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Research Paper

IMPLEMENTATION OF PMSG WITH REDUCED Z-SOURCE NEUTRAL POINT CLAMPED INVERTER IN WIND ENERGY SYSTEMS

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In the past few decades, growth in the wind energy sector has been more phenomenal between all renewable energy sources. In such applications, the output of the traditional voltage source inverters (VSI) and current source inverters (CSI) are not constant with varying wind velocity. To overcome this problem a relatively recent topology named Z source inverter (ZSI) is used with which constitutes both voltage buck and voltage boost capability. This paper shows the operation and control of PMSG with reduced Z-source neutral point clamped inverter using space vector modulation which provides betterment of both implementation and harmonic performance in varying wind energy systems. The simulations have been done in MATLAB/SIMULINK platform and the respective results are included.

Keywords: Reduced Neutral Point Clamped (R-NPC), Space Vector Modulation (SVM), Z Source inverter

INTRODUCTION

Power generation through non-conventional energy sources is becoming more popular due to stringent environmental regulations. Among all the renewable energy sources, wind energy is still more prominent because of its availability throughout the year. The output of wind generators associated with rectifiers are dc type and not producing constant voltage level due to variations in insulation strength of wind velocities during the day. In order to obtain a constant ac voltage and frequency from the wind sources, it is important to select an inverter with buck-boost operation. In these applications the inverter has to generate boosted output voltage during cloudy and low wind speed conditions and at the same time the inverter has to generate the desired voltage without boost condition when wind speed is high. For such operations the traditional VSI and CSI are not suite because they require fixed dc voltage or current source, wherein comes the Z Source inverter which has the attractive feature of single stage buck-boost capability that makes it more suitable for wind energy systems. There are many developments on ZSI such as (i) Embedded ZSI ,(ii) Tapped inductor ZSI, (iii) Quasi

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ZSI,(iv)Trans ZSI,(v)Neutral Point Clamped ZSI. The NPC inverter improves the output waveform as like a matrix converter i.e., more close to sinusoidal. The switching losses can be reduced while using NPC whereas it is not possible in matrix converter. The traditional Z source NPC inverter consists of two Z source networks, two isolated dc sources, and a modulator balancing the boosting of each Z-source network. Therefore, contribution of this paper is development of PMSG based reduced Z source-NPC inverter with a space vector modulation control for betterment in both implementation and harmonic performance.

SYSTEM DESCRIPTION

A. Power Circuit Configuration

PMSG converts the wind power captured by wind turbine and transfers to the grid via a rectifier in series with a reduced Z-source NPC inverter. The circuit diagram is shown in fig. The function of the generator side controlled PWM rectifier is to ensure sinusoidal generator currents and also a LC filter is designed to absorb the harmonics being injected to generator by the controlled rectifier.

The grid side reduced Z-source NPC with SVPWM control is chosen to be an alternative for both conventional inverter and NPC inverter due its merits such that it has inherent voltage buck and voltage boost capability using the shoot through states in each phase leg of the NPC inverter and single impedance network along with a clamping capacitor is used that enables the compact and efficient design.

Figure 1: Proposed PMSG-Based Wind System

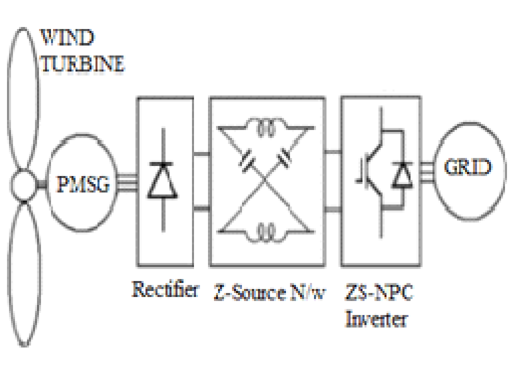
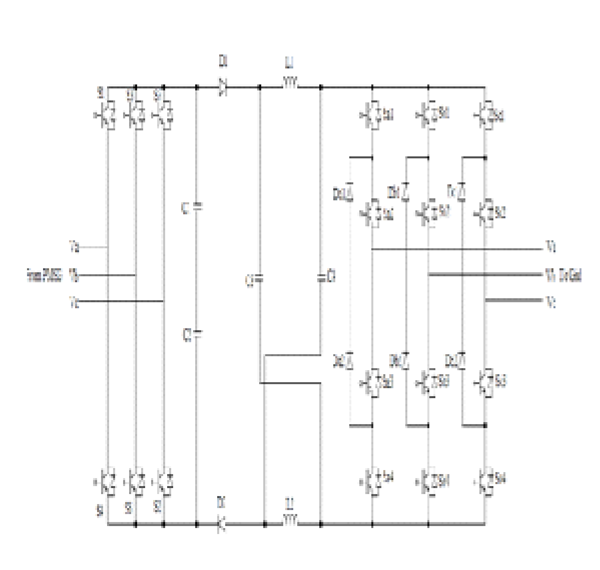


Figure 2: Proposed Grid Interface Circuit for PMSG



B. Wind Turbine Model

Wind energy is converted into electrical energy using wind turbine. The power obtained from the wind is given by,

$$P_{wind} = 0.5\rho A V_{wind}^{3} \qquad (1)$$

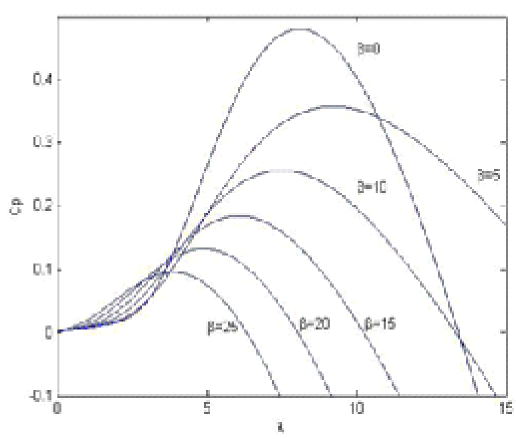
Where, ñ is the air density of air, A is the rotor swept area in m^2, R is the radius of the rotor blade, and V_{wind} is the wind speed in m/s. The kinetic energy delivered to the turbine is predicted by power co-efficient C_p and is given by:

$$P_{KE} = 0.5\rho A V_{wind}^{3} C_p \qquad (2)$$

The wind velocity determines the rotational speed of the wind turbine and the generator. The power coefficient C_p is a nonlinear function of the blade pitch angle β (in degrees) and the tip-speed ratio λ.

The power coefficient Cp reaches a maximum value equal to Cp = 0.593 [9] which means that the power extracted from the wind is always less than 59.3% (Betz's limit), because various aerodynamic losses depend on the rotor construction (number and shape of blades, weight, stiffness, etc.). This is the well-known low efficiency to produce electricity from the wind.

Figure 3: C_P as function of λ and β



$$Cp(\lambda,\beta)=C_1(C_2/\lambda_i-C_3\beta-C_4)e^{-C_5/\lambda i}+C_6\lambda i \quad (3)$$

The amount of aerodynamic torque (T_e) in N-rn is given by the ratio between the power extracted from the wind (P) in Watts, and the turbine rotor speed (ñ), in rad/s, as follows

$$T_e=\frac{P}{\omega} \quad (4)$$

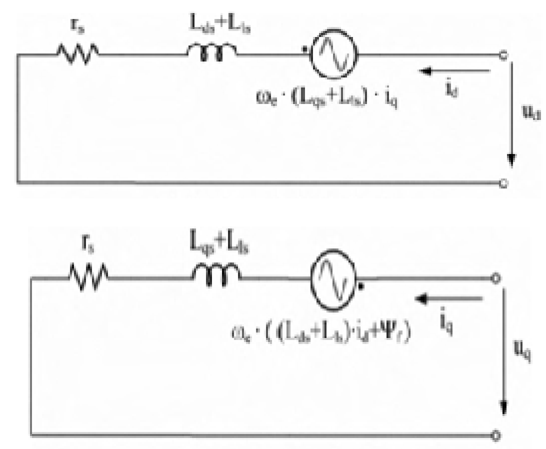
Since there is no gearbox, it should be noted that the mechanical torque transmitted to the generator is the same as the aerodynamic torque. This implies the gear ratio as n_g=1.

$$T_e=T_{wg} \quad (5)$$

C. Dynamic Model of PMSG

PMSG provides an optimal solution for variable speed wind turbines, of gearless configuration. A high efficiency can be achieved, while keeping the mechanical structure of the turbine simple.

Figures 3a and b: Equivalent Circuit of d-axis and q-axis



The model of the PMSG is obtained from the two pole synchronous reference frame, which the 0.q-axis is 90% ahead of the d-axis with respect to the direction of rotation. It is illustrated by the following equations;

Where V_d and V_q are the PMSG voltages in d-q frame, i_d and i_q are the two-axis currents, L_d and L_q are the equivalent inductances, Rs is stator resistance, $ù_m$ is the mechanical angular velocity of the rotor and $ë_f$ is the fundamental harmonic component of the flux. The electromagnetic torque is calculated by,

$$T_e=\frac{3}{2}P_m[\lambda_f+(L_d-L_f)i_d]i_q \quad (6)$$

$\omega_e = P\omega_m$; where ω_e is the electrical rotating speed (rad/sec) of the generator and P is the number of poles.

D.Z-Source Inverter Concept

Z-Source is a two port network that consists of split inductors (L1 and L2) and capacitors (C1 and C2) connected in X-shape. The peerless mark of Z-source inverter is that the output ac voltage can be varied between zero and infinity irrespective to the dc voltage source .Thus, the Z-source acts as a buck-boost inverter. In ZSI, it is important to generate the shoot through switching pulse in addition to normal six switching pulses, to control the ac output voltage. In shoot through period, the switches in same leg were shorted. During this period the energy stored in the inductor will be transferred to the capacitor. By changing the shoot through duty ratio, the inverter can be operated in either buck or boost mode.

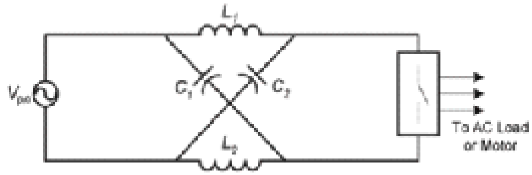
The capacitor voltage of the Z-source network can be expressed as

$$V_C = V_1 = V_{C2} = \frac{1-D}{1-2D}V_{pn} = \frac{B+1}{2}V_{pn} \qquad (7)$$

$$\left.\begin{aligned} B &= \frac{1}{1-2D} \\ V_{dc} &= \frac{2B}{B+1}V_C = B \\ V_{ac} &= MB\frac{V_{pn}}{2} \end{aligned}\right\} \qquad (8)$$

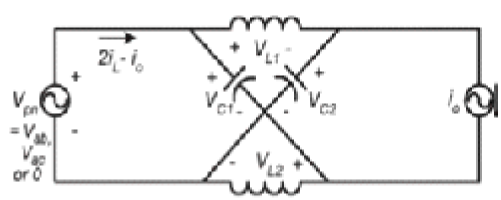
where $D=T_{st}/T_s$ is the shoot through duty cycle.V_{c1} and V_{c2} are the voltages across capacitors in Z-Source Network, T_{sh} and T_s are the time schedule for shoot through state and time period of the cycle, V_L and V_{pn} are the line to line ac input voltage and output dc voltage of the rectifier, M and B are the modulation index of PWM and boost factor of ZSI. V_{dc} and V_{ac} are the input dc voltage after boosting and output peak ac voltage of the inverter. Equation (7) can be used to implement the variable speed operation of the PMSG.

Figure 4: Equivalent Circuit of ZSI

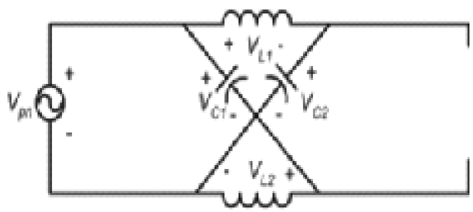


From the above equivalent circuit three modes of operation can be achieved as follows,

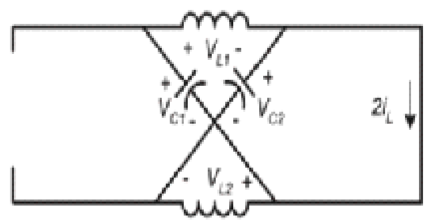
Figure 5 (a), (b), (c) Equivalent circuit modes of the ZSI



a. Mode I



b. Mode II



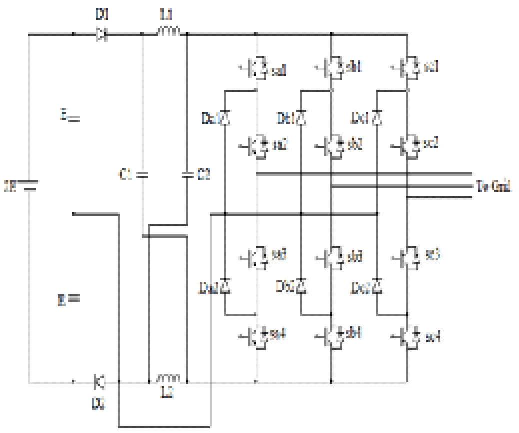
c. Mode III

Mode I: Operates in one of the six non-zero vectors, thus acting as a current source when viewed from Z-source network. Therefore the current in the inductor is symmetric.

Mode II: Operates in one of the two zero vectors, thus acting as an open circuit viewed from the Z-source network. Therefore the current in the inductor is non-linear.

Mode III: Operates in one of the seven shoot through states. Therefore the rectifier separates the dc link from the ac line and the voltage can be boosted by adjusting the shoot through duration.

Figure 4: Topology of reduced Z-source NPC inverter



TOPOLOGY OF REDUCED Z SOURCE NPC INVERTER

The operating principle of reduced Z-source NPC inverter is shown in fig.4, the operation of one phase leg is taken into account. In such way that, each phase leg is represented by three switching states P, O, and N. "P" represents the upper two switches are gated ON , "N" represents the lower two switches are gated ON and "O" represents the inner two switches are gated ON. Withal above switching states, three extra switching states occur when all the four switches in any phase leg re gates ON [Full Shoot through (FST)], or the three upper switches in any phase leg are gated ON [upper shoot through (UST)] or the three bottom switches in any phase leg are gated ON [lower shoot through (LST)]. These shoot tough states are forbidden in the traditional NPC inverter because they would cause a short circuit of the dc side capacitors. The Z-source inverter makes use of these shoot through states and provides the boost operation. The switches in each phase is controlled with combinations presented in Table 1, thus each output phase voltage containing three possibilities $V_i/2$, 0, $-V_i/2$. When the Z-source NPC inverter is operated without any shoot-through states, then Vi is equivalent to 2E. As noted earlier, with this kind of operation, the maximum obtainable output line-to- line voltage cannot exceed the available dc source voltage (2E).

Table 1: Switching states of an Reduced Z-source NPCI

Type	ON switches	ON diodes	V_{xo}	Switching state
NST	sx1,sx2	D1,D2	$V_i/2$	P
NST	sx2,sx3	D1,D2Dx1/Dx2	0	O
NST	sx3,sx4	D1,D2	$-V_i/2$	N
FST	sx1,sx2,sx3, sx4	–	0	FST
UST	sx1,sx2,sx3	Dx2,D1	0	UST
LST	Sx2,sx3,sx4	Dx1,D2	0	LST

Note: x - Phase a, b, c.

Therefore, to obtain an output line-to-line voltage greater than 2E, shoot-through states are carefully inserted into selected phase legs to boost the input voltage to Vi > 2E before it is inverted by the NPC circuitry. Thus, the REC Z- source inverter can boost and buck the output line-to-line voltage with a single-stage structure. In [5], two new switching states namely the UST and LST states were identified, in addition to the FST state and the non-shoot through (NST) states (P, O, and N) that had been reported earlier in [10]. Although operation using the FST and NST states possible (termed the FST operating mode), it is generally preferable to use the UST and LST states in place of the FST states (termed the ULST operating mode). The ULST operating mode is preferred because it produces an output voltage with enhanced waveform quality. The simplest FST operating mode requires all four switches in a phase leg (see Table I) to be turned ON. This is not a minimal loss approach since, for example, switching phase A from +E through FST to 0 V would require switches {Sa1, Sa2, Sa3,Sa4} changing from {ON, ON, OFF, OFF} through {ON,ON, ON, ON} to {OFF, ON, ON, OFF}. An alternative FST operating mode which gives minimal loss uses two phase legs to create the shoot-through path. This requires, for example, synchronization of the turn ON instants of switches Sa1 from phase A and Sc4 from phase C at the start of an FST state. Doing so creates a time interval during which switches {sa1, sa2, sa3} from phase A and {sc2, sc3, sc4} from phase C are gated ON simultaneously to create a shoot-through path. However, the output line-to-line voltage obtained using the minimal loss FST approach has higher harmonic distortion (compared to the ULST approach) in its output voltage waveform because the voltage levels produced do not have adjacent level switching [35]. Therefore, in this paper, the ULST operating mode is used for controlling the quasi Z-source NPC inverter. Assuming that the Z-source network is symmetrical (L1 = L2 = L and C1 = C2 = C), then VL1 = VL2 = VL and VC1 = VC2 = VC and the voltage expressions for the NST state are as follows:

NST

VL = 2E – VC (7)

VP = +Vi/2, VN = “Vi/2 (8)

VI = 2(VC – E) (9)

UST

VL1 = E (10)

VP = 0 V, VN = E – VC1 (11)

LST

VL2 = E (12)

VP = E + VC2, VN = 0 V (13)

The duration of NST, UST, and LST are denoted by period T_N, T_U, T_L respectively and the switching period of T. As the operation is symmetrical T_U and T_L are equal and denoted by $T_{ULST.}$ At steady state, the average voltage across the inductors is zero; therefore, averaging the inductor voltage over one switching period, we get

$$\frac{(2E - V_C)T_N + E.T_U + E.T_L}{T} = 0 \quad (14)$$

Dc link voltage V_i is given as such,

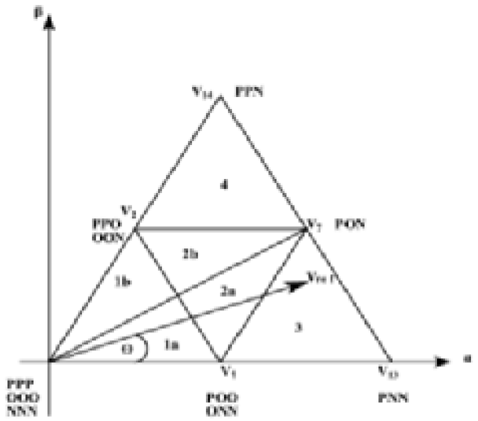
$$V_i = V_P - V_N \quad (15)$$

The dc link voltage during the UST and LST states are given by,

$$V_{i\_UST} = V_{i\_LST} = \frac{E}{1 - T_{ULST}/T} \quad (16)$$

From equations (15 & 16), noted that the higher dc link voltage is present during the NST states and it is twice the dc link voltage during the UST and LST states.

Figure 5: Space Vector diagram of sector 1



The reference vector V_{ref} can be expressed as,

$$V_{ref}(t) = \frac{2}{3}[V_{ao}(t)e^{j0} + V_{bo}(t)e^{j2\pi/3} + V_{co}(t)e^{j4\pi/3} \quad (17)$$

The duty cycle is calculated with respect to fig.5.In SVM, the reference vector is calculated with two active vectors and either one null vector, which are selected based on the triangle in which the reference vector is located at the sampling. If reference vector is located in triangle 3, then vectors V_1, V_7 and V_{13} are considered. The duty ratios are denoted by d_1, d_2

and d_3 , therefore ;

d_1=2-2Msin (π/3+θ) (18)

d_2=2Msinθ (19)

d_3=2Msin (π/3-θ)-1 (20)

High quality waveform can be obtained with minimum number of switching transitions. The minimal number of switching sequence is obtained from a seven segment SVM. The switching sequences and insertion of shoot through states for triangles 2-4 are given below

Table 2: Switching Sequences and Insertion of Shoot-Through states in Triangles 2-4

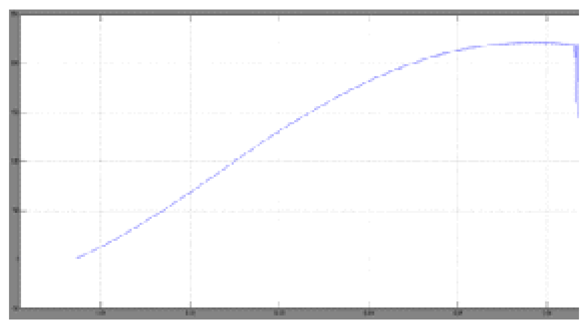
Triangle	Switching states
2a	ONN,UNN,OON,PON,POL,POO
2b	PPO,PPL,POO,PON,UON,OON
3	ONN,UNN,PNN,PON,POL,POO
4	OON,UON,PON,PPN,PPL,PPO

A similar switching pattern is followed for sectors 2 – 6. However, no shoot through states are inserted in triangle 1 because this corresponds to a low modulation index which causes the inverter to degenerate into three level line-to-line voltage switching with no voltage boost operation.

SIMULATION AND RESULTS

The proposed wind energy system with PMSG-reduced Z-source neutral point clamped inverter is modelled in MATLAB/SIMULINK .The generator voltage, generator current, inverter voltage & current grid voltage & current are shown in the fig.8-10.

Figure 6: Z-source NPC inverter boost voltage



The following fig.6 and 7 shows the results Z-source NPC inverter when not integrated with wind energy systems. As, mentioned earlier

From fig.6 it is seen that with help of Z source network the input voltage of 150V is boosted upto 210V and fig.7 shows the waveform of Z-source NPC inverter with Space Vector Modulation control.

Fig.8 -11 shows the PMSG output voltage, output current, Grid voltage and Grid Current. From the above results it's shown that the output is normalized constant with help of reduced Z-source Neutral Point Clamped for varying wind speed .A small value of LC filter is designed to reduce the harmonics level near the grid side.

Figure 7: Z-source NPC inverter output voltage waveform

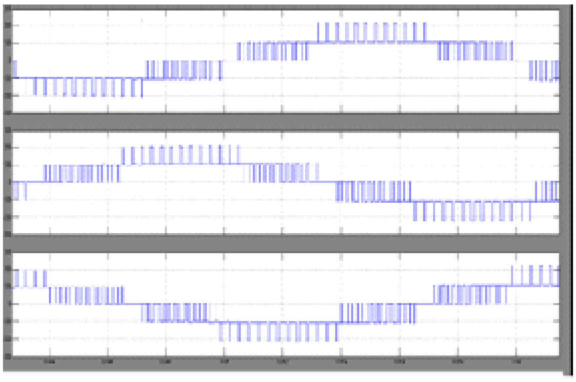


Figure 8: PMSG output voltage

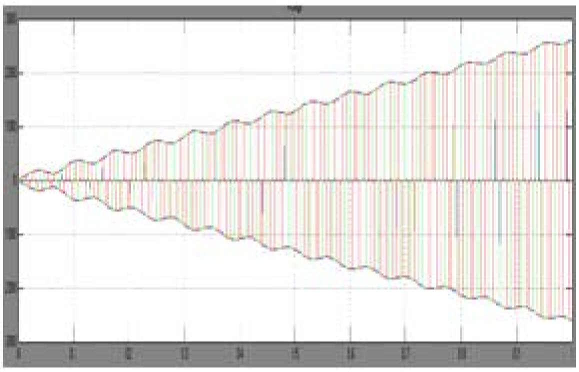


Figure 9: PMSG output current

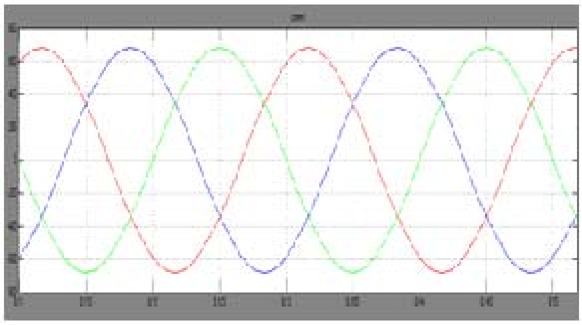


Figure 10: NPC inverter output voltage

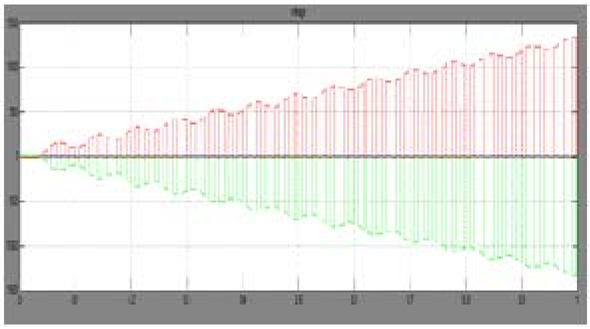


Figure 10: Grid Voltage

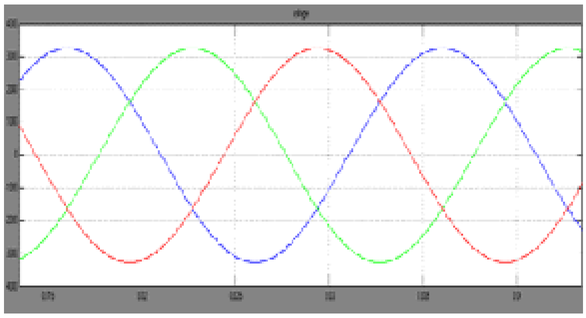


Figure 11: Grid Current

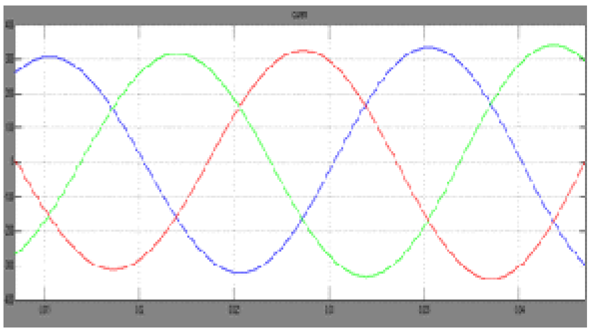
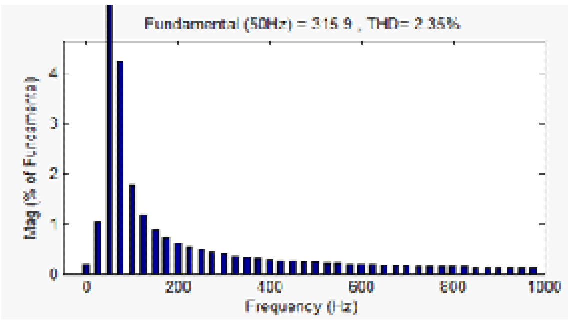


Figure 12: THD Analysis



CONCLUSION

From the above accomplished wok the power generation capability of variable speed generators were determined successfully with Z Source Neutral Point Clamped Inverters. Also the simulation results show the better harmonic performance in varying wind energy systems.

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