Design and Control of a Quasi-Z-Source Inverter Based for Wind Power Generation using PMSG

A. Hussien
Dept. of Elec. Power and Mach.
Cairo University
Giza, Egypt 12613
a.hussien.rashsad@gmail.com

M. Taha
Dept. of Elec. Power and Mach.
Cairo University
Giza, Egypt 12613
mohamd.taha@ cu.edu.eg

Ossama A.Mahgoub
Dept. of Elec. Power and Mach.
Cairo University
Giza, Egypt 12613
osamamahgoub14@gmail.com

***Abstract*—In this paper, a complete quasi-Z-source inverter based for wind power generation system is modelled and analysed. The overall system is introduced in two main configurations, one is open loop and the other is closed loop. The open loop system is designed in such away to extract the maximum wind energy from the open loop configuration using the modified Space Vector Pulse Width Modulation based on the maximum constant boost of the quasi Z source inverter. The closed loop system is used to control the dc link voltage. Results extracted from both cases are described, analyzed and compared. A 600 watt Permanent Magnet synchronous generator is used to generate the output power from the wind turbine. A complete MATLAB simulation for the analysis and design is introduced. A hardware setup of the wind turbine emulator coupled with the Permanent Magnet synchronous generator based on the Z-source inverter and controlled by the DSP TMS320F28335 is under construction for the hardware verification.**

Keywords—Z-source; Wind Energy; PMSG; MSVPWM;QZSI

I. INTRODUCTION

The utilization of the renewable energy sources is very important nowadays for many reasons, one of them is that the environmental impacts caused by gases emitted from burning fossil fuels used in conventional power stations can be avoided, the non-renewable nature of the fuel used threats the ability to continue producing electricity using it because it can deplete in any time in contrast, renewable energy sources are always available for utilization in electrical energy generation and storage[1], the main drawbacks of renewable energy generation are the complexity, increased cost, reduced efficiency and reduced reliability of the renewable energy conversion system so, researchers are working on reducing such drawbacks by developing new converters and machines with high efficiency and reliability.

Usually in conventional wind energy conversion systems different types of power electronic converters are used for different purposes, rectifier to rectify the generator output, boost converter to boost the output of the rectifier before feeding the inverter as the output of the inverter is always less than the input voltage and finally the inverter to convert the dc into ac providing power to the AC load, in this conventional system many converters are used which result in reduced system efficiency and reliability, also dead-time existing between switches of each leg causes distortion in the output waveform[2].

In [3], four quasi circuits are proposed.The Quasi Z source Inverter (QZSI) system can be used to enhance the overall system performance. The QZSI based system can perform both the boosting and inversion action, accordingly the boost converter can be eliminated [4]. As a result, the system cost decreases, and weight also decreased.

The QZSI Theory of operation includes the shoot-through period in which two switches in one inverter limb could be biased together eliminating the dead time and interlock between the switches in the conventional Voltage Source Inverter (VSI), Accordingly this would increase the system reliability [3-4]. Shoot through period could be controlled using different methods, simple boost, maximum boost control or maximum constant boost control [6]. Maximum constant boost control is chosen for this design is one of the best choices as it reduces the stress on the switching devices [6].

Pulse wide modulation can be done using the conventional sinusoidal pulse width modulation methods like Sinusoidal pulse width modulation (SPWM), third harmonic injection and space vector pulse width modulation (SVPWM). Minor modifications are required to manipulate the operation of the shoot through periods[4],[8].

Several electric machines could be used for generating the wind power energy. One of the best machines is the surface permanent magnet synchronous generator (SPMSG) due to the highest power density and efficiency [1-2].

In this paper the open loop and closed loop operation of an isolated load feed from wind energy generation system through QZSI is investigated. Many remarks on the operation and the design of the system are presented and analyzed in this paper.

II. QZSI CIRCUIT BASICS

There are many configurations of the impedance source inverter [4]. The QZSI shown in Fig.1 has many advantages making it suitable for many applications. Some of these advantages are the voltage rating of C_2 is lower than voltage rating of C_1 which reducing the overall price of the impedance network this can be conclude from (1) and (2), moreover the series inductance with the source is smoothing the supply current, also the common point between input and output reducing noise effects.

In [4] The basic equations representing the operation of the QZSI are;

$$v_{c1} = \frac{1-D}{1-2D} v_{in} \quad (1)$$

$$v_{c2} = \frac{D}{1-2D} v_{in} \quad (2)$$

$$v_{dc} = \frac{1}{1-2D} v_{in} \quad (3)$$

$$D = \frac{T_{sh}}{T} \quad (4)$$

$$B = \frac{1}{1-2D} \quad (5)$$

Where, D is the shoot through duty ratio, T_{sh} is the shoot-through period, T is the switching period, B is the boost factor, and V_{dc} is the peak dc link voltage.

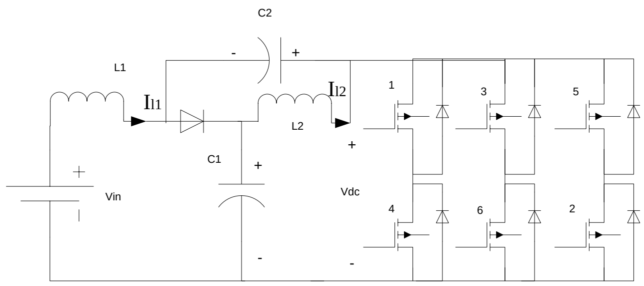

Fig.1 Quasi Z source inverter

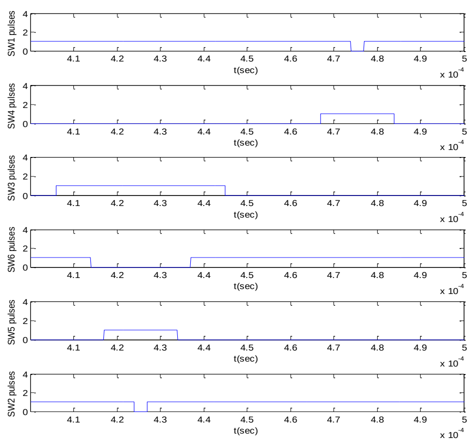

Fig.2. switching pulses of the six switches

III. Modified SVPWM

The modified SVPWM algorithm in [8] is implemented using MATLAB to generate the control pulses for the QZSI control. All advantages of the traditional SVPWM such as lower output total harmonic distortion, better utilization of input dc source still exist. Modification is done to generate shoot-through state. The pulses of the switches are no longer complementary.

The implemented MSVPWM algorithm can be summarized by the following equations;

$$T_a = \frac{\sqrt{3}}{2} T_s M \sin(60-\theta+60(n-1)) \quad (6)$$

$$T_b = \frac{\sqrt{3}}{2} T_s M \sin(\theta-60(n-1)) \quad (7)$$

$$T_o = T_s - (T_a + T_b + T_{sh}) \quad (8)$$

$$T_{\min} = \frac{T_o}{2}, T_{mid} = T_b + \frac{T_o}{2}, T_{\max} = T_a + T_b + \frac{T_o}{2} \quad (9)$$

$$T_{\max u} = T_{\max} + T_{sh}, T_{midu} = T_{mid} + \frac{2T_{sh}}{3}, T_{\min u} = T_{\min} + \frac{T_{sh}}{3} \quad (10)$$

$$T_{\min l} = T_{\min} + \frac{T_{sh}}{3}, T_{midl} = T_{\min} + T_a + \frac{2T_{sh}}{3}, T_{\max l} = T_{\max} + T_{sh} \quad (11)$$

Where, T_a ,T_b are the action time of the active state vectors during one switching cycle, T_0 is the action time of the non-shoot through zero state, T_{sh} is the shoot through period during one switching cycle, θ is the position of the reference vector in the sector, n is the sector number, T_{max},T_{mid},T_{min} in (9) are the maximum, middle and minimum value of the switching vector transition time of the traditional SVPWM. In (10) and (11), include the modified calculated values used to control the upper and lower switches in the bridge inverter.

The switching pulses per one cycle are shown in Fig. 2. Each 2 successive graphs represent pulses of one inverter leg.

The shoot-through period is divided equally on the 3-legs of the inverter. This means that the shoot-through period is divided into six parts. This pulse pattern has great advantages when using it with the Q-ZSI, it reduces significantly the size of the inductors and capacitors of the impedance network, because it allows to the inverter to operate in shoot through period for only one sixths of the overall shoot through period between active and non-shoot through zero states in every switching cycle.

IV. Wind Turbine model

The power extracted from the wind depends on the wind speed, air density, turbine swept area and power coefficient (cp) which depends on the pitch angle and Tip speed ratio (λ).

$$P_W = 0.5 \rho A V^3 C_P(\lambda, \beta) \quad (12)$$

Where ρ is the air density (1.225 Kg/m^3), A is the swept area of the blades (m^2), V is the wind speed (m/s), and C_p is the power coefficient.

$$C_p = 0.22(\frac{116}{\gamma} - 0.4\beta - 5)e^{-12.5/\gamma} \tag{13}$$

$$\gamma = 1/(\frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1})$$

The power-speed curve of the simulated turbine parameters at 14, 12 ,10 m/s wind speed is shown in Fig.3.

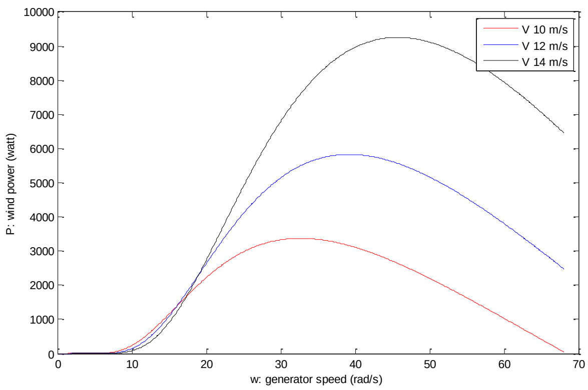

Fig.3. Power-Speed curve for the wind turbine

V. Impedance Network design:

Impedance network design is done to keep the current and voltage ripples are 10% and 1 % respectively. (16) & (17) are used to calculate these values.

VI. Open loop system design

A QZSI based wind energy extraction system shown in Fig.4 is designed and simulated to supply power to an inductive load with the following parameters

TABLE I. Load Parameters

Load Parameters		
P(watt)	***V_L(V)***	***P.F(lagg)***
400	220	0.8

TABLE II. Simulation Parameters

Simulation Parameters			
f(KHZ)	***V_{wm} (m/s)***	***B***	***C_{rec}(μF)***
10	14	7.88	10000

Where; P is the load power in watts, V_L is load line voltage, P.F.is the load power factor, *f* is the switching frequency, B is the boost factor, and V_{wm} is the maximum wind speed.

Fig. 5. illustrates the flow chart of the open loop system MATLAB algorithm based on the Maximum Constant Boost Control (MCBC) method. As in [6] the relationship between the boost factor and the modulation index is

$$B = \frac{1}{\sqrt{3}M - 1} \tag{14}$$

$$G = \frac{M}{\sqrt{3}M - 1} \tag{15}$$

Where, G is the inverter gain.

From (5), the maximum shoot through duty ratio can be chosen to be 0.49. On the other hand the rectifier output voltage and the extracted wind power are depending on the maximum boost factor. Keeping the load impedance constant, the boost factor is controlling the extracted power and the dc link voltage.

Based on the above analysis an optimum value of the boost factor limit of 7.88 is selected by the simulation trials, at which the power injected from the wind turbine at any wind speed is maximum and the output voltage of the rectifier is also maximum. Any further increase or decrease in the boost factor limit would results in lower injected wind power and lower rectifier output voltage. From Fig. 6 (b) and (d) it is clear that the maximum injected wind power at 14 m/s wind speed is 300 W at 65 V rectifier output voltage, Accordingly the rated input current is 4.6A.Table III shows the calculated design parameters to be used to determine of L & C values used in simulation, finally A 5 mH inductor and A 20 µF capacitor is used in the simulated system.

$$\Delta I_{rated} = \frac{V_{c1}}{L} * \frac{T_{sh}}{6} \tag{16}$$

$$\Delta V_{c1} = \frac{I_{l2}}{C_1} * \frac{T_{sh}}{6} \tag{17}$$

TABLE III. Calculated Parameters

Calculated Parameters						
I_{rated}(A)	***Δ I_{l2}(A)***	***B***	***T_{sh} (µs)***	***D***	***V_{c1} (V)***	***ΔV_{c1} (V)***
4.6	0.46	7.88	43.65	0.4365	288.405	2.884

As the boost factor decreases the oscillations becomes smaller, system becomes faster, larger power is injected and higher rectifier output voltage is obtained until reaching optimum value smaller than it degradation in results starts occurring.

The simulation is carried out at 3 different wind speeds 14, 12, 10 m/s generator side waveforms are attached at Fig. 6.

A. Simulation Results and Discussion

The following 2 points can be observed from generator side results, as the wind speed decreases the injected wind power decreases, the generator speed decreases and the rectifier voltage decreases also. Another important point the input voltage rises smoothly which prevents large overshoot in inductor current and capacitor voltage which may result in components damage. The results in Table. IV can be highlighted from QZSI waveforms shown in Fig. 7.

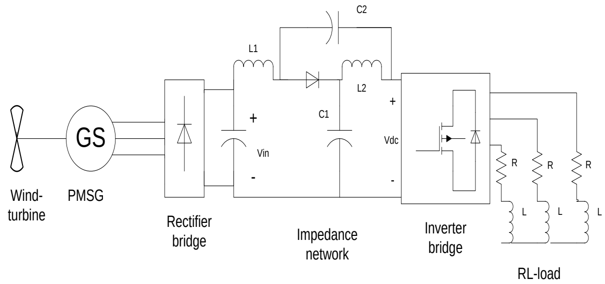

Fig.4. Overall system Block diagram.

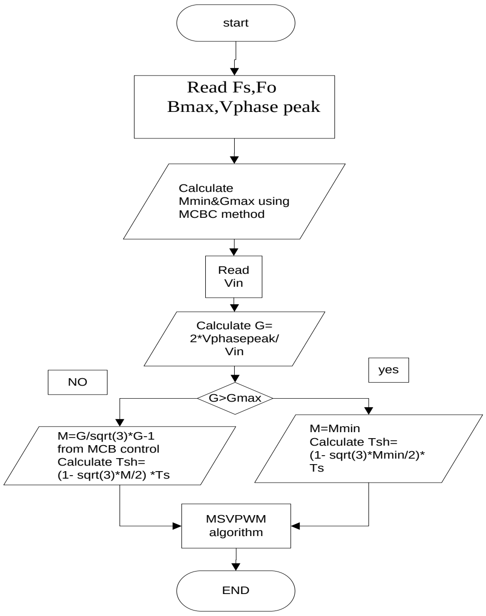

Fig.5. flow chart of the open loop algorithm

The obtained results in table IV. Matches the theoretical analysis with high accuracy. It can be seen that at each wind speed $V_{dclink}=V_{c1}+V_{c2}$, $V_{diode}= - (V_{c1}+V_{c2})$ when reverse biased, and $V_{in}=V_{c1}-V_{c2}$. Also, it can be seen that the input voltage is boosted by a factor greater than 7 as designed.Another important remark the ripples appearing in L_1 seem to be higher than that appeared in L_2 this is because of the ripples in rectifier voltage reflects directly on the ripples appeared in L_1 current because Vin contributes in the charging and discharging of L_1 but L_2 charges from C_1 only and discharges from C_2 only so, to reduce ripples in L_1 ripples in input voltage must decrease also.

TABLE IV. SIMULATION RESULTS

Simulation Results					
V_{wind}	V_{in}	V_{c1}	V_{c2}	V_{dclink}	V_{diode}
14	65	265	200	470	-460
12	56.5	232.5	180	415	-410
10	48.5	200	150	345	-342

VII. CLOSED LOOP SYSTEM DESIGN

It can be seen from the open loop results in Fig. 8 (a), (b) and (c) that the dc link voltage varies with variations in wind speed and hence, the output load voltage varies also.

So, a closed loop control system is developed to control the dc link voltage and hence, the output load voltage. The flow chart of the closed loop system is indicated in Fig.9. A closed loop controller is implemented to regulate dc link voltage at 400 volts. Closed loop simulation results in figure are summarized in the following table

TABLE V. CLOSED LOOP SIMULATION RESULTS

Closed Loop Simulation Results			
V_{wind}	V_{in}	D	V_{dclink}
14	80.5	0.3995	400
12	67	0.417	400
10	54	0.434	400

From Table. V it can be seen that the dc link voltage is kept constant at 400 volts at any wind speed, and the boost factor-duty ratio relationship in (5) is also verified.

VIII. CONCLUSIONS

In this paper an open loop and closed loop QZSI based system has introduced and analyzed in order to extract the wind energy from a PMSG. Wind emulator has been introduced and simulated. A careful design steps for the impedance network has been introduced as well in order to minimize the voltage and current ripples. A MSVPWM is implemented to apply the shot through periods on the conventional SVPWM. It can be concluded that the open loop system the extracted power is fully dependent on the maximum boosting ratio which affecting the dc link voltage value. A closed loop system controlling the dc link voltage is introduced and analyzed to have a constant dc link voltage with different wind speeds. The system shows a robust performance in the closed loop operation, however in the open loop operation an extra effort to be applied in order to select the maximum boost ratio which is affecting the amount of the extracted energy from the wind turbine. A complete hardware setup-DSP based is under construction to validate the theoretical simulation.

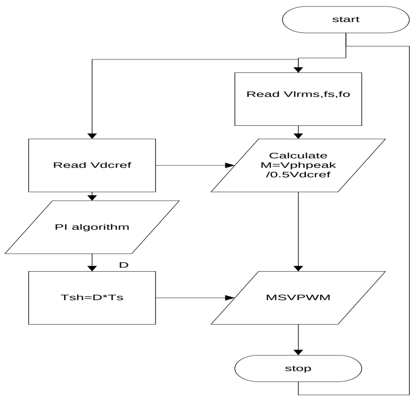

Fig.9. closed loop system flow chart

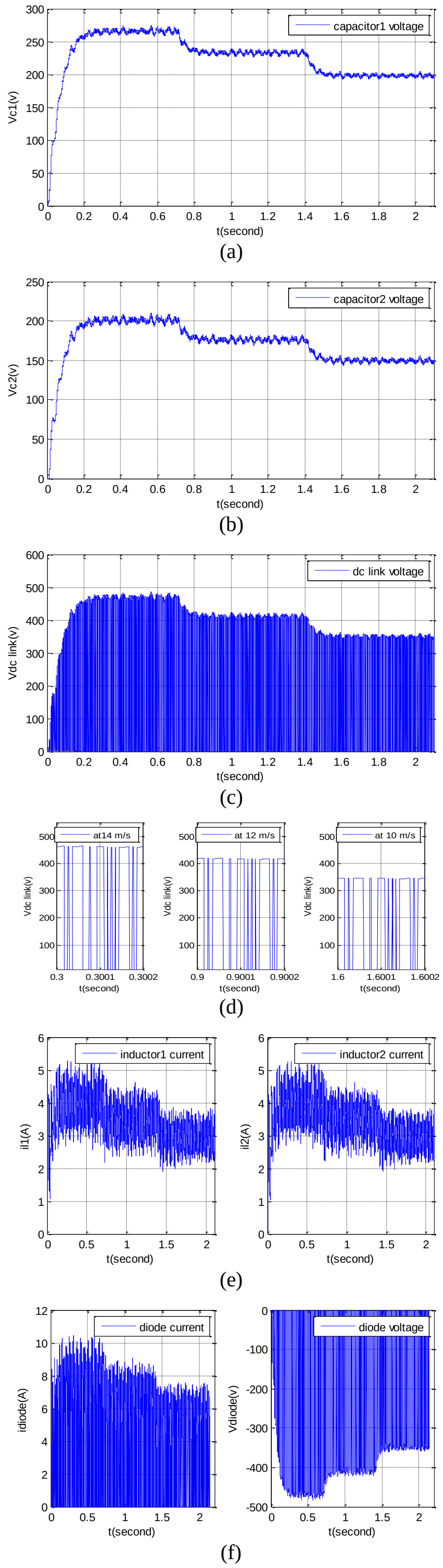

Fig.7. Overall system block diagram QZSI network simulation waveforms. (a)Capacitor1 voltage. (b)Capacitor2 voltage. (c)DC link voltage. (d)DC link voltage for 2 Switching cycles at 14, 12, 10 m/s wind Speed. (e)inductor1 and inductor2 currents. (f)Diode current and voltage.

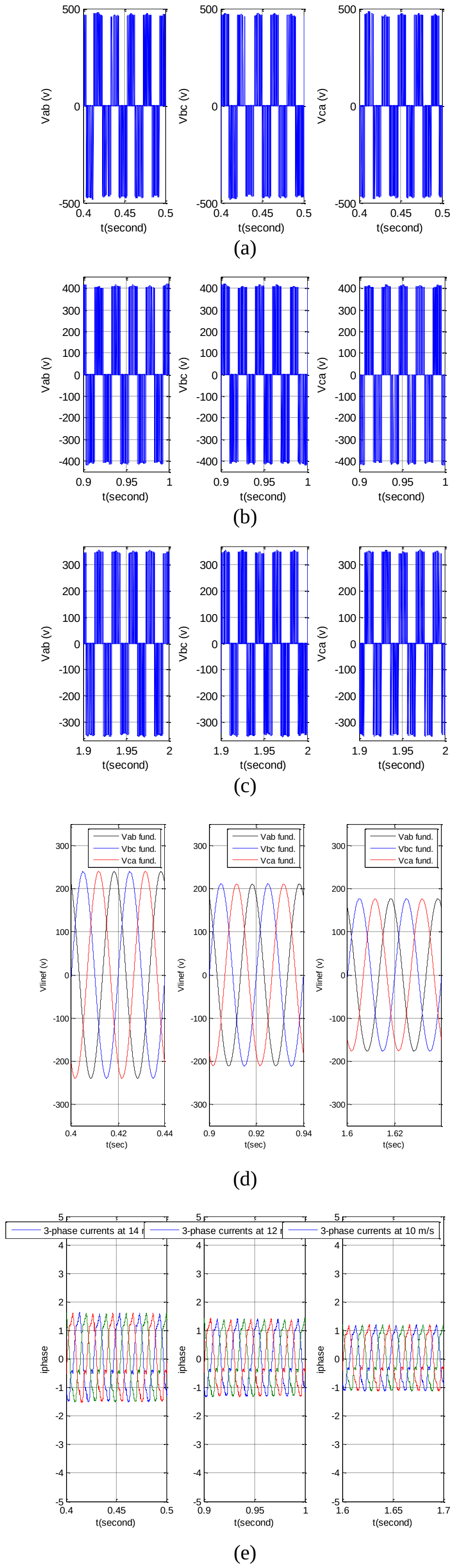

Fig. 8. Load side simulation waveforms.(a),(b),(c) are output line voltage at 4, 12, 10 m/s wind speed.(d) fundamental 3-phase line voltage at 14, 12, 10 m/s wind speed.(e) line currents at 14,12,10 m/s wind speeds.

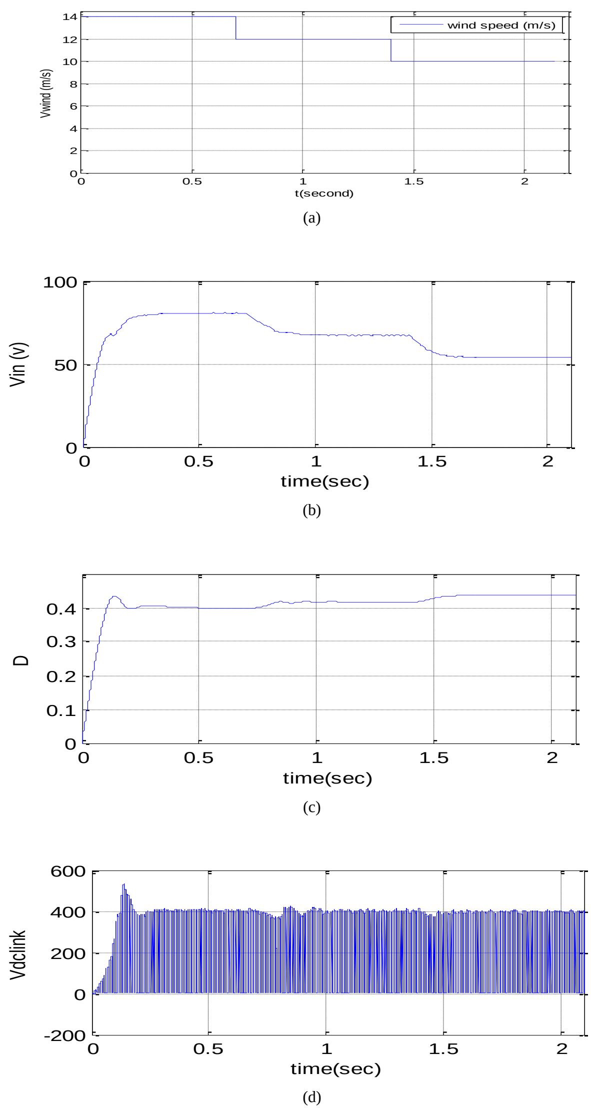

Fig. 10. closed loop results; (a)wind speed (m/s), (b) rectifier output voltage (v) (c) controller output duty ratio (d) dc link voltage (v)

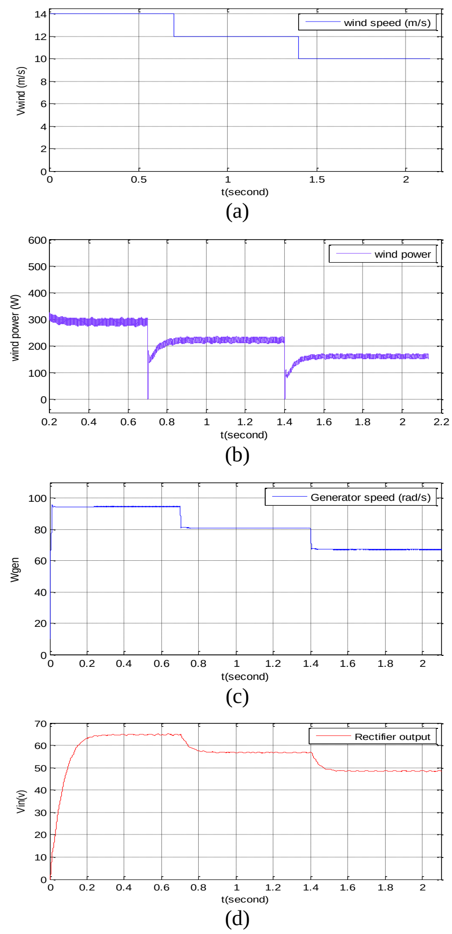

Fig.6. QZSI input stage simulation results (a)Wind speed. (b)Wind power, (c) Generator speed,(d) Rectifier output voltage.

References

[1] D. S. Zinger, E. Muljadi, "Annualized Wind Energy Improvement Using Variable Speeds," IEEE Transaction on Industry applications, vol.33, November/December 1997,pp. 1444-1447.

[2] F. Blaabjerg, Z. Chen, and S.B. Kjaer, "Power Electronics as EfficientInterface in Dispersed Power Generation System," IEEE Transactionon Power Electronics, vol. 19, November 2004, pp. 1184-1194.

[3] J. Anderson and F. Z. Peng, "Four quasi-Z-source inverters," in *Proc. IEEE-PESC*, Jun. 2008, pp. 2743–2749.

[4] F. Z. Peng, "Z-source inverter," *IEEE Trans. Ind. Appl.*, vol. 39, no. 2, pp. 504–510, Mar./Apr. 2003.

[5] F. Z. Peng and Miaosen Shen, Zhaoming Qian, "Maximum Boost Control of the Z-source Inverter," in Proc. of IEEE PESC 2004.

[6] M. Shen, F. Z. Peng, and Z. Qian, "Maximum Constant Boost Control of the 2-Source Inverter," IEEE IAS Annual Meeting, 2004.

[7] Yushan Liu, , Baoming Ge, , Haitham Abu-Rub, and Fang Zheng Peng, "Overview of Space Vector Modulations for Three-Phase Z-Source/Quasi-Z-Source Inverters,"IEEE Trsns. Power elctronics, VOL. 29, NO. 4, APRIL 2014.

[8] Kun YU, Fang Lin LUO, Miao ZHU, "implementation of maximum constant boost control of Z-source inverters based on space vector modulation technique," *IEEE Trans. Ind.* Appl., vol. 49, no. 2, pp. 866–872, Mar./Apr. 2011.