\{\mathop{E}_{z(k)}\left[\begin{array}{l}\zeta\varphi\left(n_R(k),w(k),I_{d,soll}(k),z(k)\right)+\\ (1-\zeta)V\left(f\left(n_R(k),w(k),I_{d,soll}(k)\right),w(k)\right)\end{array}\right]\right\} \tag{25}$$

with $0 < \zeta < 1$.

The discount factor ζ indicates to what an extent the costs of the actual state $f(n_R(k),w(k), I_{d,soll}(k),z(k))$ are decisive for the newly calculated expected remaining costs $V(n_R(k),w(k))$. This way it has influence on how quickly the remaining costs and thus the control law are changed. For practical applications this means that the parameter z determines how quickly the operation management of the plant is able to adapt itself to other wind conditions, e.g. to a changed frequency distribution $P(z \mid w)$.

To determine the minimum, only those dc-link currents $I_{d,soll}(k)$ are considered, which maintain a given limitation for the approximated speed in the next operation state $f(\boldsymbol{x}(k), I_{d,soll}(k), k)$. At the same time, a speed limitation is realized by the electrical counter-torque. All $V(\boldsymbol{x}(k), k)$ and the control law $Rg(\boldsymbol{x}(k), k)$ are determined as follows [3]:

For all discrete $\boldsymbol{x}(k)$, e.g. all $n_R(k)$, $w(k)$,

  For all $I_{d,soll}(k)$:

    Calculate $\tilde{n}_R(k+1) := f(n_R(k), w(k), I_{d,soll}(k))$,

    If $n_{min} \le \tilde{n}_R(k+1) \le n_{max}$:

      Calculate:

$$\begin{aligned}J_k\left(I_{d,soll}(k)\right)&=\mathop{E}_{z(k)}\Big[\zeta\varphi\left(n_R(k),w(k),I_{d,soll}(k)\right)+\\&\quad(1-\zeta)V\left(f\left(n_R(k),w(k),I_{d,soll}(k)\right),k+1\right)\Big]\\&=\sum_{z(k)}\Big[\zeta\varphi\left(n_R(k),w(k),I_{d,soll}(k)\right)+\\&\quad(1-\zeta)V\left(f\left(n_R(k),w(k),I_{d,soll}(k)\right),k+1\right)\Big]P\left(z(k)\middle|w(k)\right)\end{aligned} \tag{26}$$

Chose smallest $J_k(I_{d,soll}(k))$, apply

$$V(\boldsymbol{x}(k),k) := \min_{I_{d,soll}(k)} J_k\left(I_{d,soll}(k)\right) =: J_k\left(\hat{I}_{d,soll}(k)\right)$$
$$\underline{Rg(\boldsymbol{x}(k),k) := \hat{I}_{d,soll}(k)} \tag{27}$$

Repeat!

Here, $P(z(k)\,|\,w(k))$ is the probability of a disturbance z(k) of the wind speed on the condition that the actual wind speed is w(k). This is defined by measurement in form of a table of relative frequencies. At a constant frequency distribution the calculation must only be repeated until the remaining costs V and the control law Rg have reached the optimal value. This becomes obvious when the control law is no more subjected to a change. In case of the wind energy converter, however, the frequency distribution changes. Therefore the calculation must be repeated successively to realize constant updating of the control law.

The value $I_{d,soll}$, for which the expected value in (25) becomes minimal, is recorded in the control law $Rg(n_R,w)$. The minimum in (25) can be found by discretization in form of finite search. Since the instantly calculated expected remaining costs contain information from the past, the stored old values $V(n_R,w)$ can be overwritten by the newly calculated ones, so that the time parameter k is eliminated and memory space saved. $V(n_R,w)$ is recorded in table form for the time and amplitude-discrete values of n_R and w. The reference current value for the given measuring values n_R und w is determined by linear interpolation of the control law $Rg(n_R,w)$.

5. Comparison of the control methods

The examined control concepts are compared in this chapter on the basis of simulation research work. For this purpose, the wind energy converter has been subjected to different wind speeds. For better reproducibility and thus better comparability of the results for a certain time range, a periodic behavior of the wind speed realized by a delta function has been used for the comparing examinations. The wind power gradient (WLG) which is relevant for the control of the wind energy converter has been adjusted for a wide range of values [1] by variation of the frequency. The WLG specifies the alteration of the covered-area related wind power per time unit and is a degree for the wind turbulence.

Furthermore, results of comparing examinations are also presented for realistic time curves of the wind speed. For this purpose, random time responses of the wind speed have been generated in accordance with an algorithm [1]. This algorithm allows for a location-specific parameterisation on the ground roughness and the so-called dynamic factor, so that stochastic characteristics of the wind speed could be used for locations in the mountains which is featured by wind speed alterations of high dynamics, as well as for a flat country location with even wind speeds. The test bench examinations have been carried out with parameters of a variable speed wind energy converter of 22 kVA nominal power. The wind energy converter model features the following characteristic data:

- Generator:
  Nominal power: 22 kVA
  Conductor voltage: 325 V
  Stator frequency: variable
  Nominal speed: 1500 rpm
- Windrotor:
  Power: 22 kW
  Rotor radius: 4,9 m
  Optimal tip-speed ratio: 4,3
  Optimal power coefficient: 0,3818
  Mass inertia of the rotors: 4,8 kgm² (related to the generator speed)

Gear ratio: 23

The methods of speed control and direct power control have been compared with the control algorithm of the discrete stochastic dynamic optimization.

In case of the speed control, the operation management calculates the speed n_R according to equation (1) at which the wind rotor generates the maximum possible power which is then given as reference value. Assuming that the optimal tip-speed ratio is always constantly λ_{opt} and the instantaneous value of the wind speed can be measured at sufficient exactness, the speed can be adjusted proportionally to the prevailing wind speed w. Herewith the wind rotor is always operated at maximum possible power coefficient $c_{P,opt}$. This becomes evident by the time response of the power coefficient in Fig. 12. The time response of the electrical power output shows, however, changes beyond wind-induced power fluctuations. The control procedures actuated to adjust the optimal speed cause additional dynamic alterations of the electrical power via the control element (dc-link converter) - depending on the layout of the speed controller - which superpose the wind caused power fluctuations. Changes in the electrical power output cause mains pollutions (for example, flicker effects) and impose high loads on the mechanical drive train components.

Particularly short-time fluctuations of wind speed initiate control procedures. But even in case of a very quick adaptation to a new optimal speed for this short time interval, they do not contribute to a considerable increase in energy yield (see Fig. 15). Improvements in this respect are shown by the methods of direct power control (methods “2" and “3"). Compared with the speed control, they avoid to a large extent oscillations of the electrical power during the control procedure (see Fig. 13). At the same time efforts are followed up when calculating the nominal value to reduce the influence of short-time peaks in the wind speed response. In case of a linear averaging, the wind speed is averaged via a defined time interval. The average is used to calculate the nominal power value. When the averaging is carried out according to the Weibull-distribution, a weighted average value is calculated from the last taken measuring values of w in line with their probability density. Hereby the time response of the power coefficient c_P shows remarkable deviations from the maximum possible value with these control procedures.

Compared with the hitherto examined control procedures, the iterative self-adapting system management (ISSM) on the basis of the algorithm of discrete stochastic dynamic optimization features a high process quality. This is supported by a constant power output (electrical power) and a high power coefficient (see Fig. 14). The time responses of the system variables prove, that the control law adapts itself iteratively to the wind speed distribution and fulfils the given process requirements.

In order to provide a better comparability of the research results for stochastic wind speed characteristic, the results have been quantified and evaluated by means of the above introduced indices.

Fig. 15 shows c_P-Index und P-Index of the compared control methods for two different location-specific wind characteristics.

The speed control features a very low c_P index and a high P-index, the same as in case of the deterministic response of the wind speed. The P-index can be reduced by the direct power control methods (methods “2" and “3"). On the other hand, a higher c_P-index must be accepted. By a suitable selection of the weighting factor g, a reduction of the P-index or c_P-index may be granted higher priority in case of the iterative adapted process control methods. The sum of the introduced indices implemented as quality criterion is hereby lower for all possible values of weighting factor g, than in case of the other examined procedures which entails a higher process quality. The minimization of the indices sum is the aim of the optimization task by formulating the cost function.

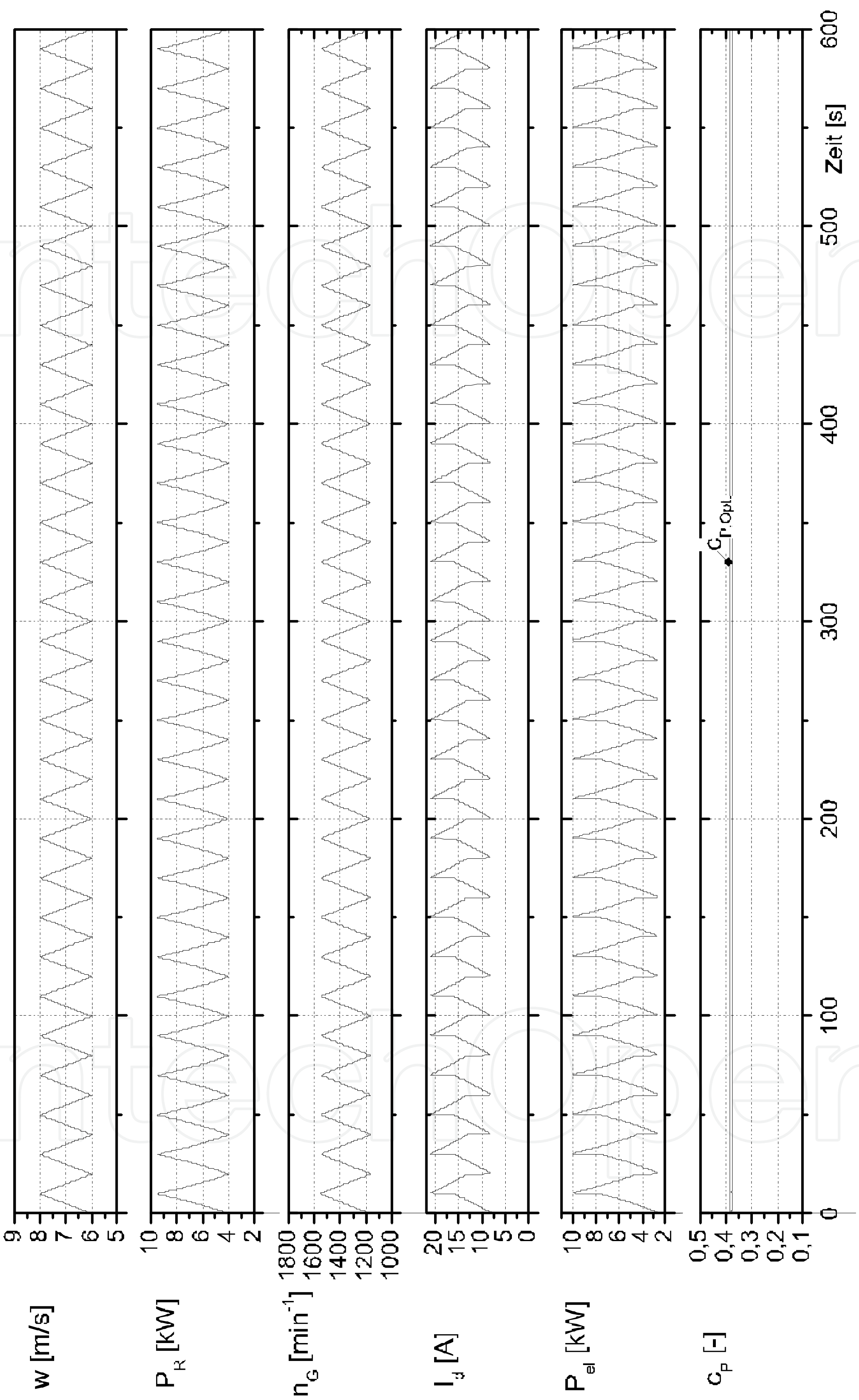

Fig. 12. Time response of system variables at speed control (method “1”); deterministic response of the wind speed

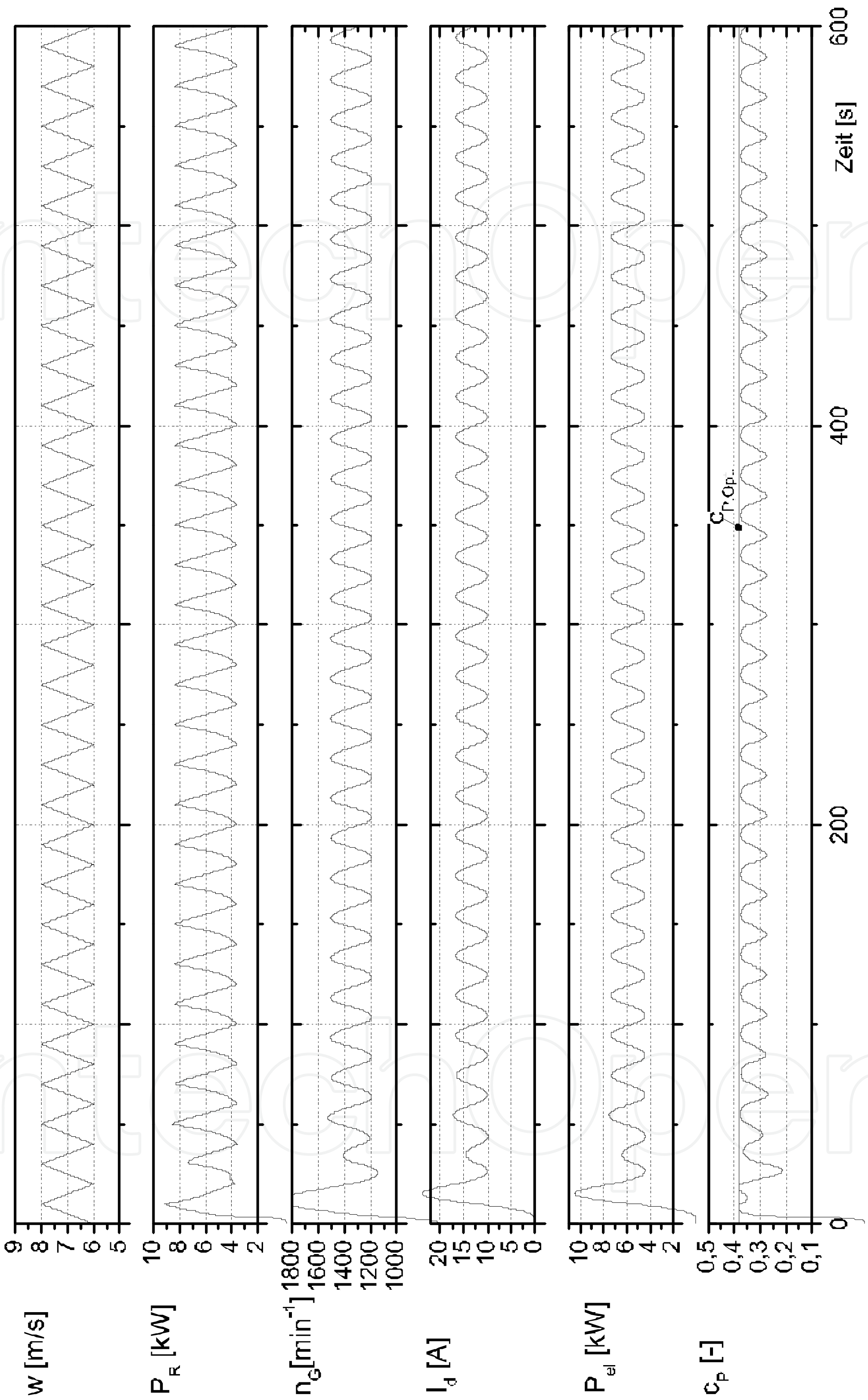

Fig. 13. Time response of system variables at direct power control (method “2) deterministic response of the wind speed

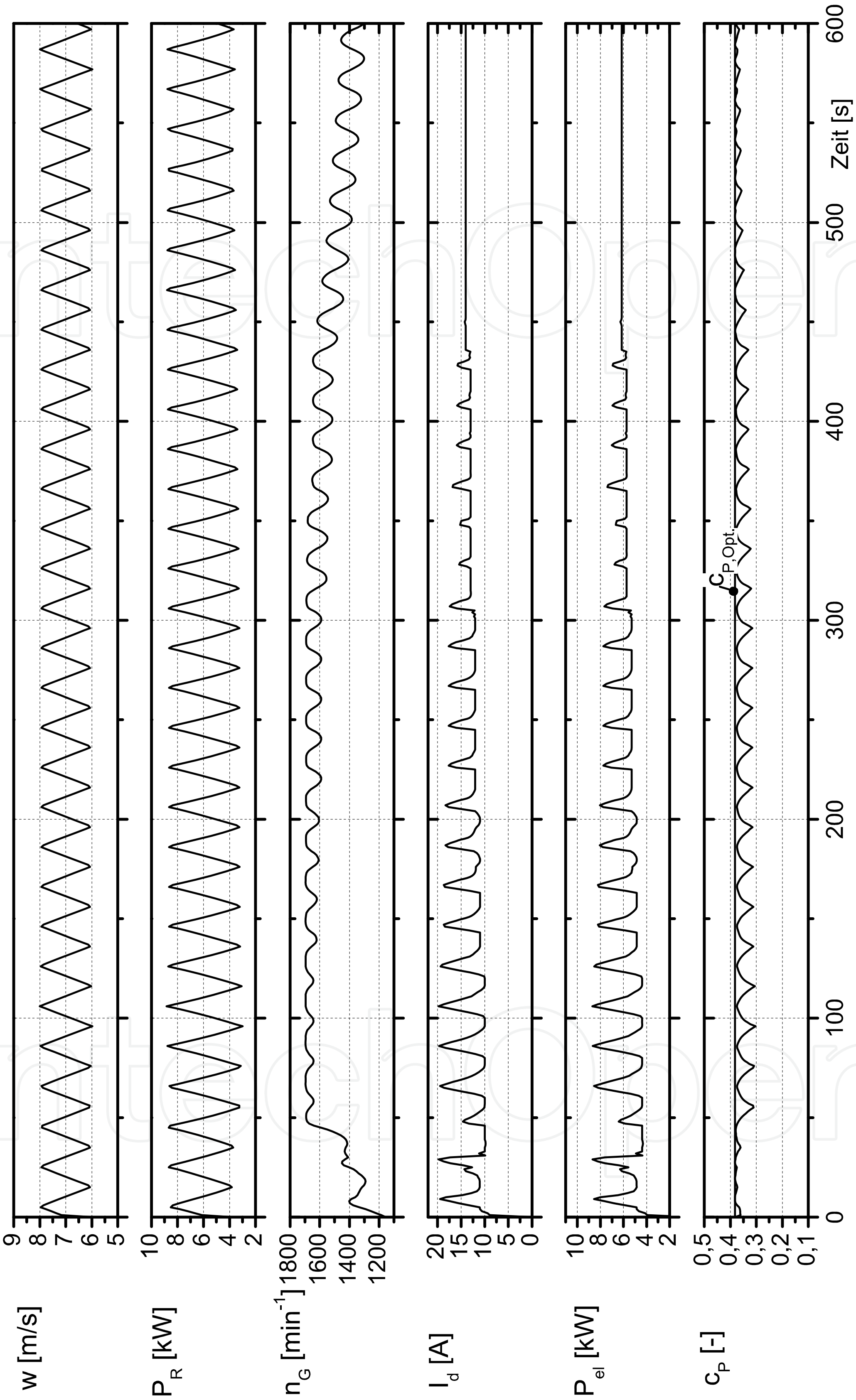

Fig. 14. Time response of system variables at iterative self-adapting system management (stochastic optimization); deterministic response of the wind speed

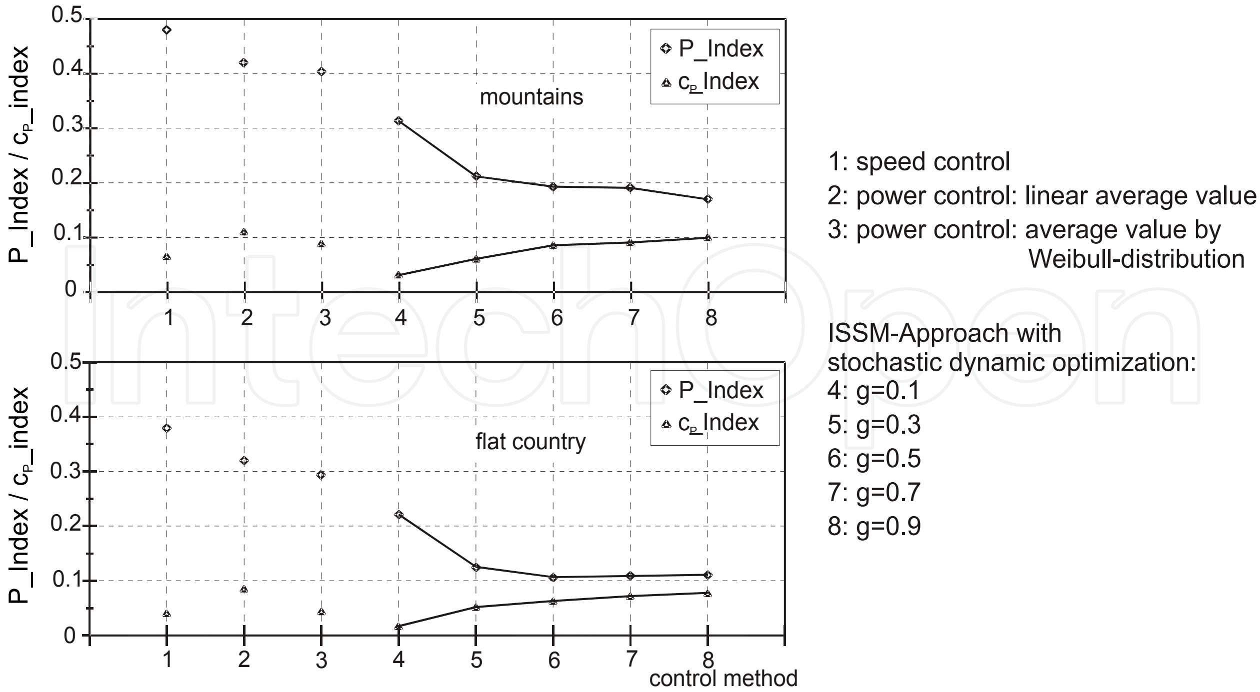

Fig. 15. Quantitative comparison of research results by means of P-index and c_P-index for two characteristic locations

The frequency distribution of the load collective in the mechanical drive train has been used for further evaluation of the results of the comparing examinations. It has been prepared by classification of the time response of the shaft torque. The shaft torque collective of the ISSM method shows a remarkable reduction of the load cycles with high amplitude as compared with collectives of the other control methods, which implies an increase of usability and life (see Fig. 16).

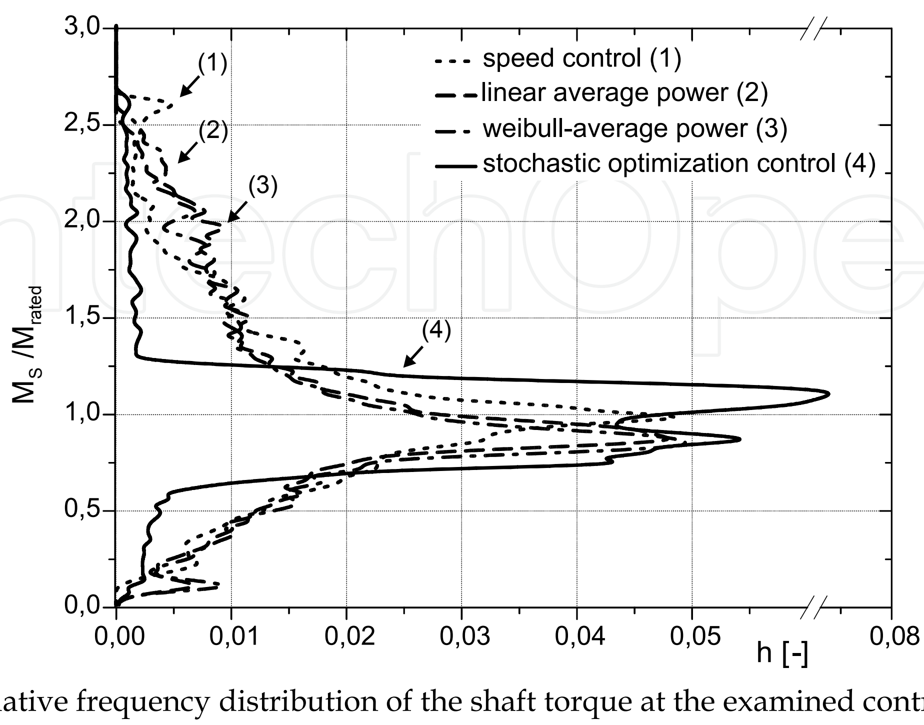

Fig. 16. Relative frequency distribution of the shaft torque at the examined control methods

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This book is the result of inspirations and contributions from many researchers of different fields. A wide verity of research results are merged together to make this book useful for students and researchers who will take contribution for further development of the existing technology. I hope you will enjoy the book, so that my effort to bringing it together for you will be successful. In my capacity, as the Editor of this book, I would like to thanks and appreciate the chapter authors, who ensured the quality of the material as well as submitting their best works. Most of the results presented in to the book have already been published on international journals and appreciated in many international conferences.