REDUCTION OF HARMONICS IN A WIND POWER CONVERSION SYSTEM BY THE OPTIMAL FUNCTION OF A VIENNA RECTIFIER AND SWITCHED INDUCTOR Z SOURCE INVERTER

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Abstract

This paper proposes the performance of Vienna rectifier and switched inductance Z-source inverter for boosting the output voltage and enhances the power quality of wind energy conversion system (WECS). A three-phase rectifier and a voltage source inverter are used for AC/DC/AC conversion in the conventional method and a separate DC/DC boost converter used to boost the voltage. The proposed method, Vienna rectifier and switched inductance z source inverter are employed for AC/DC/AC conversion and boost the output voltage of wind energy conversion to the required level without using an additional DC-DC converter. The PI control method is used for Vienna rectifier (VR) to increase the quality of rectifier output and simple boost technique is used in switched inductance z source inverter (SLZSI) to boost the voltage and to improve the quality of the system. The proposed method uses less number of switches to increase the output voltage. The proposed system provides good performance which increases the quality and reduces the Total Harmonic Distortion (THD) and cost. The proposed system is simulated using simulation software and performance is validated by simulation and experimental results.

Key words: *Wind Energy Conversion System, Vienna rectifier, Switched inductance z source Inverter, Total Harmonic Distortion.*

I. INTRODUCTION

Renewable energy sources such as solar, wind, geothermal and hydropower can give sustainable energy. Among them, wind energy is the efficient power generation system in the fastest developing non-conventional energy sources because it is inexhaustible and removal of harmful emissions is possible [1]. In Wind Energy Conversion System (WECS), variable speed wind turbine system needs to get maximum power under various wind conditions when compared to fixed speed wind turbine system. The drawback of fixed speed wind turbine system is transmitting all fluctuations of wind speed into variations of mechanical torque, which leads to large variation in output voltage [1,2]. To overcome the drawback, variable speed wind turbine design uses power electronic converter topology to provide a constant voltage and also reduces the issue of harmonic distortion in output voltage. The variable speed wind turbine system with power electronic converter topology has the following advantages: torque fluctuations are not passed on to the grid, less mechanical stress, while the rotor speed is below the rated speed, which is controlled to obtain maximum efficiency [3,4].

The variable speed WECS accuracy can also be increased considerably by Permanent Magnet Synchronous Generator (PMSG). The PMSG has more convenient than the other type of generators such as the ability of self-excitation, effective operation and simple structure [4,5].

In WECS, the extracted power from wind is delivered to load with high quality which is done by power converter used in both generator side and the load side [6]. A three-phase rectifier and three phase inverter (Voltage source Inverter) are traditionally used topologies on generator side and load side of WECS which is shown in fig. 1. Although the three-phase rectifier has reliable advantages, however, the following disadvantages (1) an additional boost converter is involved to boost the DC voltage (2) cost of the system increases due to additional power stage conversion (3) forces more stresses on the switching devices which decrease the efficiency of the system. In order to rectify the above disadvantages, Vienna rectifier is utilized on the generator side of WECS [6]-[10].

The Voltage Source Inverter (VSI) is widely used on the load side of WECS. But it has the following limitations. (1) The upper and lower switching devices of every phase leg cannot be gated on at the same time. Otherwise, shoot through would take place and damage the device. (2) The major killer of converter's reliability is misgating on the devices by shoot through problem. Z Source Inverter (ZSI) has overcome these problems. The ZSI can produce the buck - boost voltage by unique topology [11, 12].

ZSI needs high duty ratio (D) to offer high boost factor for the practical applications. The higher value of the duty ratio provides the low value of modulation index [13,14,15]. Due to this reason, the ZSI not gives the sufficient boost ability with good THD value. To solve the above problem, switched inductance Z Source Inverter used. The boost factor of SLZSI has been improved from 1/ (1-2D) to (1+D) / (1-3D) which raises the boost ability with low THD value and power quality of the system [16,17,18]. The combination of Vienna rectifier and switched inductance z source inverter topology makes a new group of power electronic converter topology which is proposed in this paper.

This proposed topology is well suited due to its ability to meet the power quality associated with lower harmonic distortion and high voltage applications. It produces more efficiency when compared to conventionally used converters. In this paper, the proposed topology consists of a Vienna rectifier (VR) and switched inductance z source inverter (SLZSI). The generator side converter is Vienna rectifier. It is the three phase / three switch, boost rectifier which boosts the conversion of AC-DC voltage. It produces three voltage levels only with three switches which decrease the blocking voltage strain on the switches, simplifies the control and reduces the cost. In addition, it enhances the power quality and improves the reliability of WECS. The load side inverter is switched inductance Z source inverter.

The switched inductance Z source inverter performs as a boost inverter with excludes the effect of DC-DC bridge inverter due to its unique circuit topology.

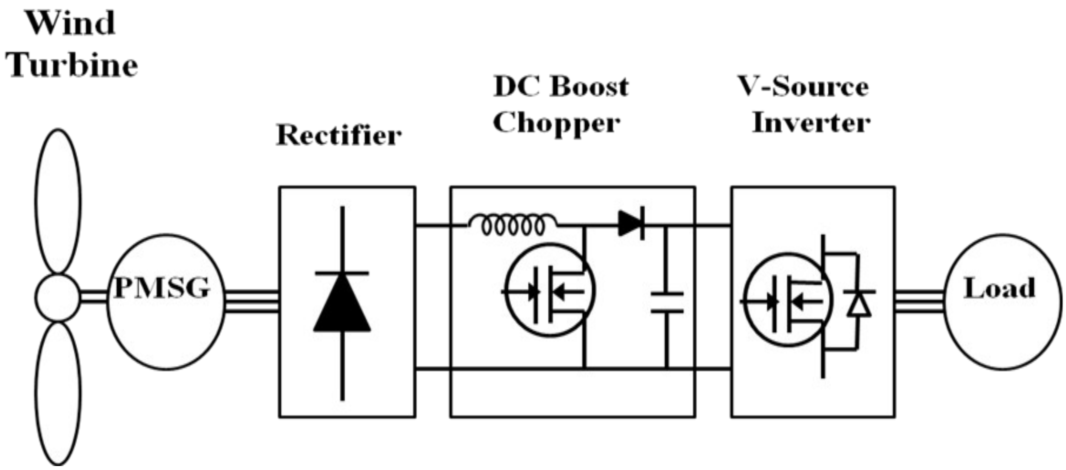


Fig. 1. Conventional WECS with DC boost chopper

It produces a high boost voltage by adding switched inductor structure with z source inverter. The operation of the proposed power electronic converter is discussed in section II. Section III discusses the result and the THD value which is compared to conventional systems. The proposed system produces a high boost voltage with less number of switches which decreases the cost and control difficulty and also improves the efficiency and power quality.

II. System Description

The system description discusses about the operation and control technique used in Vienna rectifier and Switched inductance Z source inverter. Vienna rectifier converts the output voltage of the generator into DC and also boosts the DC voltage. The output voltage of Vienna rectifier is again boosted by switched inductance Z source inverter and then boosted voltage applied to the load. In the proposed method, the voltage is boosted by both converter and inverter, so it is used for reducing the voltage sag and step up voltage applications without using a transformer. The proposed WECS with new grouping power electronic converter topology is shown in fig. 2.

A. Vienna Rectifier operation

Vienna rectifier is an unidirectional rectifier. It is a three switch / three phase PWM rectifier. The phase voltage of each phase is decided by selecting on/off position of the switches and phase current direction. The switches jointly with input inductance and diode generate the boost converter system. The DC link capacitor is split into two parts with equal values. The switching position of vienna rectifier is controlled by PI control technique.

Whereas the phase current is +ve,

$$V_K = \begin{Bmatrix} +\frac{V_O}{2} & S_k = 0 \\ 0 & S_k = 1 \end{Bmatrix} \tag{1}$$

While the phase current is -ve,

$$V_K = \begin{Bmatrix} -\frac{V_O}{2} & S_k = 0 \\ 0 & S_k = 1 \end{Bmatrix} \tag{2}$$

Vienna rectifier contains three input inductors (L_1,L_2,L_3), i_k (k = a,b,c) is input phase current, V_K (K =A, B, C) is the phase voltage, Controlled switch is S_k (S_k = 0 indicates off state and S_k = 1 indicates on state). The fig. 3 shows the time deviation of phases voltages v_a, v_b, v_c and phase currents i_a, i_b, and i_c.

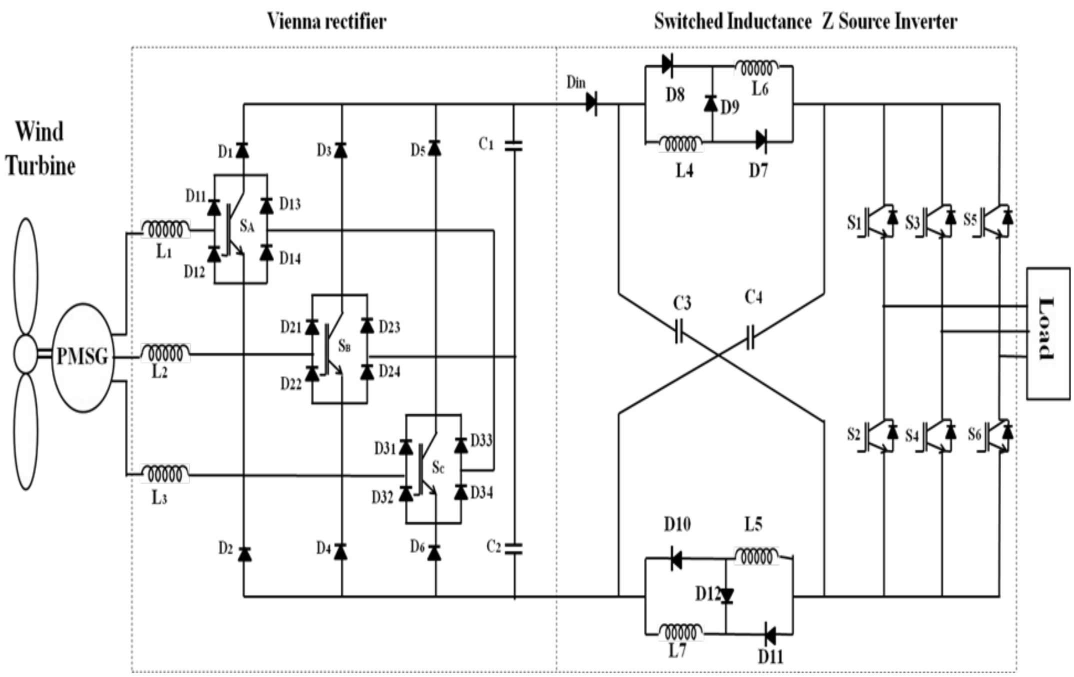


Fig. 2. Proposed WECS with VR-SLZSI

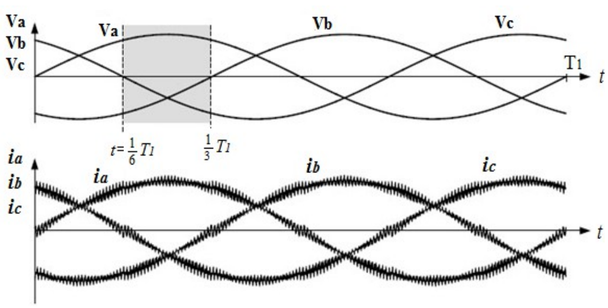
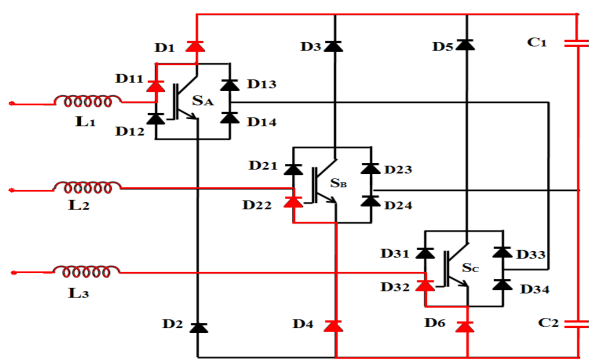
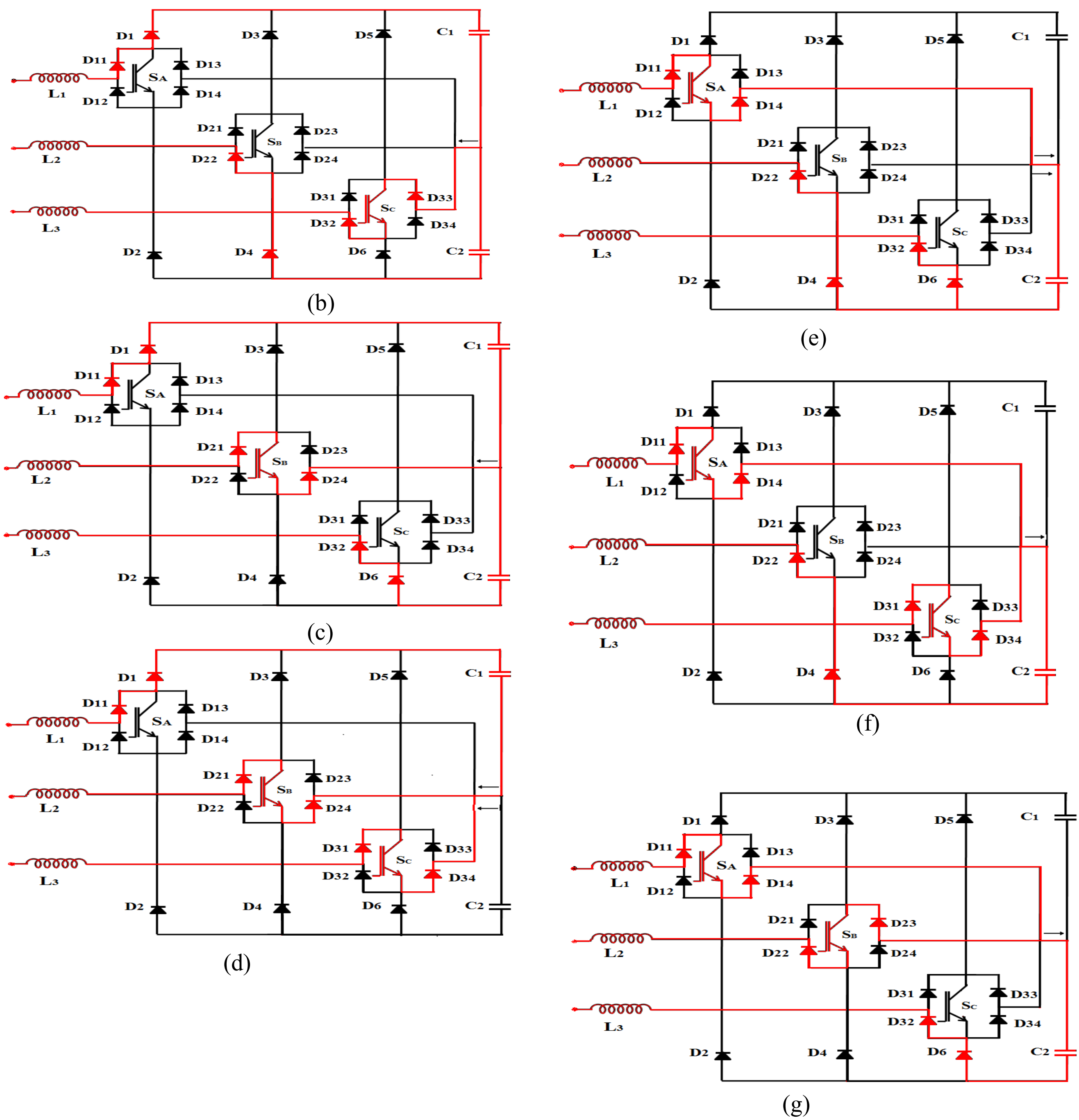


Fig. 3. Three phase voltage and Current waveform



(a)

The darkened section of fig. 3 shows the phase voltage Va is +ve and V_b, V_c are -ve. Fig. 4 shows the operating position of Vienna rectifier, for i_a>0, i_b, i_c<0. The arrow specifies the physical direction of the current.


D1
D3
D5
C1
D11
D13
SA
L1
D12
D14
D21
SB
D23
L2
D22
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SC
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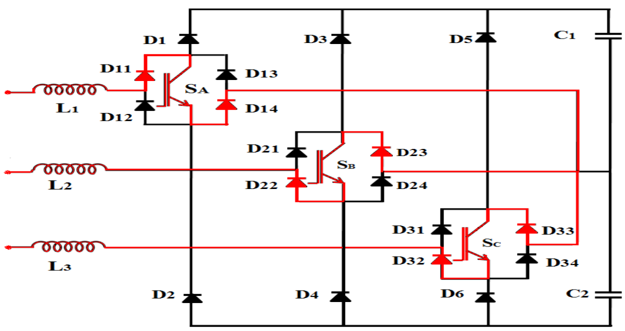

(h)

Fig. 4. Vienna rectifier operating position

The table 1 shows the switching positions of the Vienna rectifier for i_a is +ve, i_b, i_c are –ve.

Table 1 Different conducting position of Vienna rectifier

S_A	S_B	S_C	V_{AN}	V_{BN}	V_{CN}
0	0	0	+V/2	-V/2	-V/2
0	0	1	+V/2	-V/2	0
0	1	0	+V/2	0	-V/2
0	1	1	+V/2	0	0
1	0	0	0	-V/2	-V/2
1	0	1	0	-V/2	0
1	1	0	0	0	-V/2
1	1	1	0	0	0

B. Control system of Vienna rectifier

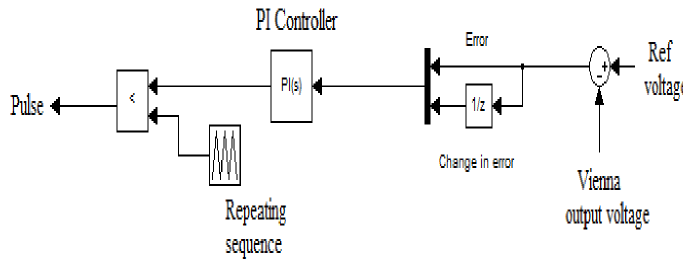

Fig. 5. Control system of Vienna rectifier

Fig. 5 shows the control system of Vienna rectifier. The Vienna rectifier output voltage is compared with the 300V reference voltage. The PI controller is used to tune the error signal which is produced by the comparator. The controller tuned pulses are given to Vienna rectifier switching devices to produce the boosted DC voltage.

C. Switched Inductor Z Source Inverter operation

The switched inductor Z source inverter topology is different from existing Z source inverter from the opinion of operation and circuit structure. As shown in fig. 6, the Switched inductance z source inverter contains four inductors (L4, L5, L6 and L7), six diodes (D7, D8, D9, D10, D11 and D12) and two capacitors (C3 and C4). The grouping of L4- L6- D7- D8- D9 achieves the function of upper SL cell. The grouping of L5- L7- D10- D11- D12 achieves the function of lower SL cell. In the switching operations of the main circuit, both cells are used to transfer and store energy from the capacitor to the DC bus.

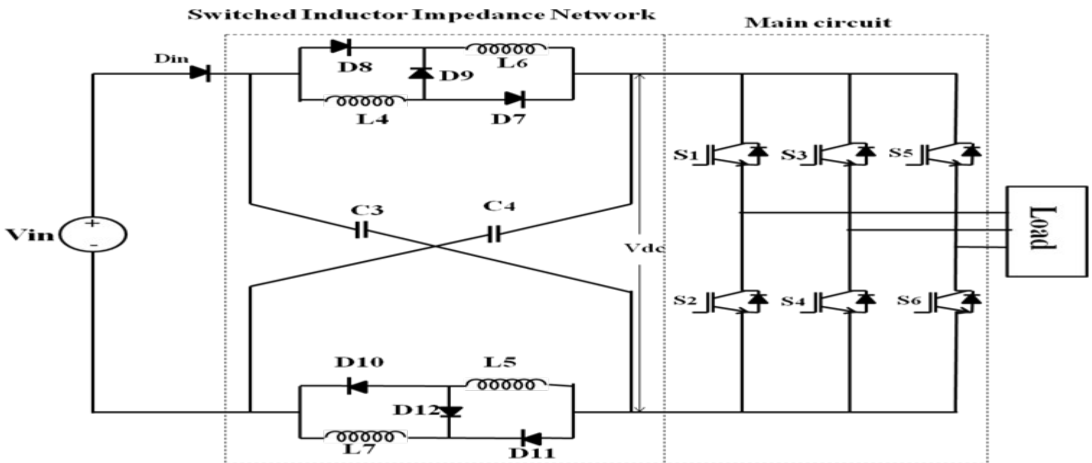

Fig. 6. Switched Inductance Z source Inverter

D. Principle of operation

The principle of operation of the proposed impedance network is similar to that of conventional Z source impedance network as per the switching functions of the main circuit. The proposed impedance network sub states are categorized into shoot through state and non shoot through state.

i) Shoot through state:

The shoot through state is generated by an extra zero state of upper and lower arms of the main circuit. The diode Din is off during this state. In the upper SL cell, D7 and D8 are ON, and D9 is OFF. L4 and L6 are charged by C3 in parallel. This state represents the extra zero state created by shoot-through events of the upper and lower arms. The equivalent circuit of a shoot through state is shown in fig. 7. The energy stored in the capacitor is absorbed by the similar function of upper and lower SL cells.

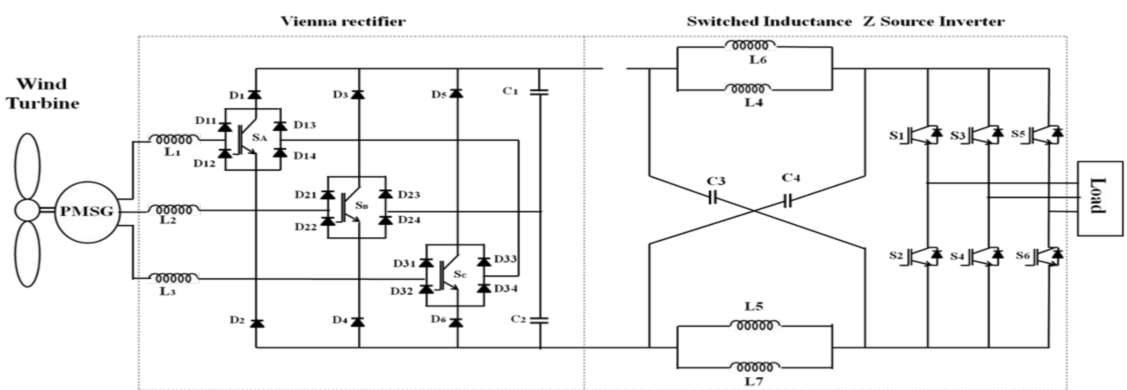

Fig.7. Shoot through zero state

ii) Non shoot through state

The non shoot through state represents the two zero states and six active states of the main circuit. During this state the diode Din is ON. The diodes D_7 and D_8 are OFF and diode D_9 will be ON for upper SL cell. L4 and L6 are joined in series, and stored energy is transmitted to the main circuit. At the same instant, C3 is charged by V_{dc} using a lower SL cell and C4 is charged by V_{dc} using the upper SL cell to increase the consumed energy of C_3 and C_4 in shoot through state. The equivalent circuit of a non shoot through state is shown in fig.8.

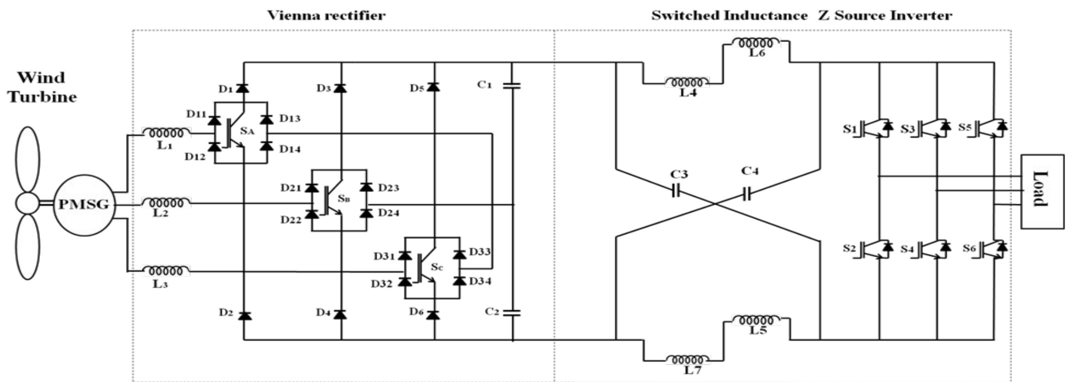

Fig. 8. Non shoot through state

D. Boost ability of SLZSI:

For the benefit of mathematical derivation, all capacitors and inductors are supposed to have equal value of capacitance(C) and inductance (L) respectively. Thus in steady state, C1 and C2 are sufficiently large, we have

$$V_{C1} = V_{C2} = V_C \qquad (3)$$

The inductor current i_{L4} rises for the duration of switching ON period and reduces for the duration of switching OFF period. For the period of switching ON, the equivalent voltage across L_4 ,$V_{L4\text{-}ON}$ which is same as to V_c. During switching OFF, the equivalent voltage across L_4, $V_{L4\text{-}OFF}$. We can get this voltage by executing the volt-second balance principle to L_4. $V_{L4\text{-}OFF}$ voltage is expressed by

$$V_{L4\text{-}OFF} = \frac{D}{1-D} V_c \qquad (4)$$

$= V_{L6\text{-}OFF}$

The inductor current i_{L6} rises for the duration of switching ON period and reduces for the duration of switching OFF period. For the period of switching ON, the equivalent voltage across L_6 ,$V_{L6\text{-}ON}$ which is same as to V_{c3} and $-(V_{c4} - V_{in} + V_{L4\text{-}OFF})$. We can get this voltage by executing the volt-second balance principle to L_6.

$$DTV_{C3} = (1-D)T(V_{C4}-V_{in}+ V_{L4\text{-}OFF}) \quad \text{or}$$

$$DTV_{in} = (1-D)\, T(V_{C4}-V_{in}+\frac{D}{1-D} V_c) \qquad (5)$$

Therefore,

$$V_c = \frac{1-D}{1-3D}$$

$$V_{in} = V_{C3} = V_{C4} \qquad (6)$$

The closed loop formed by C_3, L_4, L_6 and V_{dc} in the period of switching OFF. So, we get

$$V_c = V_{dc} + V_{L4\text{-}OFF} + V_{L6\text{-}OFF}. \qquad (7)$$

Hence,

$$V_{dc} = \frac{1+D}{1-3D} V_{in} = BV_{in} \qquad (8)$$

The SLZSI boost factor expressed by

$$B = \frac{1+D}{1-3D} = \frac{1+(T0/T)}{1-3(T0/T)} \qquad (9)$$

The fig.9 shows the curves of boost factor (B) versus duty ratio (D) of classical ZS network and SLZS network respectively. When compared to classical ZS network, the SLZS network boost factor improved significantly.

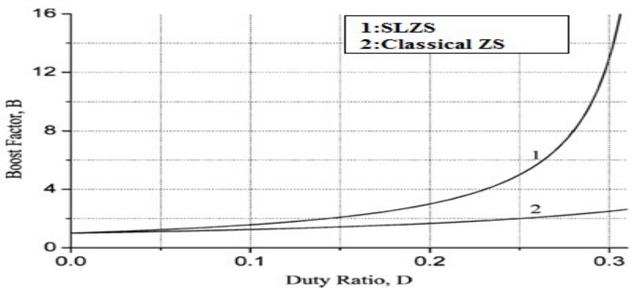

Fig. 9. Comparison of the boost ability of SLZSI network with classical ZSI network

E. Control system of switched inductance z source inverter

The fig. 9 shows the simple boost control scheme of SLZSI. In this control scheme, two straight lines are used to recognize the shoot through duty ratio (D_0). The first line is same to maximum value of three phase reference sinusoidal voltage and the second line is negative of the first line. Every time, the carrier signal of triangular wave is greater than the positive straight line or lesser than the negative straight line, the inverter will function in shoot-through or else it functions as a conventional PWM inverter. The resulting shoot through duty ratio (D_0) reduces with increasing the value of modulation index (M).

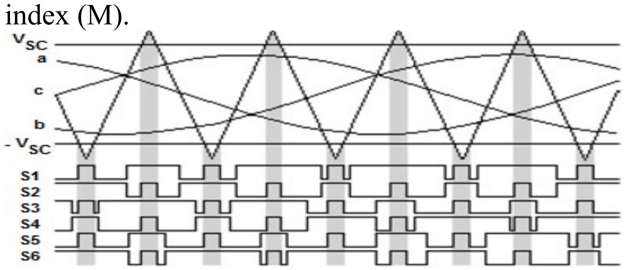

Fig. 9. Simple boost PWM

$$D_0 = 1\text{-}M \qquad (10)$$

The inverter gain,

$$G = \frac{M}{1-2D0} = \frac{M}{1-2(1-M)} = \frac{M}{2M-1} \qquad (11)$$

The gain of the inverter can be varied by changing the value of modulation index.

III. RESULT AND DISCUSSION

A. Simulation results

MATLAB/Simulink software is used to facilitate the performance of proposed topology for the Permanent Magnet Synchronous Generator (PMSG) based WECS. The proposed topology simulation diagram is shown in fig. 10. It contains wind generation, Vienna rectifier, Switched Inductance Z Source Inverter (SLZSI) and load.

Table 2 Simulation parameters of proposed system

Parameter		Value
Wind speed		12 rad/sec
PMSG output voltage (AC)		150V
Vienna rectifier output voltage (DC)		300V
SLZSI output voltage		600V
SLZSI output current		22A
Capacitor C_1, C_2	Vienna rectifier	5mF
Inductor L_1, L_2, L_3	Vienna rectifier	1mH
Capacitor C_3, C_4	SLZSI Network	800µF
Inductor L_4, L_5, L_6, L_7	SLZSI Network	1mH
Switching Frequency		10kHz

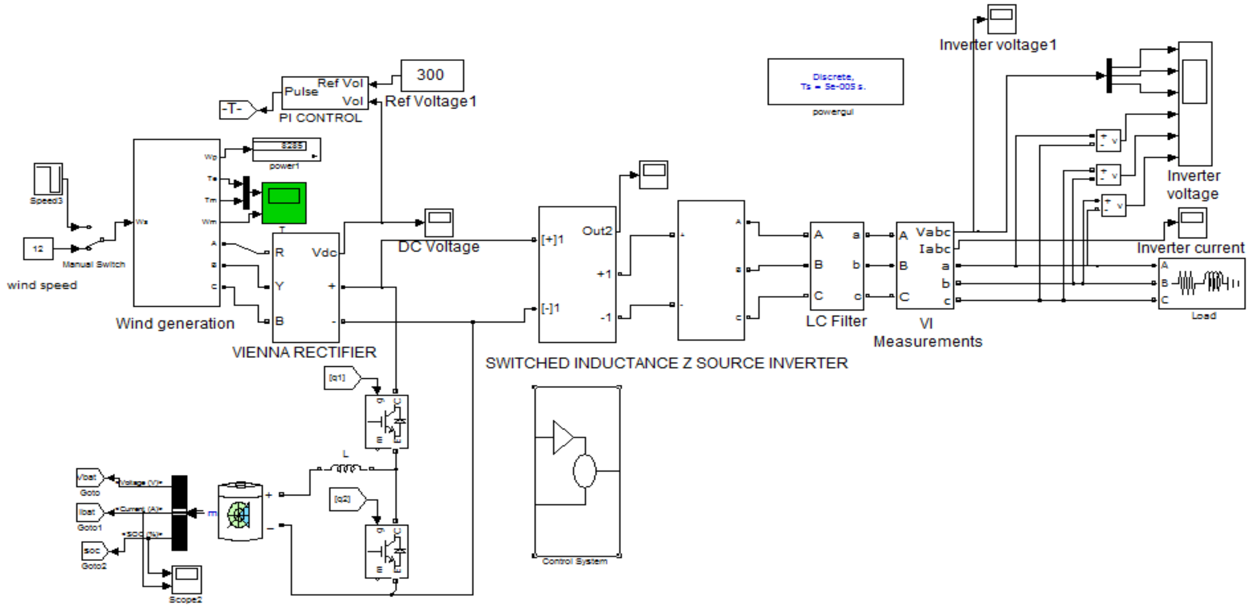

Fig. 10. Simulation diagram of SLZSI

The wind generation consists of a wind turbine and PMSG. The PMSG generates 150V, 25A AC for wind speed of 12 rad/sec which are shown in fig. 11 and fig. 12. The output voltage of PMSG is converted into DC by Vienna rectifier. The selected simulation parameters of Vienna rectifier is C_1= C_2 = 5mF and L_1 = L_2 = L_3 = 1mH and Switched Inductance Z Source Inverter is L_4=L_5=L_6= L_7 = 1mH and C_3=C_4 = 800µF. The switching frequency was 10 kHz. Table 2 shows the simulation parameters of the proposed system.

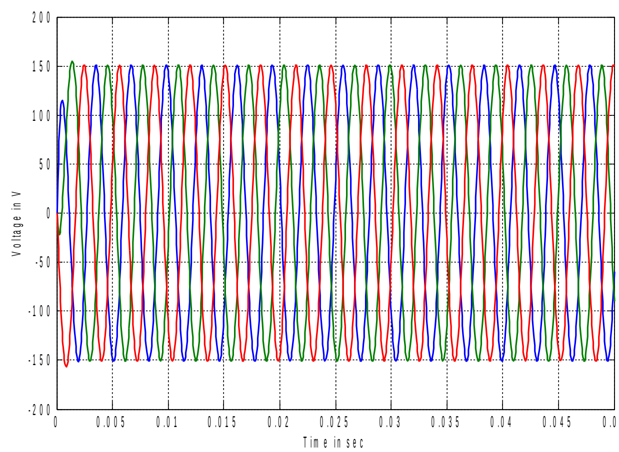

Fig. 11. PMSG output voltage

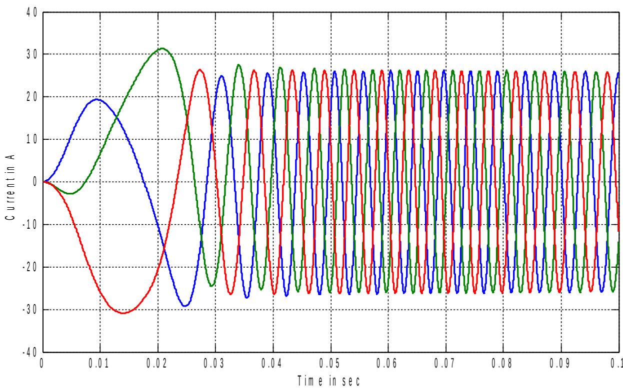

Fig. 12. PMSG output current

The Vienna rectifier converts the AC voltage to DC voltage and boosts the voltage to 300V. The vienna rectifier output voltage is shown in fig. 13. The output voltage of Vienna rectifier is again boosted by switched inductance Z source network up to the level of 600V which is shown in fig. 14. The PMSG output voltage is boosted double times by Vienna rectifier and SLZSI to reduce the voltage sag. The voltage can be boosted to the required level without using a transformer. Therefore the cost of the proposed system is reduced considerably.

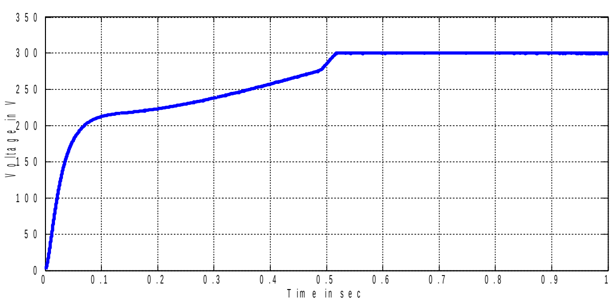

Fig. 13. Vienna rectifier output voltage

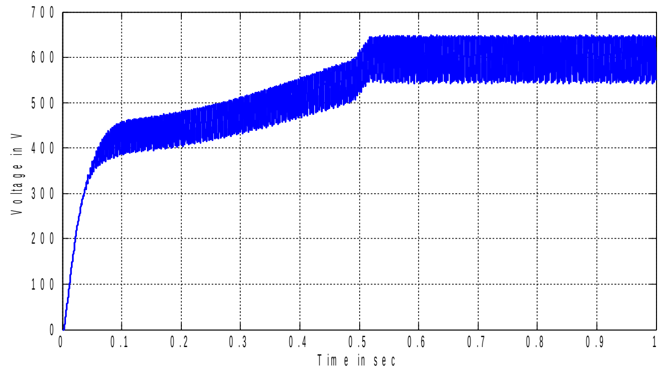

Fig. 14. Switched inductance z source network voltage

LC filter used smoothens the output of SLZSI. The fig. 15 and fig. 16 show the output voltage and current of SLZSI. The peak voltage and current values are 600V and 22A respectively.

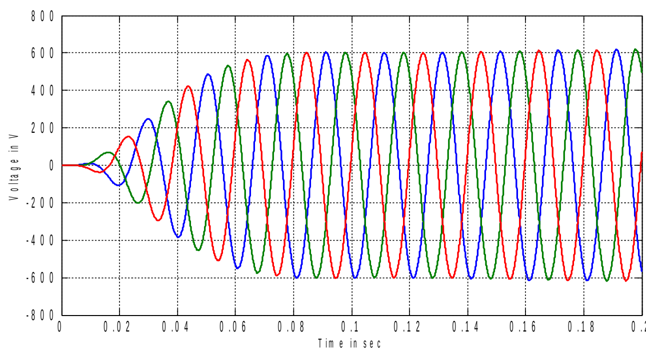

Fig. 15. SLZSI output voltage waveform

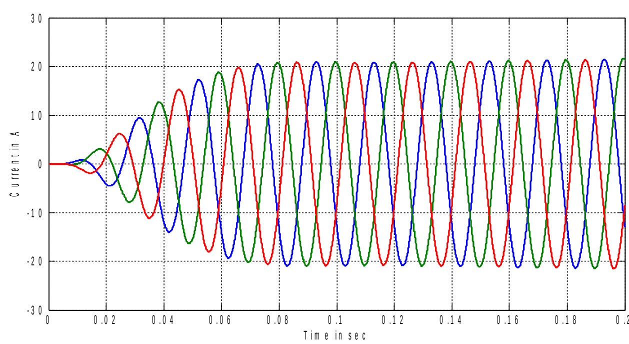

Fig. 16. SLZSI output current waveform

Figure 17 and 18 shows the load phase and line voltages of switched inductance z source inverter with modulation index 0.6 and 0.8. From this, we are clear that, if the modulation index value increases the output voltage value also increases. When the modulation index value is 0.6 the peak value of phase voltages is around 400V and line voltages around 250V. When the modulation index value is 0.8, the peak value of phase voltages is around 600V and line voltages around 450V. Table 3 presents the comparison of voltage THD of the proposed system with conventional systems. From this, we are clear that the proposed system has less THD value.

Table 3 THD comparison among conventional system and proposed system

S.No.	Topologies used in the system	No. of Switches used	Voltage THD in %
1	Voltage Source Converter jointly with Current Source Inverter	12	2.17%
2	Vienna rectifier jointly with Z Source Inverter	9	2.07%
3	Vienna rectifier jointly with Switched Inductance Z Source Inverter	9	0.35%

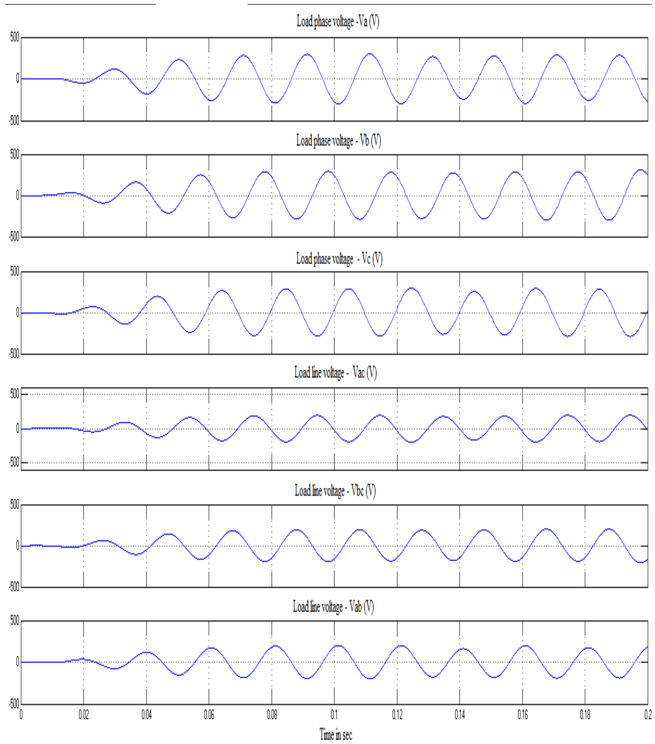

Fig.17. Load phase and load line voltages with modulation index of 0.6

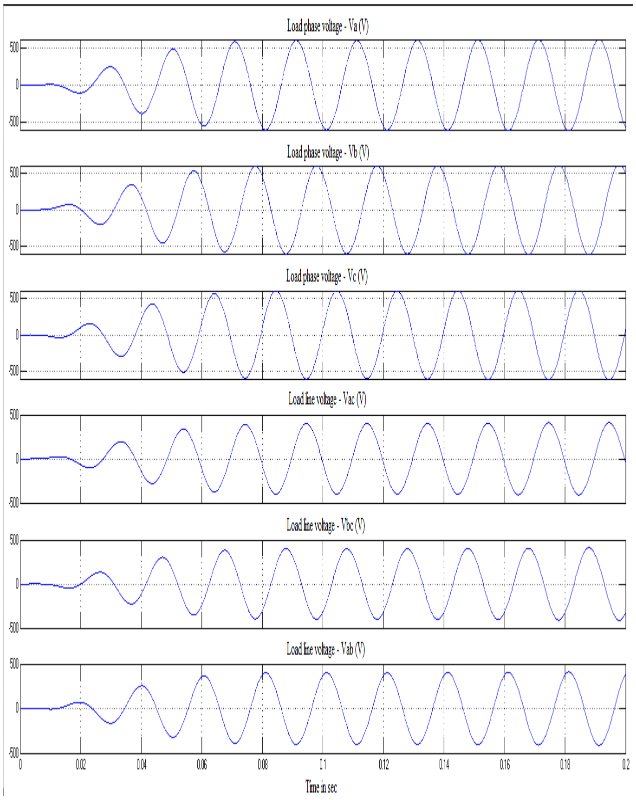

Fig. 18. Load phase and load line voltages with modulation index of 0.8

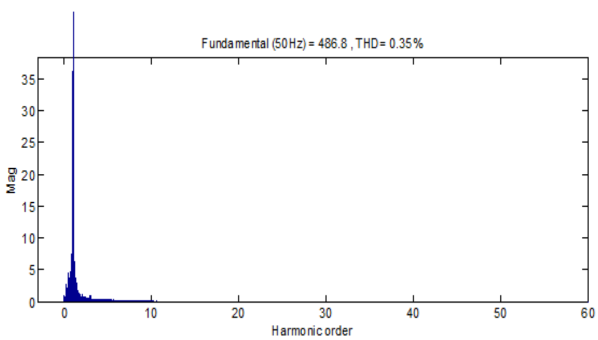

Fig. 19. Voltage FFT spectrum of proposed system

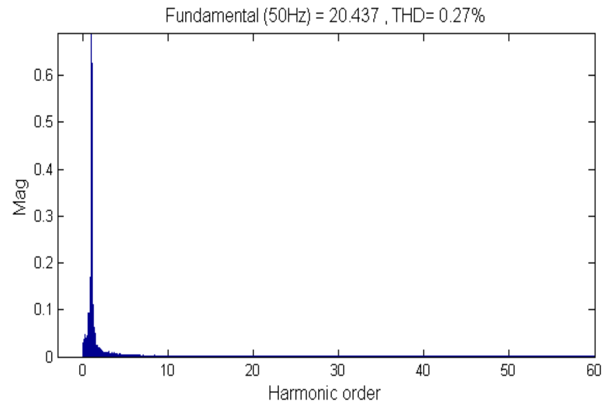

Fig. 20. Current FFT spectrum of proposed system

The voltage and current FFT spectrums of the proposed system have shown in fig. 19 and fig. 20.

B. Experiment results

The control system is executed for the prototype of the Vienna rectifier and Switched Inductance Z Source Inverter by PIC16F87U3 microcontroller. Fig. 21 shows a photograph of hardware equipment of the proposed system. On the system, the MOSFET is acting as a switching device. Instead PMSG, single phase transformers are used to give AC supply to the Vienna rectifier. The output of Vienna rectifier is 64.4V, which is shown in fig.21. The Vienna rectifier output is given to the switched inductance z source inverter, which is again boosted up to 100V. The output of switched inductance z source network is shown in fig.22. The fig.23 shows the output voltage of the SLZSI. The table 4 shows experimental requirements of the proposed system. The FFT spectrum of conventional system and proposed system are shown in Fig. 24 and fig. 25. When compared to conventional system THD value, the proposed system has less value. The proposed system has feasible performance.

Table 4 Proposed system experimental requirements

Parameter	Specification	Value

Power MOSFET	IRF840	500V,8A
MOSFET driver circuit	CLP350	2MHz,30V
Controller	PIC16F87U3	-
Diode	MUR3040	600V, 30A
Output capacitor	C_1, C_2	220µF,400V

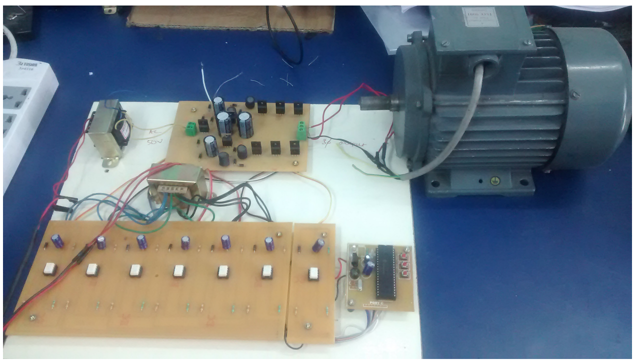

Fig. 21. Prototype of proposed system

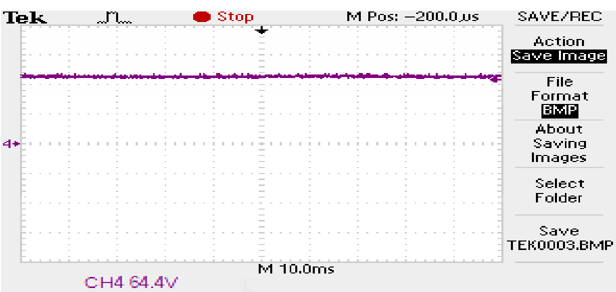

Fig. 21 Vienna rectifier output voltage

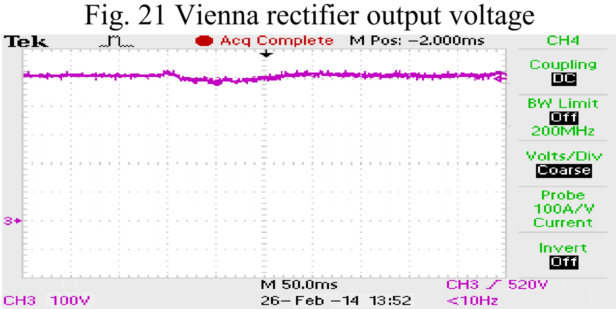

Fig. 22 Output voltage of switched inductance z source network

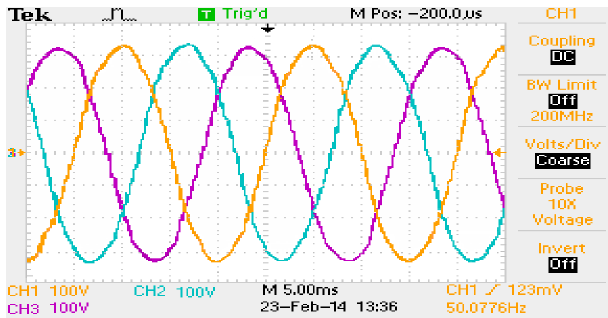

Fig.23 Output voltage of proposed system

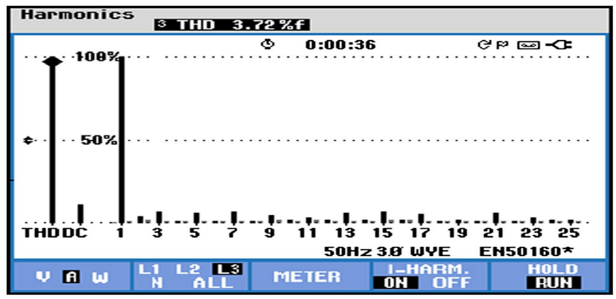

Fig. 24 Conventional system FFT spectrum

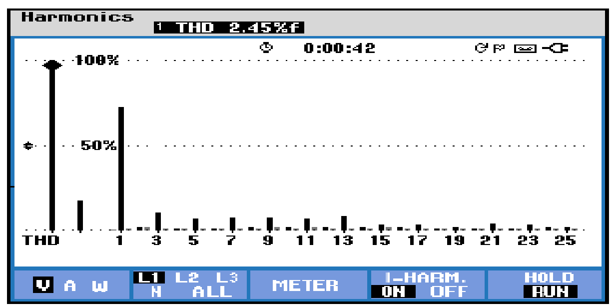

Fig. 25 Proposed system FFT spectrum

IV. CONCLUSION

The proposed Vienna rectifier and switched inductance z source inverter for PMSG based WECS have been simulated. High effectiveness of PMSG is now exposed and it obtains maximum power from the wind with high efficiency. The proposed topology produces boosted output voltage. It has very low THD value when compared to conventional topology and also has a lesser amount of switching loss. Hence the proposed system has better performance and consistency. Simulation and experimental results signifies the efficiency of the Vienna rectifier and switched inductance z source inverter for PMSG based WECS.

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