CHAPTER 6
MODELLING, SIMULATION AND ANALYSIS OF
HRES USING MATLAB / SIMULINK

6.1  INTRODUCTION

In the recent years, the increasing concerns towards the depletion of fossil fuel reserves and global warming threats have led to the integration of renewable energy sources like Photovoltaic (PV), wind, biomass and fuel cells. The penetration of renewables are associated with power quality issues leading to voltage instability/violation from the nominal value that needs appropriate solution. This chapter deals with the augmentation/ integration of multiple Renewable Energy Sources (RES) like Solar-PV, Fuel Cell and Wind energy to the grid via STATCOM interface to bring about the best utilization of the available resources and improve the stability, reliability of the power system. The load demand of the textile industry, particularly the power loom unit which requires uninterrupted power supply of about 10-15 KW is met with HRES. The coordinated PWM based control strategy of STATCOM for active, reactive power control, voltage stabilization at the point of common coupling (PCC) and power factor correction using the conventional PI controller is considered. The performance of the system is analysed by replacing the PI controller and comparing with fuzzy and ANN Controller. The proposed method uses simple control strategy for the integration of the renewable sources with reduced number of inverters and without synchronization requirements.

6.2  CONFIGURATION OF THE PROPOSED HRES

A block schematic diagram of the STATCOM interface for PV, Wind and Fuel cell system is shown in Figure 6.1. The Hybrid Renewable Energy
System (HRES) proposed is meant to supply industrial loads where the grid power supply is interrupted frequently. It consists of three phase source (grid) of 400V, 50 Hz and linear load of 15 KW real power and 15 KVAR reactive power. The renewable energy sources are connected to the grid via STATCOM interface. Since the required active and reactive power is generated locally, most of the power quality problems faced by the loads can be solved. Sudden and short duration requirements of real power at the grid can be met out from the HRES supported STATCOM which the source may not be able to cope up in time. The voltage across of the point of common coupling will be maintained by injecting appropriate quantity of reactive power by the STATCOM. This relieves the source from reactive power burden and also maintains the source power factor at a higher value closer to unity. The STATCOM is a three leg, three phase bridge converter with a DC side and three phase AC side. The three phase AC side is connected across the three phase AC transmission lines at the PCC through a voltage transformer and a series reactor. The modelled STATCOM using VSC topology is being used in the proposed system to supply reactive power, to increase the transmittable power and to make it more compatible with the prevailing load demand. This utility-interactive HRES scheme offers the following advantages.

1. Unlike the conventional approach, where the distinct energy sources are connected to the grid through independent inverters, in the proposed scheme, the sources are connected to the DC link of the single inverter (STATCOM) and integrated to the grid. Thus, paralleling of inverters’ outputs is replaced by paralleling of dc–dc converter outputs, which is an easier and better scheme. This is because, in the latter, only the magnitudes of dc output voltages need to be matched, whereas both the magnitude and phase need to be matched in case of paralleled inverters.
2. Due to the presence of dc–dc converters in front of the WECS, FC stack and PV array, a stable dc bus voltage is ensured at the input of the inverter. This eliminates the possibility of injecting sub-harmonics into the grid.

3. The number of controllable power devices reduces because one inverter is used instead of three inverters. This increases the overall reliability.

4. The scheme offers independent control of active and reactive power for the entire range by controlling the power angle and modulation index, respectively, of the inverter.

5. It is capable of MPPT in the PV array and Wind energy system. A bulky transformer is not required and the required boosting is provided by the dc–dc converters.

6. The inverter is operated with sine-triangle pulse width modulation (PWM) that ensures low harmonic distortion in the generated power.

Figure 6.1 Block diagram schematic of the proposed HRES
Squirrel cage induction motors (IMs) are largely used for driving the textile machines in spinning mills. The efficiency and power factor of the IMs can be improved by making motor excitation as a function of load. To achieve this goal, IM should be either redesigned or fed through an inverter (Thanga Raj et al 2009). Hence, the effectiveness of the proposed system is verified with a sensitive linear RL load, which is connected to the distribution line and fed through STATCOM- HRES. The parameters used in this simulation model are given in Table 6.1.

Table 6.1 Proposed system parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC source voltage</td>
<td>400 V, 50 Hz</td>
</tr>
<tr>
<td>Source Impedance</td>
<td>R = 3 Ω, L = 15 mH</td>
</tr>
<tr>
<td>DC link capacitor of STATCOM</td>
<td>6600 μF</td>
</tr>
<tr>
<td>PWM switching frequency</td>
<td>10 kHz</td>
</tr>
<tr>
<td>PEMFC stack</td>
<td>65 cells, 6 kW, 45 V DC</td>
</tr>
<tr>
<td>PV system</td>
<td>5 KW</td>
</tr>
<tr>
<td>WECS</td>
<td>15 KW</td>
</tr>
<tr>
<td>Linear RL load</td>
<td>P=5 KW and Q=5 KVAR in all three phases</td>
</tr>
</tbody>
</table>

5 KW PV system and 6 KW FC system are chosen for simulation. Since the consistency of wind is low compared to solar 15 KW wind energy system is modeled. The assumptions of the proposed system are that the DC link capacitor has no leakage, converters are assumed to have lossless components and power output of HRES is always less than the load demand.

6.3 MODELLING OF HRES COMPONENTS AND STATCOM

A hybrid renewable energy sources consisting of solar photovoltaic, wind energy system, and a fuel cell system is proposed in this work. The solar photovoltaic system is modelled with DC-DC converter along with a maximum power point tracking to achieve a regulated DC output voltage. The wind energy
system is modeled with a wind-turbine prime mover with varying wind speed and fixed pitch angle to drive permanent magnet synchronous generator (PMSG). Proton Exchange Membrane (PEM) fuel cell system is considered owing to its high efficiency and reliability.

### 6.3.1 Solar –Photovoltaic Energy System

A solar cell is basically a p-n semiconductor junction, that generates current when exposed to the light. The equivalent circuit of a solar cell consists of a current source parallel with a diode as shown in Figure 6.2 (a).

![Figure 6.2 (a) Equivalent circuit of solar cell](image)

The V-I characteristics of the PV cell can be determined by following equations. The diode current is given by:

\[ I_D = I_O \left[ \exp\left(\frac{q(V + IR_S)}{KT}\right) - 1 \right] \]  \hspace{1cm} (6.1)

and output current of the solar cell is given by

\[ I = I_L - I_D - I_{sh} \]  \hspace{1cm} (6.2)

\[ I = I_L - I_O \left[ \exp\left(\frac{q(V + IR_S)}{KT}\right) - 1 \right] - \left( V + IR_S \right) / R_{sh} \]  \hspace{1cm} (6.3)

where \( I \): Solar cell current (A); \( I_L \): Light generated current (A); \( I_O \): Diode saturation current (A) \( q \): Electron charge \( (1.6 \times 10^{-19} \text{ C}) \); \( K \): Boltzman constant \( (1.38 \times 10^{-23} \text{ J/K}) \); \( T \): Cell temperature in Kelvin (K); \( V \): Solar cell output voltage (V); \( R_S \): Solar cell series resistance (Ω); \( R_{sh} \): Solar cell shunt resistance (Ω).
The technical specifications of Shell Power 85 W solar module have been used while developing the PV system model in HRES. The simulation model has been developed by using the parameters shown in Table 6.2. The calculated values of $R_s$ and $R_{sh}$ are 0.22 $\Omega$ and 414 $\Omega$ respectively.

### Table 6.2 PV Panel Parameters

<table>
<thead>
<tr>
<th>Panel model</th>
<th>Shell PowerMax™ Ultra SQ-85P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturing Technology</td>
<td>crystalline</td>
</tr>
<tr>
<td>Power at maximum power point</td>
<td>$\text{P}_{\text{mpp}}$ 85 W</td>
</tr>
<tr>
<td>Open circuit voltage $V_{\text{oc}}$</td>
<td>22.2 V</td>
</tr>
<tr>
<td>Short circuit current $I_{\text{sc}}$</td>
<td>5.45 A</td>
</tr>
<tr>
<td>Voltage at maximum power point $V_{\text{mpp}}$</td>
<td>17.2 V</td>
</tr>
<tr>
<td>Current at maximum power point $I_{\text{mpp}}$</td>
<td>4.5 A</td>
</tr>
</tbody>
</table>

Figures 6.2 (b) and (c) show the simulated values of $I$–$V$ and $P$–$V$ characteristics of the PV array considered in this work. The characteristics are observed for the radiation values of 200, 400, 600 800 and 1000 W/m$^2$. From Figure 6.2, it is observed that with decreasing irradiance, there is a negligible change in the maximum output voltage and there is a marginal decrement in output current and a noticeable drop in the maximum power point (MPP).

![Figure 6.2 (b) PV characteristics](image1)

![Figure 6.2 (c) IV characteristics](image2)
6.3.1.1 MPPT algorithm for PV array

The MPPT feeds the desired PV array voltage to the boost converter through change in duty cycle as a gating signal (Villalva et al 2009). Perturb and observe is one of the most commonly used MPPT technique. This algorithm measures the voltage and current inputs and arbitrarily increments or decrements the voltage with a step size of 0.001. Then the new data is compared to the previous readings. If the power increases the voltage is moved in the same direction as the last adjustment. This continues until the new value shows less power than the previous one. The direction is then changed to try and reach the peak power input. The flow chart is given in Figure 6.3.

Figure 6.3 Flow chart for the P&O method for solar

6.3.2 Wind Energy Systems

Wind energy systems harness the kinetic energy of wind and convert it into electrical energy or used it to do intended work. Like the other renewable energy sources, wind energy is clean and safe. The aerodynamic power at the rotor of the turbine is given by the following equation:
\[ P_t = \frac{1}{2} \rho \pi R_t^2 v^3 C_p(\lambda, \beta) \]  

(6.4)

where \( \rho \) (kg.m-3) is the air density, \( R_t \) (m) is the turbine radius, \( v \) (m.s-1) is the wind speed and \( C_p(\lambda, \beta) \) is the power coefficient which represents the aerodynamic efficiency of the turbine and also depends on speed ratio \( \lambda \) and the pitch angle \( \beta \).

The speed ratio \( \lambda \), is given by:
\[ \lambda = \frac{R_t \Omega_t}{v} \]  

(6.5)

\( \Omega_t \) is the mechanical turbine speed (rad/s).

The mechanical torque produced by the turbine is expressed as follows:
\[ C_t = \frac{1}{2} \rho \pi R_t^2 v^2 C_m(\lambda, \beta) \]  

(6.6)

where \( C_m(\lambda, \beta) \) is the torque coefficient.

### Table 6.3 Wind turbine parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical power output (KW)</td>
<td>15</td>
</tr>
<tr>
<td>Wind Turbine power coefficient</td>
<td>0.48</td>
</tr>
<tr>
<td>Tip Speed ratio, (( \lambda ))</td>
<td>8.1</td>
</tr>
<tr>
<td>wind speed (m/s)</td>
<td>12</td>
</tr>
<tr>
<td>Pitch angle, (( \beta ))</td>
<td>0</td>
</tr>
</tbody>
</table>

#### 6.3.2.1 Wind Generator

Several types of generators such as induction generators (squirrel cage, wound rotor with slip control and doubly fed) and synchronous generator are used for wind turbine systems. However, variable speed direct driven multi-
pole PMSG turbines have been considered as high performance drive system for typical WECSs due to the offered reliable, self-excited, low wear and tear, compact, efficient, low noise performance. The permanent magnet synchronous generator is modeled in dq reference frame and the modeling equations can then be written as:

\[
\frac{d}{dt} i_d = \frac{1}{L_d} v_d - \frac{R}{L_d} i_d + \frac{L_u}{L_d} \omega_p i_q
\]  
(6.7)

\[
\frac{d}{dt} i_q = \frac{1}{L_q} v_q - \frac{R}{L_q} i_q + \frac{L_u}{L_q} \omega_p i_d - \frac{\lambda}{L_q} \omega_p
\]  
(6.8)

\[
T_c = 1.5 p [\lambda i_q + (L_d - L_q) i_d i_q]
\]  
(6.9)

where

- \(L_q, L_d\) : q and d axis inductances;
- \(R\) : Resistance of the stator windings
- \(i_q, i_d\) : q and d axis currents
- \(V_q, v_d\) : q and d axis voltages
- \(\omega_r\) : Angular velocity of the rotor
- \(\lambda\) : Amplitude of the flux induced by the permanent magnets of the rotor in the stator phases
- \(P\) : Number of pole pairs
- \(T_c\) : Electromagnetic torque

Figure 6.4 shows turbine mechanical power as a function of rotor speed at various wind speeds. The power for a certain wind speed is maximum at a certain value of rotor speed called optimum rotor speed. This is the speed which corresponds to optimum tip speed ratio. The turbine should be always operated at optimum tip ratio in order to achieve maximum possible power. PMSG output voltage is rectified and a DC-DC buck converter is used to achieve maximum power (Dali et al 2010).
6.3.2.2 MPPT algorithm for PMSG

Starting from the fact that PMSG output currents and voltages are proportional to the torque and rotor speed, thus perturbing the output voltage will cause varying in the generator rotor speed and consequently varies the output power. The method to follow the optimal mechanical number of revolutions to reach maximum power generation is known as MPPT control.

The wind generator consists of a wind turbine coupled with a permanent magnet synchronous generator (PMSG). The rectifier is a three phase diode rectifier for converting AC voltage to DC voltage. The buck converter is a DC-DC converter that the voltage input-output ratio is controlled by a PWM (Pulse width modulation) signal from the MPPT controller. The MPPT controller read the voltage and current of the wind generator output to determine the PWM signal. The Schematic of the Wind Energy Conversion System (WECS) is shown in Figure 6.5 and the flowchart for P&O algorithm is illustrated in Figure 6.6.
Figure 6.5 Schematic diagram of wind energy conversion system

Figure 6.6 Flow Chart for P&O algorithm
The P&O algorithm operates by varying the duty cycle of the buck converter, thus varying the output voltage of the wind generator, and observe the resulting power to increase or decrease the duty cycle in the next cycle. If the increase of duty cycle produces an increase of the power, then the direction of the perturbation signal (duty cycle) is the same as the previous cycle. In contradiction, if the perturbation duty cycle produces a decrease of the power, then the direction of perturbation signal is reversed. The $P_m$ versus $V_{dc}$ graph for wind speeds 4, 6, 8 and 10 m/sec is shown in Figure 6.7. With reference to power output graph, for every wind velocity, there is one particular point where power delivered is maximum. The maximum power point corresponds to a specific dc voltage. In this figure, the power output and dc voltages pertaining to different wind velocities are given.

![Figure 6.7 Pm Vs Vdc graph for WECS](image_url)
6.3.3 Fuel Cell

The simplified model of a fuel cell stack operating at nominal conditions of temperature and pressure is as shown in Figure 6.8. The parameters of the equivalent circuit can be modified based on the polarization curve as shown in Figure 6.9. The inputs are the value of the voltage at no load, as well as the nominal and the maximum operating points, for the parameters to be calculated. A diode is used to prevent the flow of negative current into the stack. The polarization curve in Figure 6.9 consists of three regions: The first region represents the activation voltage drop due to the slowness of the chemical reactions taking place at electrode surfaces. Depending on the temperature and operating pressure, type of electrode, and catalyst used, this region is more or less wide. The second region represents the resistive losses due the internal resistance of the fuel cell stack. Finally, the third region represents the mass transport losses resulting from the change in concentration of reactants as the fuel is used. The polarization curve is helpful in explaining the chemistry and physics associated with fuel cell operation. The voltage versus current density characteristics of the PEMFC stack follows the polarization curve to account the ohmic loss, activation loss and concentration loss considered in fuel cell model.

The Nedstack 6 KW PEMFC stack is modelled. In this work, the activation loss, ohmic loss and concentration loss are included in the proposed PEMFC stack. The anode pressure \( P_A \), cathode pressure \( P_C \), fuel cell initial temperature \( T_i \) and room temperature \( T_R \) are the inputs and fuel cell voltage \( V_{FC} \) is the output of the proposed PEMFC model. The current from the fuel cell \( I_{FC} \) determines the internal temperature \( T \). The \( T \) and \( I_{FC} \) are taken as feedback, which is also used to calculate the \( V_{FC} \).
The constant $\eta$ is added to the above equation to get the empirical equation for activation voltage drop ($V_a$).

$$V_a = \frac{RT}{\alpha ZF} \ln\left( \frac{I}{I_0} \right) = T[a + b \ln(I_{FC})] \quad (6.10)$$

The constant $\eta$ is added to the above equation to get the empirical equation for activation voltage drop ($V_a$).

$$V_{a1} = \eta + a(T - 298) \quad (6.11)$$
\[ V_{a2} = T \times b \ln (I_{FC}) \] (6.12)

\[ V_{a1} \] is the activation voltage drop which is affected only by the \( T \) of the fuel cell, while \( V_{a2} \) is affected by both \( T \) and \( I_{FC} \) of the fuel cell.

\[ V_a = V_{a1} + V_{a2} = [(\eta + a(T - 298)) + (T \times b \ln (I_{FC}))] \] (6.13)

where, \( a \) and \( b \) are Empirical constant terms and \( \eta \) is temperature invariant part of \( V_a \) in volts (\( \eta = 20.145 \)).

The Eq. (6.14) is used to calculate the ohmic voltage drop (\( V_o \)).

\[ V_o = \sum_{\text{o, anode}} V_{o, \text{anode}} + V_{o, \text{membrane}} + V_{o, \text{cathode}} \] (6.14)

The concentration voltage drop is mainly occurred due to the slow transportation of reactants to the reaction sites during high current densities. The concentration overpotential (\( V_c \)) is obtained by using Eq. (6.15).

\[ V_c = -\frac{RT}{zF} \ln \left( 1 - \frac{I_{FC}}{I_{\text{lim}}} \right) \] (6.15)

where, \( I_{\text{lim}} \) = Limitation current (A), \( z \) = number of electrons participated.

The double-layer charging effect is integrated into the modeling, by using \( V_{c1} \) instead of \( V_{a2} \) and \( V_c \), to calculate \( V_{FC} \). The output voltage of the fuel cell is obtained by using Eq. (6.16).

\[ V_{FC} = E - V_{a1} - V_{c1} - V_o \] (6.16)

The reversible potential (\( E \)) is calculated by using the Nernst equation (Kortum 1965).

\[ E = E_0 + \frac{RT}{2F} \ln \left( p_{H_2} \times \sqrt{P_{O_2}} \right) \] (6.17)

\[ E_0 = E_0^* - k_e(T - 298) \] (6.18)
Where,
\[ E_0 = \text{Reference potential which is a function of } T \]
\[ R = \text{Gas constant, } 8.3143 \text{ J/(mol.K).} \]
\[ F = \text{Faraday constant, } 96487 \text{ coulombs/mol.} \]
\[ E_0^o = \text{standard reference potential at standard state, } 298 \text{ K and 1 atm pressure.} \]

The PEMFC output voltage is boosted up by using the DC-DC boost converter. The output voltage of the PEMFC is 45 V and is connected to the boost converter to convert the voltage of 1200 V. The inductor and the capacitor values of the boost converter are 500 \( \mu \text{H} \) and 10000 \( \mu \text{F} \), respectively. The ratio of dc output voltage to the stack voltage is given by
\[
\frac{V_{DC}}{V_{FC}} = \frac{1}{1-D} \tag{6.19}
\]

Where \( D = T_{ON}/(T_{ON}+T_{OFF}) \), \( D \) is the Duty cycle, \( T_{ON} \) and \( T_{OFF} \) are the ON and OFF time, \( V_{FC} \) is the output voltage of the PEMFC stack and \( V_{DC} \) is the output voltage of the boost converter.

### 6.3.4 STATCOM

The major components of a STATCOM are shown in Fig 6.10. It consists of a dc capacitor, three-phase inverter (IGBT, thyristor) module, reactance, ac filter, coupling transformer. The basic single line diagram of the STATCOM in distribution system is the voltage sourced inverter that converts an input dc voltage into a three phase output voltage at fundamental frequency. An IGBT-based PWM inverter is implemented using Universal bridge block from Power Electronics subset of Power System Blockset (PSB).
The controller of the STATCOM is used to operate the inverter in such a way that the phase angle between the inverter voltage \( V_i \) and the system voltage \( V_s \) is dynamically adjusted so that the STATCOM generates or absorbs the desired VAR at the point of common coupling (PCC). The phase of the output voltage of the inverter \( V_i \), is controlled in the same way as the distribution system voltage \( V_s \).

### 6.4 CONTROL SCHEME

To operate the proposed HRES with compensation feature and other requirements, an efficient and fast acting control logic is needed. The other desirable attributes of the system to be taken care of are:

1. MPPT of the PV array and wind energy system are to be implemented to make the system efficient
2. Independent control of active and reactive power is necessary
3. A stiff dc output voltage to the inverter necessary to prevent the inverter from spilling sub harmonics in to the grid.

**Figure 6.10 Components of STATCOM**
The output parameters to be monitored are power output of PV array-$P_{PV}$, Wind power output- $P_{wind}$, Fc stack output- $P_{FC}$, STATCOM active power output $P_{stat}$ and reactive power output $Q_{stat}$.

For PV array

$$P_{PV} = V_{PV} I_{PV}$$

$$P_{PV} = I_{PV} V_{dc} (1 - D_{PV})$$ \hspace{1cm} (6.20)

where $V_{PV}$ and $I_{PV}$ are PV voltage and current respectively. $V_{dc}$ is the dc bus voltage of inverter and $D_{PV}$ is the duty cycle of the boost converter on the PV side. Similarly for FC system,

$$P_{FC} = I_{FC} V_{dc} (1 - D_{FC})$$ \hspace{1cm} (6.21)

For wind side dc-dc converter,

$$P_{wind} = I_{wind} V_{dc} (1 - D_{wind})$$ \hspace{1cm} (6.22)

STATCOM can be independently controlled for real and reactive power. Mainly, the control is encompassing two PI controllers. One is for angle order and another is for the order of modulation index. The shunt converter is operated in such a way as to demand this DC terminal power from the line keeping the voltage across the storage capacitor $V_{dc}$ constant.

The active power output of the STATCOM is given by

$$P_{stat} = \left( \frac{V_{grid}}{X} V_{inv} \right) \sin \hat{\theta}$$ \hspace{1cm} (6.23)

where $V_{grid}$ is the grid voltage, is the power angle. $V_{inv}$ is the rms value of the fundamental component of the inverter output voltage and is given by

$$V_{inv} = \left( \frac{V_{dc} M}{\sqrt{2}} \right)$$ \hspace{1cm} (6.24)

where $M$ is the modulation index.
Substituting (6.24) in (6.23), the active power can be given as

\[ P_{\text{stat}} = \left( \frac{V_{\text{grid}} V_{\text{dc}} M}{X \sqrt{2}} \right) \sin \varphi \]  
(6.25)

For reactive power,

\[ Q_{\text{stat}} = \left( \frac{V_{\text{grid}} V_{\text{dc}} M}{X \sqrt{2}} \right) \cos \varphi - \left( \frac{V_{\text{grid}}^2}{X} \right) \]  
(6.26)

For the decoupled control of real and reactive power the Parks transformation has been adopted. In the Park’s transformation the voltage or current quantities in the time varying three vector format is transformed into time invariant dq0 quantities. The dq quantities are quadrature quantities and a control of d or q can be carried out without affecting the other. The Park’s transformation is given in equation 6.27. The conversion of the three phase voltages denoted as \( V_{abc} \) into \( V_d \) and \( V_q \) in the rotating frame is known as DQ transformation. The vector \([vavbvc]\) can be transformed into another vector \([V_d V_q V_0]\) with the help of a transformation matrix.

It can be viewed that

\[
\begin{bmatrix}
V_d \\
V_q \\
V_o
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
\sin \theta & \sin(\theta - \frac{2 \pi}{3}) & \sin(\theta + \frac{2 \pi}{3}) \\
\cos \theta & \cos(\theta - \frac{2 \pi}{3}) & \cos(\theta + \frac{2 \pi}{3}) \\
\frac{1}{2} & \frac{1}{2} & \frac{1}{2}
\end{bmatrix}
\begin{bmatrix}
v_a \\
v_b \\
v_c
\end{bmatrix}
\]  
(6.27)

The vector \([V_a V_b V_c]\) and the elements of the transformation matrix are time varying but the output vector \([V_d V_q V_0]\) is not time varying. However any change in the amplitude of either of \(V_a\) or \(V_b\) or \(V_c\) is reflected in the vector elements \([V_d V_q V_0]\). One of the two controllers used in the control scheme make use of the ‘d’ component of the PCC voltage in reactive power control. A control strategy is developed to generate pulse width modulated signals for STATCOM.
The control scheme for independent control of active and reactive power is shown in Figure 6.11.

Two controllers are associated with the control scheme. The first controller of the shunt converter is used to maintain the DC link voltage, the second controller associated with the shunt converter is used to maintain the AC voltage at the point of common coupling. The PCC voltage and DC link voltage across capacitor are measured to calculate the amount of reactive power to regulate the line voltage and consequently the modulation index is varied in such a way as to calculate reactive power can be injected at the point of connection and thus the shunt FACTS device acts as a voltage regulator. A sine PWM generator generating synchronized switching pulses, trigger the six switches of the three leg shunt converter, the STATCOM. The PWM firing pulses to the STATCOM are obtained by comparing the PWM carrier signal and the reference sine wave.
The amplitude of reference sine wave is 1 Volt and frequency is 50 Hz which is similar to system operating frequency. The carrier frequency is set at 1.5 KHz which is 30 times the system operating frequency. The phase lock loop (PLL) plays an important role in synchronizing the switching to the system voltage and lock to the phase at fundamental frequency. The converter is consisted of 6 IGBTs and the controller controls the firing pulses from G1 to G6 which are sinusoidal pulse width modulated signals.

The objectives of the STATCOM can be achieved by supplying appropriate switching pulses. A three phase reference signal is created according to the control law adopted. The generation of the switching pulse is governed by the three phase reference signal which is produced by the contribution of two controllers. Reactive power injection is accomplished by the proper generation of reference signals with help of two PI controllers.

Three different control schemes have been studied and compared. A PI based control scheme, fuzzy based and ANN based scheme are compared in terms of power transaction, power factor and voltage profile. The fuzzy logic and artificial neural network controllers have been designed with the help of “fuzzy tool” and “nntool” of MATLAB. These controllers are implemented in STATCOM-HRES system and their performances have been compared with conventional PI controlled STATCOM-HRES system. The purpose of STATCOM interface is to perform active, reactive power control, voltage stabilization at the point of common coupling (PCC) and power factor correction.

**The PI Control scheme**

In the proposed work, the STATCOM has been designed with a PI control scheme. In the case of the shunt converter the controlled parameters are the DC link voltage and the d component of the dq transformed three phase voltage at the point of common coupling. In this case the manipulated
parameters are respectively the angle theta and the amplitude (Modulation Index) of the reference voltage.

The parameters of the system may change frequently depending on the load condition as well as availability of different RE sources. Since the system parameters change from time to time either PI controller has to be tuned according to different operating conditions or intelligent controllers are to be used. Also, application of Artificial Intelligence (AI) techniques is considered as an effective tool to design the control circuit for power electronic devices. In this work, Fuzzy and ANN based control is proposed.

**Fuzzy logic control scheme**

Fuzzy Logic Controller (FLC) is one of the successful approach in using qualitative knowledge to design a controller. The operation and performance of fuzzy logic controller rely on how effective are the linguistics rules of the fuzzy controller. The proposed controller is based on Mamdani’s fuzzy controller, which uses “if-then” rules for inference engine. The error and rate change of error are used as input variables and fuzzified by proper membership functions. The input membership functions assigned to each input variable are shown in Fig. 6.12. The rule base of fuzzy controller contains all possible combinations of inputs and proper outputs for each of them. The linguistic terms used are NB: Negative big, NS: Negative small, ZE: Zero, PS: Positive small and PB: Positive big. The rule base which is used for the proposed controller is shown in Table 6.3. Inference engine determines the behaviour of the controller based on the rules and finally defuzzification converts the linguistic labels into crisp solution variables (Mikkili & Panda 2012). The crisp output is calculated by centroid method. The centroid method selects the output crisp value corresponding to the center of gravity of the output membership function which can be given by the expression
\[ \Delta U_c = \int \frac{w\mu(w)dw}{\mu(w)} \]  

(6.28)

where \( \Delta U_c \) is Defuzzification result, \( w \) = output variable, \( \mu \) = membership function.

The output of FLC control switches of the inverter to maintain the real and reactive power. The two PI controllers are replaced by two fuzzy controllers one for angle and the other for modulation index order. The results obtained are compared with the PI controller.

![Fuzzy membership functions](image)

**Figure 6.12 Fuzzy membership functions**

**Table 6.3 Rule base**

<table>
<thead>
<tr>
<th>Error</th>
<th>NB</th>
<th>NS</th>
<th>ZE</th>
<th>PS</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error rate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NS</td>
<td>ZE</td>
</tr>
<tr>
<td>NS</td>
<td>NB</td>
<td>NB</td>
<td>NS</td>
<td>ZE</td>
<td>PS</td>
</tr>
<tr>
<td>ZE</td>
<td>NB</td>
<td>NS</td>
<td>ZE</td>
<td>PS</td>
<td>PB</td>
</tr>
<tr>
<td>PS</td>
<td>NS</td>
<td>ZE</td>
<td>PS</td>
<td>PB</td>
<td>PB</td>
</tr>
<tr>
<td>PB</td>
<td>ZE</td>
<td>PS</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
</tr>
</tbody>
</table>
ANN control scheme

ANN presents two principal characteristics, i.e. it’s not necessary to establish specific input-output relationship, but it is formulated through a learning process or through an adaptive algorithm, and it can be trained online without requiring large amounts of offline data. The major advantages of the ANN are the simplicity of controller’s design and the compromise between the complexity of conventional non-linear controller and its performance. The back propagation algorithm has been used for the training of feed-forward neural networks as it updates the network weights and biases in the direction so that the performance function, usually the sum of square errors, decreases most rapidly. The implementation consists of a feed-forward Artificial Neural Network which is trained for two input variables, i.e. error and change of error, and required signals at its output. The control objective of the ANN is to provide the wanted proper gating patterns for IGBT’s so that the performance of integrated STATCOM-HRES controller can be enhanced. The output signal of controller is fed to the firing circuit of inverter. The ANN controller is trained with the results of the PI controller. The Network has 3 layers and 20 neurons, and has been trained using 1000 epochs. The topology of neural network is given in Figure 6.13. The two PI controllers are replaced by two ANN controllers and the results obtained are compared with the conventional PI controller.

![ANN topology](image-url)
6.5 RESULTS AND DISCUSSION

The performance of controllers in STATCOM-HRES has been analyzed through the simulation results. The performance of the proposed system is evaluated under the following headings: augmentation of renewable energy sources, DC bus voltage regulation, reactive power compensation and power quality improvement.

6.5.1 Augmentation of real power from HRES

Under normal conditions, the three phase source (grid) is solely responsible to supply the real and reactive power to the RL load of the textile mill. The STATCOM forms an effective interface between the grid and the RE sources thereby accomplish the real power exchange from RE sources to the grid and the load. When load requires more power than supplied by the grid, the STATCOM provides the necessary real and reactive power support. Similarly, when the output of the HRES is higher than the load power, STATCOM delivers the excess power back to the grid. This case has been verified in the simulation and the obtained results are tabulated for the proposed controllers.

Table 6.4 and 6.5 compares the power balance in the cases of PI, ANN and FLC methods of control schemes before and after augmenting renewable energy sources respectively. All the values are in per unit (PU). From the Table 6.4, it can be seen that the STATCOM absorbs real power for its operation before augmenting RE sources as indicated by the negative sign. After augmenting the RE sources, STATCOM supplies real power to the load as indicated by the positive sign.
Table 6.4 Before augmenting renewable energy sources

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PI</th>
<th>Fuzzy</th>
<th>ANN</th>
</tr>
</thead>
<tbody>
<tr>
<td>P from Source</td>
<td>0.22PU</td>
<td>0.212PU</td>
<td>0.249PU</td>
</tr>
<tr>
<td>Q from Source</td>
<td>0.023</td>
<td>0.029</td>
<td>0.029</td>
</tr>
<tr>
<td>P From STATCOM</td>
<td>-.02</td>
<td>-.023</td>
<td>-.024</td>
</tr>
<tr>
<td>Q From STATCOM</td>
<td>.247</td>
<td>0.2477</td>
<td>0.25</td>
</tr>
<tr>
<td>Source side PF</td>
<td>.951</td>
<td>.98</td>
<td>0.99</td>
</tr>
</tbody>
</table>

Table 6.5 After augmenting renewable energy sources

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PI</th>
<th>Fuzzy</th>
<th>ANN</th>
</tr>
</thead>
<tbody>
<tr>
<td>P from Source</td>
<td>0.22PU</td>
<td>0.21PU</td>
<td>0.21PU</td>
</tr>
<tr>
<td>Q from Source</td>
<td>0.023</td>
<td>0.023</td>
<td>0.023</td>
</tr>
<tr>
<td>P From STATCOM</td>
<td>0.04</td>
<td>0.042</td>
<td>0.121</td>
</tr>
<tr>
<td>Q From STATCOM</td>
<td>0.247</td>
<td>0.2477</td>
<td>0.25</td>
</tr>
<tr>
<td>Source side PF</td>
<td>0.951</td>
<td>0.98</td>
<td>0.982</td>
</tr>
</tbody>
</table>

Table 6.5 reveals that with the inclusion of renewable energy sources into the DC link of the STATCOM, the real power drawn from the main source/generator (Gen) is reduced and STATCOM supplies the real power demand required. This happens more efficiently with the ANN controller than with the PI controller and Fuzzy Logic Controller.

In order to demonstrate, how additional real power sources like Fuel cell, Wind and Photo Voltaic Solar power sources augmented into the DC link of the STATCOM are supplementing the seamless performance of the STATCOM, simulations are carried out without RE and with the combination of PV, PV and FC and PV, Wind and FC. The results of simulation are tabulated in Table 6.6.

With reference to Table 6.6, the power flow trend can be considered in four scenarios. In the first case, the absence of the renewable energy sources is considered, where the main AC source is the only source to meet the demand of 0.25 PU, the reactive power however is supplied by the STATCOM. In the second scenario, the PV comes into action and the load demand is partially met by the STATCOM as derived from the PV source. The total demand of 0.25 PU
is shared by the main AC source and the PV source as 0.1253 PU and 0.0125 PU respectively. In the third scenario the PV and the FC sources are operative and the total demand remains the same 0.25 PU output in which the main AC source serves only 0.1186 PU and the PV and the FC sources together serve 0.134 PU, thus meeting the total real power demand of 0.25 PU. In this scenario the reactive power supplied by the STATCOM is reduced and the mains AC power now sources more reactive power. This becomes necessary to load the STATCOM within the allowable VAR value. In the fourth scenario the PV, wind and the fuel cell sources are active and the total demand remains the same as 0.25 PU. The real power supplied by the main AC source is further reduced and it stays a 0.1062 PU and the entire remaining demand is met combined by the PV, wind and the fuel cell sources. Since the STATCOM has to route more real power and to maintain its capacity the reactive power supplied by the STATCOM now comes down further and thus increasing the reactive burden on the main source. However, considering the magnitude of the reactive power loading of the main source, this condition can be considered operational.

Out of the three combinations of RE sources, real power exchange is higher in case of STATCOM with PV, Wind and FC as seen in Table 6.6 and it is the best option for uninterrupted power supply for the textile industry.

**Table 6.6 Performance of STATCOM-HRES**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Without RE</th>
<th>With PV</th>
<th>With PV and FC</th>
<th>With PV, Wind and FC</th>
</tr>
</thead>
<tbody>
<tr>
<td>P from Source</td>
<td>0.2497</td>
<td>0.1253</td>
<td>0.1186</td>
<td>0.1062</td>
</tr>
<tr>
<td>Q from Source</td>
<td>0</td>
<td>0.0626</td>
<td>0.0636</td>
<td>0.065</td>
</tr>
<tr>
<td>P From STATCOM</td>
<td>0</td>
<td>0.125</td>
<td>0.134</td>
<td>0.145</td>
</tr>
<tr>
<td>Q From STATCOM</td>
<td>0.25</td>
<td>0.187</td>
<td>0.184</td>
<td>0.180</td>
</tr>
<tr>
<td>P demand</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Q demand</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
</tr>
</tbody>
</table>
6.5.2 Voltage regulation and reactive power compensation

Under normal conditions the grid supplies the required real and reactive power demand of the RL load. The voltage and current waveforms of proposed system during normal conditions are shown in Figure 6.14. During fault condition, grid cannot provide the required real power demand. In such a case, STATCOM fed with renewable energy sources can deliver real power support. Consider a three phase fault to occur near the source and the fault duration is from 30 ms to 35 ms. Simulations are carried out for a linear RL load and the results are shown in Figure 6.15. It can be seen from the figure that STATCOM responds to this voltage dip by injecting three phase voltage component with phase shift voltage to correct the load voltage.

Figure 6.14 Voltage and current waveforms without STATCOM
Figure 6.15 Voltage and current waveforms with STATCOM-HRES

Figure 6.16 Reactive power compensation without STATCOM
Reactive power compensation with STATCOM

STATCOM provides the required reactive power demand and improves the power factor through effective control strategy. Figures 6.16 and 6.17 show the real and reactive power delivered by the STATCOM when there is a fault near the source and improve the power factor.

**Power quality improvement**

The source current waveform is analysed without and with STATCOM. The Fourier analysis of this waveform is expressed and the Total Harmonic Distortion (THD) of the source current during three-phase fault without and with STATCOM is shown in Figures 6.18 and 6.19.

The THD occurred in the load before compensation during three-phase fault have been 27.91%. SATCOM reduces the THD level from 27.91% in three-phase fault condition to 0.12% and offers better performance in harmonic compensation. The THD level is less than 5% accomplishing the IEEE 519-1992 standard range.
The THD level has been reduced considerably and within the norms of the standard waveform is shown in Figure 6.19. The proposed control scheme not only supports the load with the HRES through the STATCOM but it also has power quality improvement feature.

6.6 CONCLUSION

In this chapter, a simple control strategy for STATCOM-HRES, has been proposed and compared to improve dynamic performance of the chosen system. Simulation results clearly indicate the effectiveness of proposed control scheme for the improvement of dynamic performance of HRES based power system. The results of the MATLAB SIMULINK based on the simulation for augmenting renewable energy sources into the DC link of the STATCOM unit has been analyzed. The results also reveal that comparatively the ANN controller performs better than the PI and FLC control scheme as tabulated.