A Power Maximization Controller for PMSG Wind Energy Conversion Systems

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Abstract- A new maximum power extraction (MPE) controller for variable speed permanent magnet synchronous generator (PMSG) wind energy conversion systems (WECS) is proposed. The proposed controller generates optimum speed reference signal for the speed control loop of the vector controlled machine side converter control system without requiring the knowledge of wind speed using only active power and air density as its inputs. The generator is operated in the speed control mode with reference speed modified dynamically in accordance with the magnitude and direction of change of active power. The control algorithm takes into account the changes in system efficiency during its operation at various operating points due to the change in wind speed. The proposed method is validated experimentally in a variable speed direct drive PMSG WECS using a wind turbine emulator. Experimental results show good performance of the proposed controller.

Keywords- Maximum Power Extraction Controller; Permanent Magnet Synchronous Generator; Wind Speed Sensorless; Wind Energy Conversion Systems

I. INTRODUCTION

Wind energy is presently the fastest growing among all renewable energy systems. Among the WECSs, variable speed ones in recent years have become the industry standard because of their advantages over fixed speed ones such as improved energy capture, better power quality, reduced mechanical stress and aerodynamic noise [1]. Further, variable speed WECS can be controlled over a wide range of wind speeds to enable the WECS to operate at its maximum power coefficient thus, allowing it to obtain a larger energy capture from the wind [2]. However, conventional variable speed WECS with speed-up gears due to its many disadvantages have given way to direct drive (DD) WECS. The DD WECS, compared to WECS with speed-up gears, have reduced overall size, lower maintenance cost in addition to having higher overall efficiency and reliability [3], [4]. In developing new DD WECS designs, PMSG is favoured more and more over electrically excited synchronous generators because of higher efficiency, higher power densities, availability of high-energy permanent magnet material at reasonable price, and possibility of smaller turbine diameter [4].

Maximum power extraction from WECS has been the subject of several recent research investigations. In order to extract maximum possible power from the available wind power, it is necessary to drive the WECS at its optimum speed of rotation using a MPE controller. The MPE control, in conventional wind energy conversion systems, is implemented using wind speed data obtained from wind speed sensors [5]-[7]. However, use of wind speed sensors raises the problem of calibration and measurement accuracy, as well as increases the initial cost of wind generation systems. Therefore, wind speed sensorless MPE control is a very active research area [8]-[25]. Tip speed ratio (TSR) control methods using estimated wind speed are presented in [8]-[12]. Estimation of wind speed requires heavy computation which however is the main disadvantage of these methods. In [13]-[17], hill climb search (HCS) control methods are presented. The HCS control methods work well with small inertia wind turbines but not very effective for large inertia ones. In [18]-[21], optimum reference torque for the control of machine side converter. The OT control methods, due to system inertia, are slow in response. Therefore, a sudden change in wind speed does not cause a sudden change in rotor speed.

Optimum turbine power curve has been used successfully by many researchers in order to develop wind speed sensorless MPE controllers [22]-[25]. In these methods, known as power signal feedback (PSF) control, using rotor speed as input, the controller generates optimum power at its output which is then tracked, using appropriate controllers, to produce maximum power. PSF control is used in [22], [23], to extract maximum power. PSF along with feedback linearization control are used in order to realize MPE control in [24]. In [25], addition of proportional controller in PSF controller is proposed to reduce the effect of turbine inertia and improve speed of response of the controller. The methods presented in [22]-[25] require the knowledge of optimum power curve of their respective turbines which are tracked through their control mechanisms. They use rotor speed as the input and generates optimum power as the output. The drawback of these methods is that the optimum power curves, which they rely on, are generated using their respective optimum power constants which actually are not constants but vary with the change in operating points of the WECS due to the change in wind speed. Moreover, these methods, similar to OT control method, are slow in response. Further, these methods don't take air density which changes considerably from season to season into account, thus, resulting in low tracking accuracy of these controllers.
In this paper, a new wind speed sensorless maximum power extraction controller for a variable speed PMSG WECS is proposed. The method uses active power and air density as inputs and generates optimum reference speed signal for the machine side converter control system to enable maximum power extraction. Unlike the optimum power constant based PSF control methods presented in [22]-[25] the proposed method takes into account the variation in the optimal power curve due to the change in system efficiency with the change in system operating point as a result of change in wind speed. Further, unlike PSF methods, the proposed method generates optimum speed reference signal and not optimum power reference signal. The method is simple to implement, and does not require the knowledge of turbine parameters for its implementation. The PMSG is operated in speed control mode with its optimum reference speed modified dynamically in accordance with the magnitude and direction of change of active power. The proposed method is validated experimentally in a variable speed direct drive PMSG WECS.

II. WIND ENERGY CONVERSION SYSTEM

A. Machine Side Converter Control System

The dynamic model of surface mounted PMSG in rotor flux reference frame is given by

\[ v_{sd} = -R_s i_{sd} - L_s i_{sd} / dt + \omega L_s i_{sq} \]  
\[ v_{sq} = -R_s i_{sq} - L_s i_{sq} / dt - \omega L_s i_{sd} + \omega \psi_r \]  

where \( v_{sd} \) and \( v_{sq} \) are the d and q components respectively of stator voltage, \( i_{sd} \) and \( i_{sq} \) are the d and q components respectively of stator current, \( \omega \) is the generator speed, \( \psi_r \) is the rotor flux, \( R_s \) is the stator resistance and \( L_s \) is the stator inductance. The electromagnetic torque is given by

\[ T = (3/2) p \psi_r i_{sq} \]  

which may be written as

\[ P_m = 0.5 \pi \rho C_p (\lambda, \beta) R^3 \omega^2 / \lambda^3 \]  

Maximum power at any wind speed that is desired to be obtained from a wind turbine may be written as

\[ P_{m, max} = K_{m, opt} \omega_{r, opt}^3 \]  

where \( K_{m, opt} \), the mechanical optimum power constant of a turbine is given by

\[ K_{m, opt} = 0.5 \pi \rho C_{p, max} R^5 \omega_{r, opt}^2 / \lambda_{opt}^3 \]  

and \( \omega_{r, opt} \), the optimum turbine rotor speed at which the TSR is optimum is

\[ \omega_{r, opt} = \lambda_{opt} \omega / R \]  

Equation (10) is the power that will be obtained from a
wind turbine if it is driven at its optimum speed of rotation for a given wind speed. The output power of the WECS using (9) may be written as

$$P_o = \eta P_m = \eta 0.5 \rho C_p (\lambda, \beta) R^3 \omega^3 / \lambda^3$$

(13)

where $\eta$ is the efficiency of the WECS. Efficiency of the WECS is a variable quantity whose value changes with the change in system operating point. The system operating point changes with the change in wind speed. For maximum power control of the WECS (13) may be written as

$$P_{max} = \eta P_{m\_max} = K_{opt} \omega_{\_opt}^3$$

(14)

where

$$K_{opt} = \eta K_{m\_max} = \eta 0.5 \rho C_{\_max} R^5 / \lambda_{opt}^3$$

(15)

Maximum power at a certain wind speed will be obtained if the turbine is driven at its optimal rotational speed corresponding to that particular speed of wind. From (14) we obtain the equation for the optimum speed of rotation as

$$\omega_{\_opt} = \sqrt[3]{P_{max} / K_{opt}}$$

(16)

This equation is used for implementing MPE controller algorithm for generating optimum speed reference signal for maximum power control. The control algorithm uses active power and air density as inputs in order to generate at its output the optimum speed reference signal for the control of machine side converter control system. The following section presents in detail the controller implementation algorithm.

2) Implementation of MPE Controller

In order to implement the controller, the values of $K_{opt}$ are required. The values of $K_{opt}$ are obtained by running the system offline at various wind speeds in the laboratory. During the experiment, the $q$ component of the reference current for the grid side converter control system is set to zero and $d$ component of reference current for the machine side converter control system is set to zero.

3) Computation of $K_{opt}$

The PMSG WECS is run in the laboratory at various wind speeds using a wind turbine emulator. The details of the PMSG WECS and the wind turbine emulator are given in the Appendix. At each wind speed the rotor speed is adjusted until we obtain maximum output power. The rotor speed at which we obtain maximum power for a particular wind speed is the optimum turbine rotational speed $\omega_{\_opt}$ at that particular wind speed. Then, the values of $K_{opt}$ are computed. $K_{opt}$ in (15) is a function of air density, efficiency and turbine parameters. The efficiency is not known. Use of efficiency and turbine parameters is avoided by computing $K_{opt}$ as

$$K_{opt} = P_{max} / \omega_{\_opt}^3$$

(17)

Changing values of air density is taken into account in the controller algorithm using another variable $K_{opt1}$, which is defined as

$$K_{opt1} = K_{opt} / \rho$$

(18)

The $K_{opt1}$ is computed and stored with the corresponding values of speed to be used later in the controller algorithm. Once the values of $K_{opt1}$ are calculated, the implementation of the controller is straightforward. The step by step procedure of the offline experiment for computing $K_{opt}$ and $K_{opt1}$ is shown in the form of a flow chart in Fig. 2.

4) Controller Algorithm Implementation

The proposed controller uses instantaneous active power and air density as its inputs and generates optimum reference speed at its output for the control of machine side converter control system. The internal structure of the MPE controller is shown in Fig. 3.
unit step delay is used for generating the $K_{opt}$ profile while implementing the controller. In the control algorithm, the values of $K_{opt}$ are obtained by performing linear interpolation of the values of $\omega : K_{opt}$ data pairs obtained earlier during offline experiment at various wind speeds. Then, $K_{opt}$ is obtained from (18) as $K_{opt} = \rho K_{opt}$ using which reference speed $\omega^*$ is generated as shown in Fig. 3. The controller implementation algorithm is shown in detail in the flow chart of Fig. 4.

$$K_{opt} = \rho K_{opt}$$

5) Controller Operation

The operation of the MPE controller is described using Fig. 5 where three active power vs. rotor speed curves corresponding to three wind speeds $v_{w1}$, $v_{w2}$ and $v_{w3}$ are shown. Let’s assume that the initial wind velocity is $v_{w2}$. The figure shows that the system was initially operating at operating point 1, generating active power $P_1$ at a speed $\omega_1$ due to the wind speed $v_{w2}$. When there is a change in wind speed from $v_{w2}$ to $v_{w3}$, the system operating point will shift from operating point 1 to operating point 2 at the same speed ($\omega_2 = \omega_1$) due to the system inertia. Here, at 2 the power is $P_2$. This gives a large positive increase in power $\Delta P = P_2 - P_1$. This increase in power output will command an increase in rotational speed by the controller and the speed will increase which in turn will bring an increase in power further reaching the operating point 3 where the speed is $\omega_3$ and power is $P_3$. Then, this increase in power will bring an increase in speed. This build up will continue until operating point 5 is reached.

Similarly, if the wind speed decreases from $v_{w3}$ to $v_{w1}$ while the system was operating at 5, the system operation will shift from operating point 5 to operating point 6. This decrease in power will bring a reduction in command speed generated by the controller due to which there will be a reduction in speed of the WECS. The reduction in speed will bring an increase in power output which will bring the speed down further. This process will continue until operating point 10 is reached where the system operates at optimum speed generating maximum power.
B. Grid Side Converter Control System

The grid side converter is vector controlled in grid voltage reference frame. In grid voltage vector reference frame the dynamic model of the grid connection is given by

\[
\begin{align*}
\frac{dv_d}{dt} &= -Ri_d - L\frac{di_d}{dt} + \omega Li_q \\
\frac{v_q}{dt} &= -Ri_q - L\frac{di_q}{dt} - \omega Li_d
\end{align*}
\]

where \(v_d\) and \(v_q\) are the d and q components respectively of grid voltage, \(i_d\) and \(i_q\) are the d and q components respectively of grid current, \(R\) and \(L\) are the grid resistance and inductance respectively and \(v_{dq}\) and \(v_{dq}\) are the inverter voltage components.

The block diagram of the grid side converter control system is shown in Fig. 6. Active and reactive power control is achieved by controlling direct and quadrature current components respectively. Two control loops are used to control the active and reactive powers. An outer dc voltage control loop is used to set the d-axis current reference for active power control. This assures that all the power coming from the rectifier is instantaneously transferred to the grid by the inverter. The second channel controls the reactive power by setting a q-axis current reference to a current control loop similar to the previous one. The current controllers provide a voltage reference for the inverter that is compensated by adding rotational emf compensation terms.

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Fig. 7. Block diagram of the PMSG WECS

Fig. 8. Laboratory set-up of the variable speed direct drive PMSG WECS

Fig. 9. MPE control on rectangular wind speed profile; (a) wind speed profile, (b) rotor speed, (c) power coefficient and (d) active power output.
\[ v_{gy} = \omega L_i q + v_d \] 
\[ v_{gd} = -\omega L_i d \]

The d and q reference voltages after coordinate transformation to stationary reference frame are used by the SVPWM to generate inverter switching signals. The grid voltage angle \( \theta_g \) is obtained using phase lock loop [26].

III. EXPERIMENTAL RESULTS

Experiment is carried out in order to validate the performance of the proposed maximum power point tracking controller. Fig. 7 shows the block diagram of the experimental set-up of the variable speed DD PMSG WECS used in this work. The proposed MPE controller is incorporated in the set-up of Fig. 7.

A 3-phase, 3 kW, 60 Hz, 1200 rpm induction motor (IM) drive is used for wind turbine emulation. The IM is vector controlled in rotor flux reference frame. The vector controlled IM drive system is operated in constant torque region. The turbine emulated has a maximum power coefficient of 0.48 and its optimum tip speed ratio is 6.597. The details of the wind turbine emulator are given Appendix. The command signals for vector controller are the reference torque and reference value of the direct component of the stator current. The reference torque is computed using the method presented in [27].

The wind generation system is a 1.12 kW, grid connected, variable speed DD PMSG WECS wherein, the wind turbine is emulated using a vector controlled squirrel cage induction motor drive. A back-to-back IGBT converter converts the variable voltage and variable frequency generator power to fixed frequency, fixed voltage grid power. The system has an in-feed ac voltage of 480 V and a dc link voltage of 600 V. Fig. 8 shows the experimental set-up of the direct drive PMSG WECS. The details of the experimental set-up are given in Appendix.

The machine side converter is rotor field oriented controlled and the grid side converter is vector controlled in grid voltage reference frame. During the evaluation, the \( d \) axis reference current of the machine side converter control system is set to zero; whereas, for the grid side converter control system, the \( q \) axis reference current is set to zero.

Controller evaluation is carried out with two wind speed profiles viz. a rectangular profile and a profile generated using the method presented in [28]. First, the rectangular wind speed profile is applied to the DD PMSG WECS incorporating the proposed controller. The applied wind speed has a maximum of 9 m/s and a minimum of 7 m/s as shown in Fig. 9 (a). The rotor speed, power coefficient and active power output are shown in Fig. 9 (b), (c) and (d) respectively. It can be seen from the experimental results that the controller has good tracking capability. The minimum value of power coefficient obtained in this case is equal to 0.405 which can be considered to be very good.

Then, the system is subjected to a wind speed profile generated using the method presented in [28]. The wind speed profile applied to the WECS is shown in Fig. 10 (a). Fig. 10 (b), (c) and (d) show respectively the corresponding rotor speed, power coefficient and active power of the WECS due to the applied wind speed profile. The minimum value of power coefficient in this case is equal to 0.312 which show good tracking capability of the proposed controller.

It is observed from the results of experiment that the proposed controller is capable of accurate operation. The maximum value of power coefficient of the emulated turbine in this work is 0.48. The performance of the controller for both the wind speed profiles is found to good. The minimum value of power coefficient observed during the experiment is 0.312 which can be considered to be very good.
IV. CONCLUSIONS

This paper dealt with a new MPE controller for variable speed PMSG wind energy conversion systems. The controller, using active power and air density, generates optimum reference speed for the machine side converter control system to enable maximum power extraction. The proposed controller does not require the knowledge of turbine parameters or wind speed. The method takes into account the variation in the optimum speed-power curve of the wind energy conversion system due to the change in system efficiency with the change in system operating point as a result of change in wind speed. The proposed method was analyzed in a variable speed direct drive PMSG WECS using a wind turbine emulator. Experimental results show good tracking capability of the proposed controller. The proposed controller is applicable to other types of variable speed WECS as well.

REFERENCE


APPENDIX

I. Permanent Magnet Synchronous Generator:  \( P_r = 1.12 \) kW, \( R_s = 8.39 \) \( \Omega \), \( L_s = 0.08483 \) H, \( n_r = 500 \) rpm

II. Wind Turbine Emulation:  \( R = 1.271 \) m, \( \lambda_{opt} = 6.597 \), \( C_{pm} = 0.48 \), \( v_w = 10 \) m/s, \( J = 1.5 \) kg.m\(^2\). Wind turbine is emulated using a vector controlled Induction Machine. The induction machine is of 3 kW, 60 Hz, 1200 rpm.