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Control of IPM Synchronous Generator for Maximum Wind Power Generation Considering Magnetic Saturation

Wei Qiao, *Member, IEEE*, Liyan Qu, *Member, IEEE*, and Ronald G. Harley, *Fellow, IEEE*

Abstract—Permanent-magnet synchronous generators (PMSGs) are commonly used for small variable-speed wind turbines to produce high-efficiency, high-reliability, and low-cost wind power generation. This paper proposes a novel control scheme for an interior PMSG (IPMSG) driven by a wind turbine, in which the d -axis and q -axis stator-current components are optimally controlled to achieve the maximum wind power generation and loss minimization of the IPMSG. The effect of magnetic saturation, which causes the highly nonlinear characteristics of the IPMSG, is considered in the control-scheme design. The optimal d -axis stator-current command is obtained as a function of the IPMSG rotor speed by solving a constrained nonlinear-optimization problem that minimizes the copper and core losses of the IPMSG. At any wind speed within the operating range, the IPMSG rotor speed is optimally controlled to extract maximum wind power. The optimal q -axis stator-current command is then obtained from the optimal IPMSG rotor speed and d -axis current. To eliminate the effects of nonlinearity caused by magnetic saturation, an input–output feedback linearization technique is applied to design the high-performance nonlinear current controllers. The proposed control scheme provides the wind generation system with the maximum efficiency and high dynamic performance.

Index Terms—Input–output feedback linearization (IOL), loss minimization, magnetic saturation, maximum wind power generation, permanent-magnet synchronous generator (PMSG).

I. INTRODUCTION

THE USE OF permanent-magnet synchronous machines (PMSMs) for wind power generation has received increasing attention in recent years [1]–[6]. The PMSMs can provide high-efficiency and high-reliability power generation, since there is no need for external excitation and no copper

losses in the rotor circuits. In addition, the high-power-density PMSMs are small in size, which reduces the cost and weight of wind turbines. Furthermore, in the wind generation system equipped with a PMSM and power-electronic converters, the wind turbine can be operated to extract the maximum power from the wind at various wind speeds by adjusting the shaft speed optimally. Therefore, the PMSMs are commonly used for small variable-speed wind turbines to produce high-efficiency, high-reliability, and low-cost wind power generation.

Among various PMSMs, the interior PMSM (IPMSM) can offer high-efficiency and high-controllability generation by utilizing the reluctance torque, in addition to the magnet torque [7], and achieve a constant power in a wide speed range by utilizing flux weakening along the d -axis [8]–[10]. However, due to the effect of magnetic saturation, the q -axis inductance of the IPMSM varies depending on the q -axis stator current [6], [10]–[12]. Consequently, the generated electrical torque and EMF of the IPMSM are nonlinear functions of the stator currents. In addition, in an IPMSM, both d -axis and q -axis components of the stator currents contribute to the developed torque. As a result, the system nonlinearity becomes severe if the IPMSM operates in the flux-weakening region where the d -axis stator-current component $i_d \neq 0$. This nonlinearity complicates direct application of well-developed linear-system theory. To solve this problem, nonlinear control schemes have been developed to improve the performance of the IPMSMs [12], [13].

Moreover, in energy production and utilization, efficiency is always an important issue, but this was not addressed in [1]–[4], [8]–[13]. In [14], the authors investigated the minimization of the core losses of a PMSM through a suitable design of magnets and slots and the choice of the number of poles. In fact, the efficiency of an IPMSM can be improved not only during the machine-design stage but also during the operation stage. By optimally controlling the d -axis component of the stator currents, the stator copper and core losses of an IPMSM can be minimized. In [15], the control-system design of the IPMSM took into account the minimization of the copper, core, and stray-load losses. However, the authors did not consider the operating limits of and the saturation effect within the IPMSM. In [16], the stator copper and core losses of the IPMSM were minimized via an online iterative search algorithm, but once again, the operating limits and saturation effect were not considered. In addition, the online search for the optimal value of i_d results in a time-consuming calculation and, therefore, reduces

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Fig. 1. Basic configuration of an IPMSG driven by a wind turbine.

the overall control-system performance. In [17], an online minimum-copper-loss control was proposed for an IPMSM, but the core loss was not minimized.

In [6], the authors proposed an output maximization control for a variable-speed wind generation system using an IPMSM but without closed-loop speed control. Both the optimal d -axis and q -axis stator-current commands were obtained as functions of the generator speed to achieve loss minimization and maximum wind power tracking. However, since there was no close-loop speed control, the maximum power point may not be able to be accurately tracked due to parameter variations in the real system operation. In addition, the effect of magnetic saturation on the dynamic performance and control of the IPMSM was not addressed. To achieve optimal power efficiency and dynamic performance of the IPMSM, magnetic saturation must be considered in designing the IPMSM controllers for torque and current control.

This paper proposes a novel control scheme for an interior PM synchronous generator (IPMSG) to achieve the maximum wind power generation in a variable-speed wind-power-generation system. The d -axis and q -axis stator-current components of the IPMSG are suitably controlled according to the IPMSG rotor speed in order to extract the maximum wind power at various wind speeds as well as to minimize the stator copper and core losses in the IPMSG. The optimal d -axis stator-current command is obtained as a function of the IPMSG rotor speed by solving a constrained nonlinear-optimization problem, which maximizes the efficiency while considering magnetic saturation as well as the voltage and current limits of the IPMSG. A speed controller is designed to generate the optimal torque commands for the IPMSG in order to extract maximum wind power at various wind speeds. The optimal q -axis stator-current commands are then obtained from the optimal torque and d -axis current commands. By adjusting the shaft speed optimally, using the close-loop speed control, the maximum power point can be accurately tracked at various wind speeds. To eliminate the effects of non-linearity caused by magnetic saturation, an input–output feedback linearization (IOL) technique [18] is applied to design the high-performance nonlinear current controllers. The proposed control scheme improves the efficiency and dynamic performance of the wind generation system.

II. WIND TURBINE GENERATOR (WTG) SYSTEM

Fig. 1 shows the basic configuration of an IPMSG driven by a wind turbine. The IPMSG converts the mechanical power from the wind turbine to ac electrical power, which is then converted

Fig. 2. C_P – λ curve of the wind turbine.

to dc power through an IGBT pulse-width modulation (PWM) converter with a dc link to supply the dc load. Control of the IPMSG is achieved by controlling the ac-side voltages of this PWM power converter. By using an additional power inverter, the IPMSG can supply the ac electrical power with constant voltage and frequency to the power grid or ac load. The mechanical power that the wind turbine extracts from the wind is calculated by

$$P_m = \frac{1}{2} \rho A_r v_w^3 C_P(\lambda, \beta) \quad (1)$$

where ρ is the air density in kilograms per cubic meter, $A_r = \pi R^2$ is the area swept by the rotor blades in square meters, R is the wind-turbine rotor radius in meters, v_w is the wind speed in meters per second, and C_P is the power coefficient, which is a function of both tip-speed ratio λ and the blade pitch angle β . In this paper, the mathematical representation of C_P is given by [19]

$$C_P = 0.5(\lambda - 0.022\beta^2 - 5.6)e^{-0.17\lambda} \quad (2)$$

where λ is defined by $\omega_t R / v_w$ and ω_t is the wind-turbine rotational speed in radians per second.

Fig. 2 shows the C_P – λ curve described by (2) for the wind turbine in this paper. In terms of Fig. 2 and the definition of λ , at any wind speed within the operating range, there is a unique wind-turbine shaft rotational speed to achieve the maximum power coefficient $C_{P \max}$. In terms of (1), when C_P is controlled at the maximum value, the maximum mechanical power is extracted from the wind energy.

III. MODELING OF THE IPMSG

Fig. 3 shows the d - and q -axes equivalent circuits of the IPMSG in a d – q rotor reference frame [20], which rotates synchronously with an electrical angular velocity ω of the IPMSG. This model includes the effects of the stator copper

Fig. 3. Equivalent circuits of the IPMSG. (a) d -axis equivalent circuit. (b) q -axis equivalent circuit.

and core losses. The core loss, which is caused by hysteresis and eddy currents, is represented by an equivalent core-loss resistance R_c . Reference [21] provided a method to determine the value of R_c , which can be represented as a linear function of the IPMSG rotor speed ω_g , given by

$$R_c = K_r * \omega_g. \quad (3)$$

For the IPMSG, burying the magnets inside the rotor introduces saliency into the rotor magnet circuit. The d -axis flux passes through a wide region of low-permeability magnets, while the q -axis flux path has a high permeability. Therefore, the IPMSG has a saliency ($L_q > L_d$), and the effect of magnetic saturation along the q -axis is dominant. When this saturation is taken into account, the dynamic equation of a three-phase IPMSG can be written in the rotor reference frame as

$$L_d \frac{di_{od}}{dt} = -R_s i_d + \omega L_q (i_q) i_{oq} + v_d \quad (4)$$

$$L_q (i_q) \frac{di_{oq}}{dt} = -R_s i_q - \omega L_d i_{od} - \omega \psi_m + v_q \quad (5)$$

where ψ_m is the magnet flux linkage, R_s is the stator resistance, L_d is the d -axis inductance and assumed to be constant, and L_q is the q -axis inductance which varies depending on the value of i_q [6], [10]–[12]. In this paper, the effect of magnetic saturation is considered by modeling L_q as a function of i_q , given by

$$L_q = L_{q0} - k|i_q| \quad (6)$$

where k is a positive constant. The inclusion of magnetic saturation in the model complicates the direct application of linear-system theory and loss-minimization algorithms to the IPMSG, but in this paper, this is solved in a nonlinear way.

When using the lumped-mass model for the WTG shaft system, the motion equation of the IPMSG can be expressed as

$$J \frac{d\omega_g}{dt} = T_m - T_g - B\omega_g \quad (7)$$

where J is the total moment of inertia of the wind turbine and the IPMSG in kilograms square meters, B is the viscous damping coefficient in kilograms square meters per second, T_m is the input mechanical torque given by $T_m = P_m / \omega_g$, $\omega_g (= 2\omega / P_n = G_r \omega_t)$ is the IPMSG rotor speed in radians per second, P_n is the number of poles of the IPMSG, G_r is the gearbox ratio, and T_g is the electrical torque of the IPMSG given by [6]

$$T_g = -\frac{3}{4} P_n [\psi_m i_{oq} + (L_d - L_q(i_q)) i_{od} i_{oq}]. \quad (8)$$

The parameters of the IPMSG and wind turbine are given as follows. IPMSG: rated power = 25 kW; rated phase voltage = 205 V; rated phase current = 40 A; rated rotor speed = 1200 r/min; $R_s = 0.1764 \Omega$; $R_c = K_r \omega_g$ ($K_r = 0.2083 \Omega/\text{rpm}$); $L_d = 6.24 \text{ mH}$; $L_{q0} = 20.5822 \text{ mH}$; $k = 0.1879 \text{ mH/A}$; $\psi_m = 0.246 \text{ Wb}$; $P_n = 6$; $J = 1.2 \text{ kg} \cdot \text{m}^2$; $B = 0.002 \text{ kg} \cdot \text{m}^2/\text{s}$. Wind turbine: rotor diameter = 11 m; rated wind speed = 10 m/s; rated rotational speed = 200 rpm.

IV. MAXIMUM WIND POWER GENERATION WITH LOSS MINIMIZATION

A. Maximum Wind Power Generation

By adjusting the wind-turbine shaft speed optimally, the tip-speed ratio λ can be controlled at the optimal value to achieve the maximum power coefficient $C_{P\max}$ regardless of the wind speed. The maximum mechanical power is therefore extracted from the wind energy. At this optimal condition, the optimal IPMSG rotor speed is proportional to the wind speed, given by

$$\omega_{g,\text{opt}} = k_\omega v_w \quad (9)$$

where k_ω is a constant determined by the wind-turbine characteristics.

B. Minimization of Copper and Core Losses of IPMSG

The losses of a PMSG can be decomposed into four components, namely, stator copper loss, core loss, mechanical loss, and stray-load loss. Only the stator copper and core losses are explicitly dependent on and can be controlled by the fundamental components of the stator currents. Therefore, in this paper, the maximum efficiency condition of the IPMSG is obtained by solving the following nonlinear-optimization problem offline to minimize the total copper and core losses of the IPMSG

$$\begin{aligned} &\text{Minimize} && P_{\text{loss}} = P_{\text{copper}} + P_{\text{core}} \\ &\text{Subject to} && P_{\text{copper}} = 1.5 R_s (i_d^2 + i_q^2) \\ &&& P_{\text{core}} = 1.5 (i_{cd}^2 + i_{cq}^2) R_c(\omega_g) \\ &&& = 1.5 \omega^2 \left[(L_d i_{od} + \psi_m)^2 \right. \\ &&& \quad \left. + (L_q(i_q) i_{oq})^2 \right] / R_c(\omega_g). \end{aligned} \quad (10)$$

Equations (1)–(3), (6), and (8)

$$\begin{aligned}
 v_d &= R_s i_d - \omega L_q (i_q) i_{oq} \\
 v_q &= R_s i_q + \omega L_d i_{od} + \omega \psi_m \\
 i_{od} &= i_d - (v_d - R_s i_d) / R_c (\omega_g) \\
 i_{oq} &= i_q - (v_q - R_s i_q) / R_c (\omega_g) \\
 T_m - T_g - B\omega_g &= 0 \\
 T_m &= P_m / \omega_g \\
 \omega &= P_n \omega_g / 2 \\
 i_d^2 + i_q^2 &\leq I_M^2 \\
 v_d^2 + v_q^2 &\leq V_M^2
 \end{aligned}$$

where P_{copper} is the copper loss, P_{core} is the core loss [6], and I_M and V_M are the maximum current and voltage, respectively, of the IPMSG.

Given an optimal IPMSG rotor speed [calculated by (9)], the solutions of the nonlinear-optimization problem (10) yield the optimal values of i_d and i_q , which minimize the total copper and core losses of the IPMSG. Therefore, at any wind speed, the solutions of (9) and (10) provide the desired optimal IPMSG rotor speed, optimal currents i_d and i_q to achieve the maximum wind power extraction, and loss minimization of the IPMSG. Without considering the effect of magnetic saturation (i.e., L_q is constant) and the variation of R_c , (10) would be a constrained nonlinear quadric optimization problem that can be solved by conventional nonlinear-optimization methods. However, the inclusion of magnetic saturation and variation of R_c results in a complex nonlinear-optimization problem that requires extensive computation effort when using conventional nonlinear-optimization methods. In this paper, a stochastic optimization technique—particle swarm optimization (PSO) [22], [23]—is employed to obtain the optimal solution of (10).

C. PSO

PSO is a population-based stochastic optimization technique. It searches for the optimal solution from a population of moving particles. Each particle represents a potential solution and has a position (vector x_i) and a velocity (vector v_i) in the problem space. Each particle keeps track of its individual best position $x_{i,\text{pbest}}$, which is associated with the best fitness it has achieved so far, at any step in the solution. Moreover, the best position among all the particles obtained so far in the swarm is kept track of as $x_{g\text{best}}$. This information is shared by all particles. The PSO algorithm is implemented in the following iterative procedure to search for the optimal solution.

- 1) Initialize a population of particles with random positions and velocities of M dimensions in the problem space.
- 2) Define a fitness-measure function to evaluate the performance of each particle.
- 3) Compare each particle's present position x_i with its $x_{i,\text{pbest}}$ based on the fitness evaluation. If the current position x_i is better than $x_{i,\text{pbest}}$, then set $x_{i,\text{pbest}} = x_i$.
- 4) If $x_{i,\text{pbest}}$ is updated, then compare each particle's $x_{i,\text{pbest}}$ with the swarm best position $x_{g\text{best}}$ based on the

fitness evaluation. If $x_{i,\text{pbest}}$ is better than $x_{g\text{best}}$, then set

$$x_{g\text{best}} = x_{i,\text{pbest}}.$$

- 5) At iteration k , the velocity of each particle is updated by

$$\begin{aligned}
 v_i(k+1) &= w \cdot v_i(k) + c_1 \phi_1 (x_{i,\text{pbest}}(k) - x_i(k)) \\
 &\quad + c_2 \phi_2 (x_{g\text{best}}(k) - x_i(k)), \quad i = 1, 2, \dots, N.
 \end{aligned} \tag{11}$$

- 6) Based on the updated velocity, each particle then changes its position by

$$x_i(k+1) = x_i(k) + v_i(k+1), \quad i = 1, 2, \dots, N. \tag{12}$$

- 7) Repeat steps 3)–6) until a criterion, usually a sufficiently good fitness or a maximum number of iterations, is achieved. The final value of $x_{g\text{best}}$ is regarded as the optimal solution of the problem.

In (11), c_1 and c_2 are positive constants representing the weighting of the acceleration terms that guide each particle toward the individual best and the swarm best positions, $x_{i,\text{pbest}}$ and $x_{g\text{best}}$, respectively; ϕ_1 and ϕ_2 are uniformly distributed random numbers in $[0, 1]$; w is a positive inertia weight developed to provide better control between exploration and exploitation; N is the number of particles in the swarm. The last two terms in (11) enable each particle to perform a local search around its individual best position $x_{i,\text{pbest}}$ and the swarm best position $x_{g\text{best}}$. The first term in (11) enables each particle to perform a global search by exploring a new search space.

Because of many attractive features, e.g., multiagent search, simple implementation, small computational load, and fast convergence, the PSO algorithm can provide a fast and efficient search for the optimal solution. These features provide PSO with superior performance over other evolutionary computation algorithms (e.g., genetic algorithms) in many applications. In addition, for many complex optimization problems that are difficult to formulate mathematically or to solve by traditional optimization methods, PSO is efficient to find the optimal solution.

D. Optimal d -axis and q -axis Stator Currents of IPMSG

In this paper, the values of the PSO parameters are chosen as follows: $c_1 = c_2 = 2$, $N = 20$, and $w = 1.4 - (1.4 - 0.4) \cdot k/K$, where k is the iteration number and K is the maximum number of iterations. The PSO algorithm only performs a 1-D search for the optimal value of i_q . The optimal value of i_d is determined by the torque equation (8) and the corresponding optimal value of i_q , where the electrical torque T_g in (8) is determined by (9) and the constraint equations of (10). The fitness-measure function is simply the total copper and core losses P_{loss} of the IPMSG. It is calculated by the first two constraint equations of (10).

By solving the nonlinear-optimization problem (10) at various IPMSG rotor speeds, the optimal values of i_d and i_q are obtained and shown as functions of the IPMSG rotor speed ω_g in Fig. 4. The relationship between the optimal d -axis and q -axis stator-current components and the IPMSG rotor

Fig. 4. Optimal d - and q -axes currents as functions of IPMSG rotor speed.TABLE I
COEFFICIENTS OF APPROXIMATING POLYNOMIALS

Coefficients of $i_{d,opt}$		Coefficients of $i_{q,opt}$	
K_{d4}	1.291×10^{-11}	K_{q3}	7.528×10^{-9}
K_{d3}	-3.523×10^{-8}	K_{q2}	-3.477×10^{-5}
K_{d2}	1.154×10^{-5}	K_{q1}	-1.648×10^{-3}
K_{d1}	-1.348×10^{-2}	K_{q0}	1.263
K_{d0}	-1.589×10^{-2}		

speed can be approximated by a fourth-order and a third-order polynomial, respectively, given by

$$i_{d,opt} = K_{d4}\omega_g^4 + K_{d3}\omega_g^3 + K_{d2}\omega_g^2 + K_{d1}\omega_g + K_{d0} \quad (13)$$

$$i_{q,opt} = K_{q3}\omega_g^3 + K_{q2}\omega_g^2 + K_{q1}\omega_g + K_{q0}. \quad (14)$$

The coefficients of both polynomials are listed in Table I. However, it should be pointed out that (13) and (14) only provide the optimal operating conditions of the IPMSG for the wind speed below the rated value. When the wind speed exceeds the rated value, the phase current and/or the terminal voltage reach their ceiling values, and therefore, the optimal speed tracking control cannot be applied. Under this condition, the current- and voltage-limited maximum output control can be applied to control the IPMSG [6].

V. CONTROL OF THE IPMSG

The control objectives of IPMSG include the following: 1) to extract the maximum power from the wind and 2) to minimize the total copper and core losses of the IPMSG. To achieve these two objectives, the optimal rotor speed of the IPMSG $\omega_{g,opt}^*$ is first determined by (9). Based on $\omega_{g,opt}^*$, the optimal stator d -axis and q -axis current commands, $i_{d,opt}^*$ and $i_{q,opt}^*$, can be obtained from (13) and (14). Two current controllers are then designed to track these two optimal current commands, respectively, to achieve the optimal operating point of the WTG system [6]. However, since there is so far no close-loop speed control, the maximum power point may not be able to be accurately tracked due to parameter variations in the real system operation.

In the proposed control scheme, the d -axis stator current is controlled with its command determined by (13), to minimize

the total copper and core losses of the IPMSG. However, in order to achieve the accurate tracking of the optimal rotor speed $\omega_{g,opt}^*$, a speed controller is designed to generate the optimal torque command. Instead of using (14), the optimal q -axis stator-current command is then determined from (8) by using the optimal torque and d -axis current commands. This speed controller ensures that the optimal IPMSG rotor speed can be accurately tracked to extract the maximum power from the wind. Moreover, to eliminate the effects of nonlinearity caused by magnetic saturation, IOL-based high-performance nonlinear current controllers are designed to control the d -axis and q -axis current components. The block diagram of the proposed control scheme for the IPMSG is shown in Fig. 5. Each block is discussed in detail in the following two sections.

A. Optimal IPMSG Rotor-Speed Tracking Control

Based on the IPMSG motion equation (7), a PI-type speed controller can be designed to track the optimal rotor speed at any moment. To overcome the windup phenomenon of PI controllers, the antiwindup scheme [24] shown as the dash-line block in Fig. 5 is applied for the speed controller in this paper. The gain k_a is given by $k_a = 1/k_p$.

The output of the speed controller is the optimal torque command $T_{g,opt}^*$ for the IPMSG, which corresponds to the maximum power point for wind power generation. By using this optimal torque command and the optimal d -axis current command from (13), the solution of (8) provides the optimal q -axis stator-current command for the inner loop current regulation. In the real application, the values of $i_{q,opt}^*$ can be generated offline over the entire operating range of the IPMSG. A lookup table or a nonlinear input–output mapping function (e.g., neural networks) can then be designed to obtain the value of $i_{q,opt}^*$ from $T_{g,opt}^*$ and $i_{d,opt}^*$ online at any operating condition.

B. IOL-Based Nonlinear Current Control

Instead of approximating a nonlinear system's dynamics locally around some operating point via linearization, the IOL technique transforms the nonlinear system into an equivalent linear system via feedback and nonlinear coordinate transformation. This is a systematic way to globally linearize a part of or all the dynamics of the nonlinear system. In such a scheme, the input–output dynamics are linearized, but the state equations may be only partially linearized. Residual nonlinear dynamics, called internal dynamics, do not depend explicitly on the system input and, thus, are not controlled. If the internal dynamics are trivial or stable at the equilibrium point, then the entire nonlinear system can be stabilized by a standard linear feedback control using the linearized input–output dynamics.

In this section, the IOL-based feedback control technique is applied to design the nonlinear current controllers for the IPMSG. Let $y_1 = x_1 = i_d$, $y_2 = x_2 = i_q$, $u_1 = v_d$, and $u_2 = v_q$, then (4) and (5) can be rewritten in the following matrix form when neglecting the core loss of the IPMSG (i.e., $i_{od} = i_d$ and $i_{oq} = i_q$):

$$\begin{pmatrix} \dot{y}_1 \\ \dot{y}_2 \end{pmatrix} = A(x) + E \begin{pmatrix} u_1 \\ u_2 \end{pmatrix} \quad (15)$$

Fig. 5. Proposed control scheme for the IPMSG.

Fig. 6. Reference signal prefilters. (a) $i_{d,opt}^*$. (b) $i_{q,opt}^*$.

where

$$A(x) = \begin{pmatrix} [-R_s i_d + \omega L_q(i_q) i_q] / L_d \\ [-R_s i_q - \omega L_d i_d - \omega \psi_m] / L_q(i_q) \end{pmatrix} \quad (16)$$

$$E = \begin{pmatrix} 1/L_d & 0 \\ 0 & 1/L_q(i_q) \end{pmatrix}. \quad (17)$$

Let

$$\begin{pmatrix} \dot{y}_1 \\ \dot{y}_2 \end{pmatrix} = \begin{pmatrix} v_1 \\ v_2 \end{pmatrix}. \quad (18)$$

Now, the relationships between the outputs y_1 , y_2 and the new control inputs v_1 , v_2 are linear. Therefore, the nonlinearity due to the variations of L_q caused by magnetic saturation is eliminated. In this design, since the internal dynamics are trivial, a linear feedback control can be designed to stabilize the nonlinear IPMSG system over the entire operating range. For tracking control, the new control inputs are given by

$$\begin{pmatrix} v_1 \\ v_2 \end{pmatrix} = \begin{pmatrix} \dot{y}_1^* + k_{11} e_1 + k_{12} \int e_1 dt \\ \dot{y}_2^* + k_{21} e_2 + k_{22} \int e_2 dt \end{pmatrix} \quad (19)$$

where $e = y^* - y$. In (19), the integral controls are added to eliminate the tracking error in the presence of parameter

variations [25]. By locating the desired poles on the left-half complex plane, the gains k_{11} , k_{12} , k_{21} , and k_{22} are calculated, and the asymptotic tracking control to the reference is achieved. Since the matrix E in (17) is nonsingular, the control law is given from (15) and (18) as

$$\begin{pmatrix} u_1 \\ u_2 \end{pmatrix} = E^{-1} \left(-A(x) + \begin{pmatrix} v_1 \\ v_2 \end{pmatrix} \right). \quad (20)$$

The block diagram of the nonlinear current controllers is shown in Fig. 5. The differentials of the reference signals $\dot{i}_{d,opt}^*$ (i.e., $\dot{y}_1$) and $\dot{i}_{q,opt}^*$ (i.e., $\dot{y}_2$) are obtained from the reference signal prefilters, as shown in Fig. 6. The values of k_{d1} , k_{d2} , k_{q1} , and k_{q2} are selected so that the time constant of the outer integral loop is about 1/100 of the corresponding inner integral-loop time constant in Fig. 6(a) and (b); moreover, the time constant of each inner integral loop is in turn about 1/100 of the corresponding d -axis/ q -axis current loop of the IPMSG determined by (4) and (5).

In some real systems, the linear function (6) may not be sufficient to represent the high nonlinearity caused by magnetic saturation. In such cases, higher order polynomials are required to represent the relationships between L_q and i_q . The resulting electrical torque and EMF are therefore highly nonlinear

TABLE II
PARAMETERS OF CONTROLLERS AND REFERENCE SIGNAL PREFILTERS

Speed Controller		Current Controllers		Reference Signal Pre-filters	
k_p	15.0	k_{11}	1.5×10^4	k_{d1}	4.0×10^5
k_i	40.0	k_{12}	2.0×10^3	k_{d2}	5.0×10^3
k_a	0.08	k_{21}	8.0×10^3	k_{q1}	4.0×10^5
		k_{22}	2.0×10^5	k_{q2}	5.0×10^3

Fig. 7. RMS phase voltage and current of the IPMSG.

functions of the stator currents. As a result, direct application of the well-developed linear-system theory can be difficult. The IOL technique used in this section provides a general solution to this problem. The nonlinear controllers based on the IOL design provide the system with high dynamic performance regardless of the degree of the system nonlinearity.

VI. RESULTS

The WTG system and the proposed control scheme shown in Fig. 5 are implemented in MATLAB/Simulink. This section presents the steady-state and dynamic performances of the WTG system to demonstrate the effectiveness of the proposed control scheme. The parameters of the speed and current controllers, as well as the reference signal prefilters, are listed in Table II.

A. Steady-State Performance of the IPMSG

In the conventional control of the IPMSG without considering loss minimization, the reference value of i_d is simply set at $i_d^* = 0$, while i_q^* is obtained from (8) using a PI regulator. However, in the proposed control scheme, when the wind speed is below the rated value, i_d^* and i_q^* are obtained optimally to generate the maximum wind power while minimizing the copper and core losses of the IPMSG. Fig. 7 shows the rms values of the IPMSG stator phase voltage and current as functions of the rotor speed by applying the proposed optimal control. The stator phase voltage increases almost linearly with the increase of the rotor speed, while the stator phase current is approximately a quadratic function of the rotor speed. The resulting mechanical input power and electrical output power are therefore cubic functions of the rotor speed, as shown in Fig. 8. In this paper, the negative values of the power indicate that the IPMSG is

Fig. 8. Mechanical input power and electrical output power of the IPMSG.

Fig. 9. Comparison of efficiency performance of the IPMSG.

Fig. 10. Efficiency improvement as a function of IPMSG rotor speeds using the proposed control scheme.

operated in the generator mode. These results agree with the general maximum power curves of the WTG systems [6].

Fig. 9 shows a comparison of the efficiency performance of the IPMSG by using the proposed optimal control scheme ($i_d^* = i_{d,opt}^*$) and the conventional control scheme ($i_d^* = 0$). The IPMSG efficiency from the mechanical input power to the electrical output power increases with the increase of rotor speed or load current. By using the proposed control scheme, the maximum efficiency reaches 94.8%, compared to only 92.7% when using the conventional $i_d^* = 0$ control scheme. As shown in Fig. 10, at any operating point, the proposed control scheme improves the efficiency of the IPMSG by more than 1% at low and medium speeds and more than 2% at high speed. These results demonstrate that a higher efficiency power generation is achieved by the proposed optimal control scheme.

Fig. 11 shows a comparison of the copper loss, core loss, and total loss of the IPMSG when using the proposed control

Fig. 11. Comparison of copper and core losses of the IPMSG.

scheme and the conventional control scheme. The proposed scheme reduces the core loss significantly at various rotational speeds while it only reduces the copper loss slightly at the high speeds for the IPMSG considered in this paper. These results are reasonable because, generally, the minimum copper loss and the minimum core loss occur at two different operating conditions. Therefore, the copper and core losses cannot be minimized simultaneously. However, by optimally controlling the d -axis and q -axis stator-current components, the combination of copper and core losses of the IPMSG are minimized.

The efficiency of an IPMSG highly depends on its electrical parameters. To further demonstrate the effectiveness of the proposed control scheme, the efficiency of the IPMSG with various different electrical parameters is investigated. Fig. 12 shows the efficiency improvement at the rated IPMSG rotor speed (i.e., 1200 rpm) using the proposed control scheme, when R_s and R_c vary but L_d and L_q are fixed. A smaller value of R_c or a larger value of R_s results in an increase of the IPMSG losses and, therefore, a decrease of the efficiency. As shown in Fig. 12, the proposed control scheme provides a better efficiency improvement when the IPMSG has a smaller R_c . If the IPMSG has an extremely low value of R_c (e.g., 50 Ω), the efficiency can be improved about 10% when using the proposed control. However, the variation of R_s has no significant effect on the efficiency improvement when using the proposed control.

Fig. 13 shows the efficiency improvement at the rated IPMSG rotor speed (i.e., 1200 rpm) using the proposed control scheme, when L_d and L_q vary but R_s and R_c are fixed. The efficiency is

Fig. 12. Efficiency improvement as a function of R_s and R_c at the rated IPMSG rotor speed (1200 rpm) using the proposed control scheme.

Fig. 13. Efficiency improvement as a function of L_d and L_q at the rated IPMSG rotor speed (1200 rpm) using the proposed control scheme.

improved more by the proposed control scheme with a larger q -axis inductance L_q . However, the variation of L_d has no significant effect on the efficiency improvement when using the proposed control.

B. Dynamic Performance of the IPMSG

To evaluate the dynamic performance of the proposed control scheme, a steep ramp change from 5 to 10 m/s is applied to wind speed at $t = 4$ s. After 2 s, the wind speed is changed back to 5 m/s, as shown in Fig. 14. Figs. 15–17 show the responses of the rotor speed, mechanical input power, electrical output power, and d -axis and q -axis stator currents, i_d and i_q , of the IPMSG, respectively.

As shown in Fig. 15, the proposed control scheme regulates the IPMSG rotor speeds at 600 and 1200 rpm, which are the optimal IPMSG rotor speeds at the wind speeds of 5 and 10 m/s, respectively. The delay of the actual rotor speed ω_g from the reference speed ω_g^* is caused by the inertia of the WTG system. Because of the relatively slow response of the WTG

Fig. 14. Ramp changes in wind speed.

Fig. 15. Responses to ramp changes in wind speed: IPMSG rotor speed.

Fig. 16. Responses to ramp changes in wind speed: IPMSG input mechanical power and output electrical power.

Fig. 17. Responses to ramp changes in wind speed: i_d and i_q .

mechanical system, during the acceleration of the WTG (from $t = 4$ s), the PI-type speed controller (Fig. 5) is saturated, and the resulting IPMSG electrical-torque command generated by the speed controller remains at its limit value of zero. As a result, the electrical output power (Fig. 16) and the q -axis stator current (Fig. 17) of the IPMSG are both regulated at zero during the saturation of the speed controller.

The speed controller is desaturated when the WTG shaft speed reaches the reference value of 1200 rpm at about $t =$

Fig. 18. Wind-speed profile.

Fig. 19. Maximum wind power point tracking: IPMSG rotor speed.

4.5 s. From this moment, the proposed control scheme regulates the IPMSG to the new optimal operating point quickly and smoothly to adapt to this significant change of the wind speed (i.e., from 5 to 10 m/s). More power is extracted from the wind (Fig. 16) because of the increase in wind speed. As shown in Fig. 17, the d -axis current i_d is controlled optimally (at a negative value instead of zero) to exploit the reluctance torque in order to minimize the stator copper and core losses of the IPMSG.

The ramp change of the wind speed from $t = 6$ s results in the deceleration of the WTG and, again, the saturation of the speed controller. During the saturation, the electrical-torque command from the speed controller remains at its negative limit value. As a result, the q -axis current and electrical output power of the IPMSG reaches their maximum values (negative). After about 500 ms, the rotor speed returns back to 600 rpm, and the speed controller is desaturated. The proposed control regulates the IPMSG back to the original optimal operating point corresponding to the wind speed of 5 m/s.

C. Maximum Wind Power Point Tracking

A more practical wind-speed profile (Fig. 18) is now used to demonstrate further the dynamic performance of the IPMSG with the proposed control. As shown in Fig. 18, the wind speed varies within ± 2.5 m/s around the mean value of 8.5 m/s.

Fig. 19 shows the speed-tracking results of the IPMSG. In terms of the actual wind speed, the optimal IPMSG speed command is obtained by (9). By applying the proposed control scheme, the optimal speed command is accurately tracked to extract the maximum power from the wind energy at any moment. The resulting tip-speed ratio λ of the wind turbine is varying around the optimal value of 11.5, as shown in Fig. 20. The variations of tip-speed ratio are caused by fast variations of

Fig. 20. Maximum wind power point tracking: Tip-speed ratio.

Fig. 21. Maximum wind power point tracking: Electrical output power of IPMSG.

Fig. 22. Maximum wind power point tracking: i_d and i_q of IPMSG.

the wind speed and the relatively slow responses of the WTG system. However, the average value of the tip-speed ratio during the wind variations is 11.57, which is very close to the optimal tip-speed ratio, $\lambda_{opt} = 11.5$, of this wind turbine. If the wind-speed profile exhibits a slower variation than that in Fig. 18, the variations of the tip-speed ratio will become smaller. These results show that the proposed control provides the WTG system with optimal operation to extract the maximum wind power during the practical wind-speed-variation conditions.

Figs. 21 and 22 show the electrical output power, i_d and i_q , of the IPMSG corresponding to the wind-speed profile in Fig. 18. The IPMSG can operate under overloading condition for a short period, e.g., a few seconds. Therefore, if the wind speed exceeds the rated value of 10 m/s for such a short time, the pitch control (if it exists) does not activate, and the IPMSG generates more electrical power than its rated value, as shown in Fig. 21. As shown in Fig. 22, the d -axis stator current is optimally controlled (instead of zero) with the q -axis stator current to achieve maximum wind power point tracking (Figs. 19 and 20) and loss minimization of the IPMSG.

VII. CONCLUSION

PMSGs are commonly used for small variable-speed WTG systems. In such systems, by adjusting the shaft speed optimally, the maximum wind power can be extracted at various wind speeds within the operating range. In addition, when using an IPMSG, the stator copper and core losses of the generator can be minimized by optimally controlling the d -axis component of the stator currents. However, to achieve the high performance of the WTG system, magnetic saturation of the IPMSG must be taken into account in the control-system design.

This paper has proposed an output-power-maximization control scheme for an IPMSG in a variable-speed wind-power-generation system. The proposed control scheme can extract the maximum wind power from the wind at various wind speeds below the rated value while minimizing the stator copper and core losses in the IPMSG simultaneously. The effect of magnetic saturation, which causes the highly nonlinear characteristics of the IPMSG, has been considered in the control-scheme design. The IOL technique is applied to design the high-performance nonlinear current controllers in order to eliminate the effects of nonlinearity caused by magnetic saturation. Implementation results have shown that the proposed control provides the wind generation system with high dynamic performance and improved power efficiency.

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