Estimation of PMSG Rotor Speed for Sensor-less MPPT Control Method in Wind Energy System

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Abstract— **Permanent magnet synchronous generator (PMSG) has a significant role in variable speed wind energy system (VSWES), so this manuscript proposes a simple scheme to estimate the rotor speed of PMSG and its rotor position angle based on back EMF (electromotive force) observer and phase-locked loop (PLL). Electrical sensor can observe the Back EMF utilizing the output terminals AC current and voltage of PMSG, these values of current and voltage can be converted from *abc* reference frame to *dqo* reference frame. The rotor speed of PMSG and its rotor position angle can be estimated utilizing the basics of PLL to adjust the frequency of the output signal using the difference between the output phase of system and the given signal phase till the output signal track the given signal phase of the frequency. The estimated rotor position angle is exploited as a reference angle in the conversion scheme from *abc* reference frame to *dqo* reference frame. It is easy to achieve sensor-less maximum power point tracking (MPPT) control scheme utilizing the estimated rotor speed of PMSG. The simulation results, using PSIM software program, confirm the accuracy of the proposed technique.**

Keywords— Maximum Power Point Tracking (MPPT); Permanent Magnet Synchronous Generator (PMSG); Phase Locked Loop (PLL); Wind Energy System (WES).

I. INTRODUCTION

Recently, the wind energy system (WES) is considered one of the fastest growing renewable energy sources in the countries of the world that are blessed with the presence of winds that dominate their climate or part of their land. Also, it can be constructed much faster than conventional power plants. Wind energy is clean, cheap, and it is friendly energy source compared with the conventional energy sources [1-3]. Permanent magnet synchronous generator (PMSG) based on variable speed WES has attained excessive development in the last recent years. It is more attractive compared with the DFIG (doubly fed induction generator), such as increasing power generation, disappearing gearbox failure, and decreasing maintenance expenses [4-9].

Variable speed wind energy system (VSWES) has numerous merits such as extracting maximum output power output while evolving low quantity of mechanical stress comparing with constant speed wind energy systems. The existence of power electronics devices is very vital with VSWES, this because the AC-DC converter as a rectifier is exploited to transform the variable voltage and frequency that produced by the PMSG into DC voltage. The DC voltage at the DC link is transformed again into AC voltage with fixed frequency by controlling of the grid side inverter. This produced voltage is fitting for electrical usage at the grid [10-12].

Most modern articles attempt to attain maximum power point tracking (MPPT) without utilizing mechanical sensors that measure the wind speed value and the PMSG rotor speed value, whereas exploiting these sensors produce in correct measurement because they contains inside mechanical parts. Therefore, sensor-less MPPT should be accomplished using another procedure other than using the mechanical sensors for measuring the wind speed or the PMSG rotor speed [13-16].

In this manuscript, estimation of PMSG rotor speed and rotor position is presented by using simple technique method by using back EMF (Electromotive force) observer and phase locked loop (PLL). Sensor-less MPPT can be easily achieved from this estimated value of rotor speed of PMSG (not included in this paper). Back to back full power converter topology interface is used in this manuscript [17-21] because it has many advantages than the other interface, which content of diode-bridge rectifier and boost converter as an interface between PMSG and the grid [22-23]. Also, as it is easy to achieve unity power factor at the generator side and eliminate the harmonics using first interface although it is more expensive than the later interface. The proposed technique of estimation the PMSG rotor speed and its rotor position angle have been proved via simulation program (PSIM).

II. WIND ENERGY SYSTEM

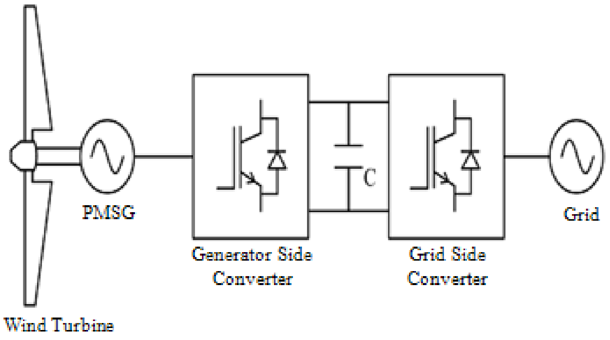


Fig. 1. Variable speed wind energy system.

The power circuit topology of a variable speed wind energy system that suggested in this manuscript is described in Fig.1. The system used contains the following components; wind turbine, 20 kW watt rated power PMSG, back to back full power converter, and the grid. The wind turbine connected directly to the PMSG, the back to back full power converter is used as an interface between PMSG and the grid, where the generator rectifier side is responsible to achieve MPPT and attain the unity power factor at generator terminal side, while the grid side inverter is responsible to obtain constant dc voltage across dc capacitor and accomplish unity power factor at the grid to get high power efficiency. Where back to back interface could be the best way to enhance strongly the system performance, where it has a flexible control method, through which the control of the generator speed and the quality of the precise grid power transmitted into the grid, can be achieved.

In this manuscript, just PMSG speed and its rotor position angle are estimated using simple technique based on back EMF and PLL and use this estimation of PMSG rotor speed to achieve sensor-less MPPT control technique to get optimum PMSG rotor speed according the variation of wind speed exploiting the generator side converter.

III. ESTIMATION OF PMSG ROTOR SPEED AND ROTOR POSITION ANGLE

Estimation of PMSG rotor speed and its rotor position can be determined utilizing back EMF observer and PLL [24-25]. Each of them depends on the another one where to estimate Back EMF, the estimated signal frequency (Rotor speed of PMSG and rotor position angle) should be obtained to transform from (*abc*) stationary reference frame into (*dqo*) rotating reference frame [26], and also estimated back EMF is essential to estimate the PMSG rotor speed. The control precision of this technique is efficient, but unfortunately it has several difficulties when the generator moves with low speed.

With estimation of the PMSG rotor speed $\hat{\omega}$ and its rotor position angle $\hat{\theta}$ and using these estimated values of signal frequency as feedback to get back EMF. In this case the value of back EMF will have some error because it uses not accurate value, this estimated back EMF generated by the PMSG generate has two components, *q*-axis and *d*-axis, these components are used to estimate the PMSG rotor position. These values are expressed as $\hat{e}_q$ and $\hat{e}_d$ respectively. If the value of estimated rotor position or back EMF has zero error, in this case the estimated of rotor position and back EMF will have the same value of actual value of rotor position of PMSG and back EMF. Where sign (∧) means the estimated value.

Using the principle of PLL technique to get estimated rotor position angle of PMSG using the conventional PI controller that used in PLL to achieve zero error control of $\Delta\theta$ as indicated in Fig. 2.

The amount of $\hat{e}_d$ and $\hat{e}_q$ can be calculated from the basic equation of PMSG, that is:

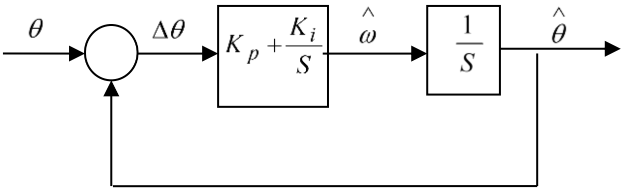


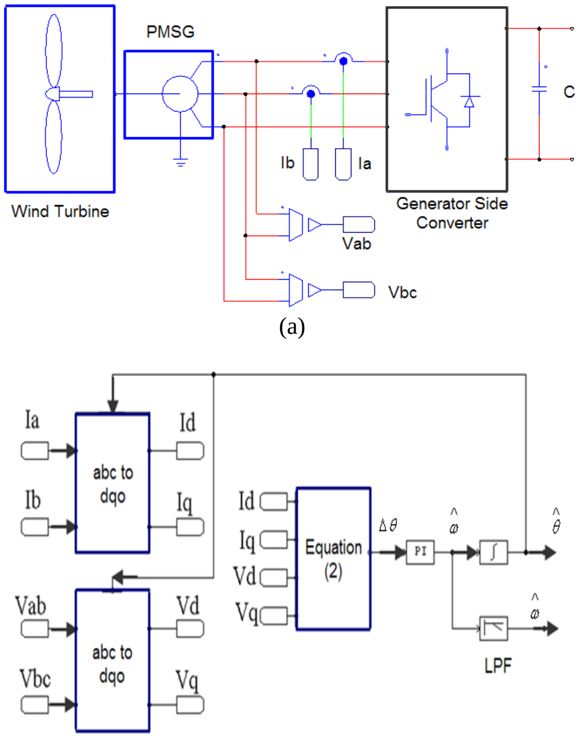
Fig. 2. Principle of PLL

$$v_d = R\hat{i}_d - L_d\frac{di_d}{dt} + \hat{\omega}L_q\hat{i}_q + \hat{e}_d$$
$$v_q = R\hat{i}_q - L_q\frac{di_q}{dt} + \hat{\omega}L_d\hat{i}_d - \hat{e}_q \qquad (1)$$

In previous equation the value of the current differential items can be neglected to compute the value of error in PMSG rotor position angle as the following:

$$\Delta\theta = tan^{-1}\left(-\frac{\hat{e}_d}{\hat{e}_q}\right) = tan^{-1}\left(-\frac{v_d+R\hat{i}_d-\hat{\omega}L_q\hat{i}_q}{v_q+R\hat{i}_q+\hat{\omega}L_d\hat{i}_d}\right) \qquad (2)$$

Where i_d and v_d refer to the *d* axis components output current and voltage of PMSG, respectively. i_q and v_q are referring to the *q* axis components output current and voltage of PMSG, respectively. L_d and $L_q$refer to the internal inductance of PMSG in *d*, *q* axis, respectively. The resistance *R* refers to the resistance of the PMSG stator, and ω refers to the PMSG electrical angular velocity.



(a)

(b)

Fig. 3. Estimation of(a) PMSG rotor speed and (b) its rotor position angle

Fig. 3 shows the part of complete system of WECS, which contents are wind turbine, PMSG, and generator side converter. In addition, it discribes how to achieve PMSG speed and rotor position by using of sensors, two sensors are employed for measuring line currnts (I_a, and I_b) and the other two sensors are used for measuring line voltages (V_{ab}, and V_{bc}). The control part in the figure indicates using the transformation techinque from stationary refernce frame abc to rotating refernce frame dqo.

Respect to current, it is easy calculate I_c from measuring I_a and I_b, where I_c takes the same maximum value but lag I_b by 120^o electrical degree in steady state condition.

Respect to voltage, the sensors measure the line output voltages of PMSG, so in this case, it is simple to get V_{ca} from knowing V_{ab} and V_{bc}, where V_{ca} takes the same maximum value but it is lag behind V_{bc} by 120^o electrical degree. Phase voltages V_{an}, V_{bn} and V_{cn} are needed to tranform from stationary refernce frame *abc* to rotating rference frame *dqo*, so phase voltage should be obtained from line voltage. Eqaution (3) describes how to get phase voltages from line voltages in stable system:

$$V_{an} = \frac{1}{3}(V_{ab} - V_{ca})$$

$$V_{bn} = \frac{1}{3}(V_{bc} - V_{ab}) \qquad (3)$$

$$V_{cn} = \frac{1}{3}(V_{ca} - V_{bc})$$

After transformation of currents and voltages from *abc* reference frame to *dqo* refernce frame as shwon in Fig. 3, the error in rotor position angle $\Delta\theta$ can be estamated by using equations 2 and 3 after getting the estimated $\hat{e}_d$ and $\hat{e}_q$components of back EMF. The PMSG speed can be estimated using the conventional PI control technique based on PLL as indicated in Fig. 2, and then the magnitude of the PMSG rotor position angle could be calculated by integral the estimated PMSG rotor speed, the feedback of the estimated PMSG rotor position angle is used as the reference in the conversion from *abc* refrence frame to *dqo* refrence frame as also indicated in Fig. 3. Low pass filter (LPF) can beutilized to attain a better estimation of PMSG rotor speed due togenerally the speed has larger fluctuations amount using this technique. The estimated PMSG rotor speed can be used esealy to get MPPT control when the estimated value of rotor speed compared with refernce speed to get MPPT expoliting generator side converter switches gate.

IV. SIMULATION RESULTS AND DDISCUSSION

To check the suggested algorithm of estimating the PMSG rotor speed and its rotor position angle, the system indicated in Fig. 3 is used. The system is simulated via PSIM software package. The simulation results indicate to the estimated PMSG speed and rotor position angle with step variations of the wind speed in VSWES. The parameters of PMSG are important in the calculation as indicated in equations (1) and (2), so the parameters of the used PMSG are presented in Table I [27].

TABLE I. THE PMSG PARAMETERS

P_r	Rated output power (kW)	20
N_r	Rated mechanical speed (rpm)	211
pole	Poles number	36
E_{LN}	Peak line-to-neutral back emf at no-load (V)	295.6
R_s	Resistance of stator winding (Ω)	0.1764
L_s	Inductance of stator leakage (mH)	4.48

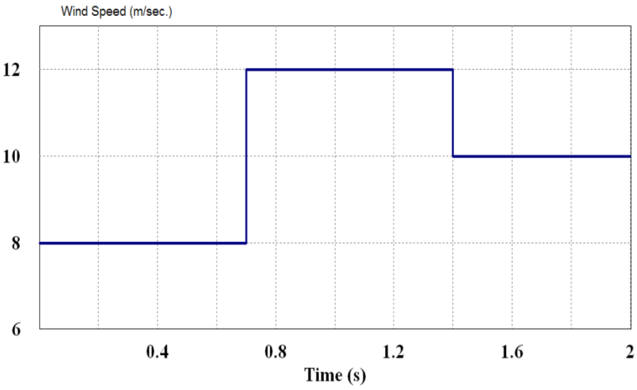
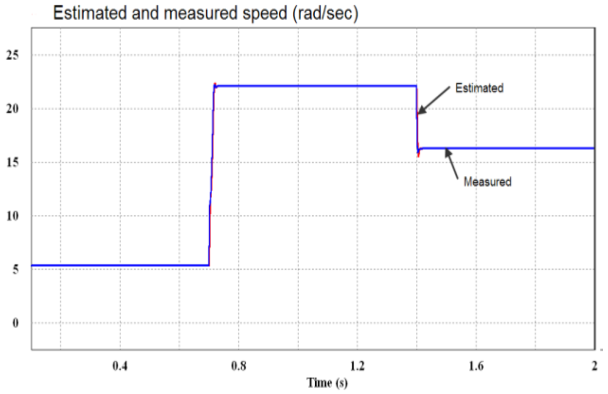
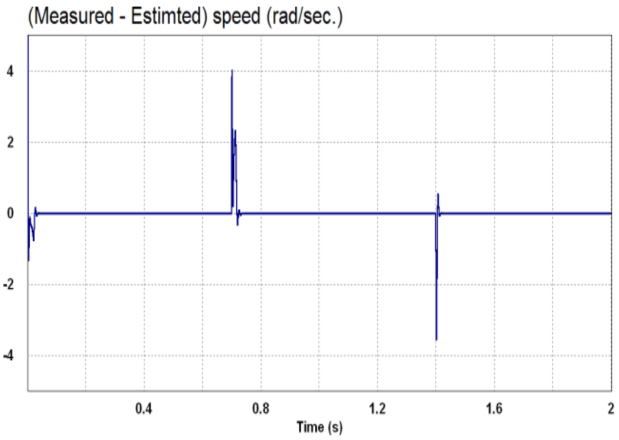


Fig. 4. Wind speed variations (m/sec.)



(a) The estimated and measured value of PMSG rotor speed (rad/sec.)



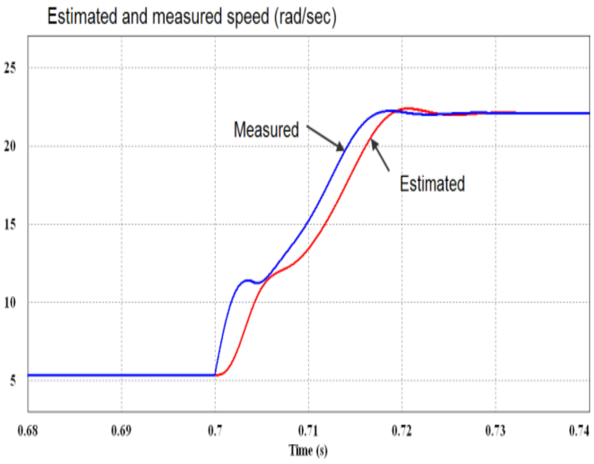
(b) The error of estimated PMSG rotor speed (rad/sec.)

Fig. 5. The estimated and measured rotor speed of the PMSG and its error

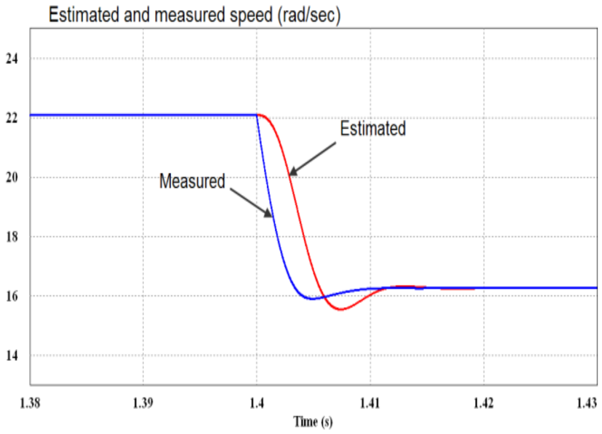
Fig. 4 shows the profile of wind speed throughout the time of simulation. It is noticed that, the wind speed rises to 12 m/sec. from 8 m/sec. at time 0.7 sec. and it falls to 10 m/sec. at time 1.4 sec. The PMSG speed and rotor position angle will change according to variation in the profile of the wind speed.

The estimated and measured PMSG rotor speed in rad/sec. is shown in Fig. 5 (a), it could be noticed that the estimated rotor speed is identical with measured rotor speed of PMSG with varying the wind speed. While, Fig. 5 (b) indicates the error between measured and estimated PMSG rotor speed in rad/sec. As indicated in this figure, a great error is produced at instant of change in wind speed, which leads to change the PMSG rotor speed.

Figs. 6 a, and b show that when making zoom in Fig. 5 (a) at instant of sharp increase and decrease of PMSG rotor speed according to increasing and decreasing wind speed respectively, huge errors will be produced at these instants as shown in Fig. 5 (b) but this error is eliminated in very short time.

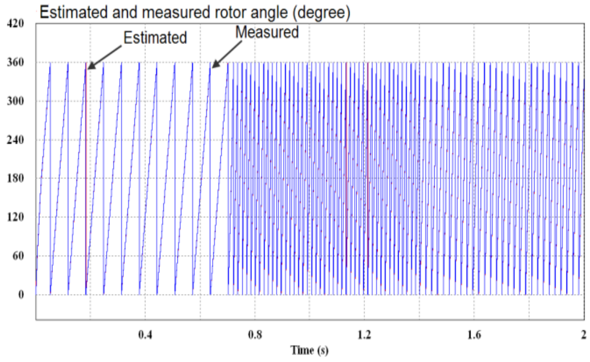


(a) Zoom of estimated and measured PMSG rotor speed (rad/sec.) at instant of increasing wind speed

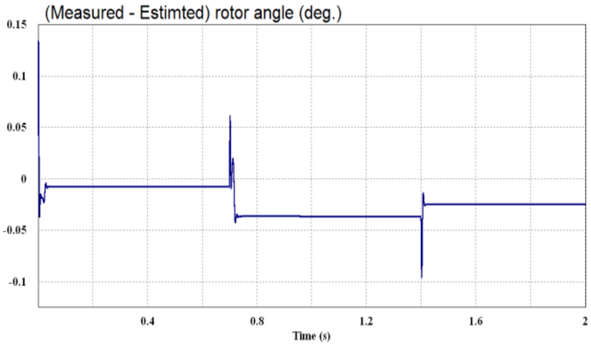


(b) Zoom of estimated and measured PMSG rotor speed (rad/sec.) at instant of decreasing wind speed

Fig. 6. Zoom of estimated and measured PMSG rotor speed (rad/sec.)

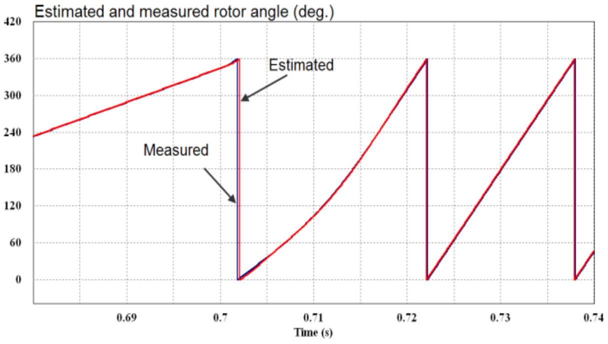


(a) The estimated and measured value of PMSG rotor angle (deg.)

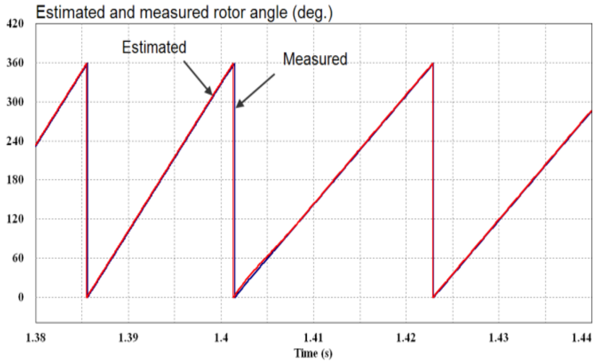


(b) Error of estimated PMSG rotor position angle (deg.)

Fig. 7. Estimated and measured rotor position angle and its error



(a) Zoom of estimated and measured PMSG rotor position angle (deg.) at instant of increasing rotor speed



(b) Zoom of estimated and measured PMSG rotor position angle (deg.) at instant of decreasing rotor speed

Fig. 8. Zoom of estimated and measured PMSG rotor position angle (deg.)

Fig. 7 (a) shows the measured and estimated PMSG rotor position angle in degree, it could be observed that the estimated angle of rotor position is identical with the measured angle of rotor position with varying the wind speed. Fig. 7 (b) shows that, the difference (error) between measured and estimated PMSG rotor position angle in degree, this error is very small error. It is less than 0.037 degree at steady state, where also the great error (less than 0.1 degree) is produced at instant of sharp change in wind speed, which leads to change the PMSG rotor position angle. This leads to a good performance of the transformation technique from *abc* reference frame to *dqo* reference because the error is very small.

Figs. 8 a, and b indicate that, when making zoom in Fig. 7 (a) at instant of sharp increasing PMSG rotor speed from 5.38 rad/sec. to 22.1 rad/sec. at time 0.7 sec. and sharp decreasing from 22.1 rad/sec. to 16.28 rad/sec. at time 1.4 sec. according to sharp increasing and decreasing wind speed respectively, the great error will be produced at these instant as shown in Fig. 7 (b) but this error reaches to zero value during very short period of time.

V. CONCLUSIONS

The estimation of PMSG speed and rotor position angle are presented in this manuscript based on back EMF observer and phase-locked loop (PLL). *d* and *q* components of back EMF can be estimated using electrical sensors of AC current and voltage of the PMSG output terminal and converted these magnitudes of current and voltage from *abc* reference frame to *dqo* reference frame. The PMSG rotor speed and its rotor position angle could be estimated using the basics of PLL. A huge error will be produced at the instant of sharp increasing and decreasing PMSG rotor speed according to sharp increasing and decreasing wind speed respectively, but this error reaches to zero value during very short period of time. From optimal estimation of PMSG rotor speed and its rotor position angle, it is cool after that achieving sensor-less maximum power point tracking (MPPT) control by getting optimum rotor speed of PMSG with any certain technique of MPPT techniques. Precision of estimated PMSG rotor speed and its rotor position angle are proved through simulation results by PSIM software program.

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