Novel three Phase Quasi Z source Multilevel Inverter Topology for Wind Turbine Driven Permanent Magnet Generator

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Abstract*—This paper presents the utilization of multilevel inverter that has been designed to reduce the circuit complexity and optimizing the use of bidirectional switches. A new three phase Quasi Z source multilevel inverter (QZS-MLI) for direct drive wind turbine generator applications has been proposed. The proposed inverter consists of an auxiliary circuit, made up of inductor and capacitor network and 5 bidirectional switches along with the full bridge inverter configuration. The proposed QZSMLI is able to produce 7 levels of staircase waveforms with only 2 shared power switches. The output voltage is similar to the conventional multilevel inverters but with less power switches and THD. A modified carrier based level shifted pulse width modulation control strategy has also been developed. The performance of the proposed inverter is analyzed through MATLAB/SIMULINK and the results are verified with experimental setup.*

Index Terms—*Permanent Magnet Generator, Quasi Z source Multilevel Inverter, Total Harmonic Distortion, Wind Turbine.*

I. INTRODUCTION

Over the past few decades, the usage of wind turbines has witnessed a significant growth in electric power generation [1]. Furthermore, the variable speed system with the advantages of less mechanical stress, reduced noise, good power quality and ability to extract maximum power from the wind overcomes the fixed speed system. Induction generators have been commonly used for wind energy conversion systems. In spite of its advantages like robust and inexpensive, they need excitation and excitation controller for its suitable operation [2]. The capacitors are bulky, expensive and space consuming.

When compared with conventional gear box coupled wind turbine generators, direct drive generator systems becomes more attractive with the advantages of less weight, less noise and increased reliability [3]. However, in order to match the wind turbine speed, a direct drive generator has to be operated at low speed.

Recently, PMG has become an interesting solution for direct coupled wind turbine generator applications. The advantages of PMG include high efficiency, high energy yield and self excitation capability [4]. Due to the absence of brushes and slip rings, the PMG has a smaller physical size, less moment of inertia, high reliability and high power density per volume [5]. As the rotor circuits are made up of permanent magnets, there are no electrical losses. Among different types of PMG, it is inferred that the torque of Radial Flux Permanent Magnet Generator is higher than that of other generator topologies [6]. RFPMG uses less magnetic material and its cooling condition is higher than other generators.

With its enormous advantages Radial Flux Permanent Magnet generator (RFPMG) provides an increased penetration into the wind energy applications. As the PMG is directly connected to the turbine without any gear box it can be operated at very low speed [7].

The wind is always fluctuating in nature. So, the output of the generator can be held constant with the use of power electronic converters. The desired output voltage and frequency can be obtained with the help of power converters [8]-[9].

Four different nine-level single-phase inverters with coupled inductors need only two dc sources in [10]. The extended nearest level control method has been proposed for switching of these converters. Conversely, the number of coupled inductors and power switches used in this inverter will be high for higher level of output voltage which in turn increases the switching loss.

In [11] a new configuration of a three-phase five-level multilevel voltage-source inverter has been constituted from the conventional three-phase two-level bridge with three bidirectional switches. However, the number of power electronic components used for the five level inverter is considerably large and also no method is used to reduce the THD level in the output voltage.

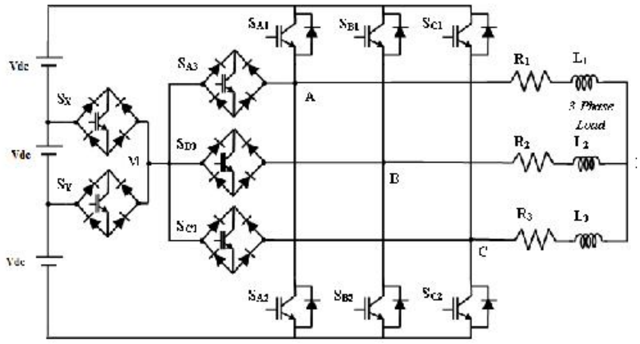


Fig.1 Eleven switch three phase multilevel inverter circuit topology

An enhanced configuration for three-phase, seven-level voltage source inverter; where there is additional auxiliary circuits which consists of six bi-directional switches has been inserted between the dc voltage source and the full-bridge power switches of the classical three-phase inverter configuration [12]. But, the proposed inverter did not have the voltage buck–boost energy conversion ability. Also, the number of power switches used in this inverter could be reduced in order to reduce the switching loss for the same output.

A new 3-phase multilevel inverter [13] that was able to generate 7 levels in line-to-line voltage with only 11 switches is shown in Fig.1. However, in the proposed multilevel inverter the output voltage amplitude is limited to DC sources voltage summation and it did not have buck boost capability.

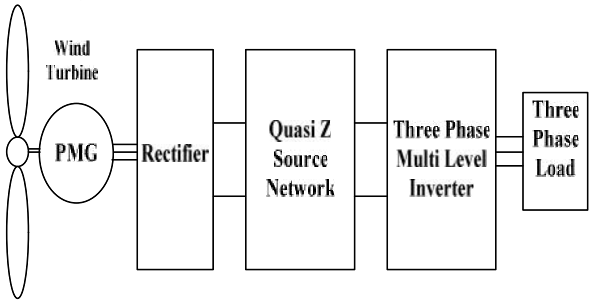


Fig.2 Proposed PMG based WECS with quasi Z-source multilevel inverter

A new topology for an enhanced-boost Z-source inverter (ZSI) with combined two Z-impedance networks is proposed in [14]. By two Z-impedance networks and low shoot-through duty cycle, the proposed inverter produces high output voltage gain. Yet, the current drawn from the dc source has been discontinuous due to the input diode and also it has greater size and cost due to extra passive components compared with the traditional ZSI.

In this paper, a novel three phase quasi z source multilevel inverter topology has been proposed for low speed wind turbine driven permanent magnet generator as illustrated in Fig.2. In this topology a dual quasi Z source network is added along with the conventional three phase multilevel inverter. Since, the short circuit across any phase leg is allowed; the reliability of the proposed system is greatly improved. The proposed topology has been simulated through MATLAB/SIMULINK and its characteristics have been analyzed.

The paper is organized as follows: Section 1 gives the description about the proposed WECS, section 2 describes the mathematical equations of wind turbine model and direct drive PMG, section 3 gives the operating principle of new three phase quasi Z source multilevel inverter topology, section 4 describes the modified carrier based level shifted PWM control strategy, section 5 presents the simulation results and discussion of proposed topology with different input and output conditions, section 6 presents the experimental results and finally section 7 gives the conclusion.

II. MATHEMATICAL EQUATIONS

A. Mathematical Equations of Wind Turbine Model

The main objective of wind turbine is to convert the wind linear motion into rotational one, which is further used to drive the shaft of the permanent magnet generator [15]. The wind turbine output power equation is given as (1),

$$P_m = \frac{1}{2} \text{®°} R^2 V_w{}^3 C_p \qquad (1)$$

Where P_m is the mechanical output power of wind turbine (W), ρ is the air density in (K_g / m^3), R is the radius of the turbine (m), V_w is the wind speed (m/s) and C_p is the wind turbine power coefficient .Tip speed ratio is the ratio of blade tip speed to wind speed [16], which is given as (2).

$$\text{a} = \frac{R \mu_t}{V_w} \qquad (2)$$

The torque value obtained by dividing the turbine power by turbine speed is given as (3),

$$T_t(V, \mu_t) = \frac{1}{2} \text{®} p R^3 C_t(\text{a}) V_w{}^2 \qquad (3)$$

The power co-efficient Cp which in turn is a function of tip speed ratio λ and blade pitch angle β (deg) is given by (4),

$$C_p(a)=\left(\frac{116}{a_1}-(0.4\ )-5\right)0.5e^{\frac{-16.5}{a_1}} \tag{4}$$

Where $$a_1=\frac{1}{\left(\frac{1}{(a+0.089\ )}-\frac{0.035}{\ ^3+1}\right)} \tag{5}$$

C_t (λ) is the torque co-efficient of the turbine, given by (6),

$$C_t(a)=\frac{C_p(a)}{a} \tag{6}$$

B. Modeling of DDPMG topology

The terminal voltage equation of the PMG may be expressed in the matrix form as,

$$[V_{abc}]=-[R_{abc}][i_{abc}]+{}^{\circ}[\cdot\ _{abc}] \tag{7}$$

The complete model of the wind turbine driven permanent magnet generator is derived in dq-coordinates [17]. The voltage equations for d and q axes in rotor reference frame are given by,

$$V_d=-R_s i_d-L_d\frac{d}{dt}i_d+\mu_r L_q i_q \tag{8}$$

$$V_q=-R_s i_q-L_q\frac{d}{dt}i_q-\mu_r L_d i_d+\mu_r\cdot\ _m \tag{9}$$

The electromagnetic torque in the rotor is given by,

$$T_e=\left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left[(L_d-L_q)i_q i_d-\cdot\ _m i_q\right] \tag{10}$$

The input torque with respect to the torque developed in the wind turbine and the rotor angular velocity of the generator μ_r is related as,

$$T_i=J\left(\frac{2}{P}\right){}^{\circ}\mu_r-T_e \tag{11}$$

III. OPERATING PRINCIPLE OF NEW THREE PHASE QZS-MLI

The proposed circuit topology as illustrated in Fig.3, consists of an auxiliary circuit made up of quasi Z source network, 5 bidirectional switches and a six switch conventional inverter configuration. Two identical quasi Z source networks [18] with three capacitors have two common connections between them. The output of the network and the two common connections will be then connected to the three phase voltage source inverters and two bidirectional switches respectively. The two bidirectional switches were shared among three phases through another three bidirectional switches.

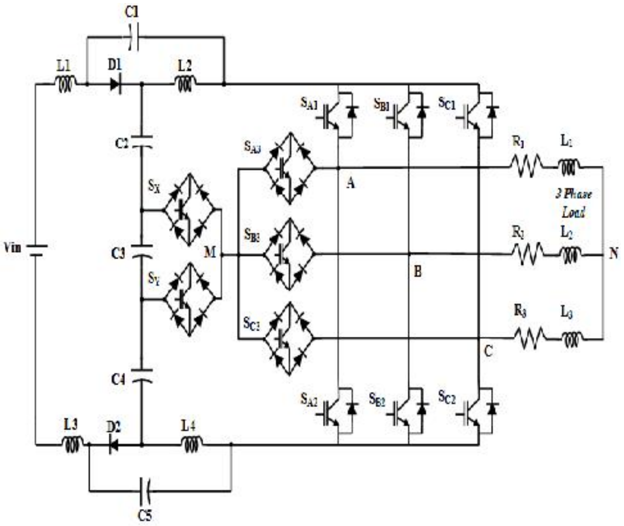


Fig. 3 Circuit of quasi Z-source multilevel inverter

The output of the inverter has seven different levels; 0, ±B. Vdc, ±B.2Vdc and ±3B.Vdc where B is the boost factor of the inverter defined as V_{DC}/V_{IN}. The fundamental period of the proposed inverter in the continuous conduction mode can be divided into 18 time intervals. Table 1.1 shows all the possible switching states of the proposed topology. The following assumptions were made for the review on the possible switching states.

- The components are identical
- Constant supply voltage
- Diode forward voltage drop is neglected.

From Table 1 it can be observed that, if the frequency of output voltage is fundamental frequency f, then S_{A1}, S_{A2}, S_{B1}, S_{B2}, S_{C1} and S_{C2} operates at the same frequency f, S_{A3}, S_{B3} and S_{C3} operates at frequency 2f and S_X and S_Y operates at a frequency 3f [19]. It can also be viewed that S_{A1}, S_{A2}, S_{A3} are used only for phase A, S_{B1}, S_{B2}, S_{B3} are exclusively utilized for Phase B and S_{C1}, S_{C2} , S_{C3} are utilized for phase C. However S_X and S_Y are shared among the three phases.

As the shoot through state causes a short circuit of the voltage source and damage to the device, it is forbidden in conventional voltage source inverters. However, the proposed topology can be operated in shoot through mode and non shoot through mode. The boost function of QZSMLI has been accomplished by applying short circuit to the dc bus periodically.

Considering all the time intervals, the behavior of the proposed system can be shown by the equivalent circuits. Fig. 4 a) shows the operation of proposed QZSMLI during shoot through state. For a shoot through time period of T_S, the switches S_{A1} and S_{A2}, S_{B1} and S_{B2}, S_{C1} and S_{C2} are turned ON simultaneously which forces diode D_1 and D_2 reverse biased and hence replaced by an open circuit. In this mode either the switches of one phase leg or all phase legs can be turned ON in order to boost the voltage with the help of energy stored in the inductors [20].

TABLE 1
SWITCHING STATES OF PROPOSED TOPOLOGY

Switching States	**Mode**	**S_{A1}**	**S_{A2}**	**S_{A3}**	**S_{B1}**	**S_{B2}**	**S_{B3}**	**S_{C1}**	**S_{C2}**	**S_{C3}**	**S_X**	**S_Y**
1	**Active**	0	1	0	0	1	0	1	0	0	0	0
2		0	0	1	0	1	0	1	0	0	0	1
3		0	0	1	0	1	0	1	0	0	1	0
4		1	0	0	0	1	0	1	0	0	0	0
5		1	0	0	0	1	0	0	0	1	1	0
6		1	0	0	0	1	0	0	0	1	0	1
7		1	0	0	0	1	0	0	1	0	0	0
8		1	0	0	0	0	1	0	1	0	0	1
9		1	0	0	0	0	1	0	1	0	1	0
10		1	0	0	1	0	0	0	1	0	0	0
11		0	0	1	1	0	0	0	1	0	1	0
12		0	0	1	1	0	0	0	1	0	0	1
13		0	1	0	1	0	0	0	1	0	0	0
14		0	1	0	1	0	0	0	0	1	0	1
15		0	1	0	1	0	0	0	0	1	1	0
16		0	1	0	1	0	0	1	0	0	0	0
17		0	1	0	0	0	1	1	0	0	1	0
18		0	1	0	0	0	1	1	0	0	0	1
19	**Zero**	1	0	0	1	0	0	1	0	0	0	0
20	**Shoot - Through**	1	1	1	1	1	1	1	1	1	1	1

Fig. 4b) and Fig 4c) shows the operation of proposed QZSMLI during active and zero state respectively. During non shoot through mode consisting of either active state or zero state, the diode D_1 and D_2 are forward biased and the energy stored in the inductor is transferred to the capacitors and load along with the dc input voltage. Thus, by varying the shoot through duty cycle the peak dc link voltage can be adjusted.

The system is modeled and the parameters considered for analysis are inductors voltages V_{L1}, V_{L2}, V_{L3}, and V_{L4} and the average voltage across the capacitors over one fundamental period V_{C1}, V_{C2}, V_{C3}, V_{C4} and V_{C5}..

The steady state analysis is performed to estimate the component's values with the help of voltage balance across the inductors and current balance across the capacitors. Hence, the average voltage across the inductors and average current across the capacitors are equal to zero [21].

$$\frac{1}{T}\int v_{L1}(t)dt = 0; \frac{1}{T}\int i_{c1}(t)dt = 0 \tag{12}$$

The converter switching period in continuous conduction mode T is given as

$$\frac{t_A}{T} + \frac{t_Z}{T} + \frac{t_S}{T} = D_A + D_Z + D_S = 1 \tag{13}$$

Where D_A is the duty cycle of Active state, D_Z is the duty cycle of zero state, and D_S is the duty cycle of Shoot through state. The fundamental switching period T is the sum of switching periods of active state t_A, zero state t_z and shoot through state t_S.

The sum of the capacitor voltages decides the peak value of the DC link voltage:

$$V_{DC} = V_{C1} + V_{C2} + V_{C3} + V_{C4} + V_{C5} \tag{14}$$

Assuming quasi Z source network is symmetrical i.e both the inductance and capacitance in the quasi Z source network is identical, then we have

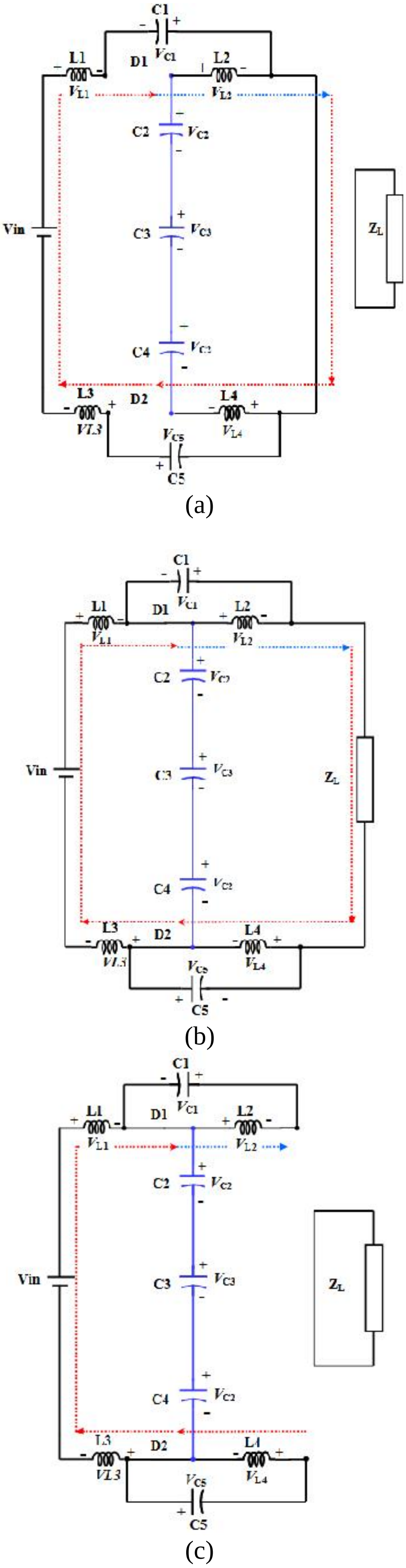
$$L_1 = L_3,\ L_2 = L_4$$
$$C_1 = C_5,\ C_2 = C_3 = C_4 \tag{15}$$

The voltages are accordingly represented as

$$V_{L1} = V_{L3},\ V_{L2} = V_{L4}$$
$$V_{C1} = V_{C5},\ V_{C2} = V_{C3} = V_{C4} \tag{16}$$

From the voltage balance across the inductors, the capacitor voltages can be found as,

$$V_{L1} = \frac{1}{T}\int v_{L1}(t)dt$$
$$= \frac{1}{T}\left(\left(\frac{3}{2}V_{C2} - \frac{V_{IN}}{2}\right)t_A - \left(V_{C1} + \frac{V_{IN}}{2}\right)t_S\right)$$
$$= \left(\left(\frac{3}{2}V_{C2} - \frac{V_{IN}}{2}\right)D_A - \left(V_{C1} + \frac{V_{IN}}{2}\right)D_S\right) = 0 \tag{17}$$



(a)

(b)

(c)

Fig. 4 Equivalent circuits of quasi Z-source multilevel inverter a) Shoot through state b) Active State c) Zero state

$$
\begin{aligned}
V_{L2} &= \frac{1}{T}\int v_{L2}(t)dt \\
&= \frac{1}{T}\left(V_{C1}.t_A - \frac{3}{2}V_{C2}.t_S\right) \\
&= \left(V_{C1}.D_A - \frac{3}{2}V_{C2}.D_S\right) = 0
\end{aligned}
\qquad (18)
$$

By considering the conditions presented above, the voltage across the capacitors is given as

$$
\begin{aligned}
\boldsymbol{V_{C1}} &= \boldsymbol{V_{C5}} = \frac{\boldsymbol{V_{IN}.D_S}}{2(1-2\boldsymbol{D_S})} \\
V_{C2} &= V_{C3} = V_{C4} = \frac{V_{IN}(1-D_S)}{3(1-2D_S)}
\end{aligned}
\qquad (19)
$$

The expression for boost factor can be obtained as,

$$B = \frac{V_{DC}}{V_{IN}} = \frac{V_{C1}+V_{C2}+V_{C3}+V_{C4}+V_{C5}}{V_{IN}} = \frac{1}{1-2.D_S} \qquad (20)$$

The possible range of D_s is from 0 to 0.5 and hence B varies from 1 to infinity. When D_s is zero, then the converter works in buck mode [22]. The proposed topology of converter can be operated in both stand alone mode and grid connected mode. In spite of the fluctuating nature of wind, the output phase voltage is to be maintained constant. The boosted multilevel phase to neutral voltage available at the inverter is derived as:

$$\mathrm{V_o} = \mathrm{M}\frac{\mathrm{V_{DC}}}{2\sqrt{2}} = \frac{\mathrm{V_{IN}}}{2\sqrt{2}(1-2\mathrm{D_S})} \qquad (21)$$

The range of modulation index is given as $M \leq 1\text{-}D_S$ [20] and so the relationship between the input voltage and shoot through duty ratio D_S are

$$\mathrm{V_o} = \frac{(1\text{-}\mathrm{D_S})\mathrm{V_{IN}}}{2\sqrt{2}(1-2\mathrm{D_S})} \qquad (22)$$

IV. MODIFIED CARRIER BASED LS-PWM CONTROL STRATEGY

To enhance the growth of multilevel inverters many new modulation strategies has been developed. In order to be used in high power converters, the multilevel inverters are to be employed with modulation schemes that have the merits such as high power quality and low switching frequency.

The modulation methods used in multilevel inverter is mostly multi carrier pulse width modulation techniques. The carriers can be arranged with horizontal shifts called phase shifted PWM and vertical shifts called level shifted PWM. Even though these high frequency modulation methods results in less harmonic distortion, it causes high switching losses, which is to be avoided in high power applications.

Fig.5 shows the new Level shifted PWM in phase disposition for three phases quasi Z source multilevel inverter using a frequency modulation index equal to 4. Three phase reference signal were compared with two triangular carriers to obtain the required pulses for the proposed topology [23]. Through this operation, different voltage levels are obtained.

The shoot through states were generated by comparing a double frequency carrier signal with a constant value Ds. Hence, due to the insertion of shoot through state, the output average phase to neutral voltage is modified. The upper and lower carriers are adjusted to Ds/2 in order to maintain the constant output average voltage. Due to this mode of operation, a uniformly distributed shoot through states are achieved at the output voltage.

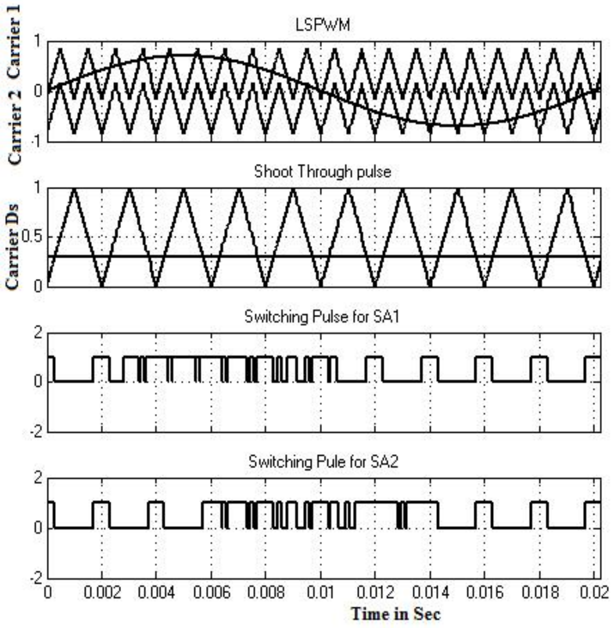


Fig.5 New Carrier based LS-PWM Control Strategy

Also, since double switching frequency shoot through states was generated, passive components used could be reduced. It is concluded that the proposed topology can be operated at low switching frequency due to which the losses were minimized. The output voltage has been boosted with the shoot through state of quasi Z source multilevel inverter.

V. SIMULATION RESULTS AND DISCUSSION

Detailed simulation of the PMG based WECS with three phase QZS-MLI has been simulated in MATLAB/SIMULINK and modified carrier based level shifted PWM technique is used to control its operation. The simulation results of PMG output voltage, rectifier voltage, capacitor voltage, %THD and inverter voltage are presented at different wind speed. The system parameters are listed in Table 5.1.

Table 5.1 SYSTEM PARAMETERS

Parameters	***Values***
Power rating	*1kW*
Output frequency	*50Hz*
Inductors (L_1 to L_4)	*160mH*
Capacitors(C_1 to C_5)	*470uH*
Switching Frequency (fs)	*1kHZ*

The wind turbine speed, PMG output voltage and rectifier output voltage for wind speed of 5m/s is shown in the Fig.6. The output voltage and current are expected to be sinusoidal thus the modeling approach of the generator has been validated.

The ac input voltage of 120V is fed as input to the rectifier which in turn given as input to the three phase QZS-MLI which is operated at the switching frequency of 1 kHz.

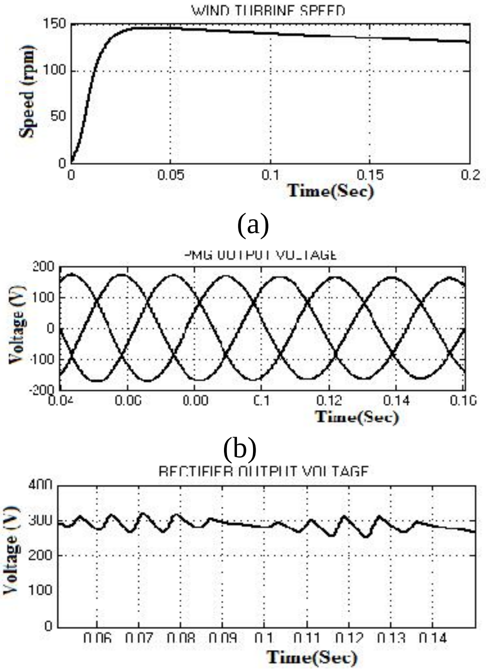


Fig.6 (a) Wind Turbine Speed (b) PMG output Voltage and (c) rectifier output voltage for Wind speed of 5m/s

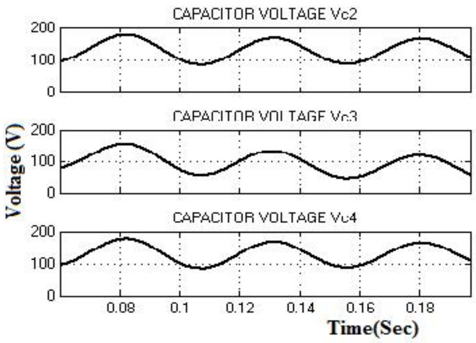


Fig. 7 Simulations of voltage across capacitors

Fig.7 shows the capacitor voltages which are connected in series across the input voltage. Fig 8 shows the Simulation results of Phase Voltages of QZS-MLI for M=0.6 and Ds=0.4. The output voltage of the proposed inverter has seven levels. From Fig 8, it is observed that the output current is in phase with the output phase voltage.

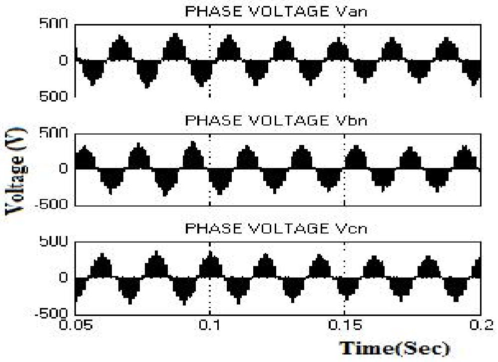


Fig. 8 Simulation results of Phase Voltages of QZSI-MLI for M=0.6 and Ds=0.4 without filter

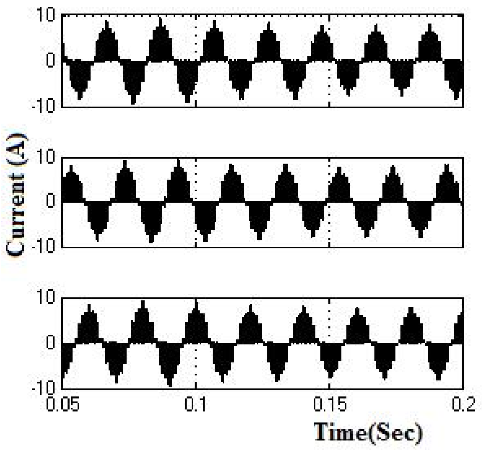


Fig. 9 Simulation results of Phase Currents of QZS-MLI for M=0.6 and Ds=0.4 without filter

The output phase voltage is boosted to a maximum of 213V with the load current of 5A as shown in Fig 9. Fig 10 shows that the THD of phase voltage is about 9.14%. From the THD profile, it is observed that the seventh harmonic component is more predominant.

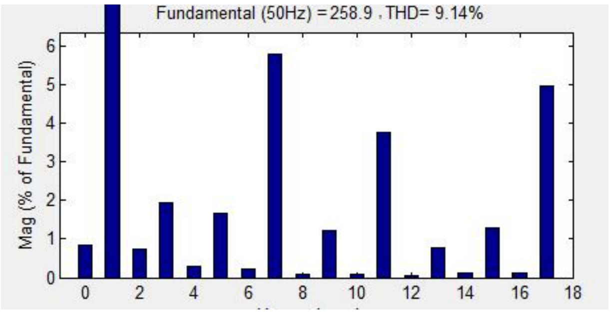


Fig. 10 THD of output phase voltage without filter

Fig. 11 shows the line voltage of the proposed inverter of about 367V and the THD value of 9.01% as in Fig.12 without filter.

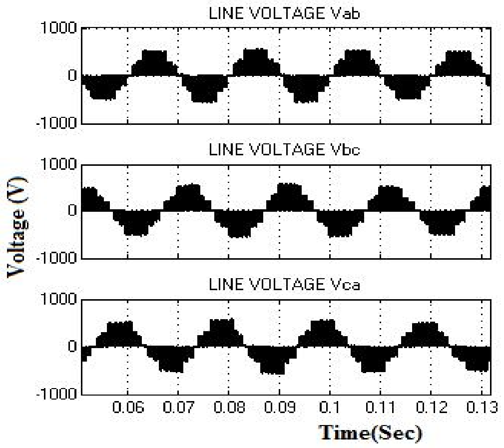


Fig 11. Simulation results of line to line voltages of QZSI-MLI for M=0.6 and Ds=0.4 without filter

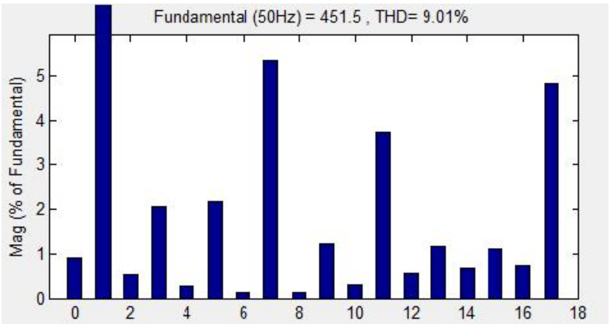
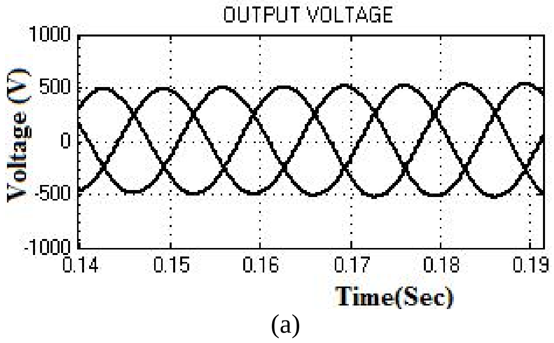
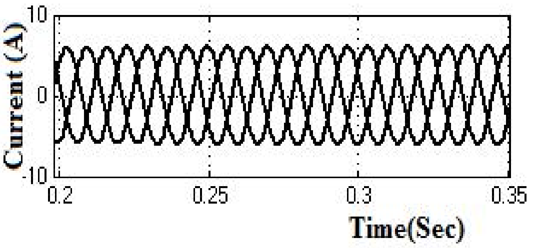


Fig.12 THD of output line voltage without filter



(a)



(b)

Fig 13. Simulation results of (a) line to line voltage and (b) line to line current of QZSI-MLI for M=0.6 and Ds=0.4 with filter

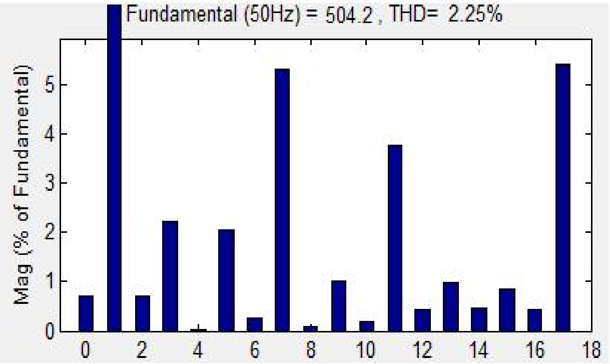
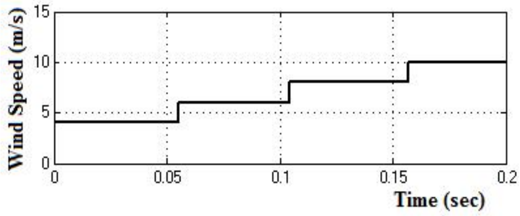


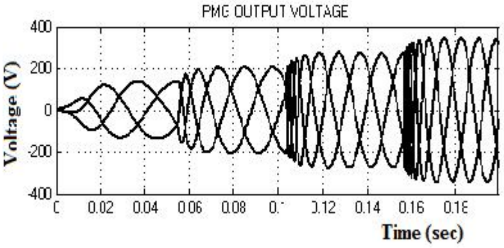
Fig.14 THD of output line voltage with filter

Fig. 13 shows the line voltage of the proposed inverter of about 356V with the THD value of 2.25 % as in Fig.14.

Fig. 15 shows the simulation results of three phase QZS-MLI with a step change in wind speed such as 4m/s, 6m/s, 8m/s and 10m/s. For the average wind speed of 6 m/s the corresponding turbine speed is 156 rpm, PMG output voltage is 141V and rectifier output voltage is 385V. The variation in wind speed influences the corresponding change in the parameters like PMG output voltage, rectifier output voltage and voltage across the capacitors.



(a)



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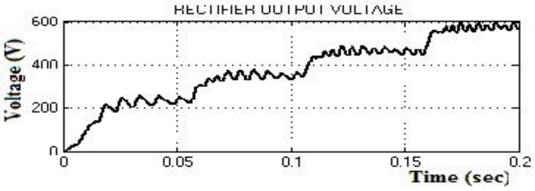
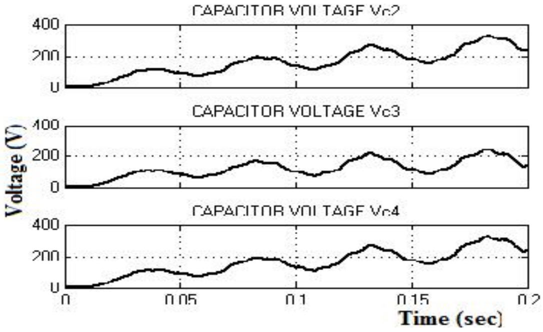
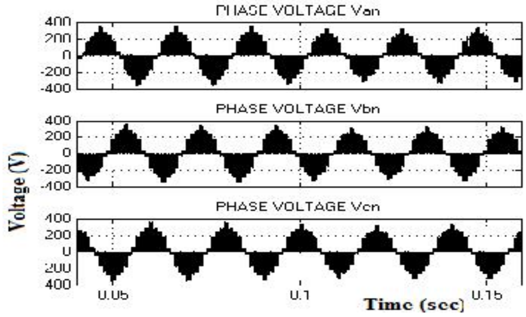


(c)



(d)



(e)

Fig.15 Simulations results of Three Phase QZS-MLI with a step changes of wind speed (a) Wind Speed Variation (b) PMG output Voltage (c)Rectifier output voltage (d) Voltage across the capacitors (e) three phase output voltage of proposed inverter

Irrespective of the variation in wind speed, the output phase voltage of three phase QZS-MLI has to be maintained constant at 230V. This has been achieved by calculating the error voltage between PMG input voltage and the output voltage of inverter and is fed to the controller in order to adjust the shoot through duty ratio and modulation index of level shifted PWM for obtaining constant output voltage. By varying the constant value, Ds/2 of level shifted PWM technique, the shoot through duty ratio of QZSMLI can be adjusted,

VI. EXPERIMENTAL RESULTS

To validate the performance of the new modulation technique and inverter in real time, an experimental set up is constructed and the algorithm is implemented on a TMS320F28335 DSP comprising logic, driver and power circuit. Fig.16 shows the experimental setup of three phase quasi Z source Multilevel Inverter.

The inverter consist of 11 IGBT power switches of voltage rating 600V, gate driver circuits and QZS network with capacitors and inductors of same value as simulation. There are five bidirectional switches and each of them consists of four hyper fast diodes and one IGBT. The input voltage that is given to the proposed inverter is varied to get the desired voltage by adjusting the shoot through time period of QZS network.

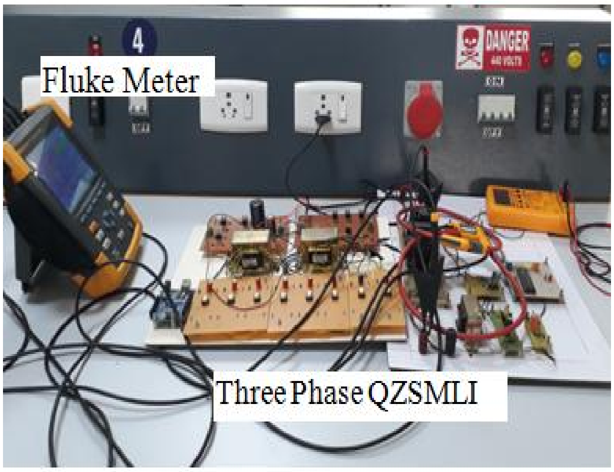


Fig. 16 Experimental Setup of three phase QZS MLI

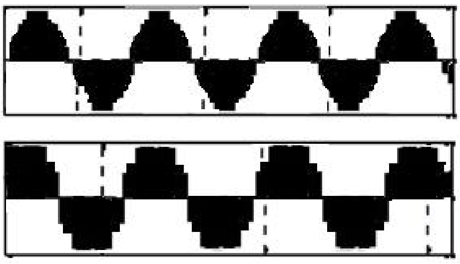


Fig.17 Experimental Phase and Line Voltages of quasi Z-source multilevel inverter

Fig.17 shows the experimental phase and line voltage of the proposed three phase quasi Z source multilevel inverter. From the input voltage, desired output voltage and frequency can be obtained by varying the shoot through time period of QZSI. The satisfactory performance of the inverter has been demonstrated and the effectiveness of the modulation method has been verified.

VII. CONCLUSION

This paper has presented a new topology from the family of buck boost inverters – the three phase quasi Z source multilevel inverter for wind turbine driven PMG. The proposed topology produces an output voltage of seven levels with two bidirectional switches. The proposed topology coalesces the merits of both QZSI and three phase multilevel inverter topologies as single stage power conversion, minimum voltage stress, and capability to withstand short circuit, and low THD of output current and voltage.

A modified carrier based level shifted modified pulse width modulation for eleven level topology with the distributed shoot though period was used. The simulation has been done using MATLAB/SIMULINK and the results are analyzed in detail. The experimental prototype model has been developed and the results are verified with modified carrier based level shifted modulation technique for various input voltage levels.

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