CHAPTER 6

ANALYSIS OF THREE PHASE HYBRID SCHEME WITH VIENNA RECTIFIER USING PV ARRAY AND WIND DRIVEN INDUCTION GENERATORS

6.1 INTRODUCTION

Hybrid distributed generators are gaining prominence over the conventional energy conversion due to great advantages like being abundant in nature, recyclable and causing too less pollution [142, 144,135,136]. There are number of schemes based on wind and PV resources [141,142]. An intelligent controller for a stand-alone hybrid generation system was discussed by [135]. It comprises the wind and solar systems integrated to a common DC bus through the necessary power electronic interface. The power electronic interface consists of a conventional rectifier which consists of six switches which leads to considerable switching losses. In this chapter, a Vienna rectifier [145] based hybrid scheme have been proposed, which can generate three voltage level with decreased number of power switches (only three), thus simplifying the control and reducing cost. It also leads to reduced blocking voltage stress on power semi conductors which can enhance reliability.

6.2 HYBRID SCHEME DESCRIPTION

Fig. 6.1 describes the hybrid scheme of solar-wind with the proposed fuzzy logic controller. Vienna rectifier will convert the AC supply into common DC supply with reduced (desired) output voltage thus in turn reduces the combined work of ordinary rectifier and DC–DC buck converter [135]. The variable output voltage of
PV module is controlled by DC-DC converter using proposed fuzzy logic MPPT controller and fed to common DC bus. The DC bus then collects the total power from the wind and photovoltaic system and used to charge the battery as well as to supply the AC loads through inverter.

![Schematic diagram of solar-wind hybrid scheme](image)

**6.3 VIENNA RECTIFIER**

The three phase Vienna rectifier is chosen as the suitable rectifier for converting a generator (variable frequency) type input, due to following advantages:

The Vienna rectifier offers the less input current harmonic distortion than the other topologies. The Vienna rectifier has only three switches, which are significantly fewer than other active rectifiers with the same performance in terms of harmonic distortion. The Vienna rectifier requires less control effort, in terms of the number of isolated gate drives required, than other active rectifier topologies with comparable performance.

Implementation of the Vienna rectifier is eased by the availability of leg modules and control is not dependent on a fixed line frequency, making it ideal for variable frequency type inputs.
The power circuit of Vienna rectifier is shown in Fig. 6.2. Where, $D_1$ to $D_6$ are fast recovery diodes, $D_{Al}$, $D_{Bl}$, $D_{Cl}$, $i = 1$ to 4 are slow recovery diodes, $S_A$, $S_B$, $S_C$ are power switches with freewheeling diodes, $C_1$, $C_2$ are equal capacitance connected across the output of the rectifier and the centre point of $C_1$, $C_2$ is connected to all the three switches.

![Fig. 6.2 Power circuit of Vienna Rectifier](image)

The switching control of Vienna rectifier is illustrated in Fig. 6.3. For the purpose of the model analysis, it is assumed that the phase-currents are in phase with the respective phase voltages. The control algorithm is described. During each 60° period one of the controlled switches is switched "on" for the duration of the 60°
period (transitional switch), whereas the other two switches' duty cycles are varied according to the relative phase currents. With reference to Fig. 6.3, and assuming the phase currents are in phase with the phase voltages and current ripple is negligible, it can be seen that the integrated area product of the phase voltage and the phase current will be equal for both the positive boost rectifier and the negative boost rectifier during the 60° control period. From the operation of the Vienna rectifier it is clear that the positive boost rectifier will transfer its energy to \( C_1 \), while the negative boost rectifier will transfer its energy to \( C_2 \). As a result of the power transferred to \( C_1 \) and \( C_2 \) being equal, the split capacitor bank comprising of \( C_1 \) and \( C_2 \) will be in balance. An example is taken from Fig. 6.3 for the period -30° to 30°. Switch \( S_a \) is switched on during the entire period and the duty cycles of switches \( S_b \) and \( S_c \) varied. For \( \alpha=\omega_{Lt} = [-30°;0°) \), \(|ic| > |ib| \) and thus \( dC < dB \) (where \( dC \) is the duty cycle of switch \( C \) and \( dB \) the duty cycle of switch \( B \)). Capacitor \( C_1 \) will be charged more than capacitor \( C_2 \) (because of the difference in duty cycles).

This will result in a variation in the distribution of the output voltage across the two capacitors with \( V_1 > V_2 \). For \( \alpha = 0° \), \(|ic| = |ib| \) and \( dC=dB \). At this point \( V_1 \) is at maximum and \( V_2 \) is at minimum. For \( \alpha = (0°;30°] \), \(|ic| < |ib| \) and thus will \( dC > dB \). Capacitor \( C_2 \) will be charged more than capacitor \( C_1 \) (because of the difference in duty cycles). This will result in a variation in the distribution of the output voltage across the two capacitors, but still with \( V_1 > V_2 \). At the end of the 60° period the energy transferred to \( C_1 \) over the 60° period will equal the energy transferred to \( C_2 \) over the 60° period and as a result \( V_1 = V_2 \). Voltages \( V_1 \) and \( V_2 \) will vary at a frequency of three times the line-to-neutral frequency, but at the beginning and end of
each 60° period will be equal to voltage $V_1$. However, the average voltage over one cycle is constant.

The simplified Fourier expression of a periodic non sinusoidal waveform is expressed as:

$$V(t) = V_1 \sin(\omega t) + V_2 \sin(2\omega t) + V_3 \sin(3\omega t) + \cdots + V_n \sin(n\omega t)$$  \hspace{1cm} (6.1)

$$V(t) = V_{a+} \sum (a_k \cos(\omega t) + b_k \sin(\omega t)) \text{ for } k=1 \text{ to } a$$  \hspace{1cm} (6.2)

Where $a_k$ and $b_k$ are the coefficients of the individual harmonic term components.

Under certain conditions, the cosine or sine terms may vanish to yield a simpler expression. If the function is an even function, meaning $f(-t) = f(t)$, then the sine terms vanish from the expression. However if the function is odd, with $f(-t) = -f(t)$, then the cosine term disappear. It is to be noted that having both sine and cosine terms affects only the displacement angle of the harmonic components and the shape of the nonlinear wave and does not alter the principle behind the application of the Fourier series. The coefficient of the harmonic terms of a function $f(t)$ contained in Equation (6.2) are determined by:

$$a_k = \frac{1}{\pi} \int_{-\pi}^{+\pi} f(t) \cos kt \, dt, \hspace{0.5cm} (k = 1, 2, 3 \ldots n)$$  \hspace{1cm} (6.3)

$$b_k = \frac{1}{\pi} \int_{-\pi}^{+\pi} f(t) \sin kt \, dt, \hspace{0.5cm} (k = 1, 2, 3 \ldots n)$$  \hspace{1cm} (6.4)

The coefficients represent the peak values of the individual harmonic frequency terms of the nonlinear periodic function represented by $f(t)$. The input current that flows through the switch is governed by
\[ i_a(t) = \frac{v_i \sqrt{2}}{2 \pi f L \sqrt{3}} (1 - \cos \omega t) \]  \hspace{1cm} (6.5)

The phase currents during this time follow

\[ \frac{d}{dt} i_a(t - t_o) = \frac{v_a(t - t_o)}{L} - \frac{v_o}{3L} \]  \hspace{1cm} (6.6)

The solution of equation (6.6) yields a set of equations

\[ i_a(t) = \frac{\sqrt{2} v_i}{3\omega L} \left( \sqrt{2} \sin \omega t + 3 \cos \omega t - 3 \right) - \frac{v_o}{3L} + 3\sqrt{2} v_i + \frac{2\sqrt{2} v_i - 2\pi v_o}{6\omega L} \]  \hspace{1cm} (6.7)

Which describe the line currents as a function of the load voltage.

### 6.4 CONTROLLER FOR VIENNA RECTIFIER

The controller principle is explained in Fig. 6.4. The actual voltage \( V_o \) is compared with reference voltage \( V_i \) in a comparator and the error ‘e’ is generated. Then the change in error ‘\( \Delta e \)’ in the sampling interval is calculated. Variables ‘e’ and ‘\( \Delta e \)’ are selected as the input variables for the proposed fuzzy logic controller. The output variable ‘u’ is the reference signal for PWM generator. A triangular carrier is given to the PWM generator as another input. The output of the PWM generator is the triggering pulses for switches in the Vienna rectifier.

![Fig. 6.4 Controller for Vienna Rectifier](image)
6.5 EXPERIMENTAL SETUP AND MACHINE PARAMETERS

As per the schematic diagram shown in Fig. 6.1, the experimental setup is fabricated (Fig. 6.5) and it consists of PV array panel, a DC-DC converter, Vienna rectifier, an inverter and a DC motor (for variable speed) driven three phase SEIG. The parameter details of solar array panel and the three phase SEIG are given in chapter 2 and 3 respectively. Using the experimental setup the steady state analysis is carried out.

![Experimental setup of solar-wind driven 3Φ SEIG hybrid scheme with vienna rectifier](image)

6.6 STEADY STATE ANALYSIS OF THREE PHASE HYBRID SCHEME

The steady state performance analyses for the following cases are carried out using the results from the experimental setup (Fig. 6.5).

- Variation of power and voltage with varying wind speed for minimum irradiation
- Variation of power and voltage with varying wind speed for maximum irradiation
- Variation of power and voltage with varying irradiation for minimum wind speed
- Variation of power and voltage with varying irradiation for maximum wind speed
The steady-state characteristics for change in synchronous speed of SEIG and minimum to maximum irradiation from 0.3 to 0.9 kW/m$^2$ of the PV cell are discussed.

Fig. 6.6(a) Variation of power and voltage with varying wind speed for minimum irradiation

From the Fig 6.6(a) it is observed that, when irradiation is approximately at a minimum value of 0.3 kW/m$^2$ in the event of decrease in wind speed, the duty cycle is varied proportionally through the proposed fuzzy logic controller to maintain the load voltage constant. When the wind speed is around 1400 rpm (below synchronous speed) the PV array power increases (by proportionally varying the duty cycle of DC-DC converter) and supplies the additional power to the load and load voltage is maintained as desired.

Fig. 6.6(b) Variation of power and voltage with varying wind speed for maximum irradiation
On the other hand, when the wind speed is around 1550 rpm (above synchronous speed) the SEIG will supply directly the additional power to the load and the load voltage is maintained as desired by varying the duty cycle of DC-DC converter to control the output PV array power.

Fig. 6.6(b) shows wind speed variation from 1400 to 1700 rpm at maximum solar irradiation of 0.9kW/m$^2$. When the wind speed is around 1400 rpm (below synchronous speed) since the solar irradiation is maximum the PV array power increases and supplies the additional power to the inverter and hence the load voltage is maintained as desired. On the other hand, when the wind speed is around 1550 rpm (above synchronous speed) the SEIG will supply directly the additional power to the load and the load voltage is maintained as desired wherein the PV array power decreases (by proportionally varying the duty cycle of DC-DC converter).

Fig. 6.6(c) Variation of power and voltage with varying irradiation for minimum wind speed

Fig. 6.6(c) shows variation of solar irradiation from 0.3 to 0.9kW/m$^2$ at minimum wind speed of 1400rpm. When the irradiation is minimum of 0.3kw/m$^2$ the PV array power has to be increased by proportionally varying the duty cycle of DC-DC converter. Thus the additional power will be supplied by the PV array
through the inverter to the load and the load voltage is maintained as desired. On the other hand, when the irradiation is maximum of 0.9kw/m$^2$ the PV array power directly supplies the additional power to the load and the load voltage is maintained as desired.

![Graph showing variation of power and voltage with varying irradiation for maximum wind speed](image)

Fig. 6.6(d) Variation of power and voltage with varying irradiation for maximum wind speed

Fig. 6.6(d) shows variation of solar irradiation from 0.3 to 0.9kW/m$^2$ at maximum wind speed of 1700rpm. When the irradiation is minimum of 0.3kw/m$^2$ the SEIG will directly supplies the additional power to the load and hence the load voltage is maintained as desired. On the other hand, when the irradiation is maximum of 0.9kw/m$^2$ the PV array power has to be decreased by proportionally varying the duty cycle of DC-DC converter and the SEIG still supplies the additional power to the load and hence the load voltage is maintained as desired.

The experimental steady state current and voltage waveform of a hybrid scheme across the load terminals for a resistive load is shown in Figs 6.7(a) and 6.7(b) respectively.
The simulated per phase load current and load voltage waveforms with PI controller (Fig. 6.8(b)) and with proposed fuzzy logic controller (Fig. 6.8(c)) are shown in Fig. 6.8. To test the capability of the proposed FLC the load current is raised from 1.6A to 2A by applying an appropriate load. It is observed that the PI controller have a voltage dip around 10 volts, wherein the proposed FLC maintained...
the load voltage almost constant to the rated value, which demonstrates the better voltage regulation of FLC when compared to the PI controller.

The THD spectrum obtained using simulation for both conventional six pulse converter and Vienna rectifier is shown in Fig. 6.9(a) and 6.9(b). It is clear that the Vienna rectifier offers a low THD value of 2.59% than the six pulse converter value of 29.29%. When the load is allowed to increase, the power switch in the relevant

![Fig. 6.9(a) THD spectrum of conventional six pulse converter](image1)

![Fig. 6.9(b) THD spectrum of vienna rectifier](image2)

![Fig. 6.9(c) Per phase input voltage and current waveforms of Vienna rectifier](image3)
phase is activated, enabling the capacitors to be suitably charged in order to maintain the voltage across the load. Per phase input voltage and current waveform of Vienna rectifier is shown in Fig. 6.9(c). The Vienna rectifier required specifications and design data sheet details are given in Appendix.

6.8 CONCLUSION

A hybrid scheme for isolated applications, employing solar and wind driven three phase induction generator with Vienna rectifier, is proposed with fuzzy logic controller, with optimized rule-base. It is very suitable for the rural electrification in remote areas where grid cannot be accessed. The simulated dynamic results and the practical steady state characteristics are focused on the proposed hybrid scheme. The results of hybrid scheme shows the operation of the proposed fuzzy logic controller for constant load voltage, had inherently resulted in balancing of power between the two sources.