

A COST-EFFECTIVE SENSOR LESS WIND ENERGY SYSTEM

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Abstract— Due to deterioration of fossil fuel and policies on greenhouse gas mitigation, wind energy systems (WESs) has gained traction as one of the most promising renewable energy systems for electric power generation during the past years. At a specific wind speed, the captured wind power by WES is a function of wind turbine speed. Only when the turbine rotates at optimum speed can the maximum power be extracted from the wind. Therefore, the maximum power point (MPP) tracking (MPPT) technique is important for wind energy conversion systems. To achieve MPPT control, the generator speed measurement is needed in each moment. Using a rotor speed sensor for this purpose poses some obstacles to practical implementation and has an impact on drive's cost, machine size, reliability, and noise immunity. In this paper a cost-effective sensorless reduced switch count PMSG based wind energy system is proposed in which the generator speed is estimated by an observer method. Simulation results are presented to verify the performance of the proposed wind energy system under steady state and transient conditions.

I. INTRODUCTION

Due to deterioration of fossil fuel and policies on greenhouse gas mitigation, wind energy systems (WESs) has gained traction as one of the most promising renewable energy systems for electric power generation during the past years [1–2]. Extracting maximum power from wind and feeding the grid with high quality electricity are two main objectives for wind energy conversion systems (WECSs) [3]. Power electronics provides the feasibility of these objectives for WESs [4] since they can perform active and reactive power control, injecting the high quality power into grid, as well as make the variable speed operation of wind turbine possible. In the variable-speed generation system, the wind turbine can be operated at the maximum power operating point (MPP) for various wind velocities by adjusting the generator speed optimally [5], [6]. Variable-speed wind energy conversion systems (VSWECSs) can be implemented with doubly fed induction generators (DFIGs), squirrel cage induction generators (SCIGs), or PMSGs [2]. Among electrical generators, PMSGs are favored in WECSs due to their advantages such as higher efficiency, high power density, reasonable price, and possibility of smaller turbine diameter in direct drive applications [7].

The most widely used power electronic circuit for PMSG-based WESs uses an AC/DC/AC bi-directional back to back converter, Fig. 1, due to their great advantages than diode rectifier-based

AC/DC/AC converters such as high power operation capability, small content of low frequent grid current harmonics, higher efficiency, increased dc link voltage and smaller dc link capacitor.

Recently, significant attention has been given to reduced switch count converters as low cost power converters in WECSs [1][7]. A recent reduced switch count structure for WECSs proposed in [8] is called six-switch AC/AC converter. This converter was first suggested as multi output inverter for control of two motors [9]. This configuration has the lowest number of active switches among three-phase to three phase AC/AC converters proposed hitherto in the literature [8]. Eliminating the generator rotor speed sensor is another trend towards cost reduction in WECS especially low power WECS [10]. Typically for measuring the generator speed, a rotor speed sensor is used that presents several disadvantages such as increasing the cost, machine size, reducing the reliability, and noise immunity. In this paper, a new sensorless six switch AC/AC converter based WES is proposed. The proposed WES has cost advantages compared to other configurations since it has the lowest number of active switches and also does not require to rotor speed sensor. The generator speed is estimated through an observer technique. The MPPT algorithm which is used in this system is based on tip speed ratio (TSR) algorithm. Section II of this paper describes operation of six-switch AC/AC converter. The proposed sensorless system is explained in Section III. The control mechanism of the proposed system is inspected in section IV. Finally, the validity of performance of the proposed system is verified by simulation results in Section V.

II. SIX SWITCH AC/AC CONVERTER

The six-switch AC/AC converter that is shown in Fig. 2 has been proposed in [9] as a low cost alternative for conventional back to back converter and nine switch converter. The six switch converter, as its name expresses, employs only six active switches and hence the number of active switches is reduced by 50% and 33%, respectively, compared with back to back and nine switch converters. This converter can be considered as two separate B4 converters with two common switches and hence a special PWM method is required to independently control its three-phase terminals, see Fig3. This method has two reference signals (V_{ref1} & V_{ref2}) for each phase legs which are related to input and output terminals respectively. In addition, two offset values ($offset_1$ and $offset_2$) are added to reference signals to prevent interferences between modulation waveforms. These signals can be determined by:

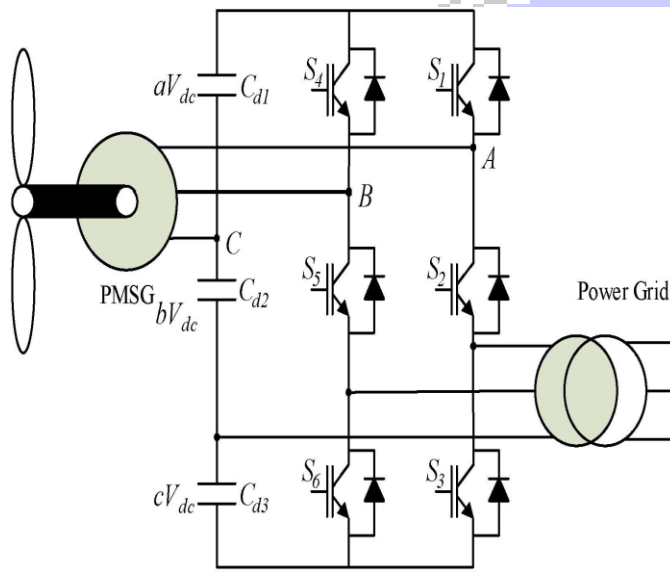
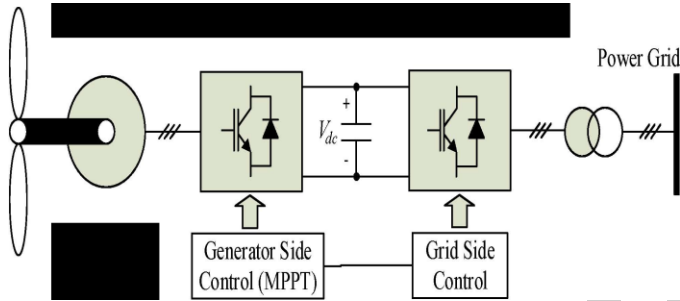


Figure 2. Variable speed wind energy systems based on six switch ACIAC converter

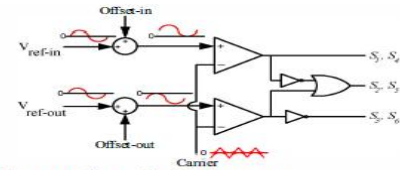
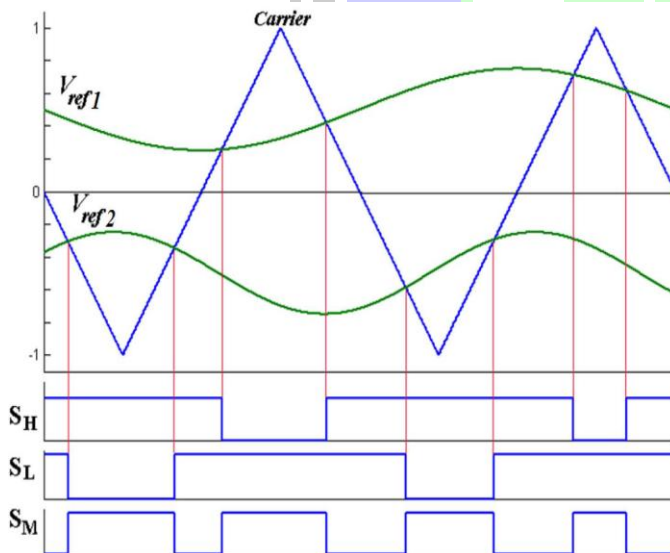


Figure 4. Block diagram of gate signal generator

$$V_{ref1} = m_1 \sin(2\pi f_1 t + \phi_1) + offset_1$$

(1)

$$V_{ref2} = m_2 \sin(2\pi f_2 t + \phi_2) + offset_2$$

(2)

where m_1, m_2 are modulation indexes, f_1, f_2 are frequencies and ϕ_1, ϕ_2 are phases. $Offset_1$ and $Offset_2$ are related to implementation of switching method and usually in variable frequency mode (VF) are set to 0.5 and -0.5 respectively [9] and therefore m_1 and m_2 are limited to 0.5. Fig. 4 shows the block diagram of gate signal generator for six switch converter. As shown in the figure, gate signals of S_1 and S_4 switches are resulted from comparing the upper modulating signal with the carrier signal. Gate signal of lower switch in each leg is the logical NOT of the value obtained by comparing the lower modulating signal (V_{ref2}) with the carrier signal. Gate signal of S_3 and S_6 are generated by logical XOR of the upper and lower gate signals in each leg. Applying this scheme, there are always two ON switches in each leg [9].

III. OBSERVER BASED ESTIMATION SYSTEM

A. Observer Method Principles

In practice, not all state variables are measured. The reasons are that this is not physically feasible or that the sensors required are probably too expensive. For this reason it is needed to demonstrate how to reconstruct the complete state information based on the measured output y . The assumption is that we know the system description (A,B,C) and that (A,C) is observable [11].

One method of estimating the state x in an observer is to construct a full order model of the plant dynamics

$$\dot{\hat{x}} = A\hat{x} + Bu \quad (3)$$

Where $\hat{x}$ is the estimate of the actual state x and A, B and u are known. If this observer can be started with the correct initial condition $\hat{x}(0) = x(0)$, it will always deliver $\hat{x}(t) = x(t)$. However, it is precisely the lack of information about $x(0)$ that requires the construction of an observer. The effect of an error in the initial condition $\hat{x}$ can be studied by defining the estimation error, $\tilde{x} = x - \hat{x}$.

$$\dot{\tilde{x}} = A\tilde{x} + Bu \quad (4)$$

$$\dot{\tilde{x}} - \dot{\hat{x}} = A(\tilde{x} - \hat{x}) \quad (5)$$

$$\dot{\tilde{x}} = A\tilde{x} \quad (6)$$

The dynamics of $\tilde{x}$ are described by the system matrix A . If it is unstable, then the estimation error diverges. If A is stable then $\tilde{x}$ converges towards zero — however, probably very slowly. Furthermore, effects like noise or errors in the system description (A,B) might cause the estimate to diverge from the true state.

The feedback in the observer is introduced to enforce stability of the error dynamics and/or for faster convergence. The difference between the measured and the estimated outputs are used to correct the estimated state, see Fig. 5.

The equation for this scheme is

$$\dot{\hat{x}} = A\hat{x} + Bu + H(y - C\hat{x}) \quad (7)$$

$$\dot{\tilde{x}} = (A - HC)\tilde{x} + Bu + HCx \quad (8)$$

resulting in the error dynamics

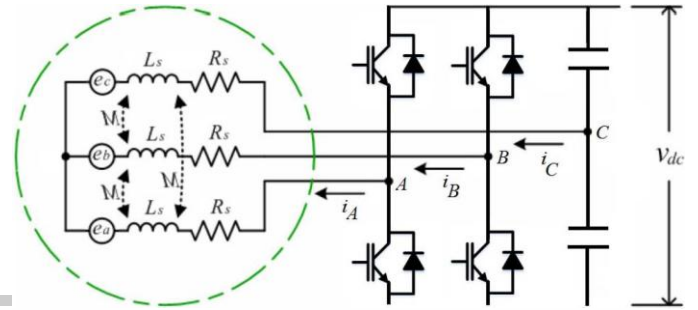
$$\dot{\tilde{x}} = (A - HC)\tilde{x} \quad (9)$$

If H is chosen such that the eigenvalues of $(A - HC)$ have negative real parts then $\tilde{x}$ will converge towards zero.

B. Modeling of Permanent Magnet Generator

The equivalent circuit of PMSG is shown in Fig. 6. Assuming that the stator resistances of all the windings are equal to zero and also self and mutual inductances are constant, the voltage equation of the three phases can be expressed as (10). In this equation, magnets, stainless steel retaining sleeves with high resistivity, and rotor-induced currents are neglected and no damper windings are modeled [12].

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_s - M & 0 & 0 \\ 0 & L_s - M & 0 \\ 0 & 0 & L_s - M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (10)$$



where v_a , v_b , and v_c are phase voltages. R_s , L_s and M are stator resistance, stator inductance and mutual inductance, respectively. i_a , i_b , and i_c are phase currents and e_a , e_b , and e_c are phase back-EMFs. Since the neutral point of PMSG is not offered, it is difficult to construct the equation for one phase. Therefore, the unknown input observer is considered by the following line-to-line equation:

$$\frac{di_{ab}}{dt} = -\frac{R_s}{L_s}i_{ab} + \frac{1}{L}v_{ab} - \frac{1}{L}e_{ab} \quad (11)$$

C. Proposed Sensorless Control System

In (11), i_{ab} and v_{ab} can be measured, therefore they are "known" state variables. On the other hand, since e_{ab} cannot be measured, this term is considered as an "unknown" state. The equation (11) can be rewritten in the following matrix form:

$$\dot{x} = Ax + Bu + Fw \quad (12)$$

$$y = Cx \quad (13)$$

H is the gain matrix of the observer in Fig. 5. As it was mentioned before, if H is selected properly, this observer can accurately estimate line to line currents and back-EMFs of PMSG and $\hat{i}_{ab}$ and $\hat{e}_{ab}$ will converge towards zero.

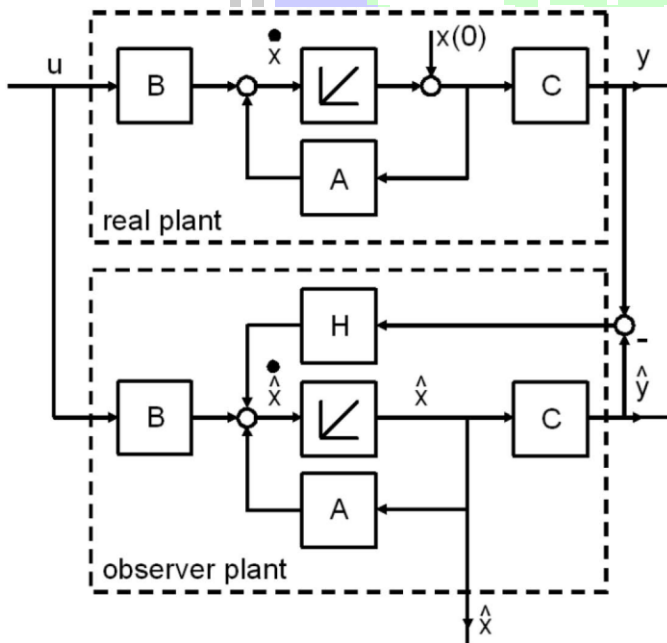
Therefore, the equation of whole observer including all of three phases is as follows:

$$\frac{d}{dt} \begin{bmatrix} \hat{i}_{ab} \\ \hat{e}_{ab} \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L} & -\frac{1}{L} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \hat{i}_{ab} \\ \hat{e}_{ab} \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} v_{ab} + \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} (i_{ab} - \hat{i}_{ab}) \quad (21)$$

Fig. 7 shows a block diagram of the proposed back-EMF observer system. Similarly we can calculate e_{bc} and e_{ca} and then from following equation the generator mechanical speed (ω_m) can be measured:

$$E = \max(E_{ab}, E_{bc}, E_{ca}) = 2P\lambda\omega_m \quad (22)$$

where E_{ab} , E_{bc} and E_{ca} are amplitudes of e_{ab} , e_{bc} and e_{ca} and P and λ are pole pairs and Flux linkage established by magnets, respectively.



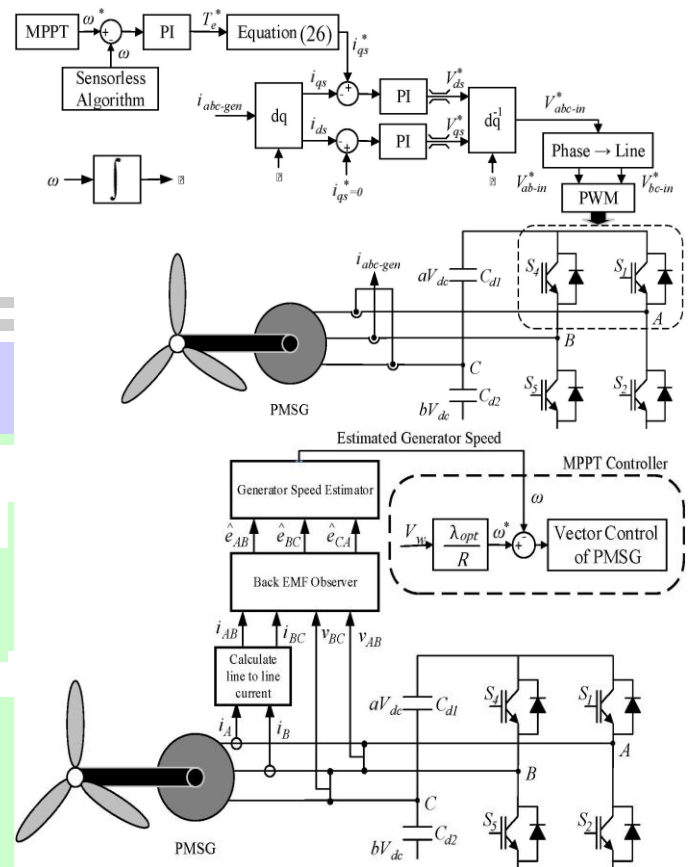


Table 1. Simulation Parameters

PMSG Parameters		
Stator resistance (R_s)		0.05 Ω
Inductances (L_d and L_q)		0.0795 mH
Flux linkage established by magnets		0.192 V.s
Inertia (J)		0.011 kg m ²
Friction factor (F), Pole pairs (p)		0.001417 N.m.s, 4
Nominal power, Nominal speed		28 kW, 3000 rpm
Grid parameters		
Phase to phase rms voltage and Frequency		380 V, 60 Hz
Source resistance and inductance		0.02 Ω , 10 mH
Converters parameters		
Switching frequency (f_{sw})		10 kHz
DC link voltage (V_{DC})		2200 V
DC link capacitors (C_{d1}, C_{d2}, C_{d3})		3000, 1500, 3000 μ F
Sensorless MPPT method parameters		
TSR	λ_{opt}/R	3 π
Sensorless	H[1], H[2]	3000, -49500

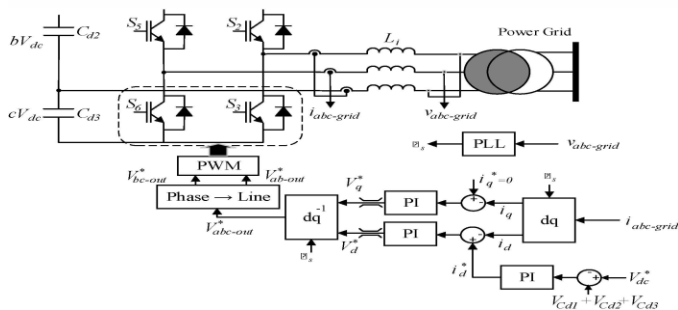
A. Control of Power Delivered to the Grid

The control of grid side three phase terminal of six switch converter is achieved through DQ current control method. According to [7], active and reactive power control injected to the grid can be achieved by controlling direct current (i_d) and quadrature current (i_q) components, respectively. In fact, when the reference frame is oriented along the grid voltage, v_q will be equal to zero and hence active and reactive power can be expressed as

$$P = \frac{3}{2} V_d i_d \quad (23)$$

$$Q = \frac{3}{2} V_d i_q \quad (24)$$

As it can be seen in Fig. 8, DC voltage is also set by controlling active power through i_d control loop (Fig. 8)



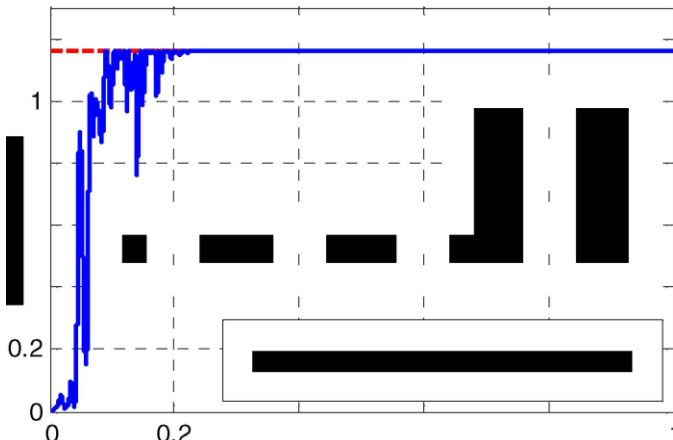


Figure 16. The maximum mechanical power of turbine and the extracted mechanical power from turbine

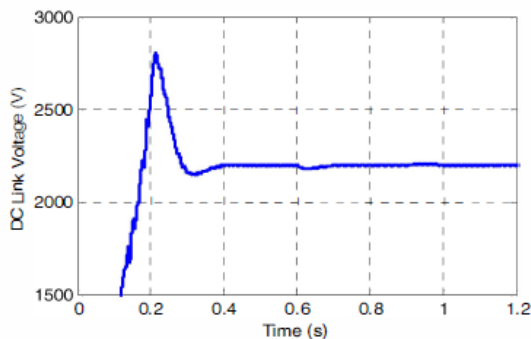


Figure 17. Capacitor voltage, transient condition

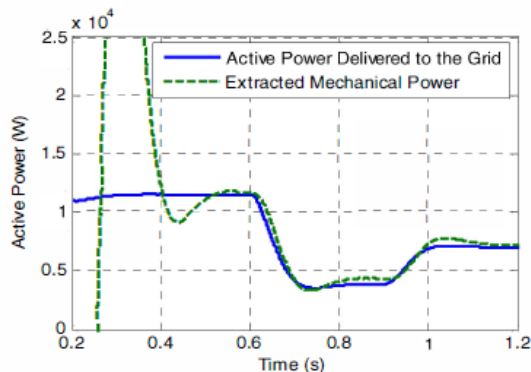


Figure 18. Active power delivered to the grid and extracted mechanical power, transient condition

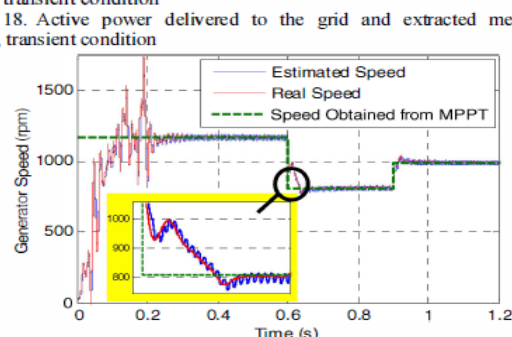


Figure 19. Real rotor speed, estimated rotor speed and the obtained rotor speed from MPPT, transient condition

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