

A NOVEL DIRECT DRIVE SENSORLESS MPPT CONTROLLER FOR DIRECT DRIVE WIND ENERGY CONVERSION SYSTEM WITH AXIAL FLUX PMG

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ABSTRACT: Wind is the safest and most abundant renewable source of energy in nature. With ever increasing concern on environmental pollution and energy crisis, generation of power from wind developing very fast. In the Wind Energy Conversion System (WECS) the variable speed wind turbine, Permanent Magnet Generator (PMG), Z-Source Inverter (ZSI), Sensorless Maximum Power Point Tracking (MPPT) controller is proposed. Though the conventional type induction generator has the advantage of robust construction and maintenance free operation it has drawbacks like low power factor and need for an ac excitation source which is overcome by the PMG. To obtain the fixed voltage and frequency PMG generated voltage is feed to power converters. Conventionally three stages of power conversion consist of rectifier, boost chopper and PWM inverter reduces the efficiency, power quality and reliability of the overall WECS. To overcome these barriers of conventional system the two stage ZSI based sensorless MPPT controller based WECS is proposed. The ZSI employs a unique impedance network can buck and boost the input voltage and increases the efficiency of the power conversion system. The maximum power point for each speed is traced using sensorless MPPT controller which estimates the rotor speed, by using Zero crossing detector. The proposed sensorless MPPT controller for direct drive WECS along with the Z-Source inverter is simulated in MATLAB/SIMULINK.

Keywords: Wind turbine, PMG, Sensorless control, MPPT, ZSI

1. INTRODUCTION

Wind energy, which is a clean and an infinite natural resource, is one of the available non-conventional energy sources. The conventional induction generator, though inexpensive, robust and having maintenance-free operation has some disadvantages such as low efficiency, lack of excitation, requires reactive power compensation and difficulty in controlling. Also the induction generator requires gear box which adds weight, generates noise, and demands regular maintenance and increase losses [5]. The direct drive wind turbine generator makes it possible to achieve maximum energy yield and minimum cost, high precision, no gear box and easy to control.

In this paper, a new variable-speed WECS with a PMG, Z-Source inverter and a Hill Climb Search algorithm is proposed. The characteristics of Z-Source inverter is used for maximum power point tracking control and also for obtaining required voltage for various wind velocities. In the conventional three stage power

conversion system, the output voltage from the PMG is rectified using a three-phase diode bridge rectifier and the output is given to Z-source inverter [6]. The Z-Source inverter employs a unique impedance network. ZSI can boost-buck voltages, minimize component count, increase efficiency, and reduce cost. The maximum power extraction technique has recently kindled more interest and many theories and literatures have been reported [1]. The Perturbation and Observation (P&O) method, Power Signal Feedback (PSF), Hill climb Search (HCS) method, anemometer based method, Fuzzy logic based method are a few to be named. In the anemometer based MPPT algorithm, the wind velocity is measured and a reference speed for the generator corresponding to the MPP of the present wind velocity is measured. The overall cost is high and the reliability of the system is low. In the P&O algorithm the speed is varied in steps and the power utilized by the MPP is researched [2]. But it takes a long time and incurs power loss during the tracking process. It is not suitable for

machine of large wind turbines. The PSF method does not require the wind velocity, the drawback is the difficulty in obtaining the maximum power curve of the wind turbine. The fuzzy control scheme is also time consuming as it is requested to compute d_{VC}/d_t for its control action [12]. The HCS control work independently in conjunction with variable pitch control. It incorporate search-remembers reuse process. This method stores the maximum power point during training in memory and reuses to track peak power points [16].

A sensorless controller that simply takes into account the cyclic nature of the generator phase current whose frequency (the number of zero crossings) is directly proportional to the speed of the generator. This empirical knowledge can be converted into the estimate of speed simply by knowing the number of rotor poles p and measuring the time lapse between two rising zero crossings (one complete cycle) of the generator phase current. To eliminate the speed sensor and improve the efficiency of the system sensorless MPPT controller is used in wind speed measurement [13]. For this system to function effectively, the accurate value of wind velocity is needed which cannot be obtained and also increases the cost. Instead of using rotor position sensor and wind velocity sensor the reliability is improved and also the cost can be minimized [15].

The main objective of this paper is to develop a sensorless MPPT controller for direct drive WECS fed three phase Z-source inverter. In this paper, the proposed two stage WECS are enhanced by Z- Source Inverter with sensorless MPPT controller are simulated in MATLAB/SIMULINK software.

The paper is organized as follows; section 2 gives the mathematical equations of wind turbine and PMG, section 3 describes about the proposed wind energy conversion system, Section 4 holds the simulation result of the modeled proposed system.

2. MATHEMATICAL EQUATIONS

A. Mathematical Equations of Wind Turbine

The model of the wind turbine consists of following equations:

The power captured by the wind turbine is given(1)

$$P = \frac{1}{2} \pi \rho R^2 V^3 C_p \sqrt{a^2 + b^2} \quad (1)$$

The power coefficient $C_p(\lambda)$ is a non-linear function of wind velocity and the blade pitch angle is highly dependent on the constructive characteristics of the turbine. It is represented as a function of tip speed ratio λ .

$$\lambda = \frac{R \omega_t}{V} \quad (2)$$

The turbine torque is obtained by dividing turbine power by turbine speed.

$$T_t(V, \omega_t) = \frac{1}{2} \pi \rho R^3 C_t(\lambda) V^2 \quad (3)$$

Where $C_t(\lambda)$ is the torque co-efficient of the wind turbine and is given by

$$C_t(\lambda) = \frac{C_p(\lambda)}{\lambda} \quad (4)$$

The power coefficient C_p is given by

$$C_p(\lambda) = \left(\frac{116}{\lambda_1} - (0.4\beta) - 5 \right) 0.5 e^{\frac{-16.5}{\lambda_1}} \quad (5)$$

Where

$$\lambda_1 = \frac{1}{\frac{1}{\lambda + 0.089\beta} - \frac{0.035}{\beta^3 + 1}} \quad (6)$$

B. Mathematical Equations of PMG

The wind turbine driven PMG can be represented in the rotor reference frame as [3]

$$V_q = -(R_s + L_q p) I_q - \omega_r L_d I_d + \omega_r \lambda_m \quad (7)$$

$$V_d = -(R_s + L_d p) I_d + \omega_r L_q I_q \quad (8)$$

The electromagnetic torque in the rotor is

$$T_e = \left(\frac{3}{2} \right) \left(\frac{P_n}{2} \right) \left[(L_d - L_q) I_q I_d - \lambda_m I_q \right] \quad (9)$$

3. PROPOSED WECS

Figure.1 shows the complete block diagram of the proposed WECS with sensorless speed estimator MPPT controller. This controller is a very smart sensorless scheme that simply takes into account the cyclic nature of the generated voltage whose frequency is directly proportional to the speed of the generator. Knowing the number of rotor poles and measuring the time between two rising zero crossings (one complete cycle) of the generated voltage the speed of the generator is found out [13]. Once the time taken for one cycle of the generated voltage is found, the corresponding frequency of the generated voltage can be obtained. PMG can easily be estimated.

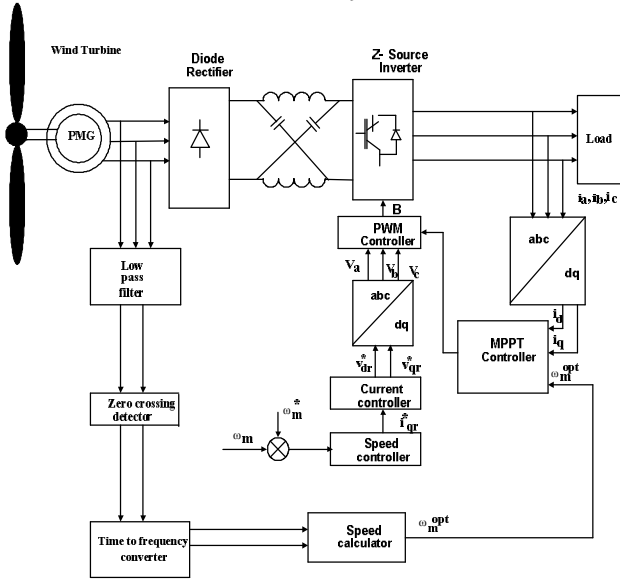


Figure 1. Complete block diagram of the proposed WECS with ZSI and sensorless MPPT controller

A. Z-Source Inverter

The circuit of PMG with ZSI is illustrated in Figure 2. Unlike the traditional inverters, Z-source inverter utilizes an impedance network that links the inverter main circuit with the rectifier unit [14]. The output of the PMG is fed as input to the diode bridge rectifier through the stator inductance and resistances of PMG [4].

The diode bridge rectifier act as the dc source whose output is fed as input to Z-source inverter. During diode commutation and shoot through mode of the inverter, the line inductance

may produce voltage surges which are suppressed with the help of the input capacitors C_a , C_b , C_c . The impedance circuit of Z-source inverter is made up of two equal inductors (L_1 , L_2) connected in series arms and two equal capacitors (C_1 , C_2) connected in diagonal arms. The voltage boost capability of Z-source inverter is facilitated by turning on both the switches in the same leg simultaneously [7]. The distinct feature of Z-source inverter is its ability to produce an ac output voltage of any value between zero and infinity, irrespective of the input dc voltage.

There are eight permissible switching states in the traditional voltage source inverter such as six active states and two zero states. Besides these eight switching states of traditional inverters, the Z-source inverter has a ninth switching state called shoot through zero state, during which the load terminals are shorted through both the upper and lower devices of any one phase leg or combination of any two phase legs or all the three phase legs. The shoot through zero state provides unique buck boost feature to the inverter. The Z-source has three operating modes such as open circuit, shoot through and active state [10] [11]. The switching sequence of three phase ZSI is given in Table I.

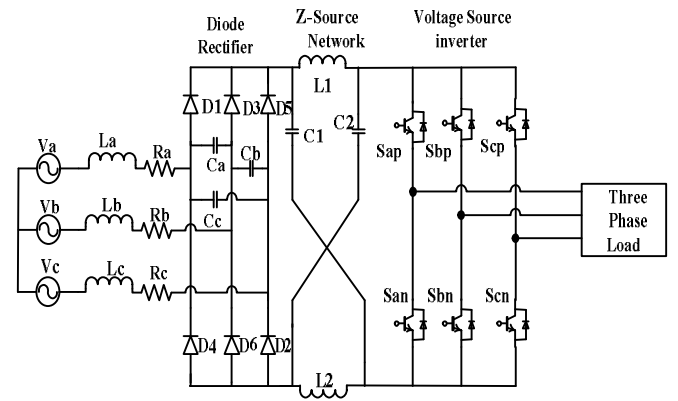


Figure 2. Complete circuit of PMG with z-source inverter and rectifier

Table I Switching Sequence of Three Phase ZSI

Active state [100]	1	0	0	1
Active state [110]	1	0	1	0
Active state [010]	0	1	1	0
Active state [011]	0	1	1	0
Active state [001]	0	1	0	1
Active state [101]	1	0	0	1
Null state [000]	0	1	0	1
Null state [000]	1	0	1	0
Shoot- Through state V ₁	1	1	S _{bp}	$\overline{S_{bp}}$
Shoot- Through state V ₂	S _{ap}	$\overline{S_{ap}}$	1	1
Shoot- Through state V ₃	S _{ap}	$\overline{S_{ap}}$	S _{bp}	$\overline{S_{bp}}$
Shoot- Through state V ₄	1	1	1	1
Shoot- Through state V ₅	1	1	S _{bp}	$\overline{S_{bp}}$
Shoot- Through state V ₆	S _{ap}	$\overline{S_{ap}}$	1	1
Shoot- Through state V ₇	1	1	1	1

The shoot through over a one switching period T and from the equivalent circuit, Figure 2.

The voltage of dc-link across three phase Inverter Bridge is

$$V_i = B V_{dc} \quad (10)$$

V_{dc} is source voltage B is boost Factor
Where

$$B = \frac{T}{T_1 - T_0} = \frac{T}{1 - \left(\frac{2T_0}{T} \right)} \quad (11)$$

The three phase output peak phase voltage

$$V_{ac} = MB \frac{V_{dc}}{2} \quad (12)$$

M is the modulation index

The capacitor voltage is represented as

$$V_c = \frac{1 - \left(\frac{T_0}{T} \right)}{1 - \left(\frac{2T_0}{T} \right)} V_0 \quad (13)$$

The rms output voltage of the ZSI can be

expressed as,

$$V_{ac} = \frac{3 V_{rms}}{\pi} B M \quad (14)$$

B. MPPT Algorithm

The variable-speed wind turbine (VSWT) has been introduced. At a given wind velocity, the mechanical power available from a wind turbine is a function of its shaft speed. To maximize the power captured from the wind, the shaft speed has to be controlled by a variable-speed method. The control algorithm for MPPT is developed as shown in Figure.3. An HCS algorithm is proposed and by using this algorithm a peak detection capability is introduced. By taking only one input the generated voltage thus the numbers of controller blocks needed are reduced. This controller generates appropriate shoot through period to the ZSI and as a result maximum power point is tracked.

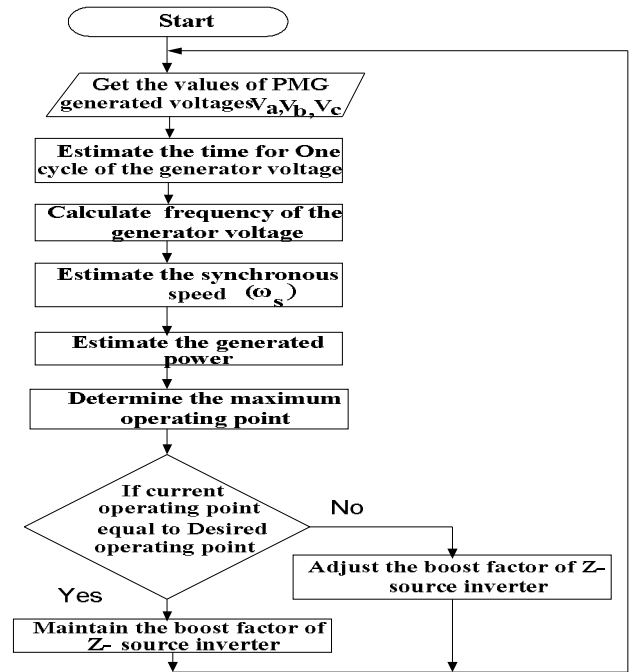


Figure 3. MPPT algorithm

The most of the MPPT control algorithm requires both voltage and current feedback. This increases the number of controller blocks which decreases the efficiency, reliability and speed [8]. The proposed control algorithm considers only one feedback as PMG stator voltage thus reducing the number of controller blocks and hence the efficiency and response time are improved. This controller generates appropriate shoot through pulses for ZSI. The output voltage from PMG is given to the zero crossing detector from that the time is calculated and that is converted to frequency and corresponding the speed value is calculated [13]. The calculated speed is given as an input to the MPPT controller.

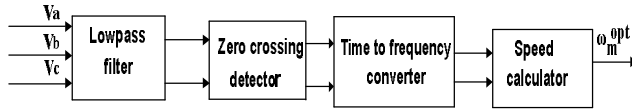


Figure 4. Block diagram of sensorless MPPT controller

C. Sensorless Controller

Figure 5 shows the block diagram of Sensorless controller. A sensorless scheme has been developed to avoid the use of mechanical sensors. The speed sensor is eliminated and improve the efficiency of the system sensorless MPPT controller is used in wind speed measurement. Using a rotary encoder for this purpose will not only increase the cost of the system but will also make the system more prone to sensor noise as the mechanical sensors always have maintenance issues and cannot be used for a long run. A very smart sensorless controller that simply takes into account the cyclic nature of the generator phase current whose frequency (and, hence, the number of zero crossings) is directly proportional to the speed of the generator [13].

This empirical knowledge can be converted into the estimate of speed simply by knowing the number of rotor poles P and measuring the time lapse between two rising zero crossings (one complete cycle) of the generator phase current. Hence, this speed-sensorless scheme is very attractive for the wide class of salient-pole generators in which the zero

crossings of the cyclic phase current depend on the rotor poles. Hence, the speed of the generator is given by

$$N = \frac{120f}{P} \quad (15)$$

Where N = Speed of the in RPM

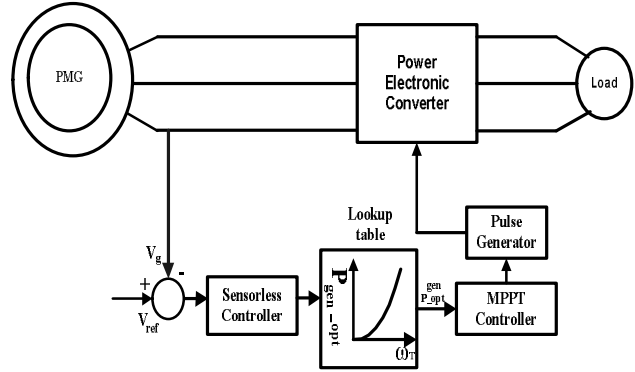


Figure 5. Block Diagram of Sensorless controller

D. MPPT Tracking Procedure

The optimal rotor speed from the sensorless speed is fed to the Look up Table-1 shown in Figure 6. The corresponding maximum power is determined. From the recorded maximum power, dc link voltage is obtained as shown in Equation (16).

$$V_{dc} = \frac{P_{opt}}{I} \quad (16)$$

For the given modulation index (M) and dc link voltage V_{dc} , the boost factor B becomes

$$B = \frac{V_{ac}}{MV_{dc}} 2 \quad (17)$$

Where V_{ac} is the Z-source inverter terminal voltage.

The shoot through time period T_0 is known by substituting the boost factor,

$$T_0 = \frac{T(B-1)}{2B} \quad (18)$$

The shoot through control voltage V_{sc} is obtained from the Look up Table-2 shown in Figure 6. With shoot through time, the required shoot through pulses for ZSI is adjusted [9].

Thus the shoot through period of the Z-source inverter is adjusted and the maximum power for each wind velocity is captured.

The two stage power converter, consists of rectifier, Z- Source inverter and sensorless MPPT controller using MATLAB/SIMULINK software. The model is simulated and analyzed for various values of wind velocity and different loading conditions.

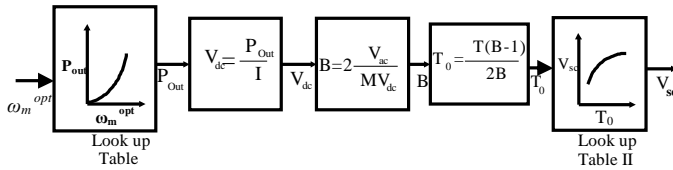


Figure 6. Block Diagram of MPPT Controller

4. RESULTS AND DISCUSSION

The Table II gives the simulation readings for different values of wind velocity without MPPT controller. From Table II the boost factor decreases, as wind velocity increases. A small value of boost factor is enough to make the generator run at required speed at higher wind velocity. The corresponding generator power and DC link voltage are tabulated. As the velocity of wind increases, the power obtained from wind also increases. But the maximum power of wind turbine cannot be obtained without using the MPPT controller. The generated power is 357.3W and the generator speed is 31rpm for wind velocity of 8m/s but corresponding actual maximum power is 477.5 watts. The ZSI terminal voltage is maintained constant as 415V (rms) for the wind velocity of 8m/s, and the corresponding boost factor is 6.58. Input current THD and output voltage THD increases as the load increases.

Table II
Simulation readings for various wind velocity without MPPT controller for 1kW load

S.No	Wind velocity (m/s)	Generator speed (rpm)	PMG Output Voltage (V)	Boost factor	DC link voltage (V)	ZSI voltage (v)	Generator power (W)	Load current (A)
1	6	54	140	11.9	70	415	168.54	1.69
2	8	68	170	8.12	102	415	357.3	1.69
3	10	86	210	6.25	133	415	638.66	1.69
4	12	107	254	4.95	167	415	983.271	1.69

Figure 7 shows the speed power curve of wind turbine driven PMG without MPPT controller for various values of wind velocity. As the wind velocity increases, the power obtained from wind also increases. But the maximum power of wind turbine cannot be obtained without using MPPT controller.

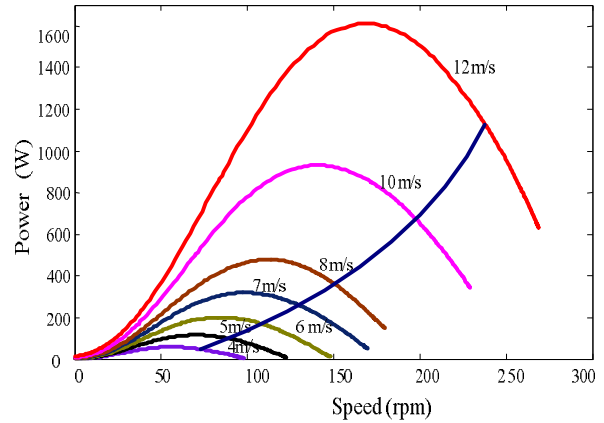


Figure 7. Speed -Power Curve Without MPPT Controller

Table III contains the simulated readings of the DDWECS with MPPT controller. From the table it is clear that, the maximum power of 477.5 watts is captured at wind velocity of 8 m/s and the Z-source inverter voltage is 415 V. The

generator power and DC link voltage values are tabulated.

Table III
Simulation reading for various loads with MPPT controller

S. no	Wind Velocity (V)	PMG Output Voltage (V)	Generator Speed (rpm)	Boost Factor	DC Link Voltage (V)	Generator Power (W)	Load Current (A)
1	6	140	54	2.33	105	201.5	2
2	8	170	68	1.75	130	477.5	2
3	10	210	86	1.32	167	932.7	2
4	12	254	107	0.75	186	1612	2

After implementing the MPPT controller the proposed wind turbine generator operates in the maximum power point region as shown in Figure 8.

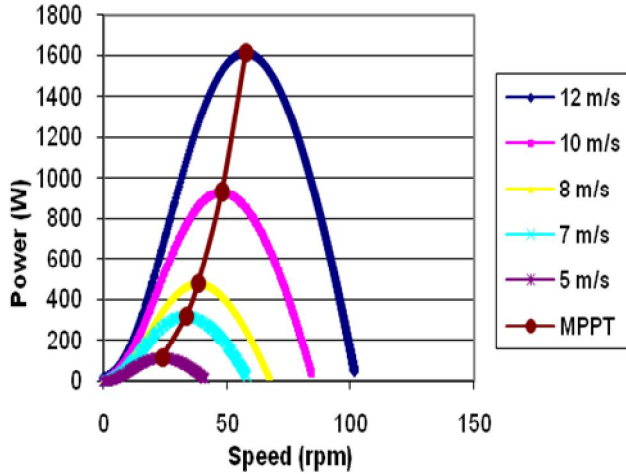


Figure 8. Speed-Power Curve with MPPT

The simulated results of proposed DDWECS with Z-source inverter is shown in Figure 9. PMG generated voltage, turbine speed and ZSI output voltage and output phase voltage before filter is shown for wind velocity of 6 m/s at a load of 1 kW.

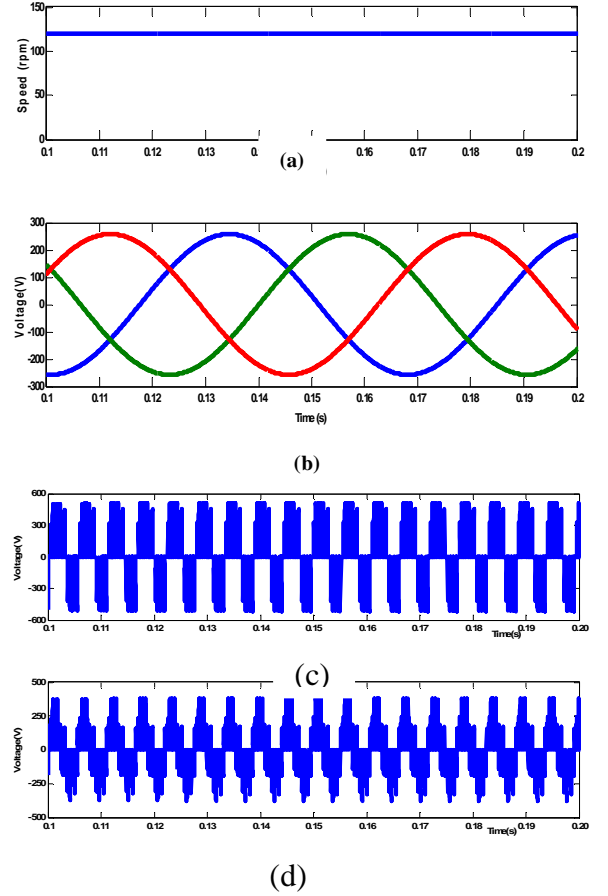


Figure 9. Simulated results of proposed DDWECS with ZSI (a) wind turbine speed (b) PMG generator voltage (c) ZSI output line voltage (d) ZSI Output phase voltage

Figure 10 clearly shows the resemblance of the MPPT with the proposed algorithm. It is noted that during the increase in wind speed from 6m/s to 8m/s, the algorithm exhibits an instant follow up of the maximum power point but the conventional algorithm gives sluggish response of maximum power for wind speed change. The conventional algorithm takes too much time to reach the maximum power point and hence becomes very inefficient. A similar conclusion can be drawn from Figure 11 which collaborates that the proposed algorithm is quite fast in reaching the optimal shoot through period, whereas the conventional MPPT controller output does not coincide with the input during wind speed change. It is clear that the terminal voltage is constant and active power only varies with step change in wind velocity.

5. CONCLUSION

In this paper the axial flux PMG with larger number of pole pairs for direct driven WECS is presented. To overcome the limitations of the conventional WECS with boost chopper the ZSI based WECS has been proposed and analyzed. The ZSI is a single stage dc-ac convertor, in which the number of switches reduced by one and has low switching stress. Hence the reliability of the system is improved. The output voltage of the ZSI entirely depends on the boost factor. For variation of wind speed the output voltage of ZSI is maintained constant by adjusted the boost factor. The simulation results of the proposed WECS are carried out for different wind velocity. In this paper a new method of sensorless MPPT controller is proposed for wind turbine driven axial flux PMG. This sensorless controller is used to avoid the mechanical sensors. The maximum power point tracker algorithm for ZSI based WECS has been presented and simulated for different wind velocities. The analysis and simulation have shown that the proposed MPPT controller has reached the objective for extracting maximum power at any wind speed.

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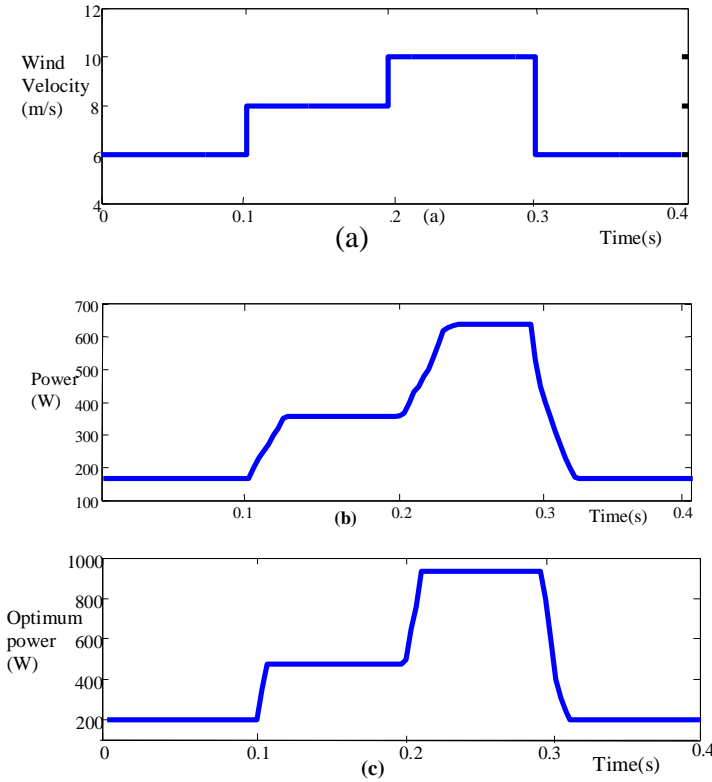


Figure 10. MPP Tracking response curve (a) sudden change of wind velocity (b) conventional method (c) proposed method

Figure 11 shows the variation of boost factor for variation of wind velocity. From the graph the PMG generated voltage increases, when wind velocity increases, the boost factor of ZSI decreases. The highest value of boost factor is 2.8 at wind velocity of 5m/s. The lowest value of boost factor is 0.75 at 12m/s.

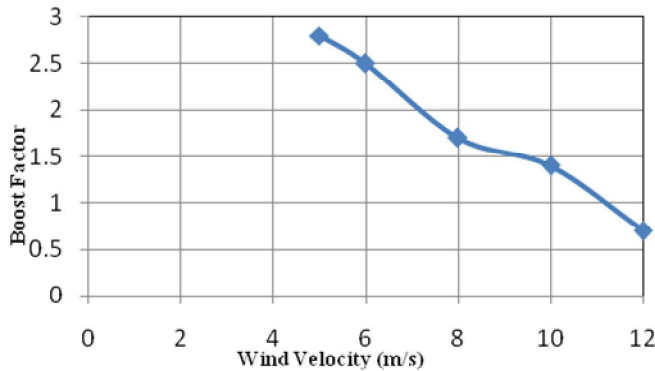


Figure 11. Boost factor for various wind velocities

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