

# Dynamic Modeling of Axial flux Permanent Magnet Synchronous Generator based Wind Turbine connected to Grid with SL Z-Source Inverter

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## Abstract

This paper explain about the connection of Axial Flux Permanent Magnet synchronous generator based variable speed wind turbine to the grid with Power electronic converters. Axial Flux Permanent Magnet Synchronous Machines have short axial length and high power to weight ratio facilitate direct compact integration with the wind turbine. The high efficiency, high power density, elimination of gearbox and fast dynamic response, These features make this kind of machines very attractive for wind applications. In this paper , a new variable speed wind turbine with Axial Flux Permanent Magnet Synchronous Generator and Multi cell Switched Inductor Z-Source Inverter is proposed to improve a voltage boost ability of convectional Z-Source Inverter. In addition to this the proposed ZSI uses a smaller shoot through duty ratio for high voltage boost ratio and reduction of the voltage stress on ZSource capacitor and inverter bridge. And we can eliminate the DC-DC converter in three stage conversion system because ZSource Inverter can control the Maximum power point tracking control. By this DC-DC converter elimination and replacement of traditional inverter with ZSI number of conversion stages decreases from three stage to two stage and then deliver power to grid. As a result, the proposed topology is more reliable under short circuits and requires less power electronic converter switches.

**Key words:** AFPMSG, Switched Inductor Z-Source Inverter, MPPT.

## 1. Introduction

Wind is the most plentiful renewable source of energy in nature and by numerous techniques we can transform wind energy into the electrical energy. World's fossil fuel stock is almost getting decreases due to increasing demand. Moreover conventional sources like thermal power generation lead to environmental degradation leading to climate changes. The nuclear disasters in Japan and oil spill in Gulf of Mexico can made the world to search for renewable energy especially wind energy. Wind energy is the clean and once the wind turbine installed the running cost comes down and hence wind energy has drawn more attention world wide.

WECS mainly classified into four groups based on the generator types 1. Fixed speed squirrel cage Induction generator 2. Wound rotor Induction Generator 3. DFIG wind generator 4. Synchronous generator and Permanent Magnet Synchronous Generator[1]. Now a days most of the WECS are made with Permanent magnet

synchronous generator because the technical necessities of WECS in different power ratings can be achieved with great flexibility by SG structure. The permanent magnet synchronous generator machine having large number of poles which makes the speed of both generator and wind turbine same, So Gearbox can be eliminated in PMSG based WECS. The PMSG structures classified into two types Radial and Axial flux machines according to the air gap flux direction[2]. Both machines having same operating principle but differ in construction. In conventional Radial flux machines the conductors are placed in parallel to the direction of air gap flux and radial to the shaft axis where in Axial flux machines the conductor are placed in radial to the shaft and air gap flux is parallel to the shaft axis[3]. In axial flux machines the radial length from the stator inner radius to the outer radius is the designed part to generate torque. The axial length is dependent on the flux density in the stator and rotor yokes. Thus, both the stator and rotor can be properly designed for this reason number of poles increases, Axial length decreases and power density increases but radial active part remains same. Hence Axial flux machines advantageous where low speed, high torque, electric drives are needed. WECS based AFPMSG is usually coupled to grid by maximum rated power electronic converters to accomplish maximum efficiency in variable speed performances[1] and power electronic converters can control the reactive power and can operate at Fault ride through condition. A ordinary topology of AC-DC-AC (three stage conversion) converters for AFPMSG [5] shown in figure 1(a). This topology consist of Diode based rectifier, DC-DC boost chopper and Inverter. In this topology DC-DC converter can control the MPPT[5]. Z-Source inverter is a new power electronic converter with boost ability first proposed in 2003[6]. In conventional inverters like VSI and CSI shoot through (short circuit) is the serious problem, But in ZSI it uses the shoot through states to increases the voltage of the inverter switching circuit. As compared to traditional inverters the ZSI reaches high efficiency, high reliability and less complications. As a result the proposed system requires less no of switches as compared to convectional systems. In different types of ZSI, in this paper SL-ZSI is incorporated to eliminate the drawbacks of normal ZSI and boost the same voltage value with less modulation index used in normal ZSI. And we can reduce the stress on Inverter bridge and Z-Network The axial type PMSG based Z-source Inverter was proposed in[7] recently, in this paper the author used radial type of PMSG model and the axial model of PMSG has not been discussed. But in This paper examines axial flux permanent magnet synchronous generator modeling and simulation of Multi cell Switched inductor Z-Source inverter. This paper is organized as follows. Section II introduces AFPMSG structure and its dynamical model. Switched Inductor Z-source inverter topology and study of its circuit are accessible in Section III. Section IV describes the control algorithm of projected topology. Simulation results on a proposed WECS are provided in Section V .

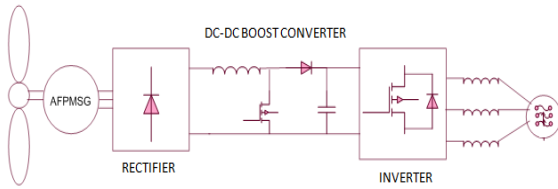


Fig 1. Conventional AFPMSG based WECS with boost chopper

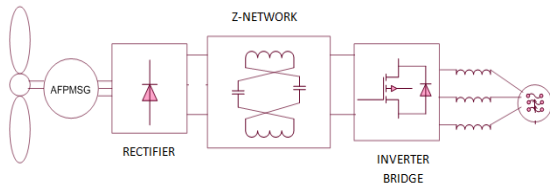


Fig 2. AFPMSG based WECS with Z-Source Inverter

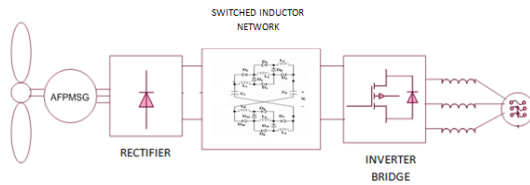


Fig 3. AFPMSG based WECS with Switched Inductor Z-Source Inverter

## 2. Axial Flux Permanent Magnet Synchronous Generator

In AFPMSG, the stator and rotor are in shape of discs stacked on the shaft and magnetic flux direction is from one disc to another disc in a path parallel to the shaft (Axial direction). AFPMSG are classified into different types based on the construction or number of stators and rotors used. Which are

1. Single Side (Single stator and Single rotor)
2. Double side ( 1. Interior Rotor axial flux machine 2. Interior Stator axial flux machine)
3. Multi stage

By comparing all the above types, Double side that is Single stator Double rotor (SSDR) configuration is start to have superior operational features and in this configuration the stator carrying three phase winding sandwiched between two rotor carrying Permanent magnet poles. To increase the strength and heat conductivity fill the gaps between stator winding. The rotor is made up of with NdFeB permanent magnets is in the form of fan like structure[1] which are axially magnetized. In these machines steel disk is not used in the rotor topology because the principal flux does not move in rotor disk. Like rotor structure to eliminate the magnetic rotor disk, Non-magnetic matter is used to replace gaps between the permanent magnet and forms a fixed structure. From these machines we can get high power to inertia ratio due to the lack of iron in the rotor.

According to basic equations of three phase electrical machines we can get the dynamic model[4] of AFPMSG. Below figure shows the equivalent circuit of AFPMSG with assuming the flux linkages of Permanent Magnet material.

$$v_d = R_s i_d + L_d \frac{di_d}{dt} - \omega L_q i_q \quad (1)$$

$$v_q = R_s i_q + L_q \frac{di_q}{dt} + \omega L_d i_d + \omega \psi_{PM} \quad (2)$$

The relation between the electro magnetic torque and AFPMSG electrical parameters is given by

$$T_e = \frac{3}{2} p (i_d i_q (L_d - L_q) + \psi_f i_q) \quad (3)$$

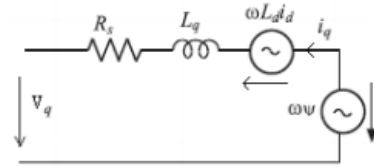


Fig 4. Equivalent circuit in q-axis

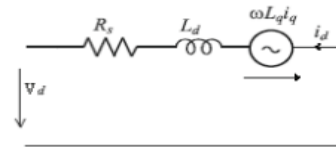


Fig 5. Equivalent circuit in d-axis

## 3. Switched Inductor Z-Source Inverter

The convectional VSI have natural drawbacks[6] like constraint of AC output voltage , short circuit occurred by miss firing from PWM, and distortion in AC output current because the presence of Dead time in PWM are eliminated by using ZSI.

Z-Source inverter also have the drawbacks[11] like rush current and resonance between Z-network capacitors and Inductors at starting, voltage and current surges and stress on capacitors and inverter bridge can be reduced for formation of switched inductor Z-Source inverter ,it is necessary to add some more inductors and diodes to the Z-Network of normal ZSI shown in figure 6. SL-ZSI can give high voltage boost ratio with same modulation index value used in normal ZSI by this we can get high ac output voltage with less stress on capacitors and inverter bridge.

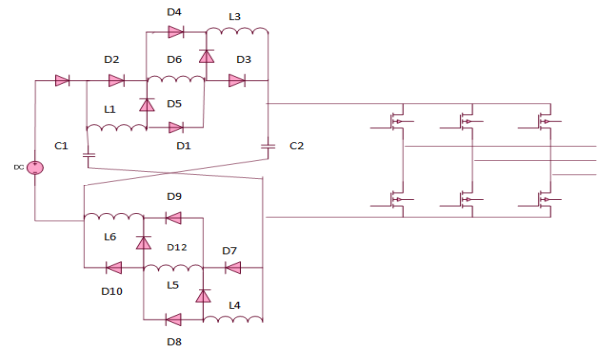


Fig 6. Switched Inductor Z-Source Inverter

In this SL-ZSI topology, according to shoot-through state and non-shoot-through state. The arrangement of inductor is changes.

### 3.1 Shoot-through state

Diode(Din) is reverse biased, In the upper branch, diodes D1, D2, D3 and D4 are in conduction mode, while two diodes D5 and D6 are in non-conduction mode. Then ,by capacitor C1 charges the parallel connected inductors L1,L2 and L3 . In the lower branch, diodes D7, D8, D9 and D10 are in conduction mode, while two diodes D11 and D12 are in non-conduction mode. Then, capacitor C1 charges the parallel connected inductors L4,L5 and L6.

### 3.2 Non-shoot-through state (including active and null state)

Diode(Din) is forward biased, In the upper branch, diodes D1, D2, D3 and D4 are in non-conduction mode, while two diodes D5 and D6 are in conduction mode. Then the series connected inductors L1,L2 and L3 are transfer the stored energy to inverter circuit. In the lower branch, diodes D7, D8, D9 and D10 are in non-

conduction mode, while two diodes D11 and D12 are in

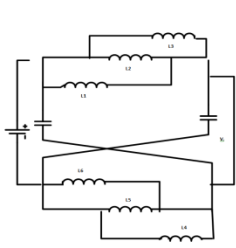


Fig 7. Shoot through state

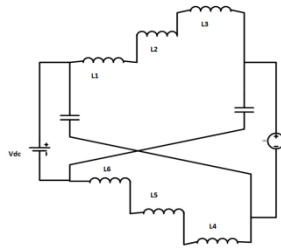


Fig 8. Non-Shoot through state

the network becomes symmetrical, by choosing the same inductance(L) value of six inductors and same capacitance (C) value of two capacitors. From symmetrical circuit, capacitors and inductor voltages become

$$V_{L1} = V_{L2} = V_{L3} = V_{L4} = V_{L5} = V_{L6} = V_L$$

$$V_L = V_C \quad (4)$$

From Shoot through state equivalent circuit shown in fig 7

$$V_L = V_C$$

$$V_i = 0 \quad (5)$$

From Non-Shoot through state equivalent circuit shown in fig 8, the voltage equation (2) can be expressed as :

$$3V_L = V_{dc} - V_C$$

$$V_i = V_C - 3V_L = 2V_C - V_{dc} \quad (6)$$

From the fact that in steady state over one switching period average voltage of the inductor should be zero, (7) can be derived by using (5) and (6)

$$V_L = v_L = \frac{T_0 V_C + (1 - T_0) \left( \frac{V_{dc} - V_C}{2} \right)}{T} = 0$$

$$V_C = \frac{1-\alpha}{1-4\alpha} V_{dc} \quad (7)$$

the inverter bridge peak DC-link voltage can be expressed in (7) and can be rewritten:

$$V_i = V_C - 3V_L = 2V_C - V_{dc} = \frac{1+2\alpha}{1-4\alpha} V_{dc} \quad (8)$$

Thus the boost factor B can be obtained by

$$B = \frac{1+2\alpha}{1-4\alpha} \quad (9)$$

The proposed ZSIÄs Voltage gain is expressed as

$$G = M.B = (1 - \alpha) \frac{1+2\alpha}{1-4\alpha} \quad (10)$$

#### 4. Design of passive component:

By the inductance value and the current we can determine the size of the inductor . And from the ratio of output power  $P_{out}$  and the input dc voltage  $V_{dc}$  , we can calculate the current through the inductor  $I_L$  shown as

$$I_L = \frac{P_{out}}{V_{dc}} \quad (11)$$

The inductors in shoot-through state the voltage is defined by  $V_C$  . Therefore, the inductor current ripple is given by

$$\Delta I_L = \frac{V_C D_0 T}{L} \quad (12)$$

Substituting (8) into (13), the necessary inductance of the Switched

Inductor ZSI can be obtained as

$$L = \frac{(1-D_0)\alpha V_{dc} T}{(1-4D_0)\Delta I_L} \quad (13)$$

In shoot-through states the Inductor current increases and in non-shoot-through state it decreases. Therefore, in Nonshoot-through state the minimum inductor current occurs.

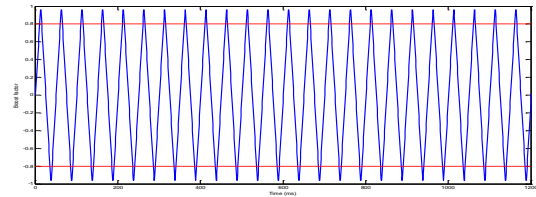


Fig 9. The algorithm of shoot through state generation

#### 5. Maximum Power Point Tracking:

Mechanical power extracted by the wind turbine is given by

$$P_{mech} = \frac{1}{2} \rho A C_p V_w \quad (15)$$

Where A= Area of turbine,  $\rho$ = air density,  $C_p$ = Coefficient of Power,  $V_w$  = Speed of Wind turbine

Fig.10 shows output power of turbine Vs speed of the generator characteristics. For different wind speeds, maximum power produced by wind turbine is at different speeds of turbine and red line indicates the Maximum power point tracking values. Eqs.(16) give steady-state relations of AFPMSG [1]:

$$T = K_t I_a$$

$$E = K_e \omega_r$$

$$E^2 = V^2 + (I_a \omega_r L_s)^2 \quad (16)$$

$\omega_r$  is speed of the rotor,  $I_a$  is the stator current, V is the phase voltage of generator and  $L_s$  is the inductance of AFPMSG. Diode rectifier output DC voltage is given by

$$V_{dc} = \frac{3\sqrt{6}}{\pi} V \quad (17)$$

The output DC voltage of rectifier concluded by Eqs. (16-17), follows as: (18)

$$V_{dc} = \frac{3\sqrt{6}}{\pi} \omega_r \sqrt{K_e^2 - \left( \frac{T L_s}{K_t} \right)^2} \quad (18)$$

The torque is associated to rotor speed and wind, according to Eqs. (8), the DC voltage is a function of speed of the rotor. As a result, the rotor speed can controlled by DC voltage[1].

Shoot-through time according to power equation decides the Boost ability of Z-source Inverter. After critical DC voltage  $V_{dc}$ , VSC is calculated by the following:

$$V_{SC} = \frac{V_c}{2V_C - V_{dc}} \quad (19)$$

The  $V_{sc}$  determines the shoot-through rate to control  $V_{dc}$ . Fig 9 shows the algorithm of shoot through state generation. In this simple boost PWM triangular carrier wave compared with two straight line  $V_{sc}$  and  $-V_{sc}$  which represents boost factor to control the shoot through state.

Shoot through state will occur, when the triangular carrier wave is higher than the  $V_{sc}$  straight line and lower than the  $-V_{sc}$  straight line, otherwise it operate as a traditional PWM.

The active and reactive powers delivered to the grid in the d-q reference frame are given as follows:

$$P = \frac{3}{2} (V_d i_d + V_q i_q)$$

$$Q = \frac{3}{2} (V_q i_d - V_d i_q) \quad (20)$$

If the reference frame is guided along the voltage of grid,  $V_q$  equals to zero. As a result, the active and reactive powers are expressed as (20):

$$P = \frac{3}{2} V_d i_d$$

$$Q = -\frac{3}{2} V_d i_q \quad (21)$$

By scheming of direct and quadrature components of current we can control the active and reactive powers. In this case, capacitor voltage is set aside constant at position value.

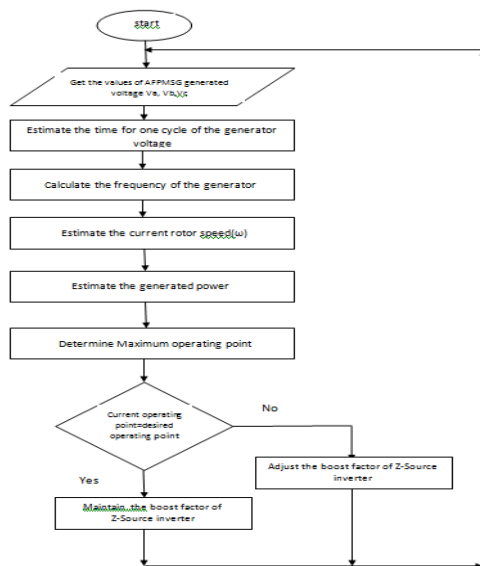


Fig 10. Proposed MPPT algorithm

Table I. Parameters of AFPMSG[4]

Parameter	Symbol	Value	Unit
Number of poles in AFPMSG	P	10	-
d-axis component of stator inductance	$L_d$	0.247	H
q-axis component of stator inductance	$L_q$	0.066	H
Permanent magnet flux linkages	$P_{si}$	1.6	Wb-turns
Power reference	$P_{ref}$	2000	VA
Moment of inertia	J	4	Kg m <sup>2</sup>
Friction Coefficient	K	0.16	Nm/rad

## 6. Simulation Results:

The proposed structure of wind turbine has been modeled to verify the performance of suggested topology. The electrical parameters of studied AFPMSG are presented in Table 1.

Rapid change in the speed of wind is subjected in order to estimate the dynamic behavior of the proposed AFPMSG. The below

figure 11 shows the characteristics between output power turbine to the speed of generator with the wind speed as parameter, and maximum power extracted by wind turbine at pitch angle is equal to zero.

This figure 12 shows the simulation output result of the Axial Flux Permanent Magnet Synchronous Generator at wind speed of 18 m/s and rotor speed at 1.4 p.u.

The output AC voltage of AFPMSG is given to rectifier bridge it converts the voltage to DC, and this converted DC output voltage given as input to the SL-ZSI. the parameters of the SL-ZSI are

1. Z-Source network  $L1=L2=L3=L4=L5=L6=300\mu H$ ,  $C1=C2=1000\mu F$ .
2. Load resistance  $R=15\Omega$
3. Switching frequency  $f_s=2KHz$

The proposed topology work with shoot through duty ratio  $D_0=0.2$  and modulation index  $M=0.8$ . In this case the boost factor  $B=7$ , voltage gain  $G=5.6$  capacitor voltage  $V_{c1}=V_{c2}=200$  V, Inverter bridge voltage  $V_i=330$  V. the peak voltage phase voltage  $V_0=140$  V.

For the case of Convectional ZSI, to get 120 V peak output AC voltage, in this inverters  $D_0=0.44$  and  $M=0.56$ , Voltages at capacitors  $V_{c1}=V_{c2}=240$  V and the inverter bridge are,  $V_i=430$  V. Very long shoot through duty ratio is required. So the voltage stress on the capacitor and inverter bridge is increased rapidly.

For proposed system to get 120 V peak output voltage at AC side. By theoretical study,  $D_0=0.19$  and  $M=0.81$ , respectively. voltages at capacitors  $V_{c1}=V_{c2}=173.5$  V, and the inverter bridge are  $V_i=297$  V, respectively. It shows it requires less shoot through duty ratio so stress on the inverter bridge and capacitor is reduced.

Fig 11 shows the results of MATLAB simulation with different wind speeds and for different pitch angle but it shows the maximum power extracted by wind turbine at zero pitch angle. Fig 12 shows the output voltage results of AFPMSG at wind speed 22 m/s and rotor speed of 1.6 pu. Fig 13 shows the output voltage result of inverter bridge without filter and same way Fig 14 shows the output voltage with second order high pass filter. Finally Fig 15 shows the three output voltage samples from power grid.

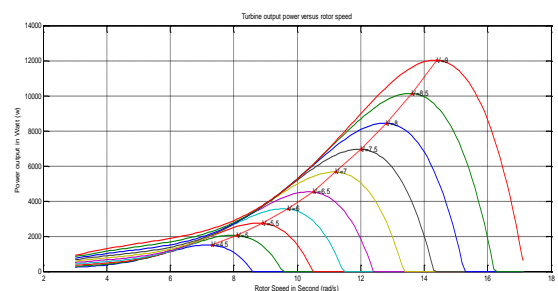


Fig 10. Turbine output power Vs generator speed

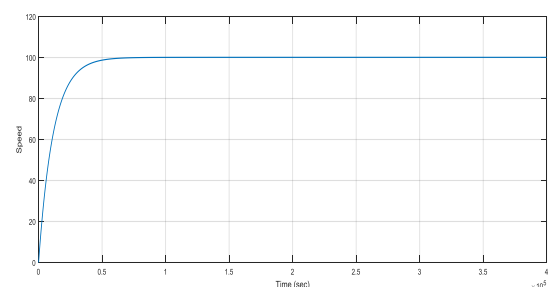


Fig 11. Turbine speed

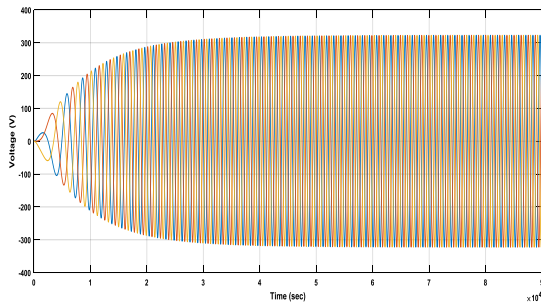


Fig 11. Output voltage of AFPMSG

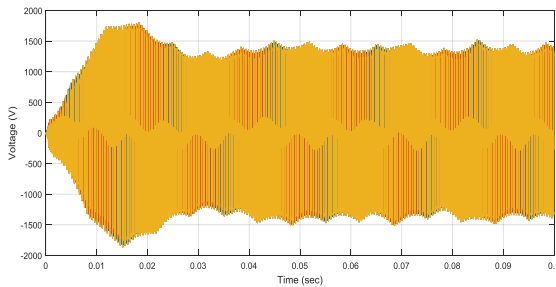


Fig 12. Output voltage of SL ZSI without filter

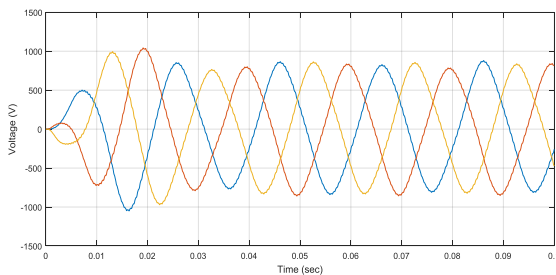


Fig 13. Output voltage of SL ZSI with filter

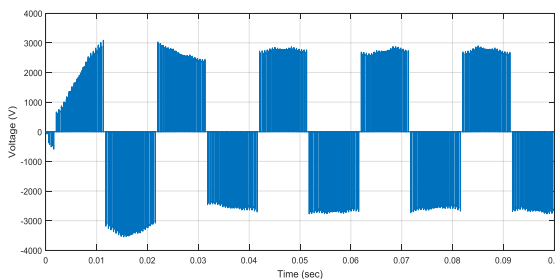


Fig 14: Line Voltage (Van)

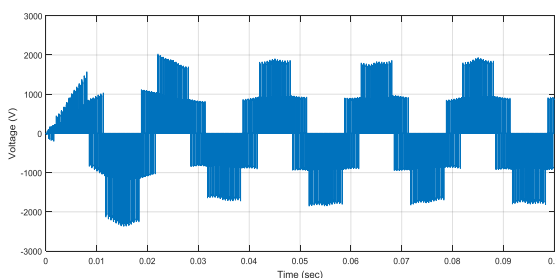


Fig 15: Phase Voltage (Vab)

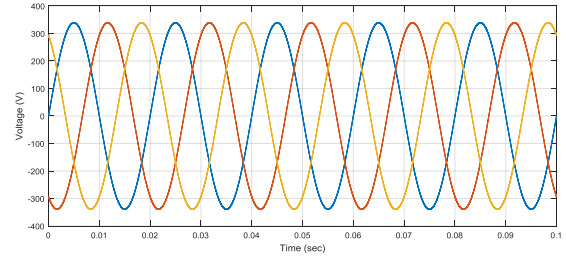


Fig 16: Transformer Output Voltage

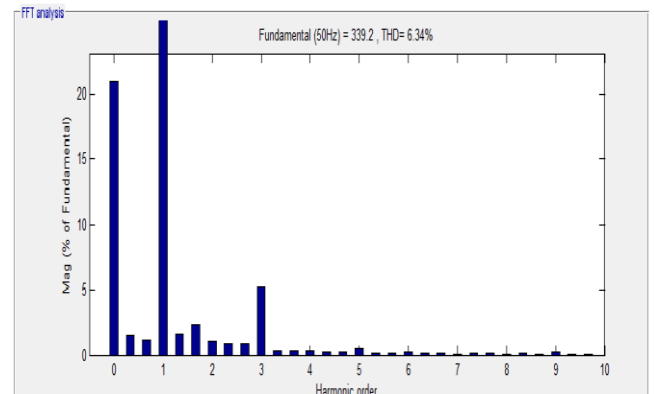


Fig 17. Harmonic Order of SL ZSI Output Voltage

For variable wind speeds and rotor speeds we can get different voltage values and those voltages are boosted by switched Inductor Z-Source Inverter and Total Harmonic Distortion values by Simple Boost Pulse Width Modulation control technique is shown in below table, Results are shown above for wind speed 12 m/s and rotor speed 0.8 pu.

Table II. Output Voltage with Different Speeds

Wind Speed (m/s)	Rotor speed (pu)	Output voltage (V)	Boosted Voltage (V)	THD %
10	1	24	108.4	6.94
14	1.2	54	272.68	6.49
18	1.4	74	377.2	6.41
22	1.6	104.5	506.7	6.34

## 7. Conclusion

This paper work explained about the connection of Axialflux permanent magnet synchronous generator (AFPMSG) based variable speed wind turbine connected to grid with power electronic converters. In This paper modeling of AFPMSG has been implemented in simulation in order to validate it and proposed inverter circuit. And AFPMSG produced different voltage values operated under different wind speeds shown in the above table 2. The SL-ZSI increases the MPPT capability and reliability of the wind turbine based AFPMSG. The simulation results shows that the SL-ZSI can boost the voltage with less modulation index compared to the convectional Z-Source inverter and it reduces the stress on the capacitor and inductors in the Z-network. The simulation results shows the ability of the proposed topology.

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