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ANALYSIS OF A WIND ENERGY CONVERTER SYSTEM WITH PMSG GENERATOR

ANALIZA PRZEKSZTAŁTNIKOWEGO SYSTEMU ELEKTROWNI WIATROWEJ Z GENERATOREM PMSG

A b s t r a c t

This article presents a variable-speed converter system for wind energy conversion. The considered system consists of a wind turbine with a permanent magnet synchronous generator (PMSG), a machine-side converter, a grid-side converter and control circuits. Mathematical models of the components of the wind energy system are described. The control algorithms of the converter systems based on the vector methods of control are also described. The considered wind energy system were studied by digital simulation. The simulation results are presented and discussed.

Keywords: *wind turbine*, *PMSG generator*, *control systems*, *simulation studies*

S t r e s z c z e n i e

W niniejszym artykule przedstawiono przekształtnikowy system elektrowni wiatrowej o zmiennej prędkości. Rozpatrywany system składa się z turbiny wiatrowej z generatorem synchronicznym z magnesami trwałymi (PMSG), przekształtnika maszynowego, przekształtnika sieciowego i układów sterowania. Opisano modele matematyczne poszczególnych elementów systemu elektrowni wiatrowej. W algorytmach sterowania przekształtników energoelektronicznych zastosowano wektorowe metody sterowania. Przeprowadzono badania symulacyjne rozpatrywanego systemu przekształtnikowego elektrowni wiatrowej. Wykonane badania symulacyjne potwierdziły prawidłowość pracy układów sterowania i dużą dokładność sterowania.

Słowa kluczowe: *elektrownia wiatrowa*, *generator PMSG*, *systemy sterowania*, *badania symulacyjne*

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1. Introduction

The world's development of energy generation from renewable sources has increased significantly in recent years. The biggest development of renewable sources is wind energy conversion system (WECS). An increasing trend is to stimulate research in the field of energy conversion in order to optimize receiving the largest values of energy from the wind.

Wind turbines can be classified into fixed-speed and variable-speed turbines [4, 5, 8]. The main advantages of the systems with variable-speed turbines are: increased wind energy output, the possibility to achieve maximum power conversion efficiency and reduced mechanical stress. Most of the major wind turbine manufacturers are now developing wind turbine systems based on variable-speed operation.

In WECS, mechanical energy of the wind turbine is converted in electrical energy with the help of an appropriate electrical generator. In the future, permanent magnet synchronous generators (PMSG) will predominate in small and large power wind turbines due to the possibility of multipole designs that eliminate the need for gearboxes [2, 4, 6].

A typical wind energy conversion system consists of: wind turbine; electrical generator; power converters; control circuits. The currently developed configuration of wind power system is presented in Fig 1. The figure shows the system in which the directly driven or geared driven PMSG generator is connected to the AC grid via a full capacity power converter system. The converter system includes a machine side converter (MSC) and grid side converter (GSC) connected in a back-to-back converter configuration.

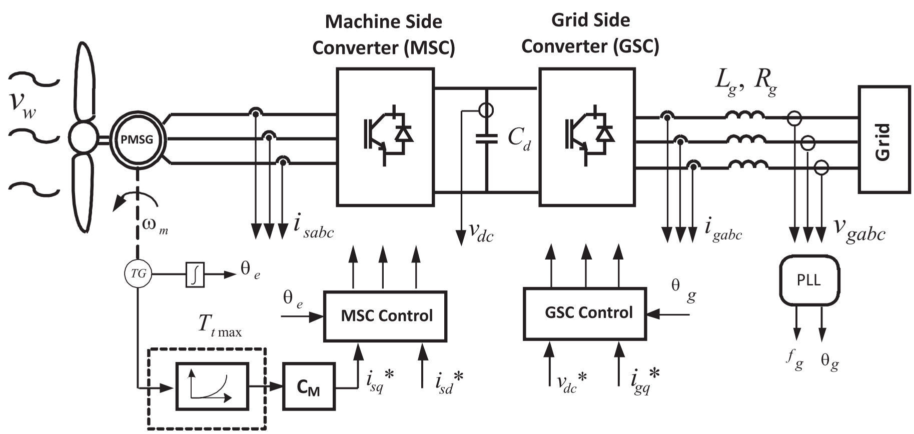

Fig. 1. Configuration of variable-speed wind turbine system with direct-driven PMSG and full-capacity converters

The aim of this paper is to analyze the converter system of a permanent magnet synchronous generator connected to a wind turbine under varying wind speeds in order to investigate the effectiveness of the wind energy conversion systems. The paper is divided into 7 sections as follows: in section 2 and 3 the wind turbine model and PMSG model are presented; sections 4 and 5 are dedicated to the description of the control system of the MSC and GSC converters; the simulation results of considered WECS are presented in Section 6; the article finishes with research conclusions.

2. Model of Wind Turbine

The wind turbine converts the wind energy into rotational mechanical energy. Wind turbine output power P_t and wind turbine output torque T_t are given by the following equations [1–5]:

$$P_t = 0.5 \cdot \rho A \cdot C_p(\lambda, \beta) \cdot v_w^3 \quad (1)$$

$$T_t = 0.5 \cdot \rho R A \cdot C_p(\lambda, \beta) \cdot v_w^2 / \lambda \quad (2)$$

where:

ρ – air density,
$A = \pi R^2$ – area swept by the rotor blades,
C_p – power coefficient of the wind turbine,
$\lambda = R\omega_m/v_w$ – tip speed ratio,
β – blade pitch angle,
v_w – wind speed,
R – radius of the turbine blade,
ω_m – angular speed of turbine rotor.

The power coefficient C_p as a function of tip speed ratio λ, and blade pitch angle β is shown in Fig. 2a). The wind turbine can produce maximum power when the turbine operates at a maximum value of C_p, i.e. at $C_{p\max}$. Therefore, it is necessary to keep the rotor speed at an optimum value of the tip speed ratio, λ_{opt}. If the wind speed varies, the speed of the rotor turbine should be adjusted to follow the wind speed changes.

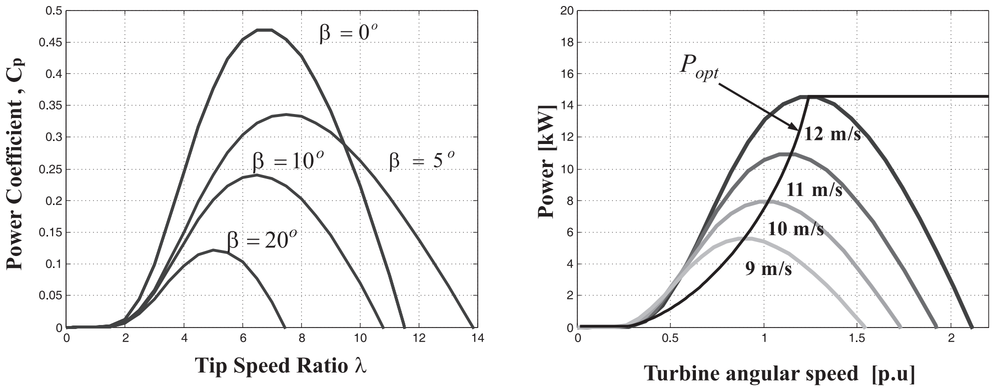

Fig. 2. Characteristics of the wind turbine: a) C_p curves as function of λ and β, b) wind turbine power curves at various wind speeds

The mechanical rotor power generated by the turbine as a function of the rotor speed for different wind speeds is shown in Fig. 2b). The optimum power curve P_{opt} shows how maximum energy can be captured from the fluctuating wind. The function of the control system with maximum power-point tracking (MPPT) is to keep the operation of the turbine on this curve, as the wind velocity varies.

3. The Model of Permanent Magnet Synchronous Generator

In the PMSG model, the following basic assumptions have been considered: the electrical and magnetically symmetry; the magnetic flux is sinusoidal distributed along the air gap; no saturation; no damping winding. Mathematical equations of PMSG are formulated in the synchronous rotating reference frame *d*-*q*, by aligning the *d*-axis with the direction of the rotor flux. Voltage equations of the generator have the following form [1, 2, 6, 7]:

$$v_{sd} = R_s i_{sd} + L_d \cdot p i_{sd} - \omega_e L_q i_{sq} \tag{3}$$

$$v_{sq} = R_s i_{sq} + L_q \cdot p i_{sq} + \omega_e L_d i_{sd} + \omega_e \psi_{PM} \tag{4}$$

where:

$$\omega_e = n_p \cdot \omega_m \,,\; p = \mathrm{d}/\mathrm{d}t \tag{5}$$

u_{sd}, u_{sq} – the stator voltages in the *d*-*q* axis,
i_{sd}, i_{sq} – the stator currents in the *d*-*q* axis,
L_d, L_q – the *d*-*q* axis stator inductances,
ψ_{PM} – rotor flux linkage established by permanent magnets,
R_s – resistance of the stator winding,
ω_e, ω_m – electrical and mechanical angular speed of the PMSG generator,
n_p – number of pole pairs of the PMSG generator,

The expression for the electromagnetic torque of the PMSG has the form:

$$T_e = (3/2)\, n_p [\psi_{PM} i_{sq} + (L_d - L_q)\, i_{sd} i_{sq}] \tag{6}$$

For a non-salient-pole machine, the stator direct and quadrature inductances L_d and L_q are equal, so the electromagnetic torque equation then takes the form:

$$T_e = (3/2)\, n_p \cdot \psi_{PM} i_{sq} \tag{7}$$

The mechanical equation of motion is given as:

$$T_t - T_e = J \cdot p\omega_m \tag{8}$$

where T_t, J – the referred to the side of generator shaft: the output torque of wind turbine and the total equivalent inertia, respectively.

4. The Model of Control System of Machine Side Converter

The machine-side converter regulates the active power and speed of the PMSG generator. The block scheme of the control system of the MSC [1, 4, 5, 8] is presented in Fig. 3.

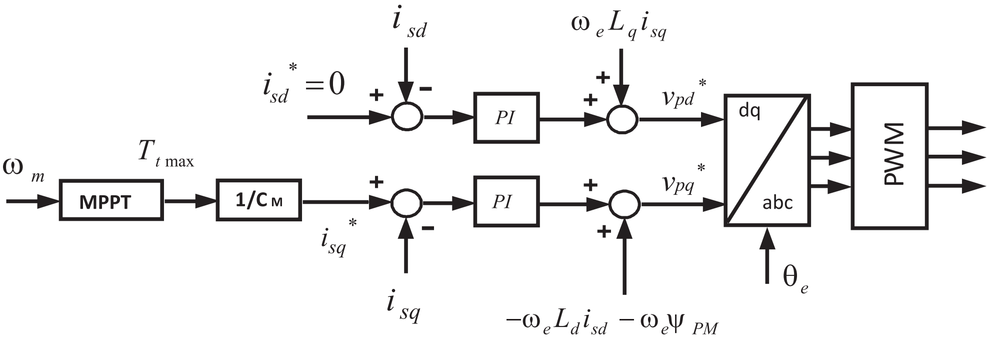

Fig. 3. Control diagram of the Machine Side Converter

In the control system, the principle of maximum power point tracking (MPPT) has been applied. The operation with maximum power is achieved through optimal control of the maximum torque generated by the wind turbine T_{tmax}, according to the equation:

$$T_{t\max} = 0.5\rho A C_{p\max} (R/\lambda_{opt})^3 \omega_w^2 = K_M \cdot \omega_m^2 \tag{9}$$

where K_M is a constant determined by the wind turbine characteristic [8].

In order to obtain the maximum power generated by the PMSG, the references components of the stator current i_{sq}^* can be calculated as:

$$i_{sq}^* = C_M T_{t\max} \tag{10}$$

where $C_M = 2/(3n_p\psi_{PM})$ – coefficient to convert the value of torque into the reference current.

The MSC control system is based on a rotor flux field orientation. The position of the rotor flux vector θ_e is obtained from the encoder or from the conversion of the signal from the speed sensor. The d-axis stator current reference i_{sd}^* is always set to zero in order to achieve the maximum torque at the minimum stator current and to achieve a linear relationship between the magnitude of the stator current and the electromagnetic torque of the generator. The q-axis stator current reference i_{sq}^* is achieved through the operation of the MPPT block on the base of the measured mechanical turbine speed ω_m. The measured stator phase currents of the PMSG are transformed into dq-axis currents, i_{sd} and i_{sq}, defined in the rotor flux synchronous frame. The dq-axis stator currents, i_{sd} and i_{sq}, are compared with the reference stator currents, i_{sd}^* and i_{sq}^*, respectively. The error signals are sent to two PI controllers.

The state variables of the PMSG are cross-coupled because in equations (3) and (4), the derivate of d-axis stator current i_{sd} is related to both d and q-axis variables, as is the q-axis stator current i_{sq}. To solve these problems, the decoupling signals are added to the PI output signals, as shown in Fig. 3. The resultant signals, v_{pd}^* and v_{pq}^*, are the *dq*-axis reference voltages for the MSC control. These two reference voltages are then transformed to three-phase reference voltages and are sent to the block of the PWM generation for the MSC.

5. The Model of the Control System of the Grid Side Converter

The grid side converter GSC feeds generated energy into the AC grid, keeps the DC link voltage stable and adjusts the quantity of the active and reactive powers delivered to the AC grid during wind variation. There are many strategies used to control the grid side converter [1–4, 8]. The control method presented in this paper is known as the grid voltage oriented control (VOC). The principle of the VOC control is based on the state equations for the grid-side circuits of the GSC converter. The state equations expressed in the *dq* rotating synchronous reference frame have the form:

$$v_{gd} = R_g i_{gd} + L_g \cdot p i_{gd} - \omega_g L_g i_{gq} + v_{gcd} \tag{11}$$

$$v_{gq} = R_g i_{gq} + L_g \cdot p i_{gq} + \omega_g L_g i_{gd} + v_{gcq} \tag{12}$$

where:

v_{gd}, v_{gq} – *d-q* components of the grid voltage vector,
i_{gq}, i_{gq} – *d-q* components of the grid current vector,
v_{gcd}, v_{gcq} – *d-q* components of the voltage vector of the grid side converter,
L_g, R_g – inductance and resistance of the grid filter,
ω_g – angular frequency of the grid voltage.

The grid-side converter controls the active and reactive power of the AC grid. The general equations describing the active and reactive power are as follows:

$$P = (3/2)(v_{gd} i_{gd} + v_{gq} i_{gq}), \quad Q = -(3/2)(v_{gd} i_{gq} + v_{gq} i_{dg}) \tag{13}$$

The VOC control of GSC is based on the orientation of the grid voltage vector such that the *d*-axis of the synchronous reference frame is aligned with the grid voltage vector. The grid voltage vector only has *d*-axis component v_{gd}, while the *q*-axis component v_{gq} is equal to zero. The phase locked loop (PLL) estimates the angle θ_z of the grid voltage vector, for the coordinates transformation. In the frame system oriented with the grid voltage vector, the active and reactive power will be proportional to i_{gd} and i_{gq} respectively:

$$P = (3/2) v_{gq} i_{gd}, \quad Q = -(3/2) v_{gd} i_{gq} \tag{14}$$

Hence, the active power *P* can be controlled by the *d*-component of the converter current, i_{gd}, whereas the reactive power *Q* can be controlled by the *q*-component of the converter current, i_{gq}.

The block scheme of the VOC control system of the grid-side converter GSC is presented in Fig. 4. In the system, there are three feedback control loops – two inner current loops for the control of the *dq*-axis grid currents, i_{gd} and i_{gq}, and one outer voltage feedback loop for the control of the DC voltage of the GSC, v_{dc}. The inputs of the control system are: v^*_{dc}, which is the reference dc-link voltage and Q^*, which is the reference for the reactive power, which can be set to zero for unity power operation, a negative value for leading power operation, or a positive value for lagging power factor operation. The PI controller for DC voltage control generates the *d*-axis current reference i^*_{gd}, which represents the active power of the system. The *q*-axis current reference i^*_{gq} is calculated on the basis of the set value of the reference for the reactive power Q^*.

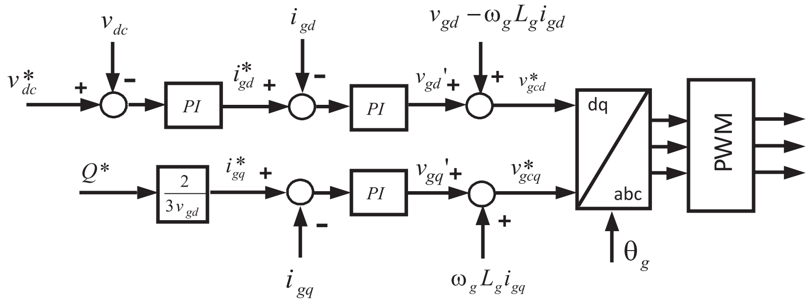

Fig. 4. Control diagram of the Grid Side Converter

The measured phase currents of the grid are transformed into *dq*-axis currents, i_{gd} and i_{sq}, defined in the grid voltage vector oriented synchronous frame. The *dq*-axis grid currents, i_{gd} and i_{sq}, are compared with reference grid currents, i^*_{gd} and i^*_{gq}, respectively. The error signals are sent to two PI controllers. The state variables of the GSC system are cross-coupled because in the equations (11) and (12), the derivate of the *d*-axis grid current i_{gd} is related to both the *d* and *q*-axis grid variables, as is the *q*-axis grid current i_{gq}. To solve these problems, the decoupling signals are added to the PI output signals, as shown in Fig. 4. The resultant signals, v^*_{gcd} and v^*_{gcq}, are the *dq*-axis reference voltages for the output AC circuits of GSC. These two reference voltages are then transformed to three-phase reference voltages of GSC and are sent to the block of PWM generation for the GSC.

6. Simulation studies

In order to evaluate the performance of wind energy converter system, a set of simulation studies has been performed. The model of the wind energy conversion system with control systems has been implemented in MATLAB/Simulink. Digital simulation studies were made for the system with the wind turbine, 3-phase PMSG (with parameters: P_N = 6 kW; R_s = 0.425 Ω; ψ_{PM} = 0.433 Wb; L_d = 8.4 mH; L_q = 8.4 mH; n_p = 5) and machine and grid-side converter (in back-to-back configuration). The FOC control with zero *d*-axis current was considered for the MSC converter and the VOC control with unity power factor for GSC converter.

The chosen results of simulation studies [4, 5] are presented in Figs. 5–10.

Figure 5 shows the considered stochastic time waveforms of wind speed acting on the wind turbine. The time variations of the mechanical torque of the wind turbine and the electromagnetic torque of the PMSG generator are presented in Figs. 6 and 7, respectively. It can be stated that both torque waveforms reflect the variations of the wind speed. Figure 8 presents the time waveform of the voltage v_{dc} in the DC link of the back-to-back converter system. The voltage v_{dc} is quite constant at variations of wind speed. It shows good performance of control circuits.

Figure 9 presents the response of the stator current vector components i_{sd}, i_{sq} in the dq-axis reference frame. The component i_{sd} of the stator current vector is kept at zero by the controller to achieve proportionality to the electromagnetic torque of the PMSG. The time values of the component i_{sq} stator current vector are fluctuated according to the wind speed changes. Figure 10 shows as an example, the time waveform of the stator phase current i_{sa} of the PMSG. The variable wind speed causes suitable changes of magnitude of the stator phase current. The presented simulation waveforms confirmed the good performance of the WECS and the quick response of the control systems.

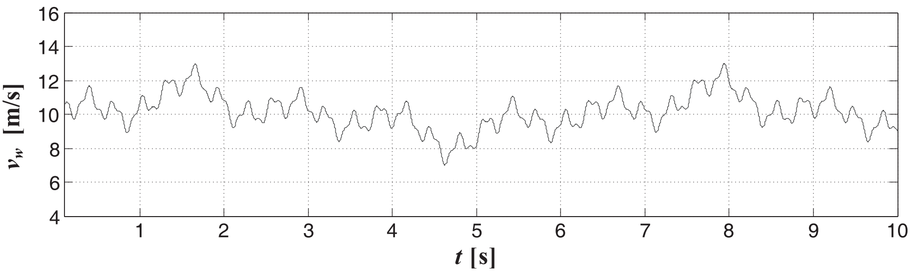

Fig. 5. Time variations of wind speed

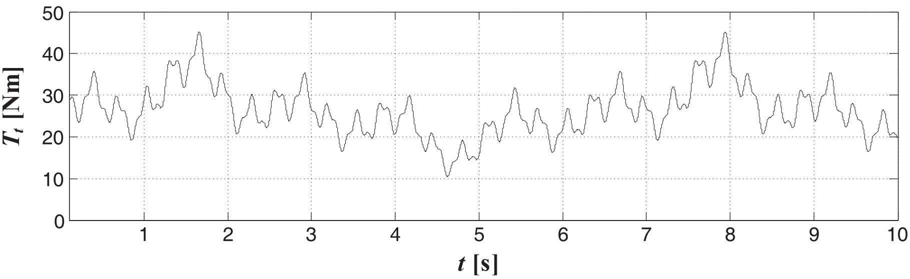

Fig. 6. Simulated waveform of mechanical torque T_t of wind turbine

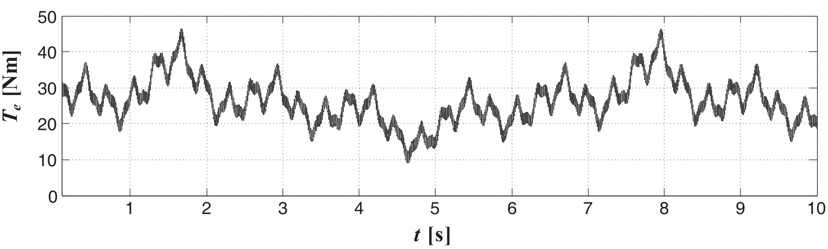

Fig. 7. Simulated waveform of electromagnetic torque T_e of PMSG

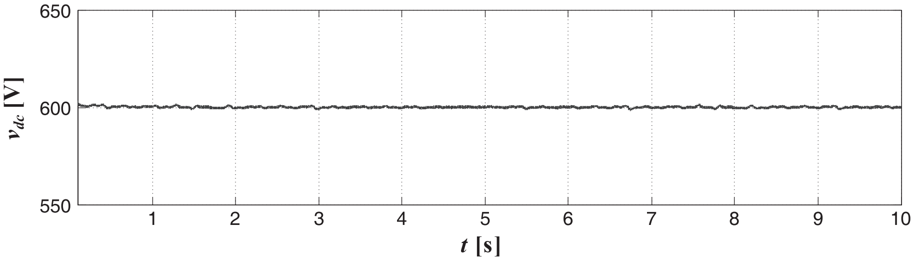

Fig. 8. DC link voltage waveform

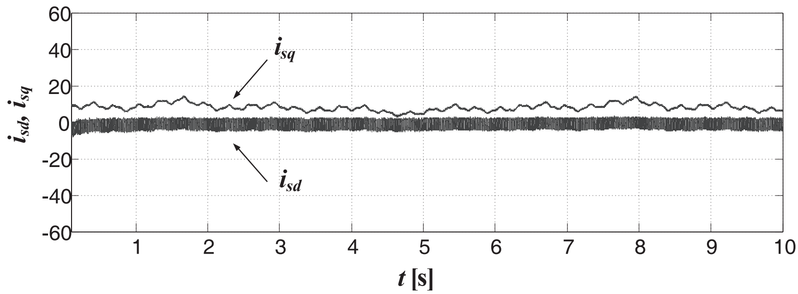

Fig. 9. Waveforms of controlled stator current vector components i_{sd}, i_{sq} of PMSG

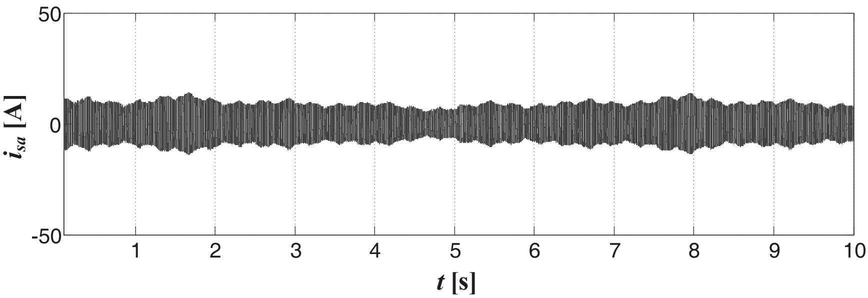

Fig. 10. Waveform of stator phase current i_{sa} of PMSG

7. Conclusions

Control strategies for a variable speed wind turbine with a PMSG have been presented in this paper. Systems with PMSG has many advantages: operation at high power factor; high efficiency; high torque to current ratio. In this paper, two methods of control have been investigated – FOC with MPPT for machine side converter and VOC for grid side converter. FOC with MPPT allows the use of optimal control of maximum torque generated by the wind turbine. VOC control is a simple method and allows keeping the DC link voltage to reference value and to adjust the quantity of the active and reactive powers delivered to the AC grid during wind variation.

Simulation studies demonstrate, that a wind turbine with PMSG, based on the vector control of back-to-back converter systems can effectively accomplish the wind turbine control objectives with superior performance of the system under both steady and variable wind conditions. The simulation results demonstrate that the control systems work very well and show very good dynamic and steady-state performance.

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