CHAPTER 5

ANALYSIS OF SINGLE PHASE HYBRID SCHEME USING PV ARRAY AND WIND DRIVEN INDUCTION GENERATORS

5.1 INTRODUCTION

Wind and solar energy conversion are gaining prominence over the conventional energy conversion due to great advantages like being abundant in nature, recyclable and causing too less pollution [135]. It can be used separately or as hybrid for three phase or single phase power generations. For remote residential power supply applications such as water pumps, village electrification etc., need single phase power generation. Hence this chapter investigates one such hybrid scheme comprises PV array and single phase self-excited induction generator.

Usually single phase induction motor is utilized as single phase induction generator. As a single phase induction motor, it has two winding namely main and auxiliary winding, here the auxiliary winding is used for starting purpose along with a capacitor. Once the machine pickups the rated speed, the starting capacitor is electrically removed through centrifugal switch. But as a generator either single winding (only main winding) or double winding (main and auxiliary winding) can be utilized. In case of main winding alone the load and excitation capacitor are connected in parallel, but in case of double winding, the load is connected across main winding and the excitation capacitance is connected across the auxiliary winding. Compared to single winding, double winding has an advantage in stability point of view as
induction generator particularly for hybrid scheme employing energy conversion from single phase induction generator and PV array. Here the PV array through DC-DC convertor can be connected to the auxiliary winding through an inverter and the load is connected across the main winding. A fuzzy controller is proposed which maintains the load voltage under varying speed and load, by providing necessary reactive power (like a variable capacitor) to the auxiliary winding through PV array and an inverter. Such a hybrid scheme is discussed in this chapter for both steady state and dynamic analysis.

5.2 HYBRID SCHEME DESCRIPTION

Fig. 5.1 describes the hybrid scheme of solar-wind with the proposed fuzzy logic controller. A self-excited single phase induction generator (SESPIG) main winding output is connected in parallel with the load. The base level excitation requirement is provided by one fixed capacitor bank. The additional excitation requirements under varying rotor speed or load is supplied by the inverter fed by solar array connected to auxiliary winding.

Fig. 5.1 Schematic diagram of solar-wind hybrid scheme
The principle of operation of the proposed hybrid scheme can be discussed under two modes of operation via wind speed lower than nominal synchronous speed or wind speed higher than synchronous speed.

Whenever, the wind speed is lower than the nominal synchronous speed or at higher load, the generated voltage from SESPIG decreases if it is operated alone. This is due to the fixed reactive power availability through shunt capacitance across the load. But in the proposed hybrid scheme the solar based inverter supplies the balance reactive power (difference in fixed capacitance var and the actual requirement) through auxiliary winding at the given speed and load condition and hence the load voltage can be maintained almost constant. On the other hand, whenever the wind speed is higher than the synchronous speed or at lower load, the generated voltage from SPSEIG increases. The load voltage can be maintained by the hybrid scheme by reduction in reactive power supplied to the auxiliary winding through solar based inverter. In both modes of operation the load voltage can be maintained to the required level by the proposed fuzzy logic controller, which varies the duty cycle of DC-DC step up converter and hence the output of the inverter which is connected to the auxiliary winding. This proves the self-regulating mechanism of the proposed scheme.

5.3 MODELING OF SINGLE PHASE HYBRID SCHEME

The steady state and dynamic equivalent circuit (dq axis) of the hybrid scheme (with inverter) is presented in this section. The dynamic and steady state behavior of the hybrid scheme under varying rotor speed and load can be predicted using the equivalent circuit.
5.3.1 Steady State Modeling of Single Phase Hybrid Scheme

The steady state equivalent circuit of SESPIG (with inverter) is shown in Fig. 5.2.

Fig. 5.2 Steady state equivalent circuit of SESPIG (with inverter)

The parameters of equivalent circuit are:

\[ Z_1 = jaX_M; \]
\[ Z_2 = Z_1; \]
\[ Z_3 = R_2 \frac{a}{a-b} + jaX_{Ir}; \]
\[ Z_4 = R_2 \frac{a}{a+b} + jaX_{Ir}; \]
\[ Z_5 = R_{1M} + jaX_{1M}; \]
\[ Z_6 = Z_5; \]
\[ Z_7 = R_{1A}/2k^2 + jaX_{1A}/2k^2 - jX_c/2ak^2 - R_{1M}/2 - jaX_{1M}/2; \]
\[ Z_L = R_L + jaX_L; \]
\[ Z_{LT} = Z_L; \]
\[ Z_{L1} = -R_L/2 - jaX_L/2; \]
\[ Z_{IT} = R_F + jaX_F; \]
\[ Z_i = Z_{iT} \]
\[ Z_{i1} = R_F / 2 + jX_F / 2 \]

The branch admittances are:

\[ Y_1 = 1/Z_1; \quad Y_2 = 1/Z_2; \quad Y_3 = 1/Z_3; \]
\[ Y_4 = 1/Z_4; \quad Y_5 = 1/Z_5; \quad Y_6 = 1/Z_6; \]
\[ Y_7 = 1/Z_7; \quad Y_L = 1/Z_L; \quad Y_{LT} = 1/Z_{LT}; \]
\[ Y_{L1} = 1/Z_{L1}; \quad Y_{IT} = 1/Z_{IT}; \quad Y_i = 1/Z_i; \]
\[ Y_{i1} = 1/Z_{i1} \]

Let \( V_1, V_2, V_3, V_4, V_5 \) and \( V_6 \) be the node voltages at nodes 1, 2, 3, 4, 5 and 6 respectively. By applying Kirchhoff’s current law at nodes 1, 2, 3, 4, 5 and 6 respectively the following equations (5.1) can be obtained.

\[ I_3 = I_1 + I_5 \]
\[ I_1 + I_7 = I_2 + I_3 + I_4 \]
\[ I_6 + I_2 + I_4 = 0 \]
\[ I_5 = I_9 + I_{10} \]
\[ I_7 + I_{11} + I_{12} = 0 \]
\[ I_6 + I_{13} + I_{14} = 0 \]  \hspace{1cm} (5.1)

where,

\[ I_1 = (V_1 - V_2)Y_1; \]
\[ I_2 = (V_2 - V_3)Y_2; \]
\[ I_3 = (V_2 - V_1)Y_3; \]
\[ I_4 = (V_2 - V_3)Y_4; \]
On substituting equations (5.2) in equations (5.1) and rearranging the resulting equations in matrix form, we can get the following matrix

\[
\begin{bmatrix}
(Y_1+Y_3+Y_5) & -(Y_1+Y_3) & 0 & -(Y_5) & 0 & 0 \\
-(Y_1+Y_3) & (Y_1+Y_2+Y_3+Y_4+Y_7) & -Y_2+Y_4 & 0 & -(Y_7) & 0 \\
0 & -(Y_2+Y_4) & (Y_6+Y_2+Y_4) & 0 & 0 & -(Y_6) \\
-(Y_5) & 0 & 0 & (Y_5+Y_{L7}+Y_{Ir}) & 0 & 0 \\
0 & -(Y_7) & 0 & 0 & (Y_7+Y_{Li}+Y_{Yi1}) & 0 \\
0 & 0 & -(Y_6) & 0 & 0 & (Y_6+Y_{Li}+Y_{Yi})
\end{bmatrix}
\begin{bmatrix}
V_1 \\
V_2 \\
V_3 \\
V_4 \\
V_5 \\
V_6
\end{bmatrix}
= \begin{bmatrix}
0 \\
0 \\
0 \\
0 \\
-V_iY_{Ir} \\
-V_iY_{Li}/2
\end{bmatrix}
\tag{5.3}
\]

The matrix equation (5.3) is formed from the per-phase equivalent circuit shown in Fig. 5.2. It can be used to find the steady state analysis of the hybrid scheme under varying speed and minimum or maximum irradiation. As a first step the matrix (5.3) can be inverted to find the node voltages \(V_1, V_2, V_3, V_4, V_5\) and \(V_6\) respectively for the known magnetization reactance \(X_M\), speed, load, other equivalent circuit parameters, inverter voltage and impedance. Once the node voltages are found, all the branch current from equation (5.2) can be obtained. Once all branch currents are known, the real power supplied by the generator can be found. The same procedure is repeated for other speed (below and above the synchronous speed). The parameters of the laboratory machine along with magnetization characteristics of the test system for predicting the steady state analysis are given in section 3.3 of chapter 3.
5.3.2 Dynamic modeling of single phase hybrid scheme.

The d-q representation of single phase two-winding induction generator (with inverter) is presented in this section.

\[ (L_{t_{ds}} ) \frac{d}{dt} (i_{ds}) = v_{ds} - r_{ds} i_{ds} - \frac{d}{dt} (\Psi_{md}) \]  
\[ (L_{t_{qs}} + L_{L}) \frac{d}{dt} (i_{qs}) = v_{qs} - r_{qs} i_{qs} - R_{L} i_{qs} - \frac{d}{dt} (\Psi_{mq}) \]  
\[ (L_{t_{dr}} ) \frac{d}{dt} (i_{dr}) = v_{dr} - r_{dr} i_{dr} - \frac{d}{dt} (\Psi_{md}) - \alpha \omega_{r} (L_{t_{qr}} i_{qr} + \Psi_{mq} ) \]  
\[ (L_{t_{qr}} ) \frac{d}{dt} (i_{qr}) = v_{qr} - r_{qr} i_{qr} - \frac{d}{dt} (\Psi_{mq}) + \frac{\omega_{r}}{a} \left( L_{t_{dr}} i_{dr} + \Psi_{md} \right) \]

The state equations of capacitor bank are derived using the d-q components of stator voltages as state variables from the Fig. 5.3.

\[ \frac{d}{dt} (v_{ds}) = - \frac{i_{ds}}{C_{sh}} \]  
\[ \frac{d}{dt} (v_{qs}) = - \frac{i_{qs}}{C_{se}} \]
The modeling of inverter – DC-DC converter - battery system

\[
\frac{d}{dt}(i_{id}) = \frac{1}{L_f} (v_{id} - R_f - v_{sd}) + \omega_{ms} i_{iq} \tag{5.10}
\]

\[
\frac{d}{dt}(i_{iq}) = \frac{1}{L_f} (v_{iq} - R_f - v_{sq}) - \omega_{ms} i_{id} \tag{5.11}
\]

where

\[\Psi_{mq} = L_{mq} i_{mq} \quad \Psi_{md} = L_{md} i_{md}\]

\[i_{mq} = i_{qs} + i_{qr} \quad i_{md} = i_{ds} + i_{dr}\]

5.4 EXPERIMENTAL SETUP AND MACHINE PARAMETERS

As per the schematic diagram shown in Fig. 5.1, the experimental setup is fabricated (Fig. 5.4) which consists of PV array panel, a DC-DC converter, an inverter and a DC motor (for variable speed) driven SESPIG. The SESPIG has two winding namely main and auxiliary winding. The load is connected across the main winding and the inverter output is connected to the auxiliary winding. The necessary reactive power to the SESPIG is supplied through the inverter. The solar panel output is

Fig. 5.4 Experimental set up of solar-wind driven 1φ SEIG hybrid scheme
controlled by a DC-DC converters, which in turn controlled by the proposed fuzzy logic controller. The parameter of solar array panel and the single phase SEIG are given in chapter 2 and 3 respectively.

5.5 STEADY STATE ANALYSIS OF SINGLE PHASE HYBRID SCHEME

The per-phase equivalent circuit is shown in Fig. 5.2. A mathematical model for the steady state analysis in matrix form (equation 5.3) is presented in section 5.3.1. The steady state model includes the equivalent circuit of the inverter and its impedance of the inverter side filter.

The steady state performance analysis of solar-wind driven single phase SEIG (similar to the solar-wind driven three phase SEIG in chapter 4) for the following cases are predicted through simulation and validated through results from the experimental setup (Fig. 5.4)

- 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 under varying rotor speed of the SESPIG from 1400 to 1700 rpm and minimum to maximum irradiation from 0.3 to 0.9 kW/m² of the PV array are discussed.

Fig. 5.5(a) shows wind speed variation from 1400 to 1700 rpm at minimum solar irradiation of 0.3kW/m². 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 auxiliary winding through 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 SESPIG will supply directly the additional power to the auxiliary winding and hence the load voltage is maintained as desired wherein the PV array power decreases.

Fig. 5.5(a) Variation of power and voltage with varying wind speed for minimum irradiation

Fig. 5.5(b) shows wind speed variation from 1400 to 1700 rpm at maximum solar irradiation of 0.9kW/m². 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 auxiliary winding through the inverter.

Fig. 5.5(b) Variation of power and voltage with varying wind speed for maximum irradiation
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 SESPIG will supply directly the additional power to the auxiliary winding and hence the load voltage is maintained as desired wherein the PV array power decreases (by proportionally varying the duty cycle of DC-DC converter).

Fig. 5.5(c) shows variation of solar irradiation from 0.3 to 0.9kW/m² at minimum wind speed of 1400rpm. When the irradiation is minimum of 0.3kw/m² 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 auxiliary winding and hence the load voltage is maintained as desired. On the other hand, when the irradiation is maximum of 0.9kw/m² the PV array power directly supplies the additional power to the auxiliary winding and hence the load voltage is maintained as desired.

Fig. 5.5(c) shows variation of solar irradiation from 0.3 to 0.9kW/m² at minimum wind speed of 1400rpm. When the irradiation is minimum of 0.3kw/m² 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 auxiliary winding and hence the load voltage is maintained as desired. On the other hand, when the irradiation is maximum of 0.9kw/m² the PV array power directly supplies the additional power to the auxiliary winding and hence the load voltage is maintained as desired.

Fig. 5.5(d) shows variation of solar irradiation from 0.3 to 0.9kW/m² at maximum wind speed of 1700rpm. When the irradiation is minimum of 0.3kw/m² the SEIG will directly supplies the additional power to the auxiliary winding and hence
the load voltage is maintained as desired. On the other hand, when the irradiation is

maximum of 0.9kw/m² the PV array power has to be decreased by proportionally
varying the duty cycle of DC-DC converter the SEIG still supplies the additional
power to the auxiliary winding and hence the load voltage is maintained as desired.

Fig. 5.5(d) Variation of power and voltage with varying irradiation for maximum
wind speed

Fig. 5.6(a) Current                        Fig. 5.6(b) Voltage

Fig. 5.6 Experimental waveforms

The experimental steady state current and voltage waveform of a hybrid
scheme across the load terminals for a resistive load is shown in Fig 5.6(a) and 5.6(b)
respectively.
5.6 DYNAMIC ANALYSIS OF SINGLE PHASE HYBRID SCHEME

The simulated per phase load current and load voltage waveforms with PI controller (Fig. 5.7(b)) and with proposed fuzzy logic controller (Fig. 5.7(c)) are shown in Fig. 5.7. To test the capability of the proposed FLC the load current is raised from 0.9A to 1.6A by applying an appropriate load. It is observed that the PI controller have a voltage dip around 12 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.

This in turn shows the inverter supplies the balance reactive power (difference in fixed capacitance var and the actual requirement) at the given speed and load condition. The result of hybrid scheme indicates the dual objectives of inherent power balance and load voltage control are achieved.
5.7 CONCLUSION

A hybrid scheme for isolated application employing solar and single phase wind driven induction generator is proposed with fuzzy logic controller with optimized rule-base. A DC-DC converter is intervened between the PV array and the inverter to obtain constant load voltage with variations in irradiation and wind speed.

Using the mathematical model described the dynamic and steady state characteristics are discussed. The simulated and experimental waveforms are focused on both the steady state and dynamic behavior which demonstrate the validity of the proposed model. The experimental results of hybrid scheme show the operation of the controller for constant load voltage had inherently resulted in balancing of power between the two sources while supplying constant power to the load. The satisfactory performance of single phase hybrid scheme under dynamic and steady state shows the suitability of its applications in wind-solar energy conversion system under isolated operation.

In solar-wind driven three phase SEIG and solar-wind driven single phase SEIG hybrid schemes, the common AC bus supplied through two source of energy, one is directly from the SEIG and the other from the inverted AC output from PV array. The load is connected directly to the common AC bus.

On the other hand, a common DC bus is also possible. This can be achieved by two sources of energy, one is directly from the PV array through DC-DC converter and the other from the converted DC output from SEIG. The common DC output is then inverted to the AC output and fed to the load.

In the later case to convert the AC output of SEIG to DC output, a Vienna rectifier can be utilized. The analysis of solar-wind driven three phase SEIG with Vienna rectifier is discussed in the following chapter.