Modeling and Analysis of Wind turbine Driven Self-Excited Induction Generator Connected to Grid Interface with Multilevel H-Bridge Inverter

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Abstract

This paper deals with the stator flux oriented vector control of wind driven self excited induction generator This paper presents an investigation of Hybrid nine level inverter (HNLI) used along with the voltage source rectifier unit as interface between Self excited induction generator and grid. Making use of HNLI benefits of low harmonics distortion, reduced number of switches to achieve the nine level output over the conventional cascaded nine level inverter and reduced switching losses results in improvement of the p.f at grid, to compensate the reactive power and to suppress the total harmonic reduction. The generated voltage of the wind driven self excited induction generator mainly depends on the wind velocity, appropriate excitation capacitance and grid conditions. The main objective of this paper is to track the maximum power of the grid connected SEIG driven by wind turbine. In previous literature there no discussion about the grid connected SEIG interface with the AC/DC link. The variable magnitude, variable frequency, voltage of the generator can be controlled by the proper modulation index.   The modulation index of the proposed HNLI is adjusted to obtain the maximum output power. The results are valid through MATLAB/SIMULINK software.

Keywords: Self excited induction generator (SEIG), Wind turbine, Hybrid nine level inverter, voltage source rectifier, grid.

1.   Introduction

A wind power generation system generates electricity from wind energy and typically comprises an Recently considerable attention is being focused on environmentally clean and safe renewable energy sources like wind, solar, hydro etc. Many types of generator concepts have been used and proposed to convert wind power into electricity. The size of the wind turbines has increased during the past ten years, and the cost of energy generated by wind turbine has decreased. The challenge is to build larger wind turbines and to produce cheaper electricity. Thus, there is a need to find a way to convert wind energy into electrical energy from wind turbines that can be scaled up in power without extremely high cost penalties. The use of an self excited induction generator [1] in general and squirrel cage self excited induction generator in particular for such applications in remote, unattended and maintenance free sites is earning

more favors over that of the synchronous alternators. The reason for the widespread popularity of induction generator is owing to it's capability to generate the power from variable speed as well as constant speed prime movers, low unit cost, reduced maintenance, rugged and brushless rotor, absence of a separate d.c. source for excitation, absence of moving contacts, inherent overload protection, improved performance due to low transient impedance, natural protection against short circuit etc.Especially in remote areas, Self-Excited Induction Generators are producing good electricity compared other generators. By using an advanced power electronic converters, the variable voltage variable frequency of the SEIG is converted into constant voltage and constant frequency. The generated voltage of the SEIG is mainly depends upon the excitation capacitance values, change in wind velocity and load conditions. The reactive power requirement by the induction generator can also be supplied by a group of capacitors. If the capacitance is insufficient, the induction generators will not build up voltage. The main drawback of the induction generator is need of reactive to build up the terminal voltage.

In the SEIG, the excitation current is supplied by the capacitors connected across its terminals. The terminal voltage is regulated against changing the speed and load conditions, by changing the terminal capacitance and the variation of the frequency depends on the operating speed range. The application of power semi conductor devices, and controlled converter circuits has resulted in suitable regulating schemes for self excited squirrel cage generators. The above papers did not mention the effect AC/DC link and shunt capacitance on active power, reactive power and power factor at grid. This paper exploits the possible ways to generate electrical power at loaded condition to extract the information regarding the active power, reactive power and powerfactor at load.As wind energy is not constant in nature this scheme could be extended to a variable speed,constant voltage wind energy conversion system.
The system we tested has the following components:

- a wind turbine
- a three-phase, 3-hp,squirrel cage induction generator driven by the wind turbine
- various sets of capacitors to provide reactive power to the induction generator
- a three-phase diode bridge to rectify the current provided by the generator
- a shunt capacitor to smooth the dc voltage ripples
- a three-phase Hybrid nine level inverter to convert the power from the dc bus to the utility.

2. Proposed system

In the proposed system, a power generation system consisting of a wind turbine with SEIG connected to the grid through a power electronic converter is considered. A proposed impedance source inverter based wind driven SEIG fed to grid is shown in Fig.1.
The wind turbine driven SEIG connected to the symmetrical grid. The power conversion efficiency of proposed method is improved compared to the traditional inverters for wind electric power generation. In traditional inverters, the upper and lower switches of each phase cannot be switched on simultaneously. The output voltage of the proposed method is limited to either greater or lesser then the given input voltage. The variable output voltage from the self excited induction generator is rectified and then inverted by using the

proposed inverter. The proposed method can produce an output voltage greater than the input voltage. This proposed scheme is used

to improve the power factor and reduce harmonic current. The parameters used in the SEIG can be obtained by conducting no load test and short circuit test on the induction generator when it is used as an induction motor. The traditional tests used to determine the parameters are the open circuit test and the short circuit test. The induction machine used as the SEIG in this investigation is a three-phase wound rotor induction motor with specification: 415V, 7.5A, 3kW, 50Hz, and 4 poles
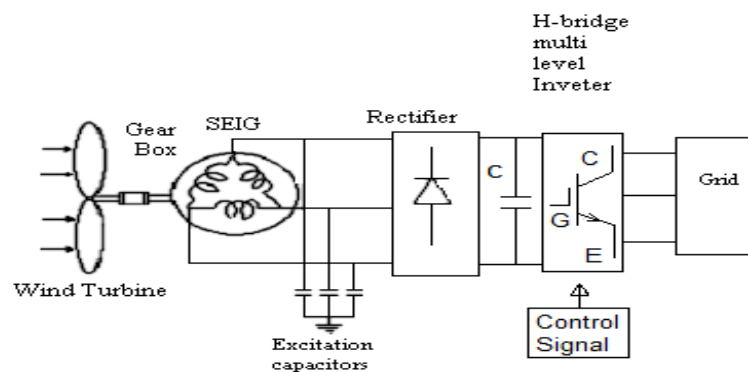
Fig.1.Proposed SEIG model connected to grid through HNLI

A. Characteristics of wind turbine

In wind parks, many wind turbines are equipped with fixed frequency induction generators. Thus the power generated is not optimized for all wind conditions. To operate a wind turbine at its optimum at different wind speeds, the wind turbine should be operated at its maximum power coefficient(Cp-optimum = 0.3-0.5). To operate around its maximum power coefficient, the wind turbine should be operated at a constant tip-speed ratio, which is proportional to ratio of the rotor speed to the wind speed. As the wind speed increases, the rotor speed should follow the variation of the wind speed. In general, the load to the wind turbine is regulated as a cube function of the rotor rpm to operate the wind turbine at the optimum efficiency. The aerodynamic power generated by wind turbine can be written as:

$$P = 0.5 \rho A \, C_p V^3 \qquad\qquad (1)$$

Where the aerodynamic power is expressed as a function of the specific density (ρ) of the air, the swept area of the blades (A) and the wind speed (V). To operate the wind turbine at its optimum efficiency (Cp-optimum), the rotor speed must be varied in the same proportion as the wind-speed variation. If we can track the wind speed precisely, the power can also be expressed in terms of the rotor speed.

$$P = K_p \text{rpm}^3 \qquad\qquad (2)$$

The power described by equation [2] will be called P_{ideal}.

This is the power to be generated by the generator at different rotor rpm. One way to convert a wind turbine from fixed speed operation to variable-speed operation is to modify the system from a utility-connected

induction generator to a self excited operation. Ideally, if the inertia of the wind turbine rotor is negligible, the rotor speed can follow the variation of the wind speed if the output power of the generator is controlled to produce the power-speed characteristic described in equation 2. Thus the wind turbine will always operate at $C_{p\text{-optimum}}$. In reality, the wind turbine rotor has a significantly large inertia due to the blade inertia and other components. The wind turbine operation can only in the vicinity of $C_{p\text{-optimum}}$. However, compared to fixed-speed operation, the energy captured in variable-speed operation is significantly higher.

With variable-speed operation and sufficiently large rotor inertia, there is a buffer between the energy source (wind) and energy sink (utility). Allowing the rotor speed to vary has the advantage of using the kinetic energy to be transferred in and out of the rotor inertia. Thus, the aerodynamic power that fluctuates with the wind input is filtered by the inertia before it is transmitted to the utility grid. This concept is very similar to the use of dc filter capacitor at the dc bus of a dc-dc converter. The dc capacitor filters the voltage ripple so that the voltage output presented to the load will be a smooth output voltage. It is expected that the turbulent content in wind input will not be transmitted directly to the mechanical drives (gearbox) of the wind turbines thus the mechanical stress and fatigues on mechanical components can be relieved. Thus, the lifetime of the mechanical drives and other components of the wind turbine can be extended by variable-speed operation.

For the wind turbine used in the study, the following form approximates C_p as function of λ, β is given by:

$$C_p=(0.44-0.167\beta)\sin\left[\frac{\pi(\lambda-2)}{15-0.3\beta}\right]-0.00184(\lambda-3)\beta \qquad (3)$$

B. Self excited induction generator

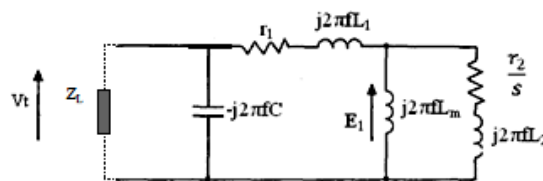The induction machine is modeled using the steady-state equivalent circuit shown in Figure 2.

Fig.2.Equivalent circuit of SEIG

The dynamic characteristics behavior of self-excited induction generator can be represented by the electromechanical equation derived in the synchronously rotating d-q reference frame [1][5].The dynamic model of the induction machine is derived by using a two phase motor in direct and quadrature axes [3].

The wind turbine drives an induction generator whose flux linkage model can be described in d- and q-axis synchronous
reference frame as [2]:

$$p\psi_{ds}=\omega_b(V_{ds}+R_si_{ds}+\psi_{qs}) \qquad (4)$$

$$p\psi_{qs}=\omega_b(V_{qs}+R_si_{qs}-\psi_{ds}) \qquad (5)$$

$$p\psi_{dr}=\omega_b(V_{dr}-R_ri_{dr})+(\omega_b-\omega_m)\,\psi_{qr} \qquad (6)$$

$$p\psi_{qr}=\omega_b(V_{qr}-R_ri_{qr})+(\omega_b-\omega_m)\,\psi_{dr} \qquad (7)$$

In the above equations, all the rotor variables are referred to the stator side. The expression for the electromagnetic torque in per (unit can be written as:)

$$T_e=\psi_{ds}i_{qs}-\psi_{ds}i_{ds} \qquad (8)$$

The wind turbine and induction generator rotors are represented as a lumped one mass. So, the dynamic equation of motion can be written as:

$$p\,\omega_m=\omega_b/2H(T_m-T_e) \qquad (9)$$

Where ω_b Base speed (377 rad/s)

The excitation capacitance and frequency of the SEIG can be calculated from the equations

$$A_4f^4+A_3f^3+A_2f^2+A_1f+A_0=0 \qquad (10)$$

$$C=\frac{af+b}{cf^3+df^2+e} \qquad (11)$$

The constants are as given in APPENDIX.

C.   Diode bridge rectifier and DC link

Three phase uncontrolled bridge rectifier is used to convert the variable voltage, variable frequency at the induction generator terminal into rectified dc voltage [3]. To simplify the analysis, all the diodes are assumed to be ideal (no power losses or on-state voltage drop).

The dc voltage vd contains six pulses (humps) per cycle of the supply frequency. The rectifier is, therefore, commonly known as a six-pulse rectifier.

The average value of the dc voltage can be calculated by

$$Vd=\left[\frac{3\sqrt{2}}{\pi}\right]\left[\frac{\sqrt{3}}{\sqrt{2}}\right]*V_{dc}*\eta_t \qquad (9)$$

Input transformer's turn's ratio is $1:\eta_i$. The series reactor (L) and shunt reactor (C_{sh}) acts as an input filter. The current ripples and voltage ripples are reduced by using the above components [5]. The dc filter capacitor Cd is assumed to be sufficiently large such that the dc voltage is ripple-free. Under this assumption, the capacitor and dc load can be replaced by a dc voltage source Vd. The value of Vd varies slightly with the loading conditions. When the rectifier is lightly loaded, Vd is close to the peak of the ac line-to-line voltage and the dc current id may be discontinuous. With the increase in dc current, the voltage across the line inductance

Ls increases, causing a reduction in Vd. When the dc current increases to a certain level, it becomes continuous and thus the rectifier operates in a continuous current mode.

D.   Multi level inverter

The diode clamped multi level inverters are used to eliminate over voltage stress and reduce the switching frequency. By increasing the voltage levels of the inverter reduces the switching losses. To connecting the switching devices in parallel connections it leads to higher current levels. Multilevel converter topologies are based on this principle, and therefore the voltages applied to the devices can be controlled and limited.

Then number of H bridges is formed as 4.The no of bridges is equivalent to $\frac{m-1}{2}$ where n is the no of levels (here 9)[6] and the no of carrier waves for PWM control is equal to (m-1) overall for the positive and negative gate pulse generators. The range of the modulation index of the inverter is $0 \leq m \leq \frac{2}{\sqrt{3}}$.The number of output phase voltage levels is M=$\frac{N-1}{2}$. The total number of active switches (IGBTs) used in the CHB inverters can be calculated by $Nsw = 6(m-1)$

The HNLI in MATLAB/SIMULINK is as shown in Fig.3 and its output waveforms are as shown in Fig.4.
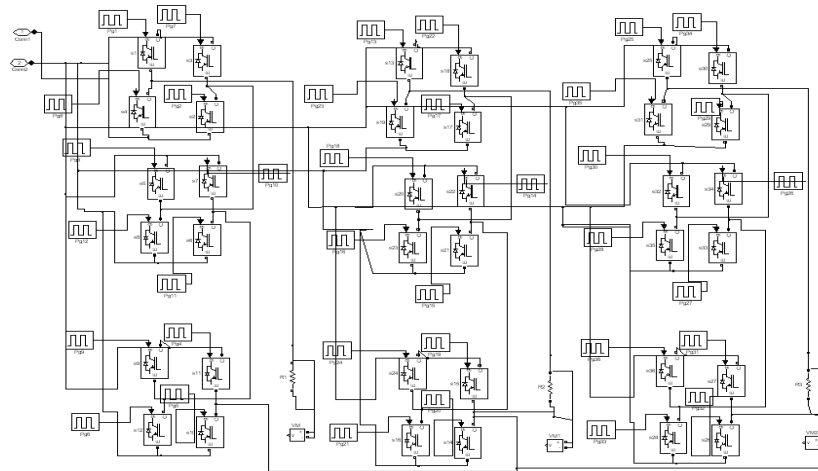
Fig.3. HNLI configuration in MATLAB/SIMULINK
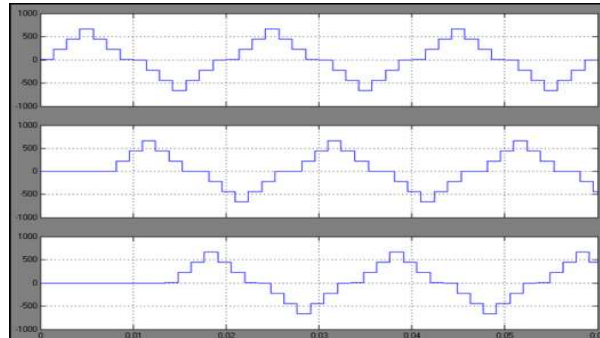
Fig.4.Line voltages of   HNLI

3.   Results and discussions

In this chapter, the wind driven SEIG fed nine levels H-bridge inverter for wind power conversion scheme has been explained with the simulation results. The Figure 5 shows the simulation model of the SEIG fed H – bridge inverter with grid. The d-q model of the self-excited induction generator is used to understand the all characteristics behavior of the generator system. The SEG voltage, rectifier voltage, inverter output voltage, current waveforms with grid has been discussed with help of simulation results.
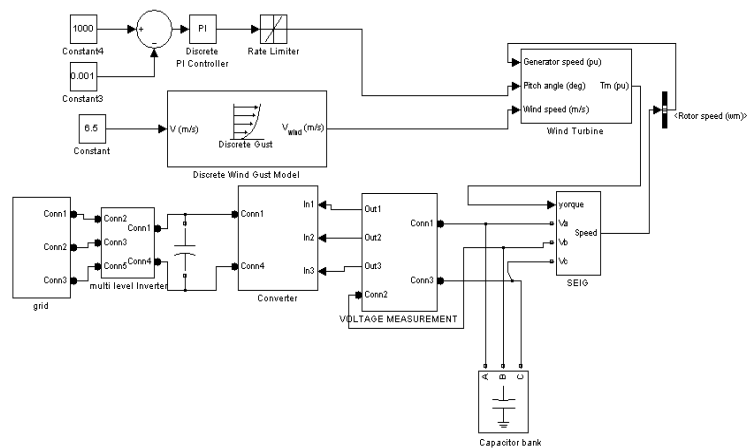
Fig.5.Simulink model of SEIG fed HNLI with grid
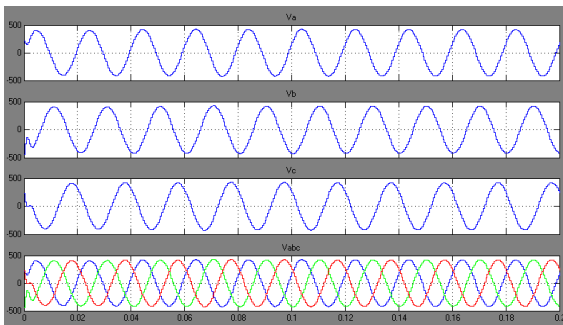
Fig.6.SEIG generated voltages   Fig.7.Rectifier voltage
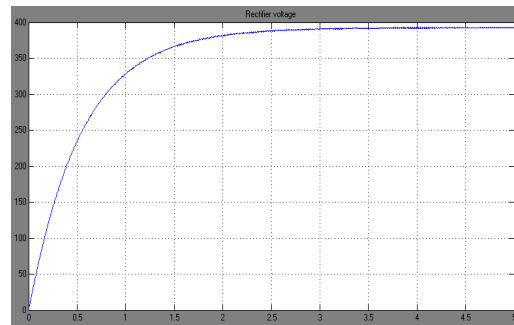
The output voltage of SEIG depends upon the wind velocity, excitation capacitance value and wind fluctuations. Excitation capacitors are used to reduce the reactive power burden of self excited squirrel cage induction generators. The variable magnitude and variable frequency output is given to the H bridge converters. This inverter produces a required voltage with low harmonic distortion compared with other traditional inverters.   The generated voltage of SEIG is shown in Figure 6. The generator produces 390volts which is fed back to the uncontrolled rectifier. The rectifier output voltage is 390volts. Figure 7 shows rectifier voltage applied to the inverter. Since all the switches are assumed to be ideal switches there is no losses in circuit .A D.C link capacitor of 450μF in parallel with the diode maintains the voltage at a voltage of 390V. As the speed is increasing the voltage builds up starts early as a result of mutual inductance variation.It reaches to its saturation value early increasing the steady state voltage. As the mutual inductance is depends on magnetizing current which in turn depends on direct axis and quadrature axis current, which is continuously increasing till the voltage reaches steady state, drawing more reactive power.
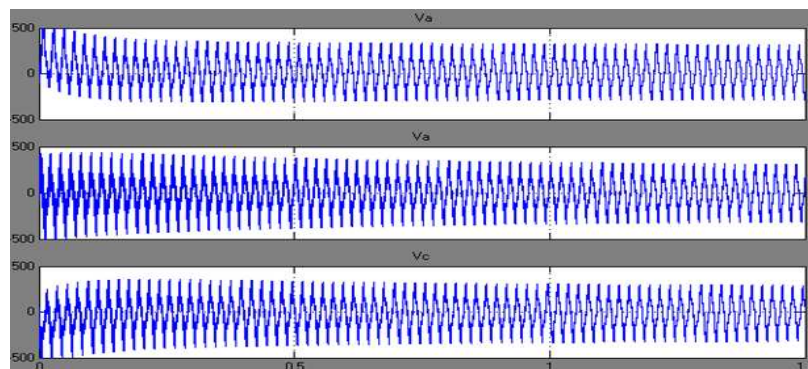
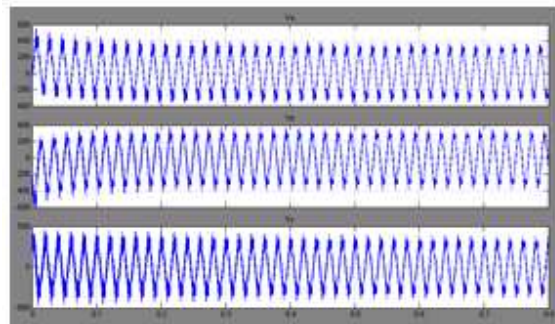Fig.8.Phase voltages at the inverter

61

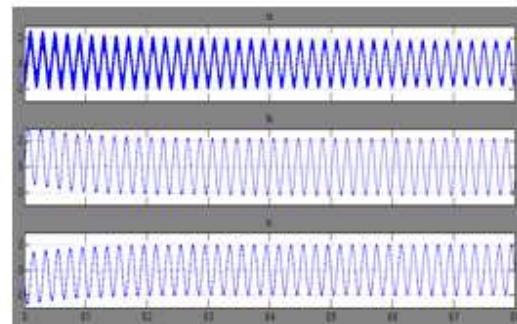Fig.9.Phase voltages at the grid

Fig.10.Phase currents at the grid

In nine level inverters, are produce high voltage in the output terminal with less harmonic interruption. The phase voltage waveform of the cascaded nine levels H – bridge inverter is shown in Fig.10. The inverter produces 390 volts in the output terminals. It took about 1.3 seconds to settle to its steady state voltage of 390V.The excitation capacitance used to excite the SEIG is 55μF. The equivalent circuit d-q model of the induction generator is helpful to analyze all its steady state characteristics. The EMI noise also reduced by choosing the proper no. of bridges formed in the inverter circuitry. The proposed cascaded H-bridge multilevel boost inverter uses a standard three-leg inverter (one leg for each phase) and an H-bridge in series with each inverter leg which uses a capacitor as the dc power source. In this topology, the need for large inductors is eliminated. A fundamental switching scheme is used to do modulation control and to output nine-level phase voltages. Experiments show that the proposed dc–ac cascaded H-bridge multilevel boost inverter without inductors can output a boosted ac voltage. Cascaded multi level inverter has the simple configuration compare than other multi level inverters. The controlled output voltage of the inverter is mainly depends upon the switching states. The output voltage of the inverter is controlled by fixed pulse width modulation technique.

The phase voltage at the grid is 390V.Assuming that there are no losses in the line and with the series reactor in the circuit the voltage at the grid is same as that of the generated voltage. It took about 0.3seconds to settle to steady state voltage of 390Volts.If there is any increase in the excitation capacitance of SEIG the generated voltage is increased and there by the increase in voltage at the grid.

The phase current waveforms at the grid are as shown in Fig.10.These currents are known as the load currents. It took about 0.3seconds to settle to steady state current of 2Amps.As the excitation capacitance and speed is increasing the load current is becoming distorted.
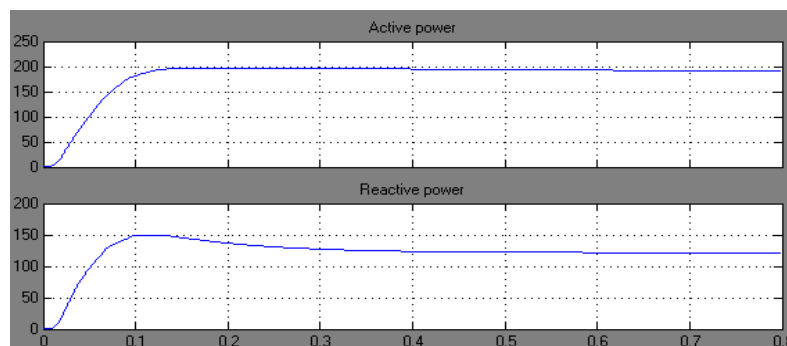

Fig.11.Active and reactive power generated by SEIG

The active and reactive power generated by SEIG are as shown in Fig.11.The active and reactive power generated by the machine at 1650r.p.m and with the excitation capacitance of 55μF are200Watts and 120VAr respectively and maintain the load as constant. If there is any increase in the speed than there is both the active and reactive power are increased. And also if there is any change in the excitation capacitance the reactive power generated by the machine is decreased. The active and reactive power reaches to steady state values at 0.5seconds.
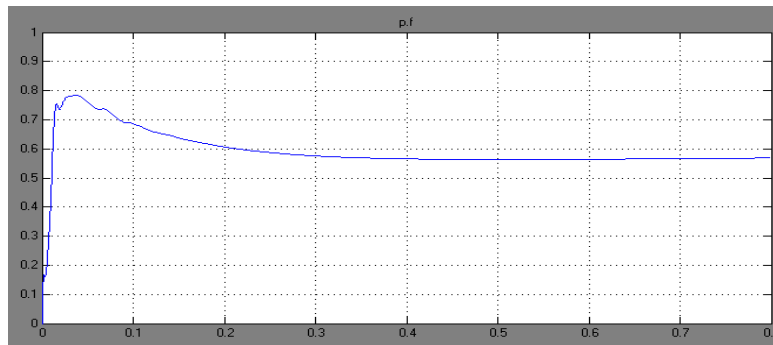
Fig.12.power factor at the SEIG

The power factor at the generator is as shown in Fig.12.The p.f generated by the generator is 0.58lead.The p.f reaches to steady state at 0.5seconds.As reactive power   and active power are varying with time and reaches to the steady state at 0.5seconds the p.f also reaches to steady state at 0.5seconds. This p.f is taken at the constant speed, excitation capacitance and load. If there is any change in these three parameters the active and reactive power are varied and hence the p.f.

   The active and reactive power at the grid are as shown in Fig.13.The active and reactive power at the grid are varying 180to220Watts and -35 to -45VAr respectively. The active and reactive power reaches to steady state values at 0.5seconds.There is almost constant variation in generated active power to received active power at the grid. But there is larger variation in the reactive power. The generated reactive power is more than that of the received reactive power at the grid. This is due to the D.C link capacitor .Some reactive power is taken by the D.C link capacitor and hence the reactive power at the grid is decreased.
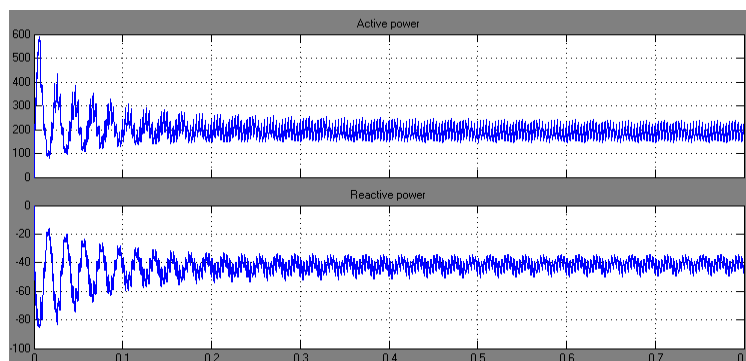

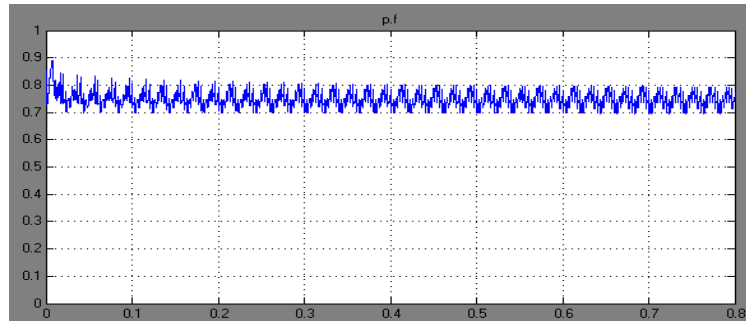Fig.13.Active and reactive power received by grid

Fig.14.power factor at the grid

The power factor at the grid is as shown in Fig.14.The p.f is varying between 0.7 to 0.8.The p.f reaches to steady state at 0.2seconds.As reactive power is decreased and having a constant active power the p.f at the grid is increased. This p.f is taken at the constant speed, excitation capacitance and load. If there is any change in these three parameters the active and reactive power are varied and hence the p.f.

Here it can be observed that due to the interface with the multilevel inverter the p.f is increased from generated end to the received end.Due to this interface the p.f is almost reached to the unity p.f.

The load voltage of the proposed inverter fed system mainly depending upon the load inductance value. The total harmonic distortion is increased which is mainly depends upon the load inductance values. The output voltage and current at the   grid is shown in Fig. 9 and 10 respectively. The harmonics presented in a output voltage is mainly depending upon the inductance value. The THD value is 2.33%.The active and reactive power at the grid is as shown in fig.13.The active and reactive powers at grid are 120W and 45W respectively. The THD value is 5.84%.The power factor at the grid is as shown in Fig.14.As the levels of the inverter are increasing the distortion can be reduced in the power at the grid.

4. Conclusions

The modeling and simulation analysis of wind driven SEIG fed H-bridge nine level inverter results are tested with the grid. The SEIG in its no load condition generated a phase voltage of 390 volts at a speed of 1650 rpm.For a wind velocity of 6.5 m/s, the proposed inverter produced an output voltage of 390 volts were obtained for grid connected SEIG driven by wind turbine. The required output voltage and active, reactive powers were obtained for a wind velocity range of 6.5m/s. From the simulation it is confirmed that as there is any variation in the excitation capacitance at a particular speed, voltage builds up faster and the magnitude of the voltage increases due to the availability of more VAr.The output voltage is controlled to give a constant voltage by D.C/A.C link .With the use of the interfacing unit there is an improvement in the p.f.The ripples in the p.f can   be eliminated with the use of the p.f loop can be maintained to unity p.f. From the FFT analysis it is also observed that PWM generates less harmonic distortion (4.35 %) in the output current and more efficient use of inverter voltage. The performance characteristics of the wind turbine SEIG are improved due to the closed loop condition and hence results in improved load performance.

5. APPENDIX

- The induction machine was three, phase3.5kW, 415V, 7.5A, 1500r.p.m, star connected stator winding. A 3-Φ variable capacitor bank or a single capacitor was connected to the machine terminals to obtain self-excited induction generator action.

  The measured machine parameters were:
  $r_1 = 11.78\Omega$; $r_2 = 3.78\Omega$; $L_1 = L_2 = 10.88H$. $L_m = 227.39H$

- To compute the coefficients A_4 to A_0 of equation(10),the following equations are first defined:

  $a = 2\pi k(L_M r_1 + L_1 r_1 + L_2 r_1 + L_M r_2 + L r_2 + r_L L_M + r_L L_2)$; $\quad$ $b = -2\pi N^* r_L(L_M + L_2)$

  $c = -8\pi^3 k(LL_M r_1 + LL_2 r_1 + LL_M r_2 - r_L L_1 L_M - r_L L_2 L_M)$; $\quad$ $d = -8\pi^3 N(r_L L_1 L_M + r_L L_2 L_1 + r_L L_2 L_M + LL_2 L_M)$

  $e = -2\pi k r_L r_1 r_2$; $\quad$ $g = -4\pi^2 k(L_1 L_M + L_1 L_2 + L_2 L_M + LL_M + LL_2)$

  $h = 4\pi^2 N(L_1 L_M + L_1 L_2 + L_2 L_M + LL_M + LL_2)$ $\quad$ $i = r_1 r_2 + r_L r_2$

  $j = -16\pi^4 k(LL_1 L_M + LL_2 L_M + LL_2 L_1)$ $\quad$ $l = 16\pi^4 N(LL_1 L_M + LL_1 L_2 + LL_2 L_M)$

  $m = 4\pi^2 k(L r_1 r_2 + r_L L_M r_1 + r_L L_1 r_2 + r_L L_1 r_2 + r_L L_2 r_1 + r_L L_m r_2)$ $\quad$ $p = -4\pi^2 N r_L L_M r_1$;

  $A_4 = cg - aj$ $\quad$ $A_3 = dg + hc + al - bj$; $\quad$ $A_2 = eg + hd + ic - ma - bl$; $\quad$ $A_1 = he + id - pa - bm$ $\quad$ $A_0 = ie - bp$;

- **Air gap voltage**:

The piecewise linearization of magnetization characteristic of machine is given by:

  $E_1 = 0$ $\quad\quad\quad\quad\quad\quad\quad$ $X_m \geq 260$
  $E_1 = 1632.58 - 6.2 X_m$ $\quad\quad\quad$ $233.2 \leq X_m \leq 260$
  $E_1 = 1314.98 - 4.8 X_m$ $\quad\quad\quad$ $214.6 \leq X_m \leq 233.2$
  $E_1 = 1183.11 - 4.22 X_m$ $\quad\quad$ $206 \leq X_m \leq 214.6$
  $E_1 = 1120.4 - 3.9.2 X_m$ $\quad\quad$ $203.5 \leq X_m \leq 206$
  $E_1 = 557.65 - 1.144 X_m$ $\quad\quad$ $197.3 \leq X_m \leq 203.5$
  $E_1 = 320.56 - 0.578 X_m$ $\quad\quad$ $X_m \leq 197.3$

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