Z-source Inverter Based Wind Power Generation System

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***Abstract*—This paper presents a wind turbine generation system based on the Z-source inverter with maximum boost control. The proposed system can boost and generate the desired output voltage efficiently when the low voltage of the generator is introduced according to the low wind speed. Moreover, when the wind speed is high, providing higher voltage, the system can also work like the traditional inverter without the boost condition. The proposed system has high performance, minimal component count, increased efficiency and reduced cost. These outstanding performance attributes make the proposed system suitable for the wind turbine distributed generation systems.**

I. Introduction

WITH world electricity demand growing steadily, demand for renewable energy sources is also expected to increase drastically. Wind, a free, clean and inexhaustible source of energy, is increasingly competitive with other energy sources [1]-[3].

Variable speed wind turbines are known to provide more effective power capture than fixed speed wind turbines [1]-[6]. Yet the grid is fixed frequency at most loads. The voltage source inverter (VSI) with a DC chopper circuit has traditionally been used for this voltage level and frequency conversion. The traditional VSI, however, has the limitation of only providing output voltages that are lower than input voltages. For this reason, the DC chopper circuit is used to add the boost feature. Even though this topology is functional, the extra active devices and controls add additional system costs and complexities [7]-[8]. Alternatively, the Z-source inverter presented recently in [9] not only overcomes the voltage limitation of the traditional inverter but also uses fewer components. Moreover, it is more efficient and reduces cost. As a result, it is well suited for the wind turbine system.

This paper presents the application of the Z-source inverter for the wind power system. The operational principle and control method of the proposed system are herein explained in detail. Simulation results are provided in order to verify the validity of the developed wind turbine generation system.

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II. Wind Turbine Characteristics

The amount of power transformed from the wind velocity, v, is described in (1) [10].

$$P = \frac{1}{2}\rho A C_p v^3 \tag{1}$$

P : aerodynamic wind power [W]
C_p : power coefficient of wind turbine
ρ : air density [kg/m^3] ;
A : swept area[m^2],
v : wind speed [m/s]

As shown in Fig.1, *Cp* is the power coefficient of a wind turbine that is the function of the tip-speed ratio λ. The tip-speed ratio is defined as the ratio of the tip speed of the turbine blades to the wind speed which is shown in (2).

$$\lambda = \frac{V_{tip}}{v} = \frac{R\omega_m}{v} \tag{2}$$

where λ = Tip-speed ratio, R = Rotor radius (m), ω_m = Rotational speed (rad/s).

There are two types of wind turbines: constant and variable speed. The maximum value of *Cp* is only achieved at one particular tip speed ratio. For the fixed - speed wind turbines, the rotor speed is constant whereas the wind speed is not. So, there is only a particular wind speed at which a wind turbine can generate the maximum power coefficient. At the other wind speeds, the power coefficient is reduced.

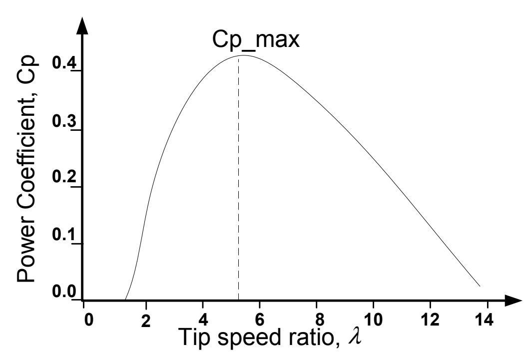

Fig. 1. Curve showing variation of the power coefficient of performance with the tip speed ratio.

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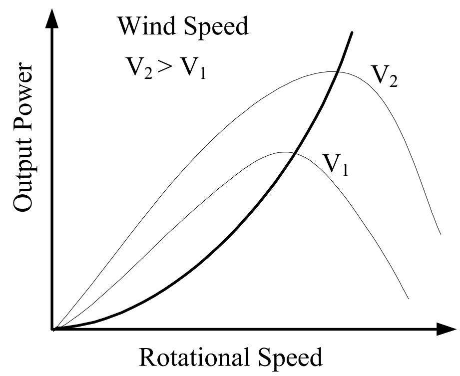


Fig.2. Relationship between the generator output power and rotational speed.

In the case of the variable speed wind turbine, rotational speed is changed in response to wind speed changes so that *Cp* is held at its maximum value. Therefore, the variable speed wind turbine is capable of more efficient power capture than the fixed speed wind turbine. Note that when the wind speed increases, the output power of the generator increases as a function of the rotational speed. Fig.2 represents the relationship between the generator power output and rotational speed regarding to wind speed changes.

III. Proposed Z-source Inverter for the Wind Power System

As mentioned above, the conventional inverter with DC/DC boost converter shown in fig.3 has more active component count and also the DC/DC controller need to be added, leading to system complexity. Alternatively, the proposed Z-source inverter for the wind power system is shown in Fig.4. The system includes a variable speed wind turbine, diode rectifier with input capacitors (C_a,C_b,and C_c), Z-source network, and inverter system connected to the utility grid. Input capacitors serve as the dc source feeding the Z-source network [11]. Electrical power can be drawn from the wind power through the wind turbine. The AC power generated from the generator is converted into the DC power through diode bride rectifier circuits and then fed to the Z-source inverter.

The operating principle of the Z-source inverter has been explained thoroughly in [12]-[14]. The inverter can work in two modes, normal, and boost operation mode. The normal operation mode is like the traditional inverter. The output voltage is dependent on the voltage across at the inverter bridge and on the modulation index. In the boost mode however, the Z-source inverter boosts the voltage of C_1 and C_2 *(see fig.4)*, thereby raising the voltage at the inverter bridge. The capacitor voltage of the Z-source network is a function of shoot- through states.

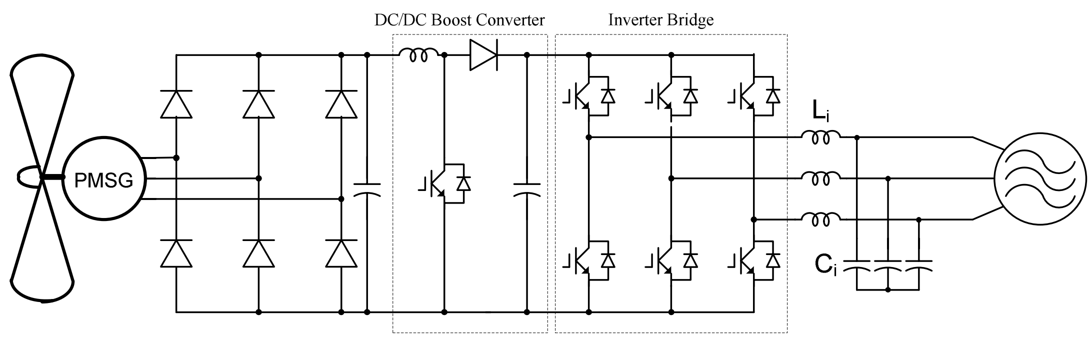


Fig.3. Conventional Inverter with DC/DC Boost Converter for the wind power system.

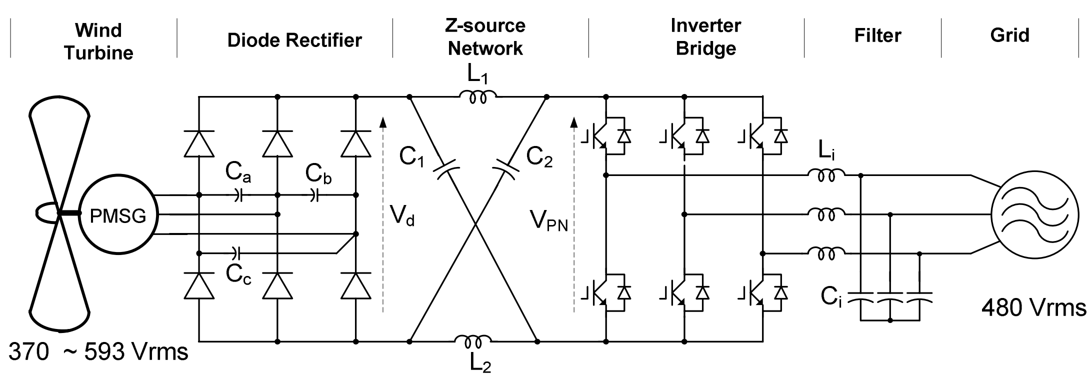


Fig.4. Proposed Z-source inverter for the wind power system.

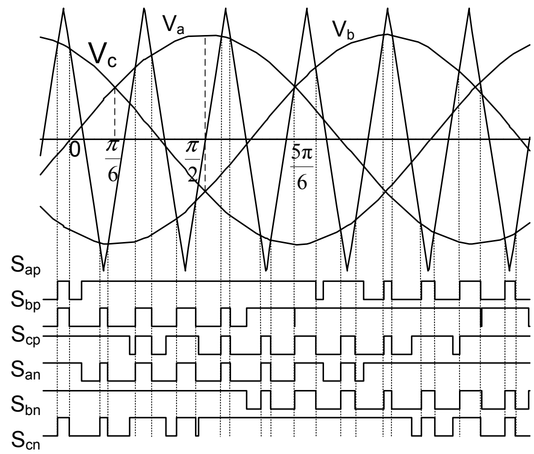


Fig. 5. Sketch map of maximum boost control [13].

The control of the shoot-through interval has been detailed as in [12]. Based on this reference, there are several methods to control the Z-source inverter: simple boost, maximum boost, maximum boost with third harmonics injection, and maximum constant boost control. Among them, maximum boost control is chosen for this design because of its lower voltage stress across inverter bridge switches. Fig.5 shows the sketch map of maximum boost control principle. In this control method, all six-active states are still unchanged, whereas all zero states are basically turned to shoot-through states. The strategy for obtaining the shoot –through states is that the triangular carrier wave is compared with reference signals. With this comparing, the shoot-through states are introduced when either the triangle wave is bigger or smaller than the reference.

$$V_{C1} = V_{C2} = V_C = \frac{1-\frac{T_0}{T}}{1-2\frac{T_0}{T}} V_d = \frac{B+1}{2} V_d \quad (3)$$

$$\frac{\overline{T}_0}{T} = \frac{2\pi - 3\sqrt{3}M}{2\pi} \quad (4)$$

$$B = \frac{1}{1-2\frac{\overline{T}_0}{T}} = \frac{\pi}{3\sqrt{3}M - \pi} \quad (5)$$

Shoot-through states are defined by (3) where V_{C1} and V_{C2} are the voltage across capacitor C_1 and C_2, respectively. V_d is the input dc voltage obtained from the diode rectifier bridge. T_0 is the shoot-through interval of one switching cycle T. T_0/T is known as the shoot-through duty ratio.

However, for maximum boost control, shoot-through duty ratio is expressed as the average of shoot through duty ratio, $\overline{T}_0/T$, as shown in (4) and B is the boost factor expressed in (5) where M is a modulation index.

$$V_d = \frac{3\sqrt{2}}{\pi} V_{LL} = 1.35 V_{LL} \quad (6)$$

$$V_{PN} = B V_d \quad (7)$$

$$\hat{V}_{ac} = M \frac{V_{PN}}{2} = MB \frac{Vd}{2} \quad (8)$$

It is assumed that the DC voltage fed to the Z-source inverter is explained in (6) where V_{LL} is line to line voltage of the generator. At the normal operation mode, the inverter bridge voltage, V_{PN}, is equal to V_d.

However, when the inverter working in the boost mode, the inverter bridge voltage is expressed as in (7) where B is the boost factor controlled by the control scheme of the Z-source inverter. In this boost mode, the output peak phase voltage, $\widehat{V}_{ac}$, generated by the inverter is expressed in (8).

Note that when the input voltage of the Z-source inverter is high enough to produce the designed output voltage, the boost mode is not needed, and with this case the Z-source inverter works in normal mode like a traditional inverter.

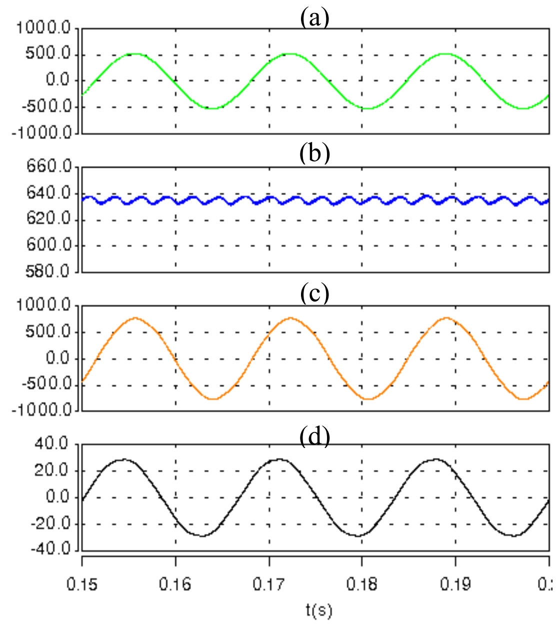
In this paper, the example chosen for illustration is summarized as follows;

- Generator rated power 50 KW.
- Generator output voltage range 370Vrms to 593Vrms.
- Inverter output 480Vrms, 60 Hz.

When the generator provides 370Vrms as the input of the Z-source inverter, the voltage at the diode bridge will be approximately calculated as 500Vdc, using (6). Without any boost mode (boost factor is equal to 1), the voltage at the inverter bridge will also be approximately 500Vdc. So, with this voltage level at the inverter bridge, the inverter can only generate a maximum of 306Vrms approximately at the output based on SPWM and the modulation index of 1. In order to obtain 480Vrms as the inverter output, the minimum voltage at the inverter bridge must be at least 783Vdc. Therefore, when the input voltage given by the generator varies between 370Vrms to less than 580Vrms or 500Vdc to less than 783Vdc at the rectified diode bridge, the voltage needs to be boosted (boost factor is greater than 1). So, at these input ranges, the Z-source with boost mode control will be used. However, if the generator produces the voltage high enough, for example, more than 580Vrms or 783Vdc at the rectifier bridge, the Z-source inverter will be operated in normal mode like the traditional inverter, to produce 480Vrms at the inverter output.

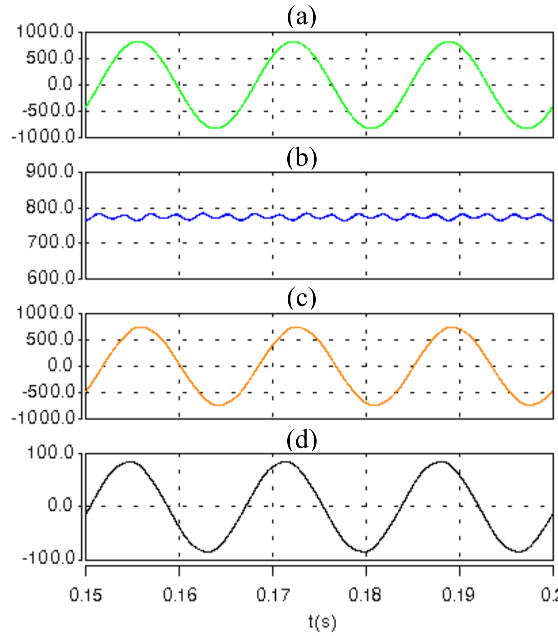
TABLE I
SYSTEM PARAMETERS

Quantity	Values
Z-source inductors (L_1= L_2)	800 μH
Z-source Capacitors (C_1= C_2)	1000 μF
Input Capacitors(*Ca,Cb*, and *Cc*)	12 μF
Switching frequency, f_S	10 kHz



(a) Generator Voltage, v_{Sab}, 370Vrms
(b) Z-source inverter Voltage, V_{C1} and V_{C2}
(c) Inverter Voltage after filter, v_{ab}, 480 Vrms
(d) Inverter Current, i_{La}

Fig.6. Simulation waveforms when the generator voltage is 370 Vrms, 15 kW with boost mode control.



(a) Generator Voltage, v_{Sab}, 580Vrms
(b) Z-source inverter Voltage, V_{C1} and V_{C2}
(c) Inverter Voltage after filter, v_{ab}, 480 Vrms
(d) Inverter Current, i_{La}

Fig.7. Simulation waveforms when the generator voltage is 580 Vrms, 45 kW without boost condition.

IV. Simulation Results

To confirm the principle presented above, simulations have been carried out. The system includes a 50 kW Z-source inverter transferring power from the wind turbine side to the grid side. The input voltage supplied from the wind turbine to Z-source inverter varies between 370 to 593Vrms. The output voltage of the inverter is held constant at 480Vrms and 60 Hz. The parameters of the system are shown in table I.

Fig. 6 shows simulation results of the Z-source inverter when the generator provides 370Vrms at the input of the system. With this input voltage level, the inverter is working in the boost mode to generate 480Vrms at the inverter output.

However, when the generator voltage provides a voltage more than 580Vrms which is high enough to produce the desired voltage, 480Vrms without using boost mode, the Z-source inverter is like the tradition inverter and the results are shown in Fig.7.

V. Conclusion

In this paper, the Z-source inverter wind turbine distributed generation system has been presented based on the maximum boost control method. For the given operational conditions of low wind speed and resulting low input voltage, the Z-source inverter can boost output voltage efficiently without any additional components or boost circuitry. Equations were shown to demonstrate this concept. Also, when wind speed is high providing higher input voltage, the Z-source inverter can also work like the traditional inverter without the boost condition. In summary, this novel circuit can provide a constant 480Vrms output voltage while input voltage varies above and below this level. Without the need for additional boost circuitry as is required by the traditional voltage source inverter, the Z-source inverter provides high performance, a minimized component count, increased efficiency and reduced cost. Simulation results of the proposed system were given to verify its ability to receive input voltage above and below its constant output voltage. This performance makes the proposed system suitable for the wind turbine distributed generation systems.

Ongoing Work

To verify the principle of the work, shown in fig. 8, the 10-kW Z-source inverter has been built and it is now in the testing process. The system generates 480 V output voltage whereas the input is varying between 370 to 593V.

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 Efficient Interface in Dispersed Power Generation System," *IEEE Transaction on Power Electronics*, vol. 19, November 2004, pp. 1184- 1194.

[3] Z.Chen and E.Spooner, " Grid Power Quality with Variable Speed Wind Turbines," *IEEE Transactions on Energy Conversion*, vol.16, June 2001, pp.148-154.

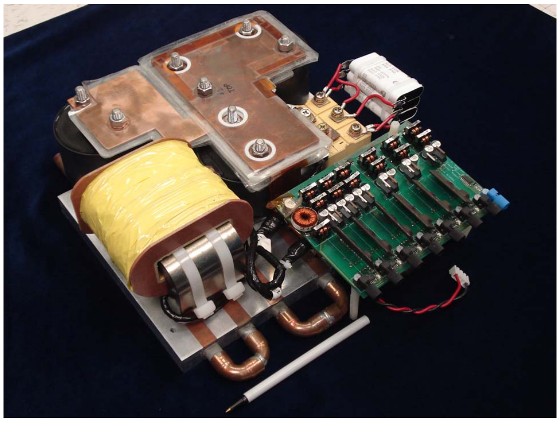


Fig. 8. A 10 kW Z-source inverter for Wind Power System

[4] E. Koutroulis and K. Kalaitzakis, "Design of a Maximum Power Tracking System for Wind –Energy –Conversion Applications," *IEEE Transaction on Industrial Electronics*, vol.53, April 2006, pp.486-494.

[5] M.G. Simoes, B.K. Bose, and R.J. Spiegel "Design and Performance Evaluation of a Fuzzy-Logic-Based Variable Speed Wind Generation System," *IEEE Transaction on Industry Application,* vol.33, July/August 1997, pp. 956- 965.

[6] L. Palma, P. Enjeti, N. Denniston, and J.L. Duran-Gomez, "A Converter Topology to Interface Low Voltage Solar/Fuel Cell Type Energy Source to Electric Utility," *IEEE Applied Power Electronics Conference and Exposition 2008*, APEC2008, 24-28 February 2008, pp.135-140.

[7] R.C. Portillo, M. Martin Prats, J.I. Leon, J. Antonio Sanchez. J.M. Carrasco, E. Galvan, and L. Garcia Franquelo, " Modeling Strategy for Back-to-Back Three- Level Converters Applied to High- Power Wind Turbines," *IEEE Transaction on Industrial Electronics*, vol.53, October 2006, pp.1483-1491.

[8] J.M. Carrasco, J.T. Bialasiewicz, R.C. Portilla Guisado, and J.I. Leon, " Power Electronics System for the Grid Integration of Renewable Energy Source: A Survey*," IEEE Transaction on Industrial Electronics*, vol. 53, June 2006, pp.1002-1016.

[9] F. Z. Peng, "Z-Source Inverter," *IEEE Transactions on Industry Applications*, vol. 39, March/April 2003, pp. 504-510.

[10] M.R. Patel, Wind and Solar Power Systems, CRC Press, New York, 1999.

[11] F.Z. Peng, A. Joseph, J. Wang, M. Shen, L. Chen, Z. Pan, E.Ortiz-Rivera, and Y. Huang, "Z-source Inverter for Motor Drives," *IEEE Transaction on Power Electronics*, vol.20, July 2005, pp.857-863.

[12] M. Shen, "Z-source inverter design, analysis, and its application in fuel cell vehicles," PhD. Dissertation, Michigan State University, Michigan, 2006.

[13] Z. Peng, M. Shen, and Z. Qian, "Maximum Boost Control of Z-Source Inverter*," IEEE Transactions on Power Electronics*, vol.20, July 2005, pp.833-838.

[14] M.Shen, J. Wang, A. Joseph, and F.Z.Peng, "Constant Boost Control of Z-Source Inverter to Minimize Current Ripple and Voltage Stress," *IEEE Transaction on Industry Applications*, vol.42, May/June 2006, pp.770-778.