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Optimal Operation of Low Cost Topology for Improving the Power Quality in the Wind Power Conversion System

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Abstract: In this paper, Vienna rectifier and Z Source Inverter (ZSI) based Wind Power Conversion System (WPCS) has been proposed with less number of switches to provide high quality power to off grid system. The three phase full bridge converter has six switches for the conversion of AC-DC and also need separate DC-DC boost converter to boost the DC voltage. In the proposed WPCS, three Phase Vienna rectifiers have only three switches for the conversion of AC-DC and also it boosts the DC voltage. The ZSI jointly with Vienna rectifier provides higher, boosted AC voltage and high quality power to the off grid system. The ZSI utilizes the shoot-through states to boost the DC link voltage and also, reduces the Electromagnetic Interference (EMI) noise. The combination of Vienna rectifier and Z source inverter shows the good performance which improves the efficiency and reduces Total Harmonic Distortion (THD). The performance of the proposed system is simulated using MATLAB/Simulink software. Simulation and experimental results expose that, this configuration is beneficial with respect to power quality improvement with less number of switches compared to a conventional converter.

Key words: Vienna Rectifier · Z Source Inverter · Wind Power Conversion System (WPCS) · Power Quality and Total Harmonic Distortion (THD)

INTRODUCTION

The power demand has been improved appreciably in the world which is moderated by the various Renewable Energy Sources (RES) because they are pollution free and inexhaustible. The WPCS is one of the most effective power generation systems that offer a feasible solution to distributed power generation for isolated communities, where the utility grids are not available [1]. In such cases, stand alone WPCS plays an important role to provide a quality output power to the electrical loads. In WPCS, various generators have been used which either are fixed speed wind turbine or variable speed wind turbine [2, 3]. Among them a variable speed wind turbine equipped with a PMSG is found to be very attractive and suitable for application in large wind farms. With gearless construction, such PMSG concept requires low maintenance, reduced losses and costs; at the same time has high efficiency and good controllability [4, 5]. Being a variable speed wind turbine, it enables operation of the turbine at its maximum power coefficient over a wide range of wind speeds, obtaining maximum energy from wind.

The WPCS is capturing larger power from the wind [6] and feeding the power to load with high-quality [7]. To feed quality power to the load, the AC–DC–AC converter is one of the best topology for WPCS [3]. To achieve the goal, the standard three phase full bridge converter and three-phase inverter are commonly used for AC-DC-AC conversion. The full bridge converter and three-phase inverter have the following drawbacks: 1) an additional DC-DC boost converter to obtain a desired DC output 2) imposes high stress to the switching devices 3) due to additional power stage conversion increases system cost and lowers efficiency. In order to rectify this problem, a low cost converter is used for AC-DC-AC conversion. A low cost converter is the combination of Vienna rectifier and ZSI, which is more efficient for step up applications. Vienna rectifier is a unidirectional rectifier, which boosts the DC voltage [8]. ZSI provides the higher, boosted voltage by elimination of shoot through fault. The proposed system simplifies the control complexity, reduces the cost and improves the power quality and efficiency [9 - 11]. Figure 1 shows the proposed block diagram of the WPCS.

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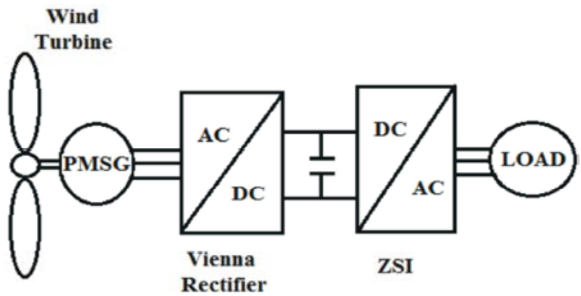


Fig. 1: Proposed WPCS with Vienna rectifier and ZSI

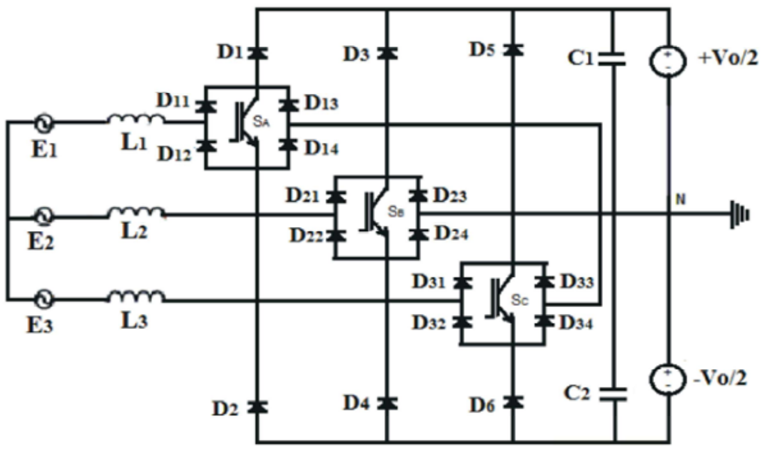


Fig. 2: Schematic diagram of Vienna rectifier

Vienna Rectifier Topology: The Vienna Rectifier is a unidirectional three-phase three-switch three-level Pulse-width modulation (PWM) rectifier. It can be seen as a three-phase diode bridge with an integrated boost converter [1,8]. The voltage of the each phase is determined by choosing the on/off state of switches and the direction of the phase current. The switches together with diode and input inductance create the boost converter system. The output capacitor is split into two parts with equal values. Two voltage sources $+V_0/2$ and $-V_0/2$ exist across each capacitor, which detect the output voltage of the circuit. Therefore, three different voltages ($+V_0/2$, 0, $-V_0/2$) are available [9]. Figure 2 shows the power circuit of Vienna rectifier.

The midpoint N is considered as a reference point with zero voltage. Therefore, the phase voltage is described as,

$$L_N \frac{di_k}{dt} = E_N - V_{KN} \tag{1}$$

when the phase current is positive,

$$V_{KN} = \begin{cases} +\frac{vo}{2} & S_k = 0 \\ 0 & S_k = 1 \end{cases} \tag{2}$$

when the phase current is negative,

$$V_{KN} = \begin{cases} -\frac{vo}{2} & S_k = 0 \\ 0 & S_k = 1 \end{cases} \tag{3}$$

where L_N is the input inductors (N=1, 2,3), i_k is the input phase current, V_{KN} is the phase voltage (K =A, B, C), S_k is a controlled switch ($S_k = 0$ corresponds to off state and $S_k = 1$ to the on state).

Figure 3 shows the modes of operation Vienna rectifier at phase A. Phases B and C operates in the same pattern.

Mode 1

- The switch S_A is turn ON when the line current is positive. The current passes through the switch S_A and phase voltage becomes zero.

Mode 2

- The line current is positive, but the switch S_A is turn OFF. The current passes through diode D_{11} and $D_{1.}$ So, the phase voltage is $+V_0/2$.

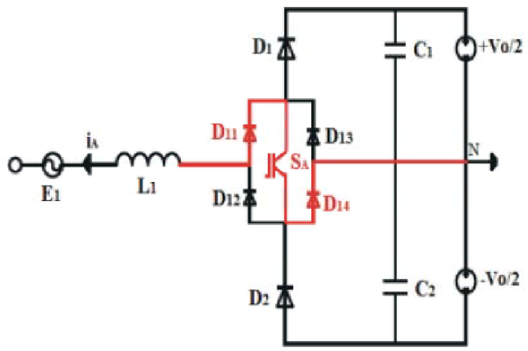


Figure 3 (a)

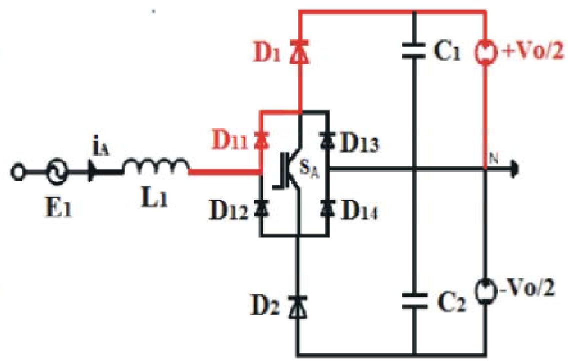


Figure 3 (b)

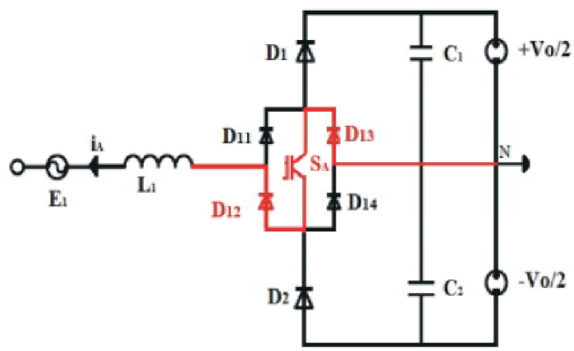


Figure 3 (c)

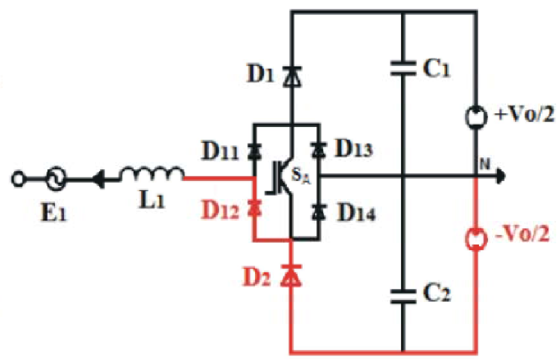


Figure 3 (d)

Fig. 3: Modes of operation of Vienna Rectifier

Table 1: Eight different switching positions of Vienna rectifier

S_A	S_B	S_C	V_{AN}	V_{BN}	V_{CN}
0	0	0	$+V_0/2$	$-V_0/2$	$-V_0/2$
0	0	1	$+V_0/2$	$-V_0/2$	0
0	1	0	$+V_0/2$	0	$-V_0/2$
0	1	1	$+V_0/2$	0	0
1	0	0	0	$-V_0/2$	$-V_0/2$
1	0	1	0	$-V_0/2$	0
1	1	0	0	0	$-V_0/2$
1	1	1	0	0	0

Mode 3

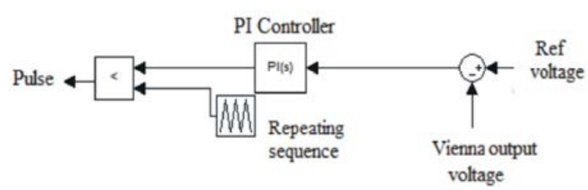
- The switch S_A is turn ON when the line current is negative. The current passes through the switch S_A and phase voltage becomes zero.

Mode 4

- The line current is negative, but the switch S_A is turn OFF. The current passes through diode D_{12} and D_2. So, the phase voltage is $-V_0/2$.

Assuming that the current of phase A is positive and phases B, C negative, the eight different switching positions can be considered and the results are shown in Table 1.

Control Strategy for Vienna Rectifier:



The reference voltage is 300V which compares with the output voltage of CFSI. The comparison produces the error signal which is tuned by a PI controller. The tuned pulses are given to the switching devices of the Vienna rectifier.

Z Source Inverter Topology: In the power conversion from DC to AC, both the switches of any phase leg can never be gated ON at the same time or a short circuit (shoot through) would occur in the conventional voltage source inverter and it will destroy the inverter. To overcome the above problems, the Z-source inverter is used for conversion of DC-AC [7-11]. The Z-network comprising of two capacitors and two inductors are connected in x-shape. This network is connected to the known three phase bridge. The Z-source inverter utilizes the shoot-through states to buck or boost the DC link voltage which is done by gating ON both the upper and lower switches of a phase leg. Due to the shoot-through state, the electromagnetic interference (EMI) noise does not destroy the circuit. Therefore, more reliable buck and boost power conversion is obtained [12-14].

This Z source network is the energy storage/filtering element for the Z-source inverter. It provides a second-order filter and is more effective to suppress voltage and current ripples than capacitor or inductor used alone in the conventional inverters. Figure 4 shows the Z-source inverter.

The conventional voltage source inverters have six active states and two zero states. However, the *Z*-source inverter has one extra zero state for boosting voltage that is called shoot-through state. The input diode is reverse biased when ZSI is in the shoot-through state; the two capacitors discharge energy to the inductors, load and the input DC source is isolated from the load. The input diode is turned ON when ZSI is in the non shoot- through state and the DC input voltage source as well as the inductor transfers energy to the load and charge the capacitors, as a result the DC-link voltage of the bridge is boosted [14]. Figure 5 shows the operation of ZSI.

As described in (Fang Zheng Peng 2003), the voltage of dc link can be expressed as

$$V_i = BV_{dc} \tag{4}$$

where V_{dc} is the source voltage and B is the boost factor that is determined by.

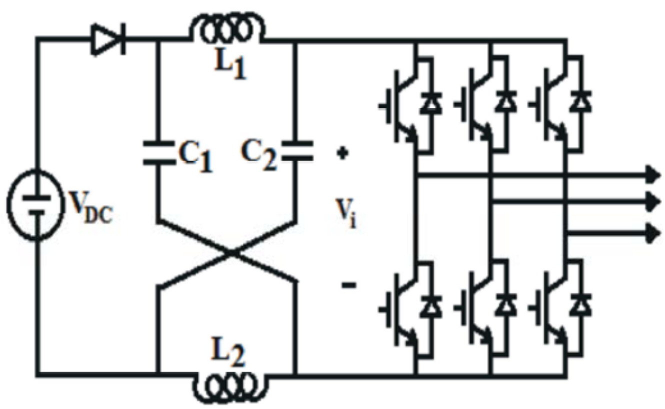
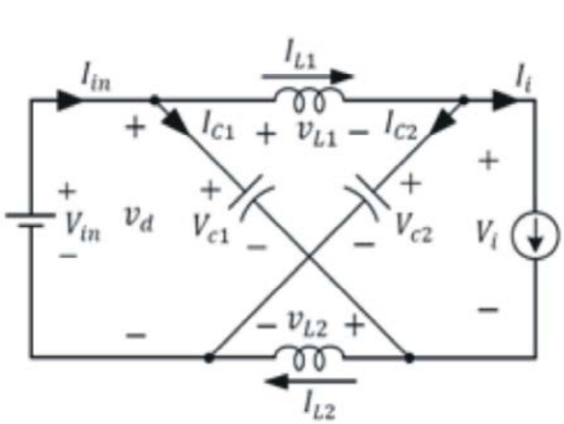
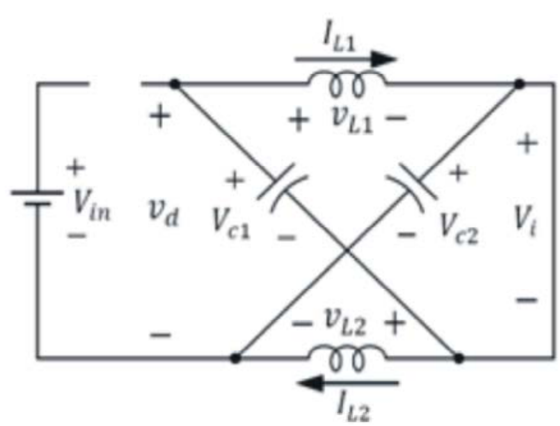


Fig. 4: Z-source inverter



a. Non-shoot-through state



b. Shoot-through state

Fig. 5: Operation of ZSI

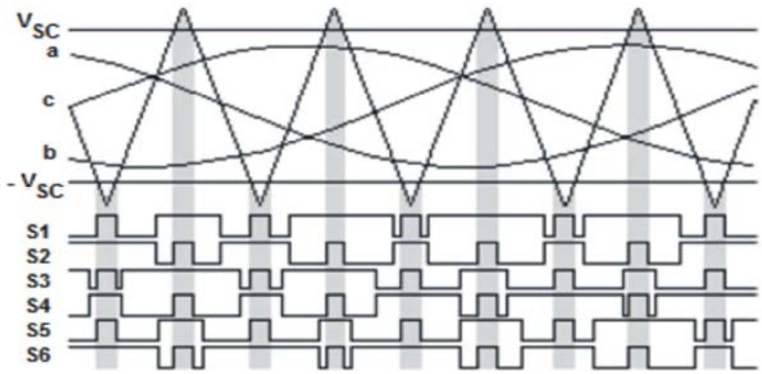


Fig. 6: PWM control method for *Z*-source inverter

$$B = \frac{1}{1-2(To/T)} \quad (5)$$

where T_o is the shoot-through time interval over a switching cycle T. The output peak phase voltage V_{ac} is

$$V_{ac} = MB(V_{dc}/2) \quad (6)$$

where M is the modulation index.

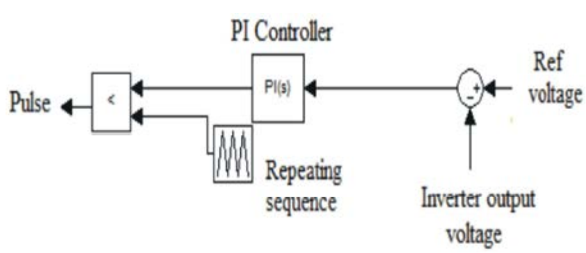
Figure 6 shows the simple boost PWM control method for Z-source inverter. In this method two extra straight lines V_{SC} and $-V_{SC}$ are employed as shoot-through signals [11,15]. When V_{SC} is smaller than the career signal or $-V_{SC}$ is greater than the carrier signal, a shoot through vector is created by the inverter. The value of V_{SC} is calculated by;

$$V_{SC} = \frac{T1}{T} \quad (7)$$

where,

$$T_1 = T - T_o \quad (8)$$

Control Strategy for ZSI:



The reference voltage is 500V which compares with the output voltage of CFSI. The comparison produces the error signal which is tuned by a PI controller. The tuned pulses are given to the switching devices of the ZSI.

RESULT AND DISCUSSION

The simulation of Vienna rectifier and Z source inverter based WPCS has been done using MATLAB/Simulink software. In the simulation study all the switches are considered to be ideal. The frequency of the output voltage is 50 Hz. In the proposed topology, only nine switches are used to obtain the required output voltage. In three phase converter together with PWM inverter, twelve power switches and boost converter are required to achieve the same output voltage. Figure 7 shows the simulation diagram of proposed topology. It consists of Wind turbine with PMSG, Vienna rectifier, ZSI and load.

In this simulation, Permanent Magnet Synchronous Generator (PMSG) used as variable speed wind turbine generator produces the AC voltage of 300V. The output of PMSG is fed to the vienna rectifier which boosts the voltage up to 380V which is shown in Figure 8. Vienna rectifier uses only three switches to the conversion AC-DC and boosts the voltage to the required level. The simulation parameters of Vienna rectifier are shown in Table 2.

The output of the Vienna rectifier is again boosted by the Z source inverter in the range of 500V and is converted to AC. Figure 9 and 10 show the inverter output voltage and current. The simulation parameters of the Z source inverter are shown in Table 3.

Figure 11 and 12 show the FFT spectrum of conventional and proposed topology. Table 4 shows the THD analysis of conventional and proposed topology.

To experimentally validate the proposed topology, hardware of the Vienna rectifier and ZSI based WPCS has been built. Nine MOSFETs are used as the switching devices. Three single phase transformers are used to get the AC input voltage to the three phase Vienna rectifier. Boosted output from the Vienna rectifier is fed to the ZSI,

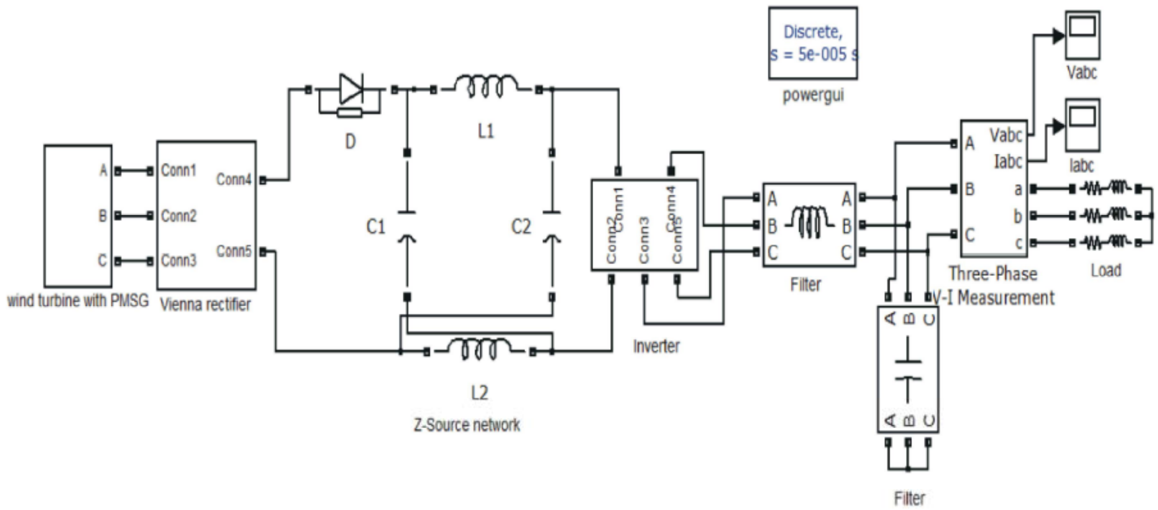


Fig. 7: Simulation diagram of proposed topology

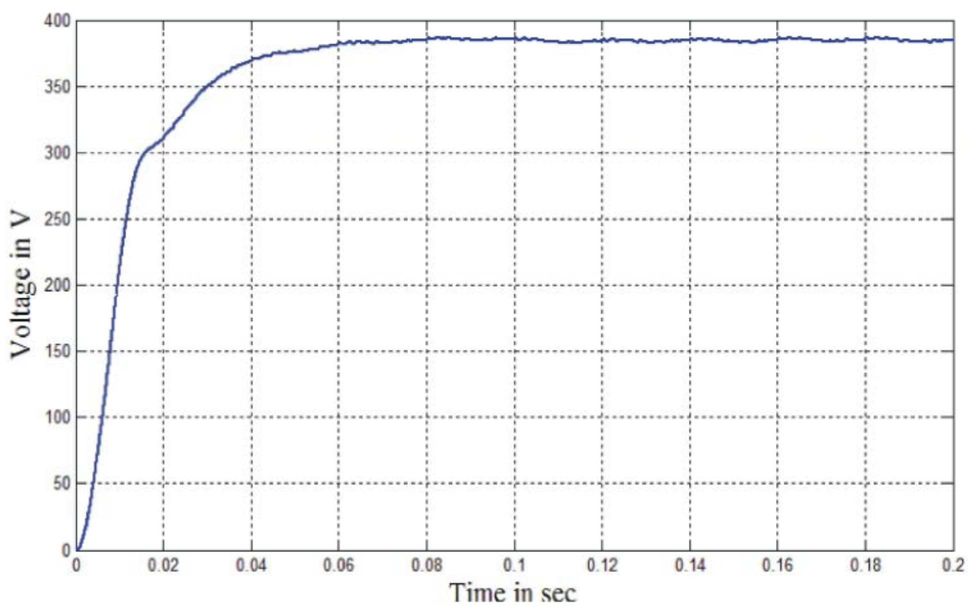


Fig. 8: Output voltage of Vienna Rectifier

Table 2: Simulation parameters of Vienna rectifier

Parameter	Value
Input voltage (AC)	300V
Output voltage (DC)	380V
$L_1=L_2=L_3$	15mH
Switching Frequency	20kHz

Table 3: Simulation parameters of ZSI

Parameter	Value
Input voltage (DC)	380V
Output voltage (AC)	500V
$L_1=L_2$	5mH
$C_1 = C_2$	5μF
Switching Frequency	20kHz

Table 4: Comparison between the conventional and proposed topology

Converter options	Number of Switches used	Control Scheme	% THD Obtained
Diode rectifier jointly with PWM inverter	12	Load side inverter controlled through PI controller	3.90%
Voltage Source Converter jointly with ZSI	12	Generator side converter simple firing angle control and load side inverter controlled through PI controller	2.57%
Vienna rectifier jointly with Z Source Inverter	9	Generator side converter and load side inverter controlled through PI controller	2.07%

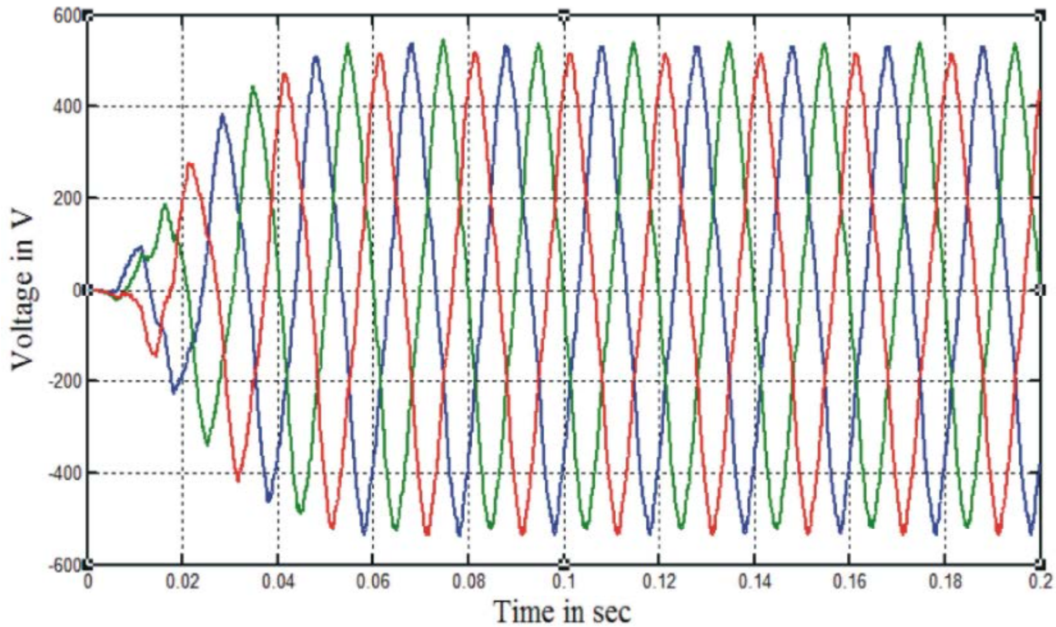


Fig. 9: Output voltage of ZSI

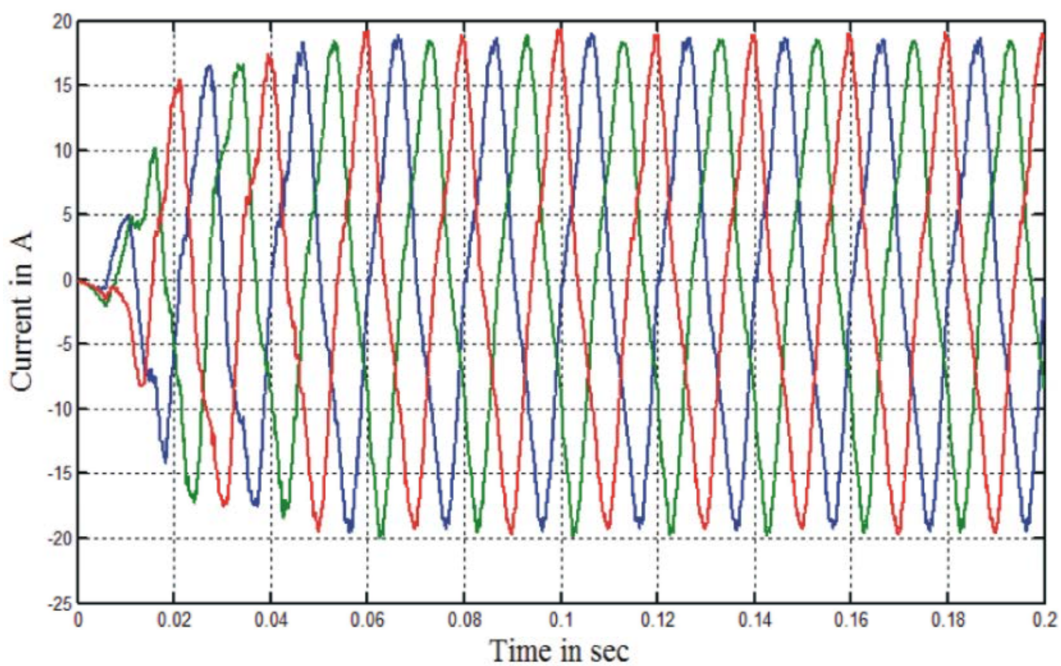
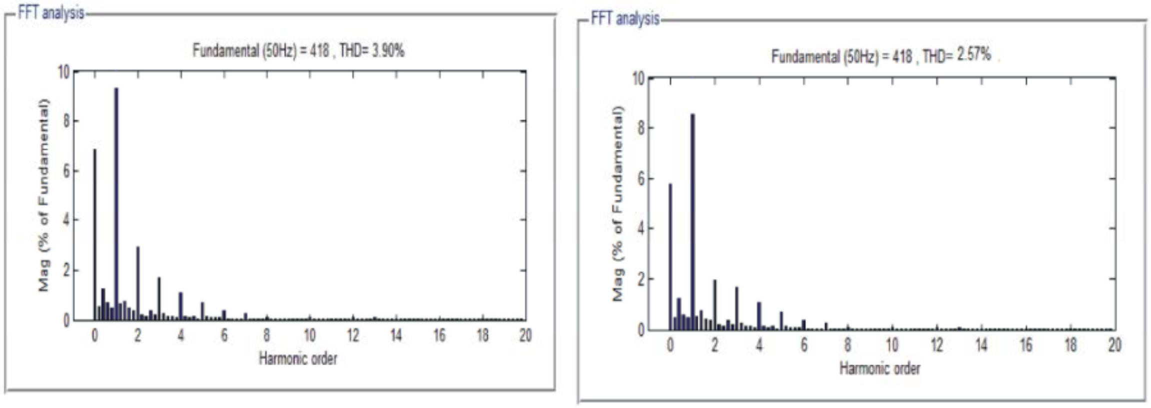


Fig. 10: Output current of ZSI



(a) (b)

Fig. 11: FFT spectrum of conventional topology

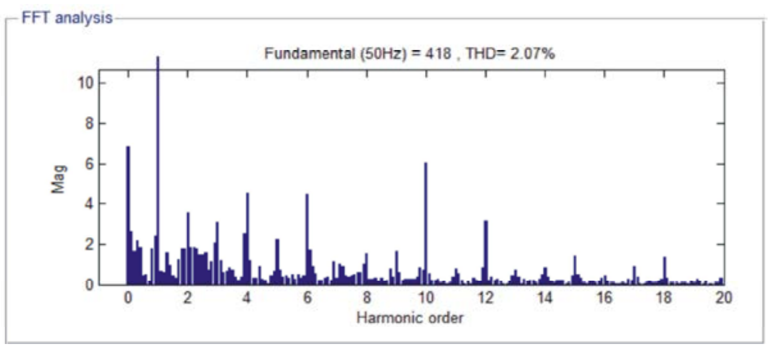


Fig. 12: FFT spectrum of proposed topology

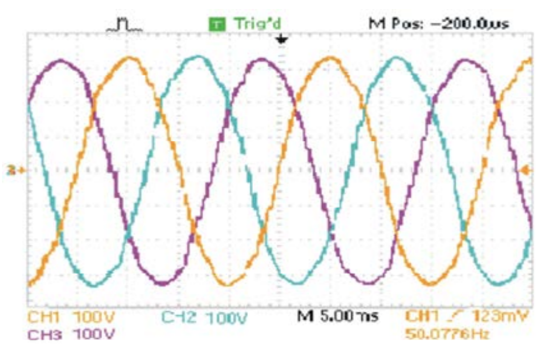


Fig. 14: Inverter output voltage waveform

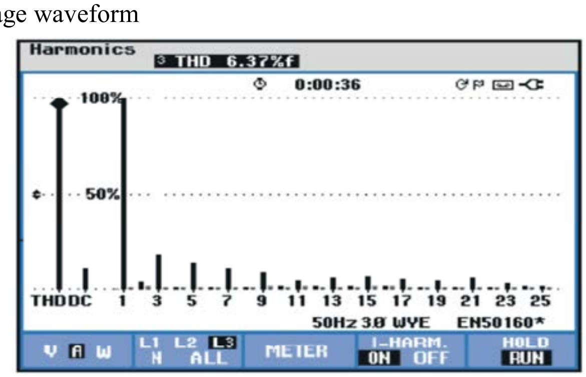


Fig. 15: FFT spectrum of conventional topology

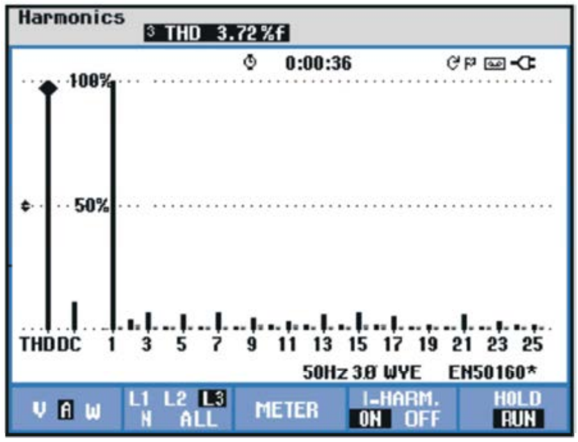


Fig. 16: FFT spectrum of proposed topology

which boosts the voltage further to high level and converts it to AC. PIC16F877A microcontroller is used to control the gate pulses of the MOSFET switching devices of Vienna rectifier and Z source inverter. Control algorithms for the switching are written in the high level language and then it is embedded in the PIC16F877A microcontroller.

Figure 14 shows the experimental output voltage of ZSI and Figure 15 shows the FFT spectrum of conventional topology and Figure 16 shows the FFT spectrum of proposed topology.

CONCLUSION

The proposed topology of Vienna rectifier and ZSI for PMSG based Wind Energy Conversion System has been simulated. PMSG is used due to high efficiency and as it is a variable speed wind generator it attains maximum power output. The concept of proposed system has been verified by simulation. The THD value of the proposed topology is very low compared with conventional topology. In order to validate the proposed system, a prototype model has been developed. The proposed system has less switching loss, high boosted voltage and reduction of harmonics. Hence the total system has good performance and reliability.

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