CHAPTER 4

ISOLATED WIND ENERGY CONVERSION SYSTEMS

4.1 INTRODUCTION

The wind energy conversion system can either be connected to the grid or it can be made to act as a source of isolated power supply. Increasing emphasis on decentralized power generation has led to growing activity in the development of stand-alone / isolated power systems. In remote locations where the utility grid does not exist, Isolated Wind Energy Conversion System (IWECS) can be used to feed local electrical load. An isolated location where the grid is not available is one of the main commercial applications of IWECS. The use of electrical power in such areas includes heating loads and voltage sensitive loads.

Wind turbine driven SEIG are mainly used in these remote areas, due to its overall operational and maintenance simplicity. These induction generators are excited by the capacitance connected across the stator terminals. Due to various operating conditions such as change in wind velocity and load, the speed of the generator varies and hence the magnitude of the terminal voltage and frequency also vary. This is not viable for sensitive loads. This problem of variations in voltage and frequency can be solved by employing a power electronic interface between the generator and load. To have regulated voltage across the stator terminals, an artificial neuro controller based DC link converter is proposed across the generator terminals.
4.2 SELF-EXCITED INDUCTION GENERATORS

The excitation for the practical generator from the three phase capacitor bank connected across the externally driven induction generator terminals without the need of a separate AC source is called as a self-excitation. The capacitors provide the necessary magnetizing current for the generator which increases the emf generated till magnetic saturation of the machine due to residual magnetism present in the core. As saturation occurs, the flux becomes constant and final steady state value of the voltage is obtained. A minimum value of the capacitance is required for self-excitation. Self excitation in induction machine depends on appropriate combination of speed, load and excitation capacitances (Bansal 2005). Figure 4.1 shows a wind turbine driven squirrel cage induction machine with its three-phase stator in parallel with star connected capacitors and a star connected resistive load.

![Block diagram of wind turbine driven self-excited induction generator](image)

**Figure 4.1** Block diagram of wind turbine driven self-excited induction generator

4.2.1 Estimation of Self-Excitation Capacitance

The concept of self-excitation has found importance, considering various performance parameters that normally represent the efficiency of the
generator. The various values of the capacitance that can provide self-excitation are found using the most preferable method. To analyze the performance of IWECS, a prototype model is developed in the laboratory. The circuit diagram of the laboratory model is shown in Figure 4.2. The wind turbine is replaced by a DC shunt motor to drive the induction machine at different speeds. The specifications of DC shunt motor and induction machine are given in Appendix.

The method for determining the self-excitation is based on the open circuit characteristics of the induction generator. The circuit diagram for determination of self-excitation capacitance is shown in Figure 4.2.

![Figure 4.2 Circuit diagram for determination of self-excitation capacitance](image)

The open circuit test on the induction generator is conducted at normal rated frequency of 50 Hz. The AC voltage source is applied to the stator of the induction generator by using the auto transformer while its rotor is driven by the DC motor at a constant speed corresponding to the synchronous speed of the machine (Li Wang et al 1999). The magnetising current is the difference between the stator current and rotor current referred
to stator. Figure 4.3 shows the open circuit characteristics of the induction machine from which the piecewise relationship between $i_m$ and $L_m$ is represented as given in Equation (4.1).

$$
M = \begin{cases} 
0.65 & i_m \leq 0.85 \\
0.7275 / (i_m - 0.0901) & 0.85 < i_m \leq 1.5 \\
0.7373 / (i_m - 0.1055) & 1.5 < i_m \leq 2.65 \\
0.8502 / (i_m - 0.1476) & 2.65 > i_m
\end{cases} \quad (4.1)
$$

From the open circuit characteristics, the critical, minimum and maximum capacitance values are calculated. Failure of self-excitation occurs when the capacitance values violate the constraints.

![Figure 4.3 Open circuit characteristics of induction generator](image)

The critical capacitance is limited by the linear region of no load curve, below this value if capacitance is chosen the voltage will never build up and excitation fails initially. From the characteristics, the critical reactance and hence the critical capacitance is obtained are given by Equations (4.2) and (4.3).
Critical Reactance $X_c = 117.64 \, \Omega$ \hspace{1cm} (4.2)

Critical Capacitance $C = \left( \frac{1}{2 \pi \times 50 \times X_c} \right) = 27.06 \, \mu F$ \hspace{1cm} (4.3)

The minimum capacitance value is limited by the voltage of the machine. The rated voltage will not be generated if this value is chosen. This value is determined by drawing a slope at rated voltage and given by Equations (4.4) and (4.5).

Minimum Reactance $X_{\min} = \left( \frac{V_{\text{rated}}}{I} \right) = \frac{240}{3.35} = 71.64 \, \Omega$ \hspace{1cm} (4.4)

Minimum Capacitance $C_{\min} = \left( \frac{1}{2 \pi \times 50 \times X_{\min}} \right) = 44.03 \, \mu F$ \hspace{1cm} (4.5)

The maximum value of capacitance used is limited by the rated current. If a capacitance exceeds the maximum value current flow will be more than the rated current which leads to heating of stator core. The values of maximum reactance and maximum capacitance are given by Equations (4.6) and (4.7).

Maximum Reactance $X_{\max} = \left( \frac{V}{I_{\text{rated}}} \right) = \frac{258}{4.2} = 61.42 \, \Omega$ \hspace{1cm} (4.6)

Maximum Capacitance $C_{\max} = \left( \frac{1}{2 \pi \times 50 \times X_{\max}} \right) = 51.82 \, \mu F$ \hspace{1cm} (4.7)

The circuit diagram of the experimental model with the self-excitation capacitance is shown in Figure 4.4. Further analysis of the self-excitation was carried out with two sets of 3-phase star connected capacitance banks of rating 50 \, \mu F and 30 \, \mu F respectively. With the capacitor bank
connected across the stator terminals of the induction generator, 415 V 3-phase AC supply is applied to the stator terminals. The field winding of the DC shunt motor is excited such that it runs just above the synchronous speed of the induction machine and the supply is suddenly disconnected. As the induction generator gets excited by itself, the voltage generated is found to be 415 V and 295 V respectively. It is seen that as the self-excitation capacitance is below the minimum value, the voltage generated also decreases.

![Circuit arrangement with self-excitation capacitor bank](image)

**Figure 4.4 Circuit arrangement with self-excitation capacitor bank**

### 4.2.2 Analysis of Excitation Failure

The self-excitation is provided to the prototype model and the power is generated in the most efficient way. But at a certain limit the occurrence of the excitation failure is found. The concept of occurrence of the excitation failure is dealt in detail by Chandan Chakraborty et al (1998) and Mohammed Orabi et al (2004). The excitation failure for both no load and load conditions are studied. Under no load, the speed of the DC motor is gradually decreased. The voltage across the capacitance is noted. For certain
speed, the voltage across the capacitor drops suddenly to zero. This stage is called excitation failure stage.

Similarly 3-phase load is connected across the generator terminals and the speed of the DC motor is reduced gradually. The respective changes in stator voltage and load current are noted. At one particular point, the speed at which excitation fails is also noted. Since the load increases the value of the speed decreases simultaneously, as a result of which the self-excitation capacitance is not able to circulate the required energy. Thus the voltage decreases to very low order bringing in excitation failure condition. The experiment is carried out for different types of loads and self-excitation capacitance combinations and the results are tabulated in Table 4.1.

**Table 4.1 Experimental results of self-excitation analysis**

<table>
<thead>
<tr>
<th>Generator Speed (rpm)</th>
<th>Generated Voltage/Phase (Volts)</th>
<th>Load Current/Phase (Amps)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No Load and</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Self Excitation Capacitor Bank of 3*50 µF</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1440</td>
<td>240</td>
<td>1.8</td>
</tr>
<tr>
<td>1310</td>
<td>192</td>
<td>1.3</td>
</tr>
<tr>
<td>1200</td>
<td>140</td>
<td>0.7</td>
</tr>
<tr>
<td>1129</td>
<td>50</td>
<td>0.4</td>
</tr>
<tr>
<td>1102</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>3-Phase Resistive Load of 400 Ω and</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Self Excitation Capacitor Bank of 3*50 µF</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1320</td>
<td>220</td>
<td>3.3</td>
</tr>
<tr>
<td>1270</td>
<td>184</td>
<td>2.9</td>
</tr>
<tr>
<td>1195</td>
<td>85</td>
<td>1.3</td>
</tr>
<tr>
<td>1170</td>
<td>67</td>
<td>0.7</td>
</tr>
<tr>
<td>1145</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Table 4.1 (Continued)

<table>
<thead>
<tr>
<th>Generator Speed (rpm)</th>
<th>Generated Voltage/Phase (Volts)</th>
<th>Load Current/Phase (Amps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-Phase Resistive Load of 200 Ω and Self Excitation Capacitor Bank of 3*30 µF</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1410</td>
<td>207</td>
<td>2.8</td>
</tr>
<tr>
<td>1365</td>
<td>165</td>
<td>2.1</td>
</tr>
<tr>
<td>1280</td>
<td>62</td>
<td>1.4</td>
</tr>
<tr>
<td>1260</td>
<td>45</td>
<td>0.8</td>
</tr>
<tr>
<td>1235</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

| 3-Phase Inductive Load of 350 Ω and Self Excitation Capacitor Bank of 3*50 µF |
|-----------------------|---------------------------------|--------------------------|
| 1310 | 215 | 2.9 |
| 1295 | 150 | 2.1 |
| 1270 | 95 | 1.6 |
| 1260 | 35 | 0.7 |
| 1250 | 0 | 0 |

4.2.3 Emulation of Wind Turbine Characteristics on Laboratory Model

For experimental studies, a DC shunt motor is replaced by the wind turbine drive. Therefore the DC motor characteristics are modified to match the characteristics of the wind turbine. The output power of the wind turbine, which equals the input power to the induction generator shaft, now becomes the corresponding output power of the DC motor simulating the wind turbine.

The typical approximate output characteristics of a wind turbine and the tip speed ratio $\lambda$ are given by Equations (2.4) to (2.6) respectively. The power coefficient $C_P$ is given by Equation (4.8) (Siegfried Heier 1998).
\[
C_p = 0.5 \left( \frac{116}{\lambda_i} - 0.4 \beta - 5 \right) e^{-16.5 \lambda_i} \tag{4.8}
\]

\[
\lambda_i = \frac{1}{\left( \lambda + 0.089 \right) - \frac{0.035}{(\beta^3 + 1)}} \tag{4.9}
\]

where \( \beta \) is the blade pitch angle in deg. The blade pitch angle can be adjusted to achieve the maximum power at rated operating conditions.

Figure 4.5 MATLAB/SIMULINK model of wind turbine

A 3 kW wind turbine is simulated in MATLAB/SIMULINK using the Equations (2.3) - (2.6) and Equations (4.8) - (4.9) where the inputs to the model are wind velocity, pitch angle, rotor diameter, air density and turbine speed. The parameters of the 3 kW wind turbine are given in Appendix I. The air density of the location is taken as 1.2 kg/m\(^3\). The complete wind turbine model is shown in Figure 4.5. For a particular value of wind velocity, the rotor speed is varied and the corresponding values of \( C_p \), \( \lambda \) and power output of the wind turbine are noted and the power curve is drawn. The turbine speed Vs power output is shown in Figure 4.6 for various wind velocities.
As detailed by Yegna Narayanan and Johnny (1986), the output power in a DC shunt motor with constant air gap flux is given by Equation (4.10).

\[ P = a I_a N \]  \hspace{1cm} (4.10)

Therefore \[ P = K I_a N \]  \hspace{1cm} (4.11)

where \( K \) is constant of proportionality
\( I_a \) is the armature current in Amps and
\( N \) is the shaft speed in RPM

For speed \( N_1 \), \[ P_1 = a I_{a1} N_1 \]  \hspace{1cm} (4.12)

Similarly for speed \( N_2 \), \[ P_2 = a I_{a2} N_2 \]  \hspace{1cm} (4.13)

\[ \therefore \frac{I_{a2}}{N_2} = \frac{P_2}{P_1} \frac{N_1}{I_{a1}} \]  \hspace{1cm} (4.14)

Hence if the value of armature current for any power which corresponds to a particular speed is known, the armature current against speed characteristics
of the DC motor can be drawn in order to emulate the wind turbine power against speed characteristics. For various wind velocities, the required armature current against speed characteristics as shown in Figure 4.7 are drawn from the no load test data of the 3 kW DC shunt motor for constant field current of 0.4 A.

![Figure 4.7 Emulated DC motor characteristics](image)

### 4.2.4 Experimental Validation

In order to obtain the required characteristics, a closed loop speed control scheme for the DC motor drive is employed. The block diagram of the scheme is given in Figure 4.8. A half-controlled converter circuit which utilizes two SCRs is used for the speed control of DC motor.

![Figure 4.8 Block diagram of speed controller](image)
The speed controller circuit shown in Figure 4.9 consists of bridge rectifier circuit, voltage regulator, charging circuit, Unipolar Junction Transistor (UJT), pulse transformer, half-controlled rectifier, field rectifier (double bridge), over current protection block and field failure protection block.

Bridge rectifier BR3510 having voltage and current ratings of 50-1000 V and 35 A respectively is used as rectifier circuit. Zener diode acts as a voltage regulator along with a parallel capacitor of 1000 µF, 25 V rating. The regulated voltage from the zener diode is \( V_z \), which then charges the charging circuit (R-C) connected to the base of the UJT 2N2646. When the capacitor gets charged more than triggering voltage of the UJT, it gets switched on. Now the capacitor discharges through the closed path of UJT’s emitter, base 1 and the primary coil of the pulse transformer. The UJT gets turned off when the capacitor voltage reaches its valley voltage \( V_v \).
The pulse transformer is used for optimized transmission of rectangular electrical pulses. The base of the SCR in half-controlled rectifier gets the pulse from the secondary of the pulse transformer. The variable resistor is tuned to increase or decrease the time of charge and discharge of the charging capacitor and thus varying the firing angle $\alpha$ from $0^\circ$ to $180^\circ$. A separate double bridge rectifier circuit is used for the field circuit of DC motor. For over current protection, a current limiter is connected to a relay circuit which trips off the entire system, when the input current value exceeds the preset value of the current limiter circuit. This relay shorts the charging capacitor and thus preventing it to charge or discharge continuously to give out gating pulse. Similarly a field failure protection block is used with a relay circuit which is connected with field coil of the DC motor. Whenever the field of the motor gets opened, the de-energized relay coil trips the circuit.

The proximity sensor gives frequency pulse proportional to the actual speed of the system. For a rated speed of 1500 rpm, the frequency is 1.5 kHz. Frequency to voltage converter is used to interface the system with the comparator. For maximum speed, reference voltage value for comparison is 12 V. The voltage corresponding to the actual speed of the set-up from the F/V converter is given to the comparator LM324. Each OP-AMP in LM324 is connected to the IC ULN2803 and a 6 V relay. When a lower signal comes from the comparator there will be no potential difference between the coil ends of the relay as ULN 2803 grounds the signal. When a higher signal comes from the comparator, a potential difference is created within the relay and it is energized. The resistor connected across the relay circuit acts as a potentiometer for speed control with reference to the pulses obtained from the proximity sensor. The hardware set-up with the speed control system is shown in Figure 4.10.
For excitation capacitor of 50 μF per phase, the plot of the actual operating speeds obtained by loading the induction generator set and the corresponding DC motor armature currents are shown in Figure 4.11 for wind velocity range from 12 m/s and 14 m/s respectively. The results are found to be satisfactory.
4.3 MODELING OF SYSTEM COMPONENTS

The proposed scheme consists of a wind turbine driven Self-Excited Induction Generator (SEIG) and a Pulse Width Modulated (PWM) inverter block suitably connected by an uncontrolled diode bridge rectifier feeding an isolated load as illustrated in Figure 4.12. The terminal voltage and frequency of the SEIG varies with the wind velocity, load and the self-excitation capacitance. This variable generated voltage and frequency is rectified and the DC power is then transferred to the load through a PWM inverter. By controlling the pulse width of the PWM inverter and the excitation capacitance value, it is possible to regulate the voltage applied to the local load. The mathematical modeling of the components of IWECS using MATLAB/SIMULINK software is detailed in brief as under.

![Block schematic of isolated wind energy conversion scheme](image_url)

Figure 4.12 Block schematic of isolated wind energy conversion scheme
4.3.1 Wind Turbine driven Squirrel Cage Induction Generator

The horizontal axis wind turbine drives the self-excited induction generator. A gear transmission \((1: \eta_{\text{gear box}})\) steps-up the low speed \(N_T\) of the wind turbine to the higher rotational speed \(N_G\) of the generator. The wind turbine model using MATLAB/SIMULINK software based on equations (2.3) – (2.6) as explained in Section 4.2.3 is integrated with the dynamic model of induction generator and other network components for detailed performance analysis.

The dynamic modeling of the induction generator can be done in either stationary reference frame or synchronously rotating reference frame. While simulating the induction generator with the DC link converter and other network components, the synchronously rotating reference frame is suitable due to the generated DC voltages and currents. It avoids two transformations, one on the rectifier side and the other on the inverter side.

For dynamic analysis of self-excited induction generator, d-q axis (direct-quadrature axis) model based on the generalized machine theory is employed (Natarajan et al 1987, Li Wang and Jian – Yi Su, 1999). The following assumptions are made:

- Leakage inductances of stator and rotor are assumed to be constant
- Magnetizing inductance is taken as the function of flux in air gap
- Core loss in the machine is neglected

A non-linear model developed by using the d-q model of induction generator in arbitrary reference frame is shown in Figure 4.13.
Figure 4.13 Generator equivalent circuits in d-q reference frame

The d-axis and q-axis stator and rotor voltages are given in Equations (4.15) and (4.16). The subscripts for stator and rotor quantities are represented by $s$ and $r$ respectively. The symbol (’) denotes the rotor quantities referred to the stator and $p$ represents time derivative.

\[
\begin{align*}
V_{ds} &= -R_s i_{ds} - \omega \lambda_{qs} + p\lambda_{ds}' \\
V_{qs} &= -R_s i_{qs} - \omega \lambda_{ds} + p\lambda_{qs}' \\
V_{dr}' &= R_r i_{dr}' - (\omega - \omega_r)\lambda_{qs}' + p\lambda_{dr}' \\
V_{qr}' &= R_r i_{qr}' - (\omega - \omega_r)\lambda_{dr}' + p\lambda_{qr}'
\end{align*}
\] (4.15)

where

\[
\begin{align*}
\lambda_{ds} &= -L_{ds} i_{ds} + L_m (i_{dr}' - i_{ds}) \\
\lambda_{qs} &= -L_{qs} i_{qs} + L_m (i_{qr}' - i_{qs}) \\
\lambda_{dr}' &= L_{ir} i_{dr}' + L_m (i_{dr}' - i_{ds}) \\
\lambda_{qr}' &= L_{ir} i_{qr}' + L_m (i_{qr}' - i_{qs})
\end{align*}
\] (4.16)

The d and q rotor voltages ($V_{dr}'$ and $V_{qr}'$) are zero as the rotor is short circuited in squirrel cage induction generator. The value of the magnetizing
inductance $L_m$, depends on the degree of magnetic saturation and it is a non-linear function of the magnetizing current $i_m$, which is given by Equation (4.17).

$$i_m = \sqrt{(i_{qs} + i_{qr}')^2 + (i_{ds} + i_{dr}')^2} = \sqrt{b^2 + c^2}$$  \hspace{1cm} (4.17)

where $b = i_{qs} + i_{qr}'$ and $c = i_{ds} + i_{dr}'$  \hspace{1cm} (4.18)

Therefore $pi_m = \frac{-b(p_i_{qs} + p_i_{qr}') - c(p_i_{ds} + p_i_{dr}')}{i_m}$  \hspace{1cm} (4.19)

Assuming the variation of $L_m$ with $i_m$ as given by (4.20), time derivative of $L_m$ is given in Equation (4.21).

$$L_m = \frac{A_i}{(i_m + A_2)}$$  \hspace{1cm} (4.20)

Hence $pL_m = \frac{-p_i_m A_i}{(i_m + A_2)^2}$  \hspace{1cm} (4.21)

Substituting Equation (4.19) in Equation (4.21),

$$pL_m = \frac{A_i (b(p_i_{qs} + p_i_{qr}') + c(p_i_{ds} + p_i_{dr}'))}{i_m (i_m + A_2)^2}$$  \hspace{1cm} (4.22)

Taking $a = \frac{A_i}{i_m (i_m + A_2)^2}$  \hspace{1cm} (4.23)

$$pL_m = ab(p_i_{qs} + p_i_{qr}') + ac(p_i_{ds} + p_i_{dr}')$$  \hspace{1cm} (4.24)
Substituting the above Equation (4.24) in Equation (4.15) the d-q axis stator and rotor currents are expressed in the state variable form by (4.25).

\[
\left[ L_1(x) \right] \begin{bmatrix} pI \end{bmatrix} = -\{ \left[ R \right] \begin{bmatrix} I \end{bmatrix} + \omega_r \left[ L_2(x) \right] \begin{bmatrix} I \end{bmatrix} + [V] \} \quad (4.25)
\]

where

\[
\begin{bmatrix} pI \end{bmatrix} = \begin{bmatrix} p_i_{qs} & p_i_{ds} & p_i_{qr} & p_i_{dr} \end{bmatrix}^T
\]

are the state variables.

\[
\left[ L_1(x) \right] = \begin{bmatrix} L_{ls} + ab^2 & abc & L_m + ab^2 & abc \\ abc & L_{ls} + ac^2 & abc & L_m + ac^2 \\ L_m + ab^2 & abc & L_{lr} + ab^2 & abc \\ abc & L_m + ac^2 & abc & L_{lr} + ac^2 \end{bmatrix}
\]

\[
\left[ I \right] = \begin{bmatrix} i_{qs} & i_{ds} & i_{qr} & i_{dr} \end{bmatrix}^T \quad (4.27)
\]

\[
\left[ V \right] = \begin{bmatrix} V_{qs} & V_{ds} & 0 \end{bmatrix}^T
\]

\[
\left[ R \right] = \begin{bmatrix} R_s & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 \\ 0 & 0 & R_r & 0 \\ 0 & 0 & 0 & R_r \end{bmatrix}
\]

\[
\left[ L_2(x) \right] = \begin{bmatrix} 0 & \omega L_{ss} & 0 & \omega L_{ms} \\ -\omega L_{ss} & 0 & -\omega L_{ms} & 0 \\ 0 & (\omega - \omega_r) L_m & 0 & (\omega - \omega_r) L_{lr} \\ -(\omega - \omega_r) L_m & 0 & -(\omega - \omega_r) L_{lr} & 0 \end{bmatrix}
\]

By solving the non-linear differential equations given by Equation (4.25), the instantaneous values of d & q axis stator and rotor currents are determined.
The self-excitation capacitor bank introduces additional state equations as given by Equations (4.32) and (4.33) (Natarajan et al 1987).

\[ pV_{ds} = \frac{i_{cds}}{C} + \omega V_{qs} \]  
(4.32)

\[ pV_{qs} = \frac{i_{cq}}{C} - \omega V_{ds} \]  
(4.33)

Taking \( V_{qs} = 0 \), as the d-axis is aligned with phase voltage, the above equations become

\[ pV_{ds} = \frac{i_{cds}}{C} \]  
(4.34)

\[ 0 = \frac{i_{cq}}{C} - \omega V_{ds} \]  
(4.35)

This implies, \( \omega = \frac{i_{cq}}{CV_{ds}} \)  
(4.36)

### 4.3.2 Uncontrolled Rectifier and Filter

As suggested by Hillowala and Sharaf (1996), a three-phase diode bridge uncontrolled rectifier with required filter components is used to convert the variable AC output voltage from the generator terminals to DC. It is expressed in terms of the peak phase stator voltage \( V_{ds} \) of the generator and the input transformer’s turns ratio \( 1: n_i \). The rectifier output voltage \( V_r \) is given by Equation (4.37).

\[ V_r = \frac{3\sqrt{2}}{\pi} \frac{\sqrt{3}}{\sqrt{2}} V_{ds} n_i \]  
(4.37)
The DC link consists of series reactor and shunt capacitor as illustrated in Figure 4.12. The series reactor reduces the ripple content in the rectifier output current and the shunt capacitor filters the DC link voltage (Rajambal and Chellamuthu, 2005). The current and the voltage across the capacitance are given by the following differential Equations (4.38) and (4.39).

\[ p_{i_{dc}} = \frac{1}{L_{dc}} (V_r - V_i - r_{dc} i_{dc}) \]  

(4.38)

\[ pV_i = \frac{1}{C_f} i_{cf} \]  

(4.39)

where \( r_{dc} \) and \( L_{dc} \) are the resistance and inductance of DC link reactor circuit respectively, \( i_{dc} \) is the DC link current, \( i_{cf} \) is the current through the filter capacitance \( C_f \) and \( V_i \) is the DC voltage to the inverter. The DC power transferred to the isolated load is given by the Equation (4.40).

\[ P_o = V_r i_{dc} \]  

(4.40)

4.3.3 PWM Inverter

The DC power from the uncontrolled rectifier is fed to a PWM inverter employing double edge sinusoidal modulation for converting into AC. The aim of the work is to control the inverter voltage, keeping its frequency constant at 50 Hz. A carrier signal of frequency 750 Hz is used for the PWM inverter. By modulating the carrier signal, the fundamental and harmonic voltage content can be varied and hence the phase voltages.

Fourier analysis of the modulated phase voltage gives the peak amplitude of the \( n^{th} \) harmonic voltage as expressed in Equation (4.41) (Hilloowala and Sharaf 1996).
where $V_i$ is the input DC voltage, $n$ is the harmonic number, $r$ is the carrier to fundamental frequency ($r = 15$), $\delta_{\text{max}}$ is the maximum displacement of the edge ($\delta_{\text{max}} = 6^\circ$) and $\theta_{1,k}, \theta_{2,k}, \theta_{3,k}$ are defined as Equation (4.42)

$$\theta_{1,k} = \frac{(2k-2)\pi}{r}; \theta_{2,k} = \frac{(2k-1)\pi}{r}; \theta_{3,k} = \frac{2k\pi}{r}$$

The peak value of the $n^{th}$ harmonic component of the line voltage waveform is given by Equation (4.43).

$$V_{n_{\text{phase}}} = \frac{1}{\sqrt{3}}V_{n_{\text{phase}}}$$

Eliminating the losses in inverter and equating the input and output powers, the following relation Equation (4.44) is obtained.

$$i_{q_{\text{inv}}} = \frac{2}{\sqrt{3}} \frac{i_{dc}}{f(1,MI)}$$

where $i_{q_{\text{inv}}}$ is the q-axis component of the inverter phase current and $f(1,MI)$ is a non-linear function of the modulation index and output voltage (Rajambal and Chellamuthu, 2005).

### 4.4 PERFORMANCE ANALYSIS

The MATLAB/SIMULINK model of a 250 kW IWECS along with the network components is illustrated in Figure 4.14.
Figure 4.14 MATLAB / SIMULINK model of IWECS with network components

4.4.1 Results and Discussion

The simulation is carried out for different operating conditions of wind velocity and load without power electronics interface. The effects of variations in the stator line voltages and stator line currents with various wind velocity and constant load of 1 p.u. are depicted in Figure 4.15. With the wind velocity of 12 m/s, self-excitation capacitance of 50 μF and load resistance of 1 p.u., the voltage reaches a steady state condition of 415 V at about 60 sec. For a step change in wind velocity to 10 m/s at 200 sec, there is a decrease in the stator line voltage to 300 V.
Figure 4.15 Dynamic response of IWECS for step change in wind velocity and constant load condition

Figure 4.16 Dynamic response of IWECS for constant wind velocity and various load conditions
In Figure 4.16, the dynamic response of the proposed scheme for various load conditions and constant wind velocity of 12 m/s is shown. It is seen that the stator voltage varies with respect to change in load resistance from 0.8 p.u. to 4 p.u. Thus a variable speed wind turbine driving an induction generator produces a variable voltage and variable frequency for change in the wind velocity and connected load. Hence a power electronic converter is required in between the generator and load to make voltage and frequency delivered to the load constant. This is essential for voltage sensitive load. The stator voltage of the generator is made constant within limited range with the help of variable capacitor bank (Kumar and Kishore, 2006). Also by varying the modulation index of the PWM inverter, it is possible to regulate the inverter voltage. To provide an optimum value of capacitance in addition to the minimum self-excitation capacitance and modulation index to PWM inverter, an artificial neuro controller is proposed (Rajambal and Chellamuthu 2005).

4.4.2 ANN Controller for the System

The conventional PID controller employed for regulating the terminal voltage in the IWECS connected to voltage sensitive loads has to be tuned dynamically, to obtain the required response. This tuning requires replacement and adjustment of analog electronic circuits which have aging and temperature effects on the system performance. Hence an alternative controller based on artificial neural networks is proposed. The neuro controller does not require a detailed mathematical model of the system and its operation is governed by the trained data of input and desired output. Thus, it is easy to implement with the help of digital computer and the same performance is endured over the years. The use of artificial neural networks in
control applications has recently experienced rapid growth. The basic objective of control is to provide the appropriate input signal to a system for getting its desired response.

Artificial Neural Network (ANN) comprises of densely interconnected processing elements. It is a computer program with several adjustable weights that are tuned from a set of predetermined data. These data represent output generated by the ANN when an input is given. Neural networks are trained based on an algorithm on predetermined data of known output, after which they are able to generalize with trained knowledge and can respond to any data. The organization of ANN is feed forward net that has a hierarchal structure that consists of several layers without interconnection between neurons in each layer and signals flow from input to output layer in one direction. Back propagation tuning method is employed for training multilayer feed forward neural networks.

4.4.3 Neuro Controller Design for Regulation of Terminal Voltage

The variation in the voltage and frequency of a self-excited induction generator is highly dependent on the wind speed, the excitation capacitance and the load demand. A number of switchable controlled capacitors and resistors can be used to provide variation in discrete steps in order to balance active and reactive power (Tarek Ahmed et al 2003).

The block diagram of the proposed scheme with the neuro controller for the regulation of the terminal voltage is depicted in Figure 4.17. The inputs to the neuro controller are wind velocity in m/s and the load resistance in p.u. The outputs of the controller are the additional excitation
capacitance value required in addition to the existing minimum required excitation capacitance and change in the modulation index of the PWM inverter (Rajambal and Chellamuthu 2005).

![Figure 4.17 Block schematic of the proposed IWECS with neuro controller](image)

**Figure 4.17 Block schematic of the proposed IWECS with neuro controller**

The ANN is trained based on the set of simulated data for the entire operating conditions such as wind velocity, additional capacitance and load resistance. From the simulated values, set of data where the speed of the system is between 700 rpm and 1120 rpm is used to train the network. The dynamic response of the system with respect to entire wind velocity range for various capacitances and load resistances in terms of stator phase voltage and generator speed are illustrated in Figures 4.18 (a, b).
Figure 4.18 (a, b) Performance of the proposed system for different self-excitation capacitances and load resistances

The self-excitation capacitance is varied between 0.6 p.u. and 1 p.u. and the load resistance is varied between 1 p.u. and 4 p.u. It is observed that the generator speed varies from 700 rpm to 1215 rpm. As the capacitance is
decreased, the speed is increased. But the stator voltage increases with
decrease in capacitance. The generator is self-excited for the capacitance of 1
p.u. during the average wind velocity range from 8 m/s to 15 m/s. However
for the value of capacitance below 0.6 p.u., the generator speed exceeds the
maximum limit of 1120 rpm. From Figure 4.18(b), it is observed that the
generator speed decreases with increased load resistance. It is also noted that
the generator voltage exceeds the rated value for wind velocities in the range
12 m/s to 22 m/s for load resistance greater than 2 p.u.

The simulation is carried out with power electronics converter for
various modulation indices. For a given modulation index, the generator
speed and stator voltage increase with increase in wind velocity in the average
wind velocity range. The self-excitation capacitances and modulation indices
obtained for different values of wind velocities and loads have been used in
the design of artificial neuro controller to obtain regulated terminal voltage
across inverter.

“C” language is used to simulate the back propagation algorithm on
the computer, since it is versatile and flexible for this specific application. As
shown in Figure 4.19, the weights are initialized randomly within the range 0
to 1 with the help of the “C” function “RAND ()”. The inputs required for
training are stored in “INPUT.DAT” file and the updated weights are stored
in “OUTPUT.DAT” file. The accuracy of the error minimization is taken as
0.0001. The algorithm is trained and validated for non-trained values. The
updated weights of both hidden and output layers are then taken for the neuro
controller design. The controller is designed using MATLAB/SIMULINK
and integrated with the existing wind energy system. Computer simulations
are used to demonstrate the validity of the proposed scheme under various
operating conditions.
Start

Get input vectors and desired output vectors

Get number of patterns and tolerance

Initialise the output and hidden layer weights

Count = Patterns

Sum Error = 0; Error = 0

Calculate actual output for updated weights

Error = Desired output – Actual output

Calculate weight change factor. Change hidden weight and output weight

Current output = Previous output + Change in output weight
Current hidden weight = Previous hidden weight + Change in hidden weight

Sum Error = Sum Error + Error

Decrement Count

If Count = Zero

If Sum Error = Zero

Store output and hidden layer weights

Stop

Figure 4.19 Flow chart of back propagation algorithm
Figure 4.20 ANN Architecture of the voltage regulator

Figure 4.21 MATLAB / SIMULINK model of IWECS with neuro controller for regulation of terminal voltage
The network architecture depicted in Figure 4.20 is included in the IWECS model for simulation. It consists of two hidden layers along with an input layer and an output layer. The inputs to the input layer are the wind velocity and load resistance while the generated outputs from the output layer are the new modulation index and additional capacitance. It is trained based on the open loop performance details using back propagation algorithm. The controller output is then fed to the system for obtaining regulated voltage irrespective of the operating conditions. The simulation model of the proposed scheme is shown in Figure 4.21 for the system given in the Appendix and the neuro controller is simulated using MATLAB/SIMULINK with the rectifier, filter and PWM inverter set-up feeding a local load.

The performance of the system for step changes in wind velocity from 10 m/s to 15 m/s and load variation from 1.5 p.u. to 0.5 p.u. are presented in Figures 4.22. It is seen that with the increasing velocity $V_w$, the mechanical power input to the system increases. Now the neuro controller comes into the operation and changes the modulation index of the PWM inverter and modifies the excitation capacitance value in order to maintain the terminal voltage almost constant at 230 V. As a result, the DC link current and the generator’s load current increases. This causes the induction generator’s rotor speed and the terminal voltage to reduce, automatically limiting the DC link voltage to the preset value.

**4.4.4 Experimental Validation**

The experimental set-up of the DC shunt motor driven SEIG discussed in Section 4.2 is used along with a power electronics interface, to verify the simulation model of the IWECS. The load is varied in steps and the output voltage is measured for the manually set values of self-excitation capacitance and modulation index. The experimental IWECS is also simulated using the program developed in Section 4.32 and the results obtained are tabulated in Table 4.2.
Figure 4.22 Simulation results of various operating conditions for regulation of terminal voltage
It is seen that the simulated values almost agree with the experimental results thus validating the simulation model.

*Table 4.2 Comparison of simulated and experimental results for different load conditions*

<table>
<thead>
<tr>
<th>Load Resistance (p.u)</th>
<th>Self-Excitation Capacitance (p.u.)</th>
<th>Modulation Index</th>
<th>Phase Voltage (RMS)</th>
<th>Phase Current (RMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Simulated (V)</td>
<td>Actual (V)</td>
</tr>
<tr>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>240</td>
<td>225</td>
</tr>
<tr>
<td>1</td>
<td>0.6</td>
<td>0.6</td>
<td>230</td>
<td>220</td>
</tr>
<tr>
<td>0.6</td>
<td>0.8</td>
<td>0.6</td>
<td>230</td>
<td>220</td>
</tr>
</tbody>
</table>

**4.5 CONCLUSION**

The self-excitation analysis of a wind turbine driven induction generator feeding a local resistive load is done. The effect of variations in the excitation capacitance and load resistance is studied for various operating conditions. An experimental set-up is developed in the laboratory to emulate the wind turbine characteristics.

The mathematical model of IWECS is obtained and a detailed performance analysis is made. It is observed that there is wide variation in the generated voltage and frequency for different wind velocities and load values. The variable amplitude, variable frequency voltage at the induction generator terminals is rectified in an uncontrolled bridge rectifier and the DC power is transferred over the DC link to a PWM inverter feeding an isolated load. The diode bridge rectifier helps to reduce the burden on the self-excitation capacitor bank, while the PWM inverter reduces the harmonic content at the local load bus.
A model of a neuro controller to maintain the terminal voltage of the induction generator used in IWECS is designed, simulated and analyzed for various operating conditions. The simulated values are validated by varying the modulation index and self-excitation capacitance manually in the experimental arrangement.