Improved Sigma Z-source Inverter-fed Grid System for Wind Power Generation

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Abstract

Renewable energy is an important solution to reduce carbon emissions for a sustainable environment. Wind energy has significantly been recognized and utilized as the most preferred renewable energy source in the present time across Australia and worldwide. The southern coastline and elevated areas of Australia have good wind resources. However, the traditional boost converter and impedance source networks fail to carter the high voltage demand of the wind power generation system. In this regard, a new topology of impedance source networks, called Improved Sigma-Z-source, is proposed which facilitates a high output voltage gain. The network replaces the conventional inductor arrangement in traditional Z-source and consists of two capacitors connected in series with secondary windings of the transformer. The proposed system has a high dc voltage gain at a low turn ratio. The relevant modeling of design parameters and simulation results are presented in the paper.

1 Introduction

Renewable energy has attracted much attention of the researchers in the last years. Solar energy and wind energy are the preferred sources for the power generation system. Wind power is at present the cheapest source of large-scale renewable energy. Over the last decade, the use of wind energy conversion systems has grown substantially due to frequent climate change, increasing energy demand of industries and developments of topologies of the power electronics converters [1]. In Australia specifically, the installed wind power output has surpassed 5 GW and promising wind power projects are currently in the development stages. According to the Australian Renewable Energy Agency (ARENA), the wind power capacity in Australia is expected to drastically increase in the near future. The wind energy will be one of Australia's main sources of renewable energy, generating enough electricity to meet 7.1 percent of the nation's total demand.

With choice among the variable speed generators, permanent magnet synchronous generator (PMSG) is widely used in the wind power generation system connected with the wind turbine [2]. The PMSG is preferred because of prominent features, such as low weight and volume, less maintenance, and high efficiency. However, due to unpredicted wind speed and dependence on seasonal variations, the wind power generation system faces the difficulty of low voltage output. To overcome this issue, it is advised to integrate the power electronic converter between the wind turbine generator and grid/load. In conventional systems, voltage source inverter (VSI) is used to obtain the desired ac output. Moreover, many high-gain dc-dc converters have been reported in the literature to obtain high dc bus output, although most are limited to a lower value at best. In view of this problem, Z-source inverter is suggested in literatures to overcome the voltage barrier for wind power generation systems. Z-source inverter (ZSI) is a single-stage power converter, which has both the buck and boost capabilities [3], [4]. By controlling the shoot-through duty ratio through the modulation index, the ZSI can provide the single-stage power conversion with an extended output voltage range. This unique characteristic eliminates the dead time, which results in low distortions in the output waveform and reliability improvement [5].

Nevertheless, the traditional ZSI suffers from limitations such as a limited range of boost capability, high surge current, and discontinuous input current [6],[7]. This paper describes a new approach to implement high gain dc-dc converters using the new topology of ZSI for the wind power generation systems. In this paper, an alternative transformer-based topology of ZSI called sigma-ZSI (ΣZSI), is utilized for the proposed wind power generation system [8]. It overcomes the shortcomings of a high turn ratio to increase the boost capability. It is realized by replacing the inductors of the traditional ZSI with the secondary transformers' windings in series with the network capacitors. The design specifications are less sensitive to the turn ratio. The proposed ΣZSI-fed wind power generation system has been validated by simulation results in this paper.

The outline of this paper is as follows: Section 2 describes the design specifications of the ΣZSI and PMSG. Section 3 explains the control strategy of the modulation scheme and control of the PMSG-wind turbine system. The effectiveness of the proposed system is validated in Section 4. In addition to it, a comparative analysis of the proposed dc-dc converter network ΣZSI with the traditional converters is discussed. Finally, a conclusion is presented in Section 5.

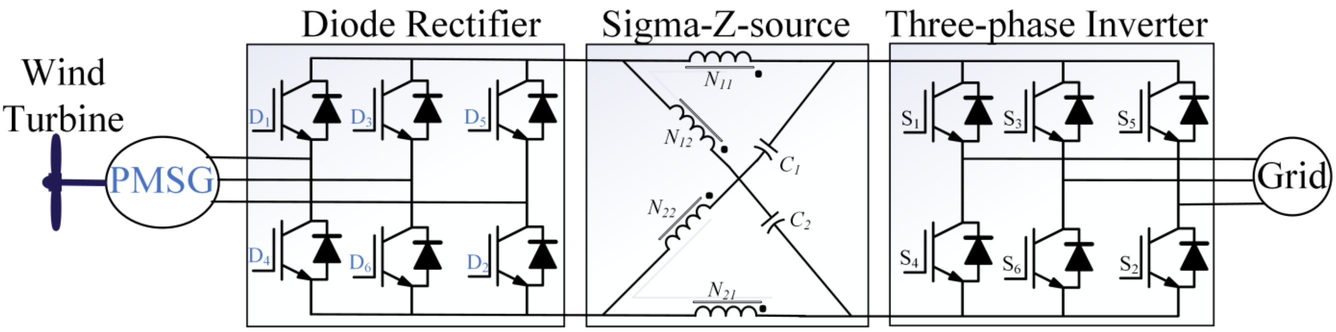


Fig. 1 Circuit diagram of the proposed system.

2. System Configuration

This study intends to provide a simple, low cost and effective power conversion system consisting of a diode rectifier and ∑ZSI for megawatt-level permanent magnet synchronous generator (PMSG) wind turbines. Figure 1 shows the overall system configuration of the proposed fed grid system for wind power generation. It consists of PMSG coupled wind turbine-fed to the ∑ZSI grid-connected system. The output voltage of the diode rectifier changes with respect to the varying wind speed conditions and it represents an unregulated dc-link. A regulated dc-link is obtained through the proposed ∑ZSI and utilized at the inverter terminals to feed the grid.
The overall system configuration is explained below.

2.1 Sigma Z-source Inverter (∑ZSI)

The proposed Sigma Z-source inverter, as shown in Fig. 2a consists of two transformers and two capacitors connected in X-shape. In this configuration, the inductors are replaced by transformers, unlike the traditional Z-source configuration.

2.1.1 Operating Modes: The proposed ΣZSI has a similar operation as of traditional ZSI. It has six active and two zero states during the buck mode. Alternatively, the shoot-through state is introduced during the zero states to boost the dc-link voltage. There are two operating modes (Fig.2b and Fig. 2c):

(a) Shoot-through Mode: During the shoot-through state, one or all the legs of the inverter module are shorted causing the transformers' windings to charge through capacitors C_1 and C_2.

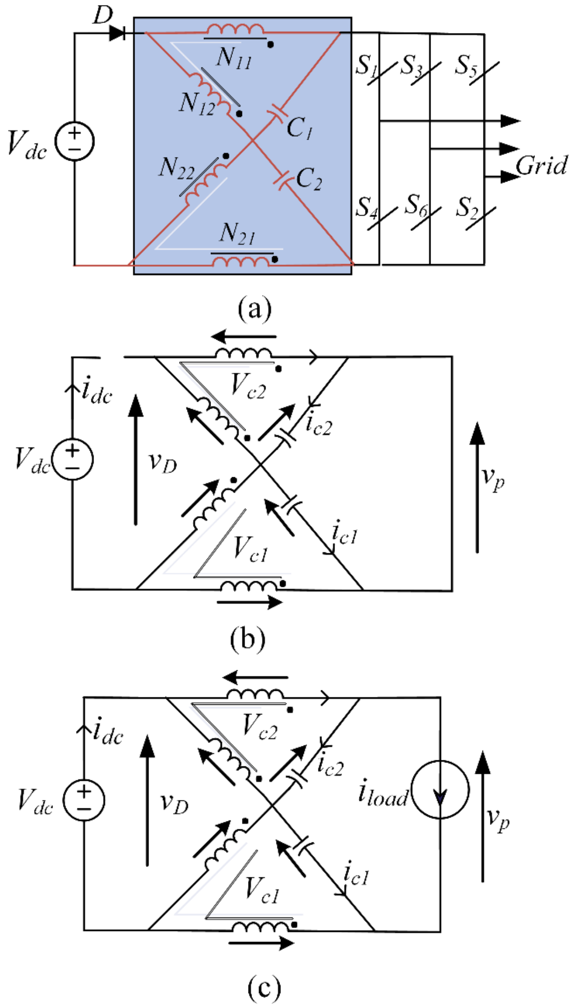
(b) Nonshoot through Mode: In this mode, the dc source excites the capacitors connected in parallel and is connected to the inverter module in series with the transformers.

2.1.2 Design Calculations: The design calculations are derived in [1]. The major advantage of the operation of the proposed ΣZSI does not affect the output volt–second balance.
The voltage across the capacitors is given as:

$$V_{c1}=V_{c2}=\frac{(\mathbf{1}-D_0)V_{DC}}{\mathbf{1}-[\left(\mathbf{2}+\frac{\mathbf{1}}{N_{T1-1}}\right)+\left(\frac{\mathbf{1}}{N_{T2}-\mathbf{1}}\right)]\boldsymbol{D_0}} \qquad (1)$$

The ac output peak voltage of the inverter is given by

$$\boldsymbol{V_{ac}}=\frac{\boldsymbol{M.B.V_{DC}}}{\mathbf{2}} \qquad (2)$$



(a)

(b)

(c)

Fig. 2 Circuit diagram for: (a) Sigma-Z-source inverter(∑ZSI), (b) shoot-through mode, (c) nonshoot-through mode.

where M is the modulation index, B is the boost factor, V_{DC} is the DC bus voltage.
The boost factor of the ∑ZSI can be written as:

$$\boldsymbol{B}=\frac{\mathbf{1}}{\mathbf{1}-[\left(\mathbf{2}+\frac{\mathbf{1}}{N_{T1-1}}\right)+\left(\frac{\mathbf{1}}{N_{T2}-\mathbf{1}}\right)]\boldsymbol{D_0}} \qquad (3)$$

where N_{T1} and N_{T2} are the turns ratios of the transformers.

In the case of proposed ∑ZSI, the boost factor can be increased by reducing the turn ratio of the transformers. It is a unique characteristic of the proposed configuration. In addition to it, the magnetizing current for ΣZSI is smaller. A small magnetizing current prevents saturation of the transformer core. The design parameters are listed in Table 1.

Table 1 Design Parameters of ∑ZSI for Simulation Studies

Parameter	Notation	Value
Input DC voltage	V_{DC}	100 V
Capacitors	C_1=C_2	2200 µF
Turns ratio	N_{T1}= N_{T2}	1.4
Duty Ratio	D_0	0.4
Switching Frequency	*f*	50Hz
Boost Factor	B	2.5

2.2 Permanent Magnet Synchronous Generator (PMSG)

The voltage equations of a PMSG in the dq-reference frame is given by

$$v_q = -R_s i_q - L_q i_q - \omega_r L_d i_d + \omega_r \lambda_m \qquad (4)$$

$$v_d = -R_s i_d - L_d i_d + \omega_r L_q i_q \qquad (5)$$

where v_d and v_q are the dq-frame voltages, i_d and i_q are the dq-frame currents, R_s is the winding resistance, L_d and L_q are dq-frame inductances, ω_r is the rotor speed and λ_m is the flux linkage.

The electromagnetic torque is given as:

$$T_e = \frac{3}{2}\frac{P}{2}[\lambda_m i_q + (L_q - L_d) i_q i_d)] \qquad (6)$$

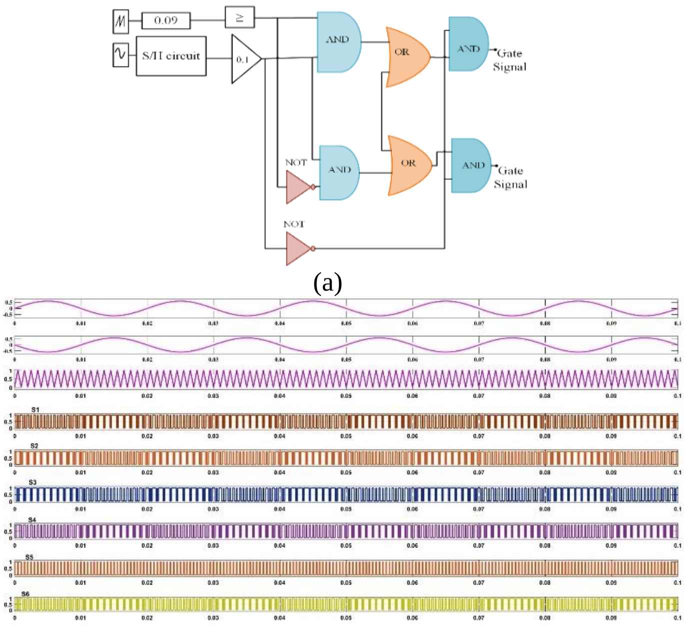
where P is the number of poles.

For the ease of operation, the current of d-axis is generally set to zero. Hence, the electromagnetic torque of the PMSG machine can be smoothly controlled by tuning of the q-axis current. The control strategy is explained in Section 3.

3 Control Strategy

3.1 Modulation Scheme for ∑ZSI

To overcome the variable output wind power and capture the maximum wind energy, it is essential to use a power converter between the wind turbine generator and grid/load. In the proposed configuration, two-stage inverters are incorporated. PMSG is connected through a diode bridge rectifier. In this system, a ∑Z-source network is placed between the diode bridge rectifier and the voltage-source inverter bridge to boost the low-level dc voltage output of the rectifier to a constant higher voltage gain as discussed in the previous section. However, the dc-dc power conversion is dependent on the modulation strategy of firing gates of the semiconductor services. It is required to facilitate both the shoot-through and nonshoot through states to obtain the higher voltage gain. In this paper, the conventional simple boost control modulation is modified. A sample and hold circuit with a gain of 0.1 is utilized to obtain a higher number of shoot-through cycles. The circuit diagram of the proposed modulation scheme is shown in Fig. 3. In case of operation with a fixed switching cycle, inserting shoot-through states with the active state intervals will not interfere the volt–sec average per switching cycle.



(a)

(b)

Fig. 3 Circuit diagram for: (a) modulation scheme (b) gate signals for the switches.

This feature allows all existing pulse width modulation (PWM) methods with slight modifications to be used for controlling any configuration of Z-source inverter circuit.

3.2 Maximum power point tracking (MPPT)

To obtain an optimal output of the wind power generation system, it is necessary to capture maximum wind energy by implementing the MPPT control for the wind turbine generator [9]-[11]. The mechanical power generated by a wind turbine is expressed as:

$$P_m = \frac{1}{2} C_p(\lambda, \beta) A \rho v^3 \qquad (7)$$

where C_p is the power coefficient of the turbine, A is the area swept by the rotor blades, *v* is the wind speed and ρ is the air density. The power coefficient of the turbine (C_p) is a nonlinear function of the tip speed ratio (λ) and the blade pitch angle (β).

Using the PQ controller, the synchronous reference frame is aligned with the flux to provide effective control of active power in terms of electromagnetic torque and reactive power in terms of rotor flux. This control strategy, as shown in Fig. 4, for active and reactive power can be achieved by regulating the rotor components of I_{qr} and I_{dr}, respectively. This control scheme is independent of the machine parameters and insensitive to the disturbances in gird voltage or frequency.

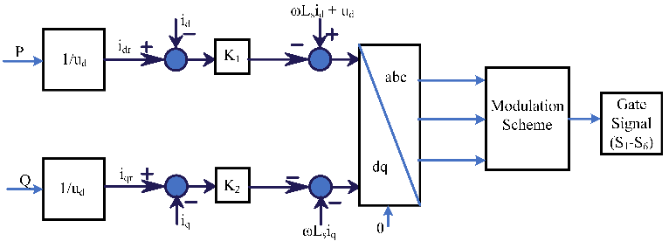


Fig. 4 Control scheme of PQ-control.

Table 2 Simulation parameters of PMSG

Parameter	Notation	Value
Mechanical Power	P_m	5 kW
Speed	η_m	1710 rpm
Phase Voltage	v_s	120 kV
Power factor	PF	0.98
Number of pole pairs	P	8
Rated Torque	T_m	318 N-m
Moment of Inertia	J	240 kg-m^2
d-axis Inductance	L_d	5.475 mH
q-axis Inductance	L_q	5.475 mH
AC load frequency	f	50 Hz

4 Simulation Results

Several time-domain simulation studies are carried out using MATLAB/Simulink to investigate the performance of the proposed system for wind power generation. Table II shows the simulation parameters of the PMSG machine. The efficacy of the proposed system is investigated through the simulations in terms of the output voltage, output current, frequency, and power.

4.1 Response of ∑ZSI

Due to the proposed modulation scheme, a high gain output voltage is obtained. The obtained boost factor is 2.5. The output voltage waveform is shown in Fig. 5. It can be seen that for an input voltage of 60 V, the output voltage is 200 V. Figure 6 shows a comparison of the performance of the proposed ∑Z-source network with that of traditional dc-dc converters in terms of voltage gain. It shows that a linear high-voltage gain is obtained for the proposed converter.

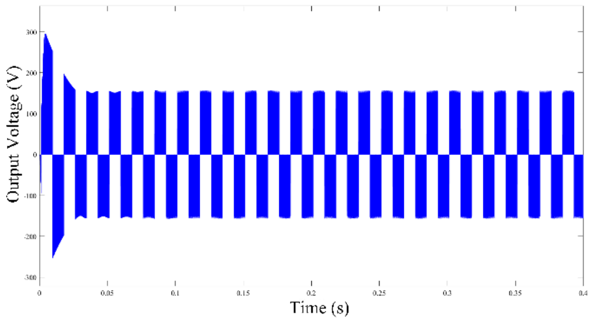


Fig. 5 Output voltage of ∑ZSI.

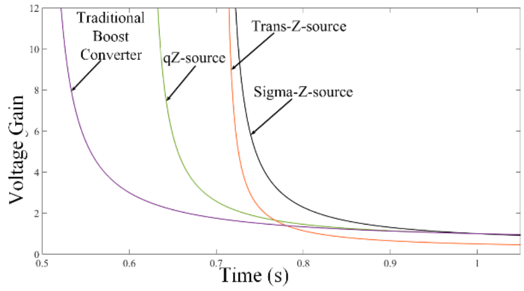


Fig. 6 Voltage gain comparison.

4.2 System Response

The proposed system is simulated in Simulink and the proposed results are shown for:

i. Output voltage	ii. Output current
iii. Active Power	iv. Reactive Power
v. DC bus voltage	vi. Speed in rpm

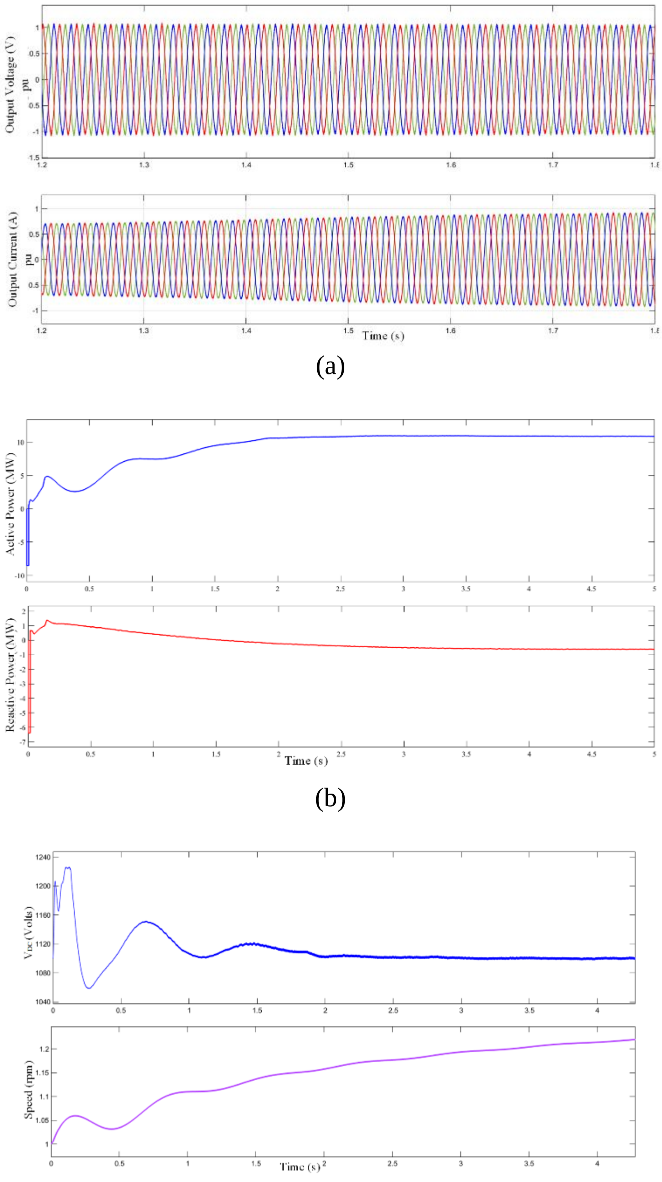


Fig. 7 Output waveforms: (a) voltage-current, (b) PQ, (c) V_{dc}-speed.

Simulation results, as shown in Fig. 7, have shown that the inverter connected to the grid need not balance the dc-link capacitor voltages, and this enables a simplified control scheme for the inverter. When the wind speed changes, the power and the voltage of the wind turbine also changes. With the increase in wind speed, the output power and output voltage also increase. Compared to conventional wind power generation systems integrated with a boost converter, the reliability of the system is improved in the case of ∑ZSI fed system, because there is no requirement for dead time in a Z-source inverter.

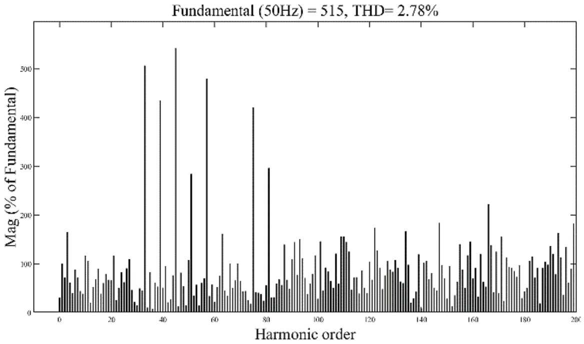


Fig. 8 Harmonic spectrum of output current.

The low switching frequency operation of the proposed system is promising and the harmonic spectrum of the output current, as shown in Fig. 8, are within the IEEE Standard limits. It is shown that a significant improvement in the grid-power quality has been achieved even with the lower switching frequency operation.

5 Conclusion

An efficient and low-cost impedance network, called sigma-Z-source, is designed and implemented with the grid for the wind power generation system. It facilitates a high dc output across the inverter module connected to the grid. The design parameters are thoroughly derived, and the performance of the system is analyzed with simulation studies. With the proposed modulation scheme and control strategy, the drop in voltage between generator and sigma-Z-source-inverter (∑ZSI) is compensated effectively. The grid receives a high voltage continuous ripple-free output. The proposed system is suitable for wind power generation system. The proposed topology will be extended for fault-tolerant operation for the power semiconductor switch failures in the converter-inverter system.

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