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Mechanical Sensorless Maximum Power Tracking Control for Direct-Drive PMSG Wind Turbines

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Abstract — Wind turbine generators (WTGs) are usually equipped with mechanical sensors to measure wind speed and rotor position for system control, monitoring, and protection. The use of mechanical sensors increases the cost and hardware complexity and reduces the reliability of the WTG systems. This paper proposes a mechanical sensorless maximum power tracking control for wind turbines directly driving permanent magnetic synchronous generators (PMSGs). In the proposed algorithm, the PMSG rotor position is estimated from the measured stator voltages and currents by using a sliding mode observer (SMO). The wind turbine shaft speed is estimated from the PMSG back electromotive force (EMF) using a model adaptive reference system (MRAS) observer. A back propagation artificial neural network (BPANN) is designed to generate the optimal shaft speed reference in real time by using the estimated turbine shaft speed and the measured PMSG electrical power. A control system is developed for the PMSG wind turbine to continuously track the optimal shaft speed reference to generate the maximum electrical power without using any wind speed or rotor position sensors. The validity of the proposed control algorithm is shown by simulation studies on a 3-kW PMSG wind turbine and experimental results on a practical 300-W PMSG wind turbine.

Index Terms—artificial neural network, model adaptive reference system (MRAS), permanent magnet synchronous generator (PMSG), sensorless control, sliding mode observer (SMO), wind turbine.

I. INTRODUCTION

Permanent magnet synchronous generators (PMSGs) are commonly used in small and medium-size wind turbine systems for electric power generation. Compared to the wind turbines equipped with induction generators, there are several advantages of using PMSGs. First, the PMSGs can provide highly efficient and reliable power generation, since there is no need for external excitation and no copper losses in the rotor circuit. Second, the high-power-density PMSGs are small in size, which reduces the cost and weight of the wind turbine generator (WTG) system. Moreover, the wind turbine equipped with a direct-drive PMSG removes the need of using a gearbox. According to the statistical data reported in [1], approximately 19.4% downtime of WTGs is caused by failures of gearboxes. Without gearboxes, the WTG systems need less maintenance and have a reduced downtime and a higher reliability.

Control, monitoring, and protection of WTGs usually requires the information of wind speed and generator rotor position. These can be measured by well-calibrated mechanical sensors, such as anemometers and rotor position sensors. However, the use of these mechanical sensors increases the cost and failure rate of the WTG systems. According to [3], sensor failures contribute to more than 14% of failures in WTG systems and more than 40% of failures are related to the failure of sensors and the consequent failures of the control or electrical systems. Repairing the failed components requires additional cost and leads to a significant loss in electric power production.

The problems incurred in using mechanical sensors can be solved through mechanical sensorless control. In [2] and [3], the wind speed was estimated based on power signal feedback but the generator rotor position or speed was still measured for wind speed estimation and WTG control. The control systems in [4]-[6] used a hill-climbing search algorithm to track the maximum power point of the wind turbine. This method does not need the information of wind speed. However, since the wind speed changes from time to time and it takes time for this method to locate the maximum power point, the WTGs may always operate at nonoptimal conditions. In [7], the wind speed was predicted for system control from an autoregressive statistical model by using historical data. Most of these works still used generator rotor position/speed measurements.

In existing WTG control systems, rotor position sensors are used not only to get the shaft speed information but also to control the frequency of the power electronic converters. The previous research on rotor position sensorless control has been focused in the area of permanent magnet (PM) motor drives. For example, in [8] a sliding mode observer was developed for rotor position sensorless control of PM motors without saliency. Reference [9] used the output voltage of the $d$-axis current regulator of the drive system to estimate the rotor position.

This paper extends the work in [2] by proposing a novel
mechanical sensorless maximum power tracking control for direct-drive PMSG wind turbines. First, a sliding mode observer is designed to estimate the rotor position of the PMSG. The turbine shaft speed is then determined from a model reference adaptive system (MRAS) speed observer. Based on the measured electrical power and estimated rotor speed of the PMSG, the optimal turbine shaft speed reference is generated in real time by a BPANN. Finally, a sensorless control is developed for the PMSG wind turbine to continuously track the optimal shaft speed reference to generate the maximum electrical power without the need for any wind speed or rotor position sensors.

II. DIRECT-DRIVE PMSG WIND TURBINE SYSTEM

The configuration of a PMSG wind turbine is shown in Fig. 1, where the wind turbine is connected to the PMSG directly. The electrical power generated by the PMSG is transmitted to a power grid and/or supplied to a load via a variable frequency converter, which consists of a machine side converter (MSC) and a grid side converter (GSC).

\[ P_w = \frac{1}{2} \rho A_v C_p \lambda^2 \omega_t \]

where \( \rho \) is the air density; \( A_v \) is the area swept by the blades; \( v_w \) is the wind speed; \( C_p \) is the turbine power coefficient; \( \omega_t \) is the turbine shaft speed. \( \lambda \) is the tip speed ratio, which is defined by:

\[ \lambda = \frac{\omega_t R}{v_w} \]

where \( R \) is the radius of the blades. In this paper, \( C_p \) is given by [10]:

\[ C_p = \frac{1}{2} \left( 5.6 \exp(-0.17\lambda) \right) \]

B. Modeling of the PMSG

The dynamic equations of a three-phase PMSG without saliency can be written in a synchronously rotating \( dq \) reference frame as:

\[ \psi = R_i + \frac{d\psi}{dt} + \omega\psi \]

where \( \psi \) is the stator flux, \( R_i \) is the stator resistance, \( \omega \) is the rotor angular velocity, and \( \psi \) is the rotor flux linkage. The electromagnetic torque can be calculated by:

\[ T_e = \frac{3}{2} \psi \psi \]

where \( \psi \) is the stator flux linkage and \( \psi \) is the rotor flux linkage.

C. Modeling of the Shaft System

As the wind turbine is connected to the PMSG directly, the shaft system of the WTG can be represented by a one-mass model. The motion equation is then given by:

\[ J \frac{d\omega}{dt} = P_w - P_e - D\omega \]

where \( J \) is the total inertia constant of the WTG and \( D \) is the damping coefficient.

III. REAL-TIME OPTIMAL SHAFT SPEED REFERENCE DETERMINATION

In a WTG system, the conversion from wind energy to generator electrical power can be illustrated by the nonlinear process in Fig. 2. If the PMSG electrical power \( P_e \) and the turbine shaft speed \( \omega_t \) are known, the wind speed \( v_w \) can be estimated from the inverse mapping of the WTG process in Fig. 2. In addition, the relationship between the wind speed and the optimal shaft speed is given by:

\[ \omega_{opt} = \frac{v_w}{R} \]

where \( \omega_{opt} \) is the optimal tip speed ratio. For the wind turbine model used in this paper, the value of \( \omega_{opt} \) is 11.55. Combining (12) and the WTG process in Fig. 2 indicates that the optimal shaft speed reference can be determined directly from the PMSG electrical power \( P_e \) and the turbine shaft speed \( \omega_t \) as shown in Fig. 2.
In this paper, a three-layer BPANN as shown in Fig. 3 is designed to provide a nonlinear mapping from \( P_e, \hat{\omega}_t, \) and \( \dot{\omega}_t \) to \( \hat{\omega}_{\text{opt}} \), where \( \hat{\omega}_t, \dot{\omega}_t, \) and \( \dot{\omega}_{\text{opt}} \) are the estimated turbine shaft speed, the derivative of \( \hat{\omega}_t \), and the estimated optimal shaft speed reference, respectively. The overall input-output mapping of the BPANN is:

\[
\hat{\omega}_{\text{opt}} = b + \sum_{j=1}^{h} v_j \text{tansig}(w_{ij}P_e + w_{2j}\hat{\omega}_t + w_{3j}\dot{\omega}_t + b_j)
\]

where \( h \) is the number of neurons in the hidden layer; \( w_{ij}, w_{2j}, \) and \( w_{3j} \) are the weights between the input and hidden layers; \( v_j \) is the weight between the \( j^{th} \) neuron in the hidden layer and the output; \( b_j \) and \( b \) are the bias terms of the hidden and output layers, respectively; ‘tansig’ is the hyperbolic tangent sigmoid transfer function, defined by:

\[
\text{tansig}(x) = \frac{2}{1 + e^{-2x}} - 1
\]

The parameters of the BPANN, including the weights, bias terms, and the number of neurons in the hidden layer, are determined online through a training process, as shown in Fig. 2. At each training time step, the optimal shaft speed reference \( \hat{\omega}_{\text{opt}} \) is generated by a hill-climbing search algorithm [4], which does not need the information of wind speed. Fig. 4 shows the principle of the hill-climbing search algorithm. In this method, the shaft speed \( \omega_t \) is continuously adjusted by a constant increment/decrement of \( d\omega_t \) in each search step. As a result, the output electric power \( P_e \) changes by \( dP_e \). If \( dP_e/d\omega_t > 0 \), \( \omega_t \) keeps increasing; otherwise, if \( dP_e/d\omega_t < 0 \), \( \omega_t \) keeps decreasing until the maximum power point is located. The corresponding shaft speed is the optimal value \( \hat{\omega}_{\text{opt}} \). If the wind speed varies slowly and the time interval of the search step is sufficiently small, the shaft speed will be always around the optimal value. \( \hat{\omega}_{\text{opt}} \) is then compared with the estimated optimal shaft speed reference \( \dot{\omega}_{\text{opt}} \) from the BPANN; and the error between them is used to adjust the parameters of the BPANN through a back-propagation algorithm [11]. The BPANN is trained until an acceptable performance is achieved. The parameters of the BPANN are then fixed operation for real-time determination of the optimal shaft speed reference.

IV. REAL-TIME PMSG ROTOR POSITION AND TURBINE SHAFT SPEED ESTIMATION

The information of the PMSG rotor position \( \theta_f \) and the turbine shaft speed \( \omega_t \) is needed for wind speed estimation and system control. In this paper, a sliding mode observer is designed to estimate the rotor position based on the work in [8], [14].

A. Rotor Position Estimation

The dynamic equations of a nonsalient PMSG in the stationary reference frame can be expressed as [8]:

\[
\dot{i}_{\text{opt}} = A \cdot i_{\text{opt}} + B \cdot (v_{\text{opt}} - e_{\text{opt}})
\]

where \( v_{\text{opt}}, i_{\text{opt}}, \) and \( e_{\text{opt}} \) are the stator voltages and currents and the back EMF in the stationary reference frame; and

\[
A = \begin{bmatrix} -R_s/L_s & 0 \\ 0 & -R_s/L_s \end{bmatrix}, \quad B = \begin{bmatrix} 1/L_s \\ 0 \end{bmatrix}
\]

\[
i_{\text{opt}} = \begin{bmatrix} i_{\alpha} \\ i_{\beta} \end{bmatrix}, \quad v_{\text{opt}} = \begin{bmatrix} v_{\alpha} \\ v_{\beta} \end{bmatrix}
\]
\[ e_{\alpha\beta} = \begin{bmatrix} e_{\alpha} \\ e_{\beta} \end{bmatrix} = K_e \cdot \omega_r \cdot \begin{bmatrix} -\sin(\theta_r) \\ \cos(\theta_r) \end{bmatrix} \]

where \( L_s \) is the stator inductance and \( K_e \) is a back EMF constant. Then the sliding mode observer is designed as follows [14].

\[ \hat{i}_{\alpha\beta} = A \cdot \hat{i}_{\alpha\beta} + B \cdot v_{\alpha\beta} + K_{sw} \cdot \text{sgn}(\hat{i}_{\alpha\beta} - i_{\alpha\beta}) \]  

(16)

where \( \hat{i}_{\alpha\beta} \) is the estimated value of \( i_{\alpha\beta} \) and \( K_{sw} \) is the switching gain of the observer.

Fig. 5 shows the block diagram of the observer, where \( k \) is the switching gain of the discontinuous control signal \( Z_{\alpha\beta} \); \( \hat{\theta} \) is the estimated rotor position. To ensure the convergence of the sliding mode observer, \( K_{sw} \) should be selected such that \( e_{\alpha} \cdot e_{\beta}^2 < 0 \), where \( e_{\alpha} = \hat{i}_{\alpha\beta} - i_{\alpha\beta} \) [14].

The estimated back EMF is obtained from the switching signal \( Z_{\alpha\beta} \) by using a low-pass filter.

\[ \begin{aligned}
\hat{e}_{\alpha} &= \frac{\omega_{\text{sw}}}{s + \omega_{\text{sw}}} \cdot Z_{\alpha} \\
\hat{e}_{\beta} &= \frac{\omega_{\text{sw}}}{s + \omega_{\text{sw}}} \cdot Z_{\beta}
\end{aligned} \]  

(17)

The rotor position is then obtained as:

\[ \hat{\theta} = -\tan^{-1}\left( \frac{\hat{e}_\alpha}{\hat{e}_\beta} \right) \]  

(18)

The low-pass filter is designed to have a variable cutoff frequency according to the rotor speed [14]. The phase angle delay caused by the filter is

\[ \Delta \theta = \tan^{-1}\left( \frac{\theta}{\omega_{\text{sw}}} \right) \]  

(19)

The delayed angle is compensated for the estimation of the rotor angle position.

V. SENSORLESS CONTROL FOR PMSG WIND TURBINES

In the proposed estimation algorithms, both the PMSG rotor position and turbine shaft speed are estimated from the measured stator voltages \( v_{\alpha\beta} \) and currents \( i_{\alpha\beta} \). The estimated rotor position \( \hat{\theta} \) is used in the MSC control system to correctly transform the three-phase stator voltages and currents into the rotor reference frame. The estimated rotor position and turbine shaft speed are integrated into the control system, leading to a sensorless control for the PMSG wind turbine, as shown in Fig. 7. The overall control system consists of two parts: control of the MSC and control of the turbine shaft speed estimation. According to (15), if the PMSG rotor speed changes slowly, i.e., \( \dot{\theta}_r = 0 \), the reference model of the induced back EMF is:

\[ \dot{e}_\alpha = -\omega_r \cdot e_{\alpha} \quad \text{and} \quad \dot{e}_\beta = \omega_r \cdot e_{\beta} \]  

(20)

The adjustable model is designed as [16]

\[ \begin{aligned}
\dot{\hat{e}}_{\alpha} &= -\hat{\omega}_r \cdot \hat{e}_\beta - L \cdot (\hat{e}_\alpha - e_{\alpha}) \\
\dot{\hat{e}}_{\beta} &= \hat{\omega}_r \cdot \hat{e}_\alpha - L \cdot (\hat{e}_\beta - e_{\beta})
\end{aligned} \]  

(21)

where \( L \) is a constant gain; \( \hat{e}_\alpha \) and \( \hat{e}_\beta \) are the back EMF components obtained from the sliding mode observer; \( e_{\alpha} \) and \( e_{\beta} \) are the estimated values of \( \hat{e}_\alpha \) and \( \hat{e}_\beta \), respectively, from the MRAS observer. The adaptation mechanism for the MRAS system is derived by using the hyper stability criteria as follows [17].

\[ \dot{\hat{\omega}} = (k_p + \frac{k_i}{s}) \cdot (\hat{e}_\alpha - e_{\alpha}) \cdot \hat{e}_\beta - (\hat{e}_\beta - e_{\beta}) \cdot \hat{e}_\alpha \]  

(22)

Fig. 6 illustrates the block diagram of the MRAS rotor speed observer. The back EMFs are normalized as follows:

\[ e = \frac{1}{\sqrt{e_{\alpha}^2 + e_{\beta}^2}} \begin{bmatrix} e_{\alpha} \\ e_{\beta} \end{bmatrix} \]  

(23)

where \( e \) stands for \( \hat{e} \) or \( \dot{\theta} \). In Fig. 6, \( J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \) and \( e \) is the estimation error of the normalized back EMF. The turbine shaft speed \( \omega_t \) can be obtained from \( \hat{\omega}_r \) directly.

\[ \dot{\hat{\omega}} = k_p \cdot \hat{e} \]  

(24)
GSC. The MSC control tracks the maximum power point of the wind turbine. The objective of the GSC is to transfer the active power generated by the PMSG to the grid and/or load by controlling a constant DC-link voltage. The GSC can also be arranged to control the reactive power, voltage, or power factor at the AC terminals.

The maximum torque per ampere is obtained by setting \( i_s = 0 \) and \( i_q = 0 \) [9]. This is set to 0 in the stability analysis. The MSC is assumed to be ideal, and therefore, is represented by a constant 1. In a well designed observer, \( T_o \) is much smaller than other time constants. Therefore, \( T_o \) is set to 0 in the stability analysis.

Define \( K_{pw} \) and \( K_{iw} \) as the proportional and integral gains, respectively, of the PI controller in the current loop. Define \( K_p \) and \( K_i \) as the proportional and integral gains of the PI controller in the speed control loop, respectively, it can be obtained from Fig. 10 that

\[
\frac{i_s}{\varepsilon_{wr}} = \frac{s}{L_s s^2 + (R_s + K_p) s + K_i}
\]

where \( \varepsilon_{wr} \) is the error of the estimated turbine shaft speed. If the PI controller is well designed, the current loop is stable and the errors of the observer do not generate steady-state errors in the current loop.

The PMSG rotor speed controller is shown in Fig. 11, where \( T_e \) is the electromagnetic torque; \( T_L \) is the load torque; \( T_o \) is the time constant of the speed observer; and \( \dot{\varepsilon}_{wr} \) is the estimation error of the speed observer. The MSC is assumed to be ideal, and therefore, is represented by a constant 1. In a well designed observer, \( T_o \) is much smaller than other time constants. Therefore, \( T_o \) is set to 0 in the stability analysis.

Define \( K_{pw} \) and \( K_{iw} \) as the proportional and integral gains, respectively, of the PI controller in the speed control loop. The outer-loop controllers regulate the dc-link voltage as well as the reactive power at the AC terminals of the GSC. The outer-loop controllers regulate the dc-link voltage as well as the reactive power at the AC terminals of the GSC at the desired values [18].
\[ \omega = \frac{1 - \frac{K_s}{s}}{\left( K_p + \frac{K_s}{s} \right) \left( K_{pw} + \frac{K_{ws}}{s} \right) + \left( L_s + R_s + K_p + \frac{K_{ws}}{s} \right) \frac{2(sJ + D)}{3p\Psi_m}} \]  

(26)

\( K_p, K_s, K_{pw}, \) and \( K_{ws} \) should be chosen such that the poles of the right hand side of (26) are all smaller than zero. Therefore, the system is stable with the observer error of \( \dot{\epsilon}_{wr} \).

VI. SIMULATION RESULTS

Simulation studies are carried out in PSCAD to validate the proposed real-time wind speed and rotor position estimation algorithms and sensorless control for a 3-kW PMSG wind turbine. The WTG system has the following parameters. For the wind turbine: the radius of the blades is \( R = 2 \) m; the air density is \( \rho = 1.15 \text{kg/m}^3 \); \( \lambda_{opt} = 11.55 \); the \( C_p(\lambda) \) is given by (3). For the PMG: the rated power is 3 kW, \( R_s = 0.2499 \) ohms; \( L_d = 34.3 \) mH; \( L_q = 34.3 \) mH; the flux linkage \( \psi_m = 1.0 \text{V} \cdot \text{s} \); the number of pole pairs is \( p = 7 \); and the moment of inertia is \( J = 1 \) kg m\(^2\).

During the simulation, the wind speed varies in the range of \( \pm 3 \) m/s around the mean value of 8 m/s. Figs. 12 and 13 compare the actual and estimated values of the PMSG rotor position and shaft speed. The results show that the proposed algorithm accurately estimates the PMSG rotor position and shaft speed, which are used for real-time control of the PMSG and converters.

Figs. 14-16 compare the estimated optimal shaft speed reference generated by the BPANN with the actual optimal shaft speed reference determined by (13) using the actual wind speed for three scenarios: 1) constant shaft speed operation (Fig. 14), 2) a ramp change in shaft speed (Fig. 15), and 3) variable shaft speed operation (Fig. 16). In first two scenarios, the maximum power tracking control is not applied; while in the third scenario, the estimated optimal shaft speed reference is applied to the control the WTG to generate the maximum power. These results show that the proposed BPANN-based algorithm correctly estimates the optimal shaft speed reference for maximum power generation during various conditions. Fig. 17 shows the shaft speed tracking results in the third scenario. The turbine shaft speed is well...
controlled to track the reference with good precision by using the estimated rotor position, shaft speed, and the proposed sensorless control algorithm.

emulates the dynamics of the wind turbine. An incremental encoder with 2500 pulses per revolution is used to measure the turbine shaft speed in real time. The proposed estimation algorithms are implemented in a dSPACE system.

To demonstrate the performance of the proposed speed estimation algorithms, the rotating speed of the induction motor in Fig. 18 is varied to emulate variable wind speed condition. By using the measured PMSG stator voltages and currents, the PMSG rotor speed (i.e., the turbine shaft speed) is accurately estimated by using the proposed method, as shown in Fig. 19.

The optimal turbine shaft speed reference is obtained from the BPANN in Fig. 3. By using the measured PMSG electrical power and the estimated turbine shaft speed, the optimal turbine shaft speed references are correctly determined from the proposed BPANN-based method. As shown in Fig. 20, the estimated optimal turbine shaft speed reference tracks the real optimal turbine shaft speed reference with good precision.

VII. EXPERIMENTAL RESULTS

A practical 300-W direct-drive PMSG wind turbine system has been set up to further validate the proposed PMSG rotor position and speed estimation and optimal turbine shaft speed determination algorithms. Fig. 18 illustrates the experimental setup. The PMSG is driven by an adjustable speed induction motor drive system, which

Fig. 15. Optimal shaft speed reference estimation results during a ramp change in shaft speed.

Fig. 16. Optimal shaft speed reference estimation results during variable shaft speed operation.

Fig. 17. Shaft speed tracking results.

Fig. 18. Experiment setup for a 300-W PMSG wind turbine

Fig. 19. Measured and estimated turbine shaft speed.
VIII. CONCLUSION

This paper has proposed a mechanical sensorless control algorithm for maximum wind power generation using direct-drive PMSG wind turbines. The values of the PMSG rotor position and speed have been estimated from the measured stator voltages and currents in real time. Based on these estimated variables and the measured PMSG electrical power, the optimal turbine shaft speed reference has been determined by a BPANN and used for optimal control of the power electronic converters and the PMSG. Therefore, the commonly used mechanical sensors in WTG systems, i.e., the wind speed sensors and rotor position sensors, are not needed. The effectiveness of the proposed sensorless control has been demonstrated by simulation results of a 3-kW PMSG wind turbine. A practical 300-W PMSG wind turbine system has been set up to further validate the proposed rotor position, shaft speed, and BPANN-based optimal shaft speed reference estimation algorithms. The proposed mechanical sensorless control algorithm reduced the cost and improved the reliability of the PMSG wind turbine systems.

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