CHAPTER 3

MODELING OF RENEWABLE ENERGY SOURCES

3.1 INTRODUCTION

In this chapter, the SPV panel, wind turbine generator (WTG), fuel cell, battery and its associated systems are modeled using MATLAB / Simulink. India being placed in the tropic of cancer has rich sunshine throughout the year in almost all parts of the country. The direct normal irradiance incident across the various parts of the country varies from 1600 – 2300 kWh/M²/year, which can be used to generate electrical energy to meet the exponentially growing demand of the country.

Small wind turbines have a lower energy output than large commercial wind turbines (Simoes et al 2006). Today there are more than fifty manufacturers of small wind turbines worldwide, and they produce one hundred plus models with low cut in speed that can be used for residential power generation. The advantage of wind energy is that it has a lower installation cost over solar energy. But the main problem is that its availability is sporadic and hence need to be backed by other power sources.

3.2 SOLAR PHOTOVOLTAIC PANEL

SPV panel is a set of SPV modules electrically connected and mounted on a supporting structure, where the SPV module is a packaged and connected assembly of solar cells. When exposed to sunlight, a photo current
proportional to the incident solar radiation is generated, if the photon energy is greater than the band gap through the photovoltaic effect.

3.2.1 Equivalent Circuit of an SPV Panel

A precise I-V characteristic of the SPV array is necessary to estimate the performance and to improve the efficiency of the SPV panel based PGS. Generally, an SPV array consists of many SPV modules and a SPV module consists of many SPV cells connected in series or in parallel. Hence an equivalent circuit of the SPV panel can be expressed as a photodiode with a large p-n junction (Huan-Liang Tsai 2010). Single diode model and double diode model are the two models of SPV panel and single diode model is developed in the proposed research work.

3.2.1.1 Single diode model of an SPV panel

The electrical equivalent circuit (Krismadinata et al 2013) which defines the entire I-V curve of an ideal solar cell shall be realized using a current source in parallel with a single-diode shown in Figure 3.1. The circuit consists of a current source, i.e., a light-induced current generator ‘I_{PV}’, a PN junction diode, a series resistor ‘R_s’ and a shunt resistor ‘R_{sh}’. The photo-generated current ‘I_{PV}’ ideally is directly proportional to the number of electron-hole pairs or the short-circuit current generated in the junction region. The practical characteristic of the panel generally deviates from the ideal SPV panel due to optical and electrical losses. Hence appropriate components are added to the ideal current source to realize the characteristics identical to a practical SPV panel. Optical losses are represented by the current source itself, as the generated current ‘I_{PV}’ is proportional to the solar irradiance incident on the panel.
The current through the diode ‘$I_D$’ represents the voltage dependent current lost due to recombination in the emitter region of the cell. The ohmic losses occurring in the practical solar cell are accounted by connecting a resistance in series and in shunt of the current source. The resistance offered by the solar cell in the path of the current flow is embodied in the series resistance while the leakage path of the current in the solar cell is represented by the shunt resistance. When a solar cell is connected to an external load, a current ‘$I_L$’ flows through the load. The characteristic equation which governs the current output of the SPV panel is given by the Equation (3.1)

$$I_L = I_{PV} - I_D - I_{SH}$$ (3.1)

where ‘$I_{PV}$’ is the photo current (A), ‘$I_D$’ the current in parallel diode (A), ‘$I_{SH}$’ is the shunt current. The diode current ‘$I_D$’, is given by the Schottky diode equation (3.2),

$$I_D = I_O \left\{ \exp \left[ \frac{q(V_D + I R_S)}{mkT} \right] - 1 \right\}$$ (3.2)

where ‘$I_O$’ is the reverse saturation current of the diode, ‘$q$’ is the electron charge, ‘$m$’ is the diode ideality factor, ‘$k$’ is the Boltzmann’s constant, ‘$T$’ is the temperature of the SPV panel and ‘$R_S$’ is the series resistance. Combining
the equations (3.2) and (3.1), the output current of the SPV panel becomes the equation (3.3),

\[
I_L = I_{PV} - I_O \left\{ \exp \left[ \frac{q(V_{PV} + IR_s)}{mkT} \right] - 1 \right\} - \frac{V_{PV} + IR_s}{R_{SH}}
\]  

(3.3)

where ‘\( R_{SH} \)’ is the shunt resistance, ‘\( V_{PV} \)’ is the output voltage of the panel and ‘\( I_L \)’ is the current delivered by SPV panel.

### 3.2.2 Simulink Model of the Proposed SPV Panel

The equivalent circuit model of the SPV panel developed in MATLAB/Simulink is shown in Figure 3.2. The proposed equivalent circuit has two inputs such as solar irradiance and panel temperature. The photo current ‘\( I_{PV} \)’ is proportional to the intensity of solar radiation and hence the insolation change affects the photon generated current and has very little effect on the open circuit voltage (Nishioka et al 2003). The temperature effect on the I-V characteristics of the SPV panel comes from the dependence of \( V_{OC} \) on temperature, where ‘\( V_{OC} \)’ is the open circuit voltage of the SPV panel; also \( V_{OC} \) in turn depends on the reverse saturation current ‘\( I_O \)’ (Equation (3.4)). The reverse saturation current \( I_O \) depends on recombination in the solar cell and can vary significantly with the temperature shown in Equation (3.5).

\[
V = V_{OC} = \frac{mkT}{q} \ln \left( I + \frac{I_{sc}}{I_0} \right) \text{ for } I_L = 0
\]  

(3.4)

where,

\[
I_0 = I_0^* \left( \frac{T}{T^*} \right) \exp \left[ \frac{e}{mk} \left( \frac{I}{T^*} - \frac{I}{T} \right) \right]
\]  

(3.5)
where $T$ is the panel temperature, $T^*$ is the panel temperature at reference condition and $\varepsilon$ is the band gap. The temperature variation affects the open circuit voltage and the short circuit current varies very marginally. The power vs voltage (P-V) characteristics of an SPV module at different irradiance levels are shown in Figure 3.3.
3.2.3 Insolation Data

The global radiation recorded for the entire 24 hours on a typical sunny day using the standard pyranometer which is collected from the REC, KEC, Erode, Tamil Nadu, India is shown in Figure 3.4. One data point in the span of every 5 minutes is extracted from the graph and hence 288 data points were extracted for a day of 86400 seconds. It is fed as the insolation data input to the developed SPV panel along with the measured panel temperature.

![Insolation Data Graph](image)

**Figure 3.4** Variation of solar irradiance in a typical sunny day at REC, KEC, Tamilnadu, India

As the change in panel temperature is marginal, its effect on generated voltage is negligible and the panel output current follows insolation (Equation (3.3)) as photon generated current is directly proportional to insolation. The voltage, current and power output of the simulated SPV panel feeding a constant load, in response to the 288 data fed as the irradiance input using the repeating sequence stair function along with the measured panel temperature is shown in Figure 3.5.
A typical SPV panel converts only 20 to 30 percent of the incident solar irradiation into electrical energy and also the power output varies with the irradiation and temperature. As the solar insolation is continually varying, MPPT algorithm is imperative to continuously track the MPP pertaining to the incident irradiation to improve the efficiency (Natsheh & Albarbar 2011). According to the maximum power transfer theorem, the power output of a circuit is maximum when the Thevenin impedance of the circuit matches with the load impedance. In general, there is a unique point on the I-V or V-P curve, called the Maximum Power Point (MPP), at which the entire SPV system (array, converter, etc.,) operates with maximum efficiency and produces its maximum output power.
By incorporating the MPPT algorithms, the SPV system’s power transfer efficiency and reliability can be improved significantly as it can continuously maintain the operating point of the SPV panel at the MPP pertaining to that irradiation and temperature. The location of the MPP is not known, but can be located, either through calculation models or by search algorithms. The MPP tracking is achieved by connecting a DC-DC boost converter between the SPV array and load. The voltage and current output of the SPV panel at the $K^{th}$ and $(K-1)^{th}$ instant is fed as the input to the MPPT controller and the computed duty cycle is fed to the MPPT boost converter.

3.3.1 Need for MPPT Controller in the Proposed PMS

The proposed PMS works via comparing the power generated by various sources with the LD on an instantaneous basis and also follows the predefined set of priority in utilization. Hence, the instantaneous power generated by the SPV system and other RES is very much needed. When the SPV panel is connected directly to the load, all the power generated in the SPV panel is not extracted by the load due to impedance mismatch. By incorporating the MPPT system to the SPV panel, the entire power generated in the SPV panel is extracted which gives the index of the instantaneous power generated in the SPV panel.

3.3.2 Types of MPPT Algorithms

Numerous algorithms (Esram & Chapman 2007) to locate the MPP have been developed so far, of which the P&O and incremental conductance (INC) algorithms (Xiao & Dunford 2004) are the most common and widely used MPPT methods. It is based on the “hill-climbing” principle, which moves the operating point of the SPV array in the direction in which power increases. It also has the advantage of easy implementation but suffers serious drawbacks.
The MPPT systems are broadly classified into two categories based on the step size of duty cycle, namely fixed step size and variable step size MPPT systems. In the fixed step size (FSS) configuration, the duty cycle of the MPPT controller varies in a fixed and constant step size. The FSS is widely used due to the ease of implementation, yet it has some problems such as the oscillation around the MPP and confusion due to rapidly changing atmospheric condition. The step size of the duty cycle in FSS systems is determined by the accuracy and tracking speed requirement. However, if the step size is increased for tracking speed up, the accuracy is decreased and vice versa.

In the variable step size (VSS) algorithms, the step size is automatically tuned according to the inherent SPV array characteristics. If the operating point is far from MPP, it increases the step size which enables a fast tracking ability. If the operating point is nearer to the MPP, the step size becomes very small that the oscillation is well reduced contributing to higher efficiency (Fangrui Liu et al 2008).

3.3.3 Modeling of the Proposed Variable Step Size Incremental Resistance (VSS-INR) MPPT Controller

Of the various MPPT techniques (Esram et al 2007) variable step size incremental resistance (VSS-INR) method (Qiang Mei et al 2011) is developed because of improved response speed, accuracy and enhanced suitability for practical operating conditions due to a wider operating range. The Simulink model of the MPPT system and the flowchart of control process pertaining to VSS-INR MPPT technique are shown in Figure 3.6 and 3.7 respectively.
The variable step-size method introduced to solve the problem is based on Equations (3.6) & (3.7).

\[
D(k) = D(k-1) \pm N \left| \frac{dP}{dV} \right| \tag{3.6}
\]

\[
D(k) = D(k-1) \pm N \left| \frac{P(k) - P(k-1)}{V(k) - V(k-1)} \right| \tag{3.7}
\]

where, \(D(k)\) is the duty cycle and '\(N\)' is the scaling factor which is adjusted at the sampling period to regulate the step size. The performance of this MPPT is decided by the optimal scaling factor '\(N\)'. For convergence of the MPPT update rule, the variable step rule must meet the following inequality (3.8)

\[
N \left| \frac{dP}{dV} \right| < \Delta D_{\text{max}} \tag{3.8}
\]

where \(\Delta D_{\text{max}}\) is the largest step size for fixed step-size MPPT and is chosen as the upper limit for the VSS. The scaling factor is obtained by the Equation (3.9)
which provides a simple guidance to determine the scaling factor ‘N’ of the VSS MPPT algorithm. The optimal value of the scaling factor ‘N’ is chosen as 3. The fixed scaling factor determined by this simple way cannot satisfy the requirement of the MPPT system while irradiation and temperature are varying quickly. The INR MPPT can be switched by extreme values of a
threshold function which is the product (C) of the exponential of SPV array output power \(P_n\) and the absolute value of the SPV array power derivative \(|dP/dI|\).

\[
C = P_n \times \left| \frac{dP}{dI} \right|
\]  
(3.10)

where \(|dP/dI|\) is the slope of power vs current curve and \(|dP/dI|\) can be expressed as

\[
\left| \frac{dP}{dI} \right| = |\tan \theta|, \quad -90^\circ < \theta < 90^\circ
\]  
(3.11)

Since,

\[
\sin \theta = \tan \theta / \sqrt{1 + \tan^2 \theta}
\]

The MPPT system duly controls the boost converter to track the MPP by repeatedly updating the operating current of the SPV panel by varying the duty cycle of the boost converter in a variable step size manner. The ‘\(I_{ref}\)’ is the reference current at which the SPV panel is forced to operate. At MPP, ‘\(I_{ref}\)’ is equal to \(I_{MPP}\) and a larger step size \((\Delta I_{ref})_{max}\) is initially selected for the fixed step-size MPPT operation which exhibits a good dynamic response, with \((\Delta I_{ref})_{max}\) chosen as the upper limit for the variable step-size INR MPPT method, the variable step rule can be given by the Equation (3.12).

\[
S_k = (\Delta I_{ref})_{max} \times \sin \theta_k \quad k=0, 1, \ldots
\]  
(3.12)

where \(S_k (k = 0, 1\ldots)\) is the variable step-size at time ‘\(k\)’ and Equation (3.12) provides a simple and effective variable step size algorithm. The step size ‘\(S_k\)’ will become very tiny as \(\sin \theta_k\) becomes very small around the MPP by which the dynamic oscillations around MPP is reduced. It enhances the steady state
performance and hence the tracking accuracy. If the operating point is far from MPP, it increases the step size of the duty cycle which enables faster tracking ability. Progressive variation of the duty cycle in steps is observed from Figure 3.8 for a change in insolation at 4sec of simulation time, i.e., for any change in insolation the step size of the duty cycle variation is larger in the beginning and is gradually reduced. The output of the MPPT converter in comparison with the output of SPV panel is shown in Figure 3.9.

**Figure 3.8 Duty cycle variations with varying step size**

**Figure 3.9 Output of MPPT converter**
3.4 MATHEMATICAL MODELING OF WTG

The wind turbine converts the kinetic energy of the wind into mechanical energy and then delivers it via a mechanical drive unit to the rotor of an electric generator.

3.4.1 Power Extraction from the Wind

The kinetic energy \( E \) (in J) of an air mass \( m \) (in kg) moving at a speed \( v \) (in m/s) is given by

\[
E = \frac{1}{2} mv^2
\]  

(3.13)

The power in the wind \( P_w \) is given by the rate of change of energy (Muyeen et al 2009)

\[
P_w = \frac{dE}{dt} = \frac{1}{2} v^2 \frac{dm}{dt}
\]  

(3.14)

where \( \frac{dm}{dt} \), the mass flow rate per second and is given by (3.15),

\[
\frac{dm}{dt} = \rho A_s \frac{dx}{dt}
\]  

(3.15)

where \( \frac{dx}{dt} \) is the distance change rate per second, \( \rho \) the density of air, and ‘\( A_s \)’ the swept area of the blade. Also \( \frac{dx}{dt} \) can be represented as in Equation (3.16)

\[
\frac{dx}{dt} = v
\]  

(3.16)
Substituting the Equation (3.16) in (3.15), the equation changes to (3.17)

\[ \frac{dm}{dt} = \rho A_v v \]  \hspace{1cm} (3.17)

From the Equation (3.14) and (3.17) power in the wind is given by (3.18)

\[ P_w = \frac{1}{2} \rho A_v v^3 \]  \hspace{1cm} (3.18)

The air density (\( \rho \)) changes slightly with air temperature and elevation. The cold air in winter is denser than warm air in summer and also the density of air reduces with elevation. The density of air can be calculated using the ideal gas law as in Equation (3.19)

\[ \rho = \frac{P}{R_{gas} A_T} \]  \hspace{1cm} (3.19)

where ‘\( P \)’ is the absolute pressure (N/m\(^2\)), \( R_{gas} \) is the gas constant, \( A_T \) is the absolute temperature.

The swept area of the turbine can be calculated from the length of the turbine blades using the equation for the area of a circle as shown in Equation (3.20)

\[ A_s = \pi R_r^2 = \frac{\pi}{4} D_r^2 \]  \hspace{1cm} (3.20)

where ‘\( R_r \)’ is the blade length and ‘\( D_r \)’ is the rotor diameter in meters.

### 3.4.2 Rotor Power Characteristics

Albert Betz, a German physicist in 1919, discovered that the theoretical maximum power efficiency of any design of wind turbine is 0.59
(Betz factor) for an ideal, frictionless flow converter. In reality, the wind turbines have a less power coefficient than the Betz factor due to the losses caused by the rotor. Considering the power coefficient, the mechanical power on the rotor can be calculated as in Equation (3.21)

\[ P_w = \frac{1}{2} \rho \pi R^2 C_p (\lambda, \beta) v^3 \]  

(3.21)

‘\( C_p \)’ is the power coefficient of the turbine, which is a function of the tip speed ratio ‘\( \lambda \)’ and pitch angle of the rotor blades ‘\( \beta \)’ (in degrees). The tip speed ratio ‘\( \lambda \)’ is given by the expression (3.22)

\[ \lambda = \frac{\omega_m R}{v} \]  

(3.22)

The generic equations used to model the ‘\( C_p \)’ is given by the Equations (3.23) and (3.24) (Abdullah et al. 2012).

\[ C_p = \frac{1}{2} \left( \frac{116}{\lambda_i} - 0.4 \beta - 5 \right) e^{\left( \frac{51}{\lambda_i} \right)} \]  

(3.23)

\[ \frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08 \beta} - \frac{0.035}{\beta^3 + 1} \]  

(3.24)

The \( C_p, \lambda \) characteristics of a wind turbine for different values of the pitch angle \( \beta \), are shown in Figure 3.10. The power coefficient and the power output are maximum at a certain value of the tip speed ratio called optimum tip speed ratio ‘\( \lambda_{opt} \)’. The maximum value of \( C_p (\lambda, \beta) \), that is \( C_{p_{max}} = 0.48 \), is achieved when \( \lambda_{opt} = 8.1 \) and \( \beta = 0^\circ \). Moreover, any change in the wind velocity or the generator speed induces change in the tip speed ratio leading to power
coefficient variation. Thus, the power extracted gets affected. This power is maximized at the particular rotational speed for various wind speed and it is obligatory to keep the generator speed at an optimum value of the tip speed ratio ‘$\lambda_{opt}$’.

\[ C_p - \lambda \text{ characteristics of a wind turbine for different values of pitch angle} \]

### 3.4.3 Wind Speed Data

The wind speed recorded for the entire 24 hours of a day using the standard recording instrument connected to an anemometer is collected from the REC, KEC, Erode, Tamil Nadu, India is shown in Figure 3.11. One data point in the span of every 5 minutes is extracted from the graph and hence 288 data points were extracted for a day of 86400 seconds, which is fed as the wind speed data input to the simulated WTG.
3.4.4 Simulink Model of Wind Turbine Generator

The Simulink model of WTG developed using an asynchronous generator is shown in Figure 3.12. The simulated wind turbine block uses a 2-D lookup table to compute the turbine torque output ($T_m$) as a function of wind speed ($w_{\text{Wind}}$) and turbine speed ($w_{\text{Turb}}$), shown in Figure 3.13. At the wind speed of more than 2 m/s, the WTG produces enough power to supply the load. As the asynchronous machine operates in generator mode, its speed is slightly above the synchronous speed (1.011 pu). According to turbine characteristics, for a 2 m/s wind speed, the turbine output torque is adjusted so as to deliver 0.5pu of power which is 200W. The simulated torque output of the wind turbine in response to the real time wind data input is given in Figure 3.14.
Figure 3.12 Wind turbine generator

Figure 3.13 Model of wind turbine

Figure 3.14 Torque output of simulated wind turbine
In practice, small WTG systems with cut-in speed as low as 2.8 m/s are commercially available in markets which are very much viable for low power stand-alone operation. The torque of the wind turbine is estimated from the basic electromechanical equation, i.e., the torque is the power upon generator speed. As the system is a standalone system, a capacitor bank is connected at the output of the asynchronous generator (Rekioua Djamila 2014) in order to supply the reactive power required by the asynchronous generator for the generation of electrical energy.

3.5 INCREMENTAL SEARCH MPPT ALGORITHM

The power output (Equation (3.22)) of WTG system is proportional to \( V^3 \) and thus \( P_w \) drastically varies with changes in wind speed. If the WTG is connected to the load directly, it is highly challenging to maintain the operating point of the WTG at the MPP continuously due to non-linear characteristics of the WTG and sporadic nature of wind velocity. Hence a dedicated MPPT controller is developed to continuously track the MPP under rapidly changing wind speed and is shown in Figure 3.15.

![Figure 3.15 MPPT system developed for wind turbine generator](image)

Figure 3.15 MPPT system developed for wind turbine generator
As the wind velocity is continuously varying the torque output of wind turbine, the voltage, current and power generated in the generator and hence the impedance of the generator keeps on varying. In many cases the load impedance is continually varying in loads like metal cutting lathes, conveyors etc. and it is constant throughout its operation in the loads like fans, incandescent lamps, etc. Hence, in case of the source and load with such nature, the load and source impedance match each other very rarely.

In this regard, to match the source and load impedance, a power electronic converter with MPPT controller is connected parallel with the load. For any changes in the source impedance, the duty cycle of the converter is varied to match the load impedance (converter and load). For this purpose, an incremental search algorithm based MPPT technique is developed by programming the embedded controller and the flowchart of MPPT algorithm is shown in Figure 3.16.

![Flowchart of incremental search algorithm](Figure 3.16 Flowchart of incremental search algorithm)
The incremental search algorithm (Kot et al 2013) is basically a hill climbing technique and the controller increases the duty cycle 'α' of the step up chopper by 0.001 (Δα) for any change in the turbine torque. If the output power of the generator increases, the controller continues to increase till the output power starts to decrease instead of increasing and vice versa if the generator output power starts decreasing. The value of ‘Δα’ is chosen as low as 0.001 so as to reduce the dynamic power oscillations around the MPP. The voltage, current and power output of the WTG without and with MPPT controller is shown in Figures 3.17 and 3.18 respectively.

![Graphs of Voltage, Current, and Power Output](image)

**Figure 3.17** Voltage, current and power output of WTG without MPPT controller
3.5.1 Necessity of MPPT Controller

To accomplish the research objective, the instantaneous power generated by all the sources is necessary. When the WTG is connected to the load directly, it may not draw all the power generated in the WTG due to impedance mismatch, hence a dedicated MPPT controller is integrated with the WTG to harvest all the power generated in the WTG in an instantaneous
basis which is mandatory from the PM perspective. The developed MPPT controller functions very well for the sudden variations in the wind speed, which shall be evidenced from the output of the MPPT system.

3.6 FUEL CELL

Of the various types of fuel cells, PEM FC (Cheng et al 2001) has many advantages such as a low operating temperature, sustained operation at a high current density, low weight, compactness, the potential for low cost and volume, long stack life, fast start-ups and suitability for discontinuous operation. These features make PEM FC’s the most promising and attractive candidate for a wide variety of power applications (Yu et al 2007) ranging from portable / micro power and transportation to large-scale stationary power systems for buildings and distributed generation.

The PEM FC (Maswood 2008) used in the proposed work needs to have an output voltage around 120V at no load condition. Hence three fuel cell stacks with the voltage rating of 24V each, with the voltage profile of 42V at ‘0’Ampere and 35V at ‘1’Ampere, are connected in series as shown in Figure 3.19 and the I-V characteristics are shown in Figure 3.20.

![Figure 3.19 Fuel cell stack](image)
Figure 3.20 V-I and P-I characteristics of the fuel cell stack

3.7 BATTERY

The battery is used as the external levelling agent to sink / source, the power delivered by the sources based on the instantaneous load demand. The lead acid batteries are preferred for both the standalone and grid – interactive applications as the maintenance and the initial costs are less. The simplest electric model of lead acid battery (Olivier Tremblay & Louis-A. Dessaint 2009) consists of an ideal voltage source in series with an internal resistance and has accurate voltage dynamics during current variations, shown in Figure 3.21. The phenomenon of charging and discharging is represented by a nonlinear dynamic system given by the Equation (3.25)

\[ E \exp(t) = B \times |i(t)| \times (-\exp(t) + A \times u(t)) \]  

(3.25)
The exponential voltage depends on its initial value \( \text{Exp}(t_0) \) and the charge \((u(t)=1)\) or discharge \((u(t)=0)\) mode.

\[
E_{\text{Charge}} = E_0 - K \frac{Q}{it-0.1Q} \cdot i^* - K \frac{Q}{Q-it} \cdot it + \text{Exp}(t) \tag{3.26}
\]

\[
E_{\text{Discharge}} = E_0 - K \frac{Q}{Q-it} \cdot i^* - K \frac{Q}{Q-it} \cdot it + \text{Exp}(t) \tag{3.27}
\]

where, \(E_0\) is the battery constant voltage \((V)\), \(K\) the polarization constant \((V/Ah)\) or polarization resistance \((\Omega)\), \(Q\) the battery capacity \((Ah)\), \(it = \int i \, dt\) the actual battery charge \((Ah)\), \(A\) the exponential zone amplitude \((V)\). \(B\) the exponential zone time constant inverse \((Ah)^{-1}\), \(R\) the internal resistance \((\Omega)\), \(i\) the battery current \((A)\), \(i^*\) the filtered current \((A)\), \(\text{Exp}(t)\) the exponential zone voltage \((V)\), \(u(t)\) the charge or discharge mode.

**Figure 3.21 Lead acid battery model**

### 3.7.1 Charging / Discharging Characteristics of the Battery

A 100V, 150Ah battery is used in the proposed work and is realized by series connection of 50 No’s of 2V, 150 Ah batteries. The rate of charging and the discharging of the battery are based on the standard specifications of
the battery handbook. The lead acid battery handbook illustrates that the charging current of the battery should be less than 0.1\(C_B\), where ‘\(C_B\)’ is the capacity of the battery. For a 150Ah battery, the charging current (3.28) should not exceed,

\[
I_{\text{BatCh}} = 0.1 \times 150 = 15A
\]  

(3.28)

Also, according to the battery handbook, the discharge current in tens of the seconds should not exceed \((0.5 – 0.7)\ C_B\) and the nominal discharge is \(0.1C_B\). Here \((C_B/5)\) is selected as the maximum discharge current. The capacity of the battery needed for delivering the power of 1.5 kW even at a minimum battery voltage of 99V and the efficiency of the IBC being 95\% \((\eta_{\text{Boost-Conv}} = 0.95)\) shall be calculated as in (3.29)

\[
C_B = \frac{P_o}{0.1 \times \eta_{\text{Boost-Conv}} \times V_{\text{Bat-min}}}
\]  

(3.29)

\[
C_B = \frac{1500}{0.1 \times 0.95 \times 99}, \quad C_B = 159.489\text{Ah},
\]

Hence a 150Ah battery is selected. The maximum discharge current (3.30) of battery at the output of the IBC to deliver a power of 1.5kW at the battery voltage of \(V_{\text{Bat-min}} = 99V\) and \(\eta_{\text{Boost-Conv}} = 0.95\) is

\[
I_{\text{BatDch}} = \frac{P_o}{\eta_{\text{Boost-Conv}} \times V_{\text{Bat-min}}} = \frac{1500}{0.95 \times 99} = 15.94A
\]  

(3.30)

3.8 SOC ESTIMATION OF BATTERY

The state of charge (SOC) of the battery is defined as the available capacity expressed as a percentage of its rated capacity. In SA and GI-HPS, the slip-in and slip-out of the battery from conduction is an imperative
function performed by the PMS. The slip-in and slip-out of battery from conduction is set at 40% SOC (Minjin Kim 2008), as the depth of discharge (DoD) to about 70 - 80% of its capacity shall damage the battery even if it is a deep cycle battery. Hence the proposed PMS is so programmed that, it discharges the battery only when the battery SOC>40%, and it tend to charge the battery with the excess power available, when the battery SOC<40%.

3.8.1 Need for Online or Real-time SOC Estimation of Battery

In order to efficiently operate the HPS and to enhance the lifetime of the battery, it should be charged and discharged within the valid limits, i.e., the battery should not be discharged when SOC ≤ 40% and should not be charged beyond SOC ≥ 90%. Also the instantaneous current reference scheme operates by comparing the instantaneous load demand with the power yielded by the sources and SOC of the battery, i.e., the charging and discharging of the battery takes place continuously based on the excess or shortage of power at the PCC. Therefore keeping a continuous track of SOC, i.e., an effective and accurate estimation of the SOC of the battery is mandatory.

3.8.2 Various Methods of SOC Estimation of Battery

Estimating the battery SOC is not an easy task (Soon Ng et al 2009) because the SOC depends on many factors such as temperature, battery capacitance and the battery internal resistance. The SOC cannot usually be determined directly (Wen-Yeau Chang 2013). The ‘discharge test method’ is the most reliable SOC estimation method, but works only with batteries that offer access to their liquid electrolyte, such as non-sealed lead acid batteries. The ‘specific gravity’ or pH of the electrolyte can be used to indicate the SOC of the battery. The hydrometer is used to calculate the specific gravity of a battery, but is not useful for closed loop or automated control. ‘Ah counting method’ uses the integral of load current to estimate the SOC. ‘Open-circuit voltage’ uses the characteristic relationship between the open-circuit voltage
and SOC to estimate SOC by measuring the open-circuit voltage, but the SOC estimation is not possible while the battery is charging / discharging Sabine Piller et al (2001). Open-circuit voltage based SOC estimation is a simple yet precise method. For accurate estimation, it demands a larger rest time of battery. The battery should be stalling for a long time so that it can obtain the stable value of open-circuit voltage. However, in HPS the battery should frequently start, charge and discharge, and the working conditions are complex.

3.8.3 **Online SOC Estimation of Battery**

Due to the volatile working current, it is difficult to estimate the SOC exactly by open-circuit voltage method. According to battery handbook, the terminal voltage can be used as the index for determining the SOC of the battery. Hence the terminal voltage and battery current based real-time SOC estimation are preferred.

3.8.4 **Embedded Controller based Online SOC Estimation of Battery**

In the real-time SOC estimation of battery the terminal voltage, the magnitude and direction of battery current are fed as input to the embedded controller (EC) as shown in Figure 3.22.

---

**Figure 3.22** Embedded controller based SOC estimator
The battery current is positive while discharging, negative while discharging and zero at rest. The EC is programmed using nested ‘if’ loop and the if-else statement allows a choice to be made between two possible alternatives. The SOC of a 100V, 150Ah battery with the terminal voltage say at 100V is different when the battery is charging, floating and discharging and is also different while it charges or discharges with different currents. As the choice must be made amongst more than two possibilities, the nested loop based programming is done to estimate the SOC.

3.8.4.1 Logic of the proposed real-time SOC estimation technique

The SOC of a 100V, 150Ah battery while floating, charging and discharging which is extracted from the terminal voltage Vs SOC characteristics at different charging and discharging rate are given in Tables 3.1 and 3.2. For example, SOC of a 100V battery with the terminal voltage of 106V and charging current of 30A can be estimated by the Equation (3.31).

<table>
<thead>
<tr>
<th>SOC (%)</th>
<th>Float State (volts)</th>
<th>AT CHARGING</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Voltage (at Cₐ/40) (volts)</td>
<td>Voltage (at Cₐ/20) (volts)</td>
</tr>
<tr>
<td>10</td>
<td>97.46</td>
<td>98.29</td>
</tr>
<tr>
<td>20</td>
<td>99.13</td>
<td>102.46</td>
</tr>
<tr>
<td>30</td>
<td>100.79</td>
<td>104.96</td>
</tr>
<tr>
<td>40</td>
<td>101.63</td>
<td>105.79</td>
</tr>
<tr>
<td>50</td>
<td>102.46</td>
<td>106.62</td>
</tr>
<tr>
<td>60</td>
<td>103.29</td>
<td>107.46</td>
</tr>
<tr>
<td>70</td>
<td>104.13</td>
<td>107.87</td>
</tr>
<tr>
<td>80</td>
<td>104.54</td>
<td>108.29</td>
</tr>
<tr>
<td>90</td>
<td>104.96</td>
<td>109.96</td>
</tr>
<tr>
<td>100</td>
<td>105.37</td>
<td>112.46</td>
</tr>
</tbody>
</table>
Table 3.2 SOC Vs Terminal voltage at various discharge currents

<table>
<thead>
<tr>
<th>SOC (%)</th>
<th>Voltage (at $C_B/100$) (volts)</th>
<th>Voltage (at $C_B/20$) (volts)</th>
<th>Voltage (at $C_B/10$) (volts)</th>
<th>Voltage (at $C_B/5$) (volts)</th>
<th>Voltage (at $C_B/3$) (volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>99.13</td>
<td>97.04</td>
<td>94.13</td>
<td>88.30</td>
<td>83.30</td>
</tr>
<tr>
<td>20</td>
<td>100.79</td>
<td>99.13</td>
<td>95.80</td>
<td>90.80</td>
<td>86.63</td>
</tr>
<tr>
<td>30</td>
<td>102.46</td>
<td>100.79</td>
<td>97.46</td>
<td>93.30</td>
<td>89.55</td>
</tr>
<tr>
<td>40</td>
<td>103.29</td>
<td>101.63</td>
<td>98.29</td>
<td>94.13</td>
<td>91.63</td>
</tr>
<tr>
<td>50</td>
<td>103.71</td>
<td>102.46</td>
<td>99.69</td>
<td>96.21</td>
<td>93.30</td>
</tr>
<tr>
<td>60</td>
<td>104.54</td>
<td>103.29</td>
<td>100.79</td>
<td>97.46</td>
<td>94.13</td>
</tr>
<tr>
<td>70</td>
<td>104.96</td>
<td>104.13</td>
<td>101.63</td>
<td>98.29</td>
<td>95.80</td>
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<tr>
<td>80</td>
<td>105.37</td>
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<td>102.46</td>
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<td>103.29</td>
<td>99.69</td>
<td>97.46</td>
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<tr>
<td>100</td>
<td>105.37</td>
<td>105.37</td>
<td>104.13</td>
<td>100.79</td>
<td>98.29</td>
</tr>
</tbody>
</table>

$$SOC = \left\{ \frac{30 - 20}{107.46 - 105.79} \times (V - 105.79) \right\} + 20 = 21.25\% \quad (3.31)$$

where $V$ is the terminal voltage of the battery at which the SOC is to be determined.

When the terminal voltage and current of the battery are not the specified values of the table, i.e., the voltage and current which lie in between the values specified in the table either in row or column wise, the SOC of the battery at that voltage and current is ascertained by calculating the terminal voltages for the given current pertaining to standard specified values of SOC (i.e., 10%, 20%, etc) in using the row wise neighbouring values of voltages between which the battery current falls.
For example, when the SOC of the battery at the charging current of 20A is required, which falls between \( \text{C}_B/5 \) and \( \text{C}_B/10 \), the column wise voltages (V1…V10) for the charging current of 20A is virtually created by the controller following the Equation (3.32), (3.33),(3.34), (3.35)... etc.

\[
V_1 = \left[ \frac{104.96 - 103.29}{\text{C}_B/5 - \text{C}_B/10} \right] \times \left( 1 - \left( \frac{\text{C}_B}{10} \right) \right) + 103.29 = 103.85 \text{V} \quad (3.32)
\]

\[
V_2 = \left[ \frac{105.79 - 104.96}{\text{C}_B/5 - \text{C}_B/10} \right] \times \left( 1 - \left( \frac{\text{C}_B}{10} \right) \right) + 104.96 = 105.24 \text{V} \quad (3.33)
\]

\[
V_3 = \left[ \frac{107.46 - 106.62}{\text{C}_B/5 - \text{C}_B/10} \right] \times \left( 1 - \left( \frac{\text{C}_B}{10} \right) \right) + 106.62 = 106.9 \text{V} \quad (3.34)
\]

\[
V_4 = \left[ \frac{109.96 - 108.29}{\text{C}_B/5 - \text{C}_B/10} \right] \times \left( 1 - \left( \frac{\text{C}_B}{10} \right) \right) + 108.29 = 108.85 \text{V} \quad (3.35)
\]

where ‘\( \text{C}_B \)’ is the capacity of battery and ‘\( I \)’ is the current at which the SOC is needed. When SOC at 106V, 20A charging is needed, the virtually created voltages (3.32), (3.33), (3.34) and (3.35) …etc, the magnitudes adjacent to 106V are substituted in the Equation (3.36) which gives the present SOC of the battery.

\[
SOC = \left( \frac{30 - 20}{V_3 - V_2} \times (V - V_2) \right) + 20 = 24.5\% \quad (3.36)
\]

where \( V \) is the terminal voltage of the battery at which the SOC is sought. \( V_2 \) and \( V_3 \) are the voltages adjacent to 106V.
3.8.4.2   Response of the proposed EC based SOC estimator

The proposed real-time or online SOC estimation by embedded programming technique performs well, and is valid as the controller output (Figure 3.22) is well supplemented by the calculated value (Equation (3.36)). Also, the controller output is compared with the manufacturer’s data sheet to validate the simulation result and it is found to be augmenting well.

3.8.5   Fuzzy Logic System

Fuzzy Logic System (FLS) is a problem-solving methodology that provides a simple way to arrive at a definite conclusion based upon vague, ambiguous, imprecise, noisy or missing input information. It is a branch of machine intelligence which includes multi-valued logic that helps computers, which have statements that are true or false, to enable them to reason in a world where things are only partially true, just as the human brain does. The structure of an FLS is illustrated in Figure 3.23 and is composed of fuzzification, inference engine and defuzzification. The components of FLS are explained in chapter 7.2.2.1 to 7.2.2.4.

![Figure 3.23 Components of fuzzy logic system](image)

3.8.6   FLC based Online SOC Estimation of Battery

The proposed fuzzy logic controller based SOC estimator is shown in Figure 3.24 and the fuzzy rule base is developed from two inputs of the
FLC: The terminal voltage of the battery and the battery current. These inputs are fuzzified and then fed into the fuzzy controller. The battery current is zero while floating, positive for discharging and negative for charging.

![FLC Based SOC Estimation of the Battery](image)

**Figure 3.24 FLC based SOC estimation of the battery**

### 3.8.6.1 Membership functions

Membership Functions (MFs) of the input variables such as battery current and the terminal voltage for developing the rule base of the FLC are carefully chosen to mimic the range of voltage, current and SOC which is presented in Tables 3.1 and 3.2. The maximum discharge current of the battery (C/3) is 50A as ‘\(C_B\)’ is 150Ah. The MFs are designed to replicate the five ranges of discharge currents. Similarly, it is also designed for the charging process, but limited to 40A as the peak possible charging current is less than 40A. Also the MFs of the input ‘voltage’ variable is so designed to replicate the ranges of voltage specified in the Tables 3.1 and 3.2. The MFs of the input variables and output variables are shown in Figures 3.25 (a), (b), (c) and (d).
(a) MFs of the input variables of the discharge mode estimator

(b) MFs of the input variables of the rest mode estimator

(c) MFs of the input variables of the charge mode estimator

(d) MFs of the output variable (SOC)

Figure 3.25 MFs of the input and output variables
3.8.6.2 Fuzzy inference system

The performance of the FLC depends heavily on its fuzzy rules. To accommodate the content of Table 3.1 and 3.2 in the rule base, three FLC’s are used. The three FLC’s house 115 rules, 111 rules and 9 rules pertaining to charging mode, discharge mode and rest condition respectively. The relationship between,

1. The terminal voltage and SOC of the battery at various charging currents
2. The terminal voltage and SOC of the battery at various discharging currents and
3. The terminal voltage and SOC of the battery at floating or rest condition

are clearly established in the rule base and the surface plots pertaining to the rule base are presented in Figures 3.26, 3.27 and 3.28 respectively.

![Surface plot of the proposed rule base that relates terminal voltage, charging current and SOC of battery](image-url)
Figure 3.27 Surface plot of the proposed rule base that relates terminal voltage, discharging current and SOC of battery

Figure 3.28 Surface plot of the proposed rule base that relates terminal voltage and SOC of battery at rest condition

3.8.6.3 Response of the FLC based SOC estimator

The fuzzy based SOC estimator is functioning perfectly as expected in estimating the SOC of the battery. It is validated from the Table 3.1 and the display block shown in Figure 3.24.