GRID CONNECTED HYBRID DISPERSED POWER GENERATORS BASED ON PV ARRAY AND WIND–DRIVEN INDUCTION GENERATOR

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A grid connected hybrid scheme for residential power supply based on an integrated photo-voltaic (PV) array and a wind-driven induction generator has been proposed in this paper. This new grid-connected configuration employs a closed loop controller at the inverter interfaced to the PV array to regulate the current fed to the grid. By varying the reference current to the controller the PV array meets the reactive power needs of the induction generator (IG) and also acts as a source of real power to the grid. A dynamic mathematical model of the hybrid scheme with variables expressed in $d-q$ synchronous reference frame has been developed. The model is implemented in the Simpower™ platform, the simulation results bring out the usefulness of hybrid operation of PV, and wind-driven IG for grid connected operations.

Key words: dispersed hybrid generators, current control, voltage source inverter, wind-driven induction generator, PV array

1 INTRODUCTION

The unbundling of the conventional electric power system in a liberalized and globalized environment had resulted in more and more private agencies setting up generators which are integrated to the distribution network. Further, as stated by [1], these distributed generators are also becoming attractive due to statutes enacted for ecological and environmental protection. In this context, domestic customers are also encouraged to put up modest power plants to meet their energy requirements [2]. These distributed resources integrated to the utility grid also contribute to peak shaving and maximum demand reduction. Further, they also serve as emergency and stand-by power supply [3]. Furthermore, strides made in distribution automation, increased emphasis on reliable supply of power to sensitive loads and development of new power generation technologies had resulted in more and more number of distributed resources being commissioned nowadays. It has been pointed out by [4] that one of the imperatives in the connection of distributed resources is the requirement to satisfy the load requirement of a consumer group even when there is a failure of grid. Hence, this paper investigates one such scheme of distributed generators, where more than one renewable source is employed, so as to supply a selective load and feed the excess power to the utility and also to supply the load in the event of a grid failure.

As a matter of fact, induction generators (IG) driven by wind-turbines have been extensively employed for feeding real power to the grid [5]. Evidently, wind-driven induction generators consume reactive power and the inductive VARs required by this generator has to be supplied by the grid. However, it is well known that for an induction generator to act as an independent dispersed power generator, capacitors are required to excite the generator [6]. The transient behavior of a wind-driven induction generator when disconnected from the grid with such capacitors at the stator terminals of the machine requires careful study, since domestic customers are involved. These isolated generators also exhibit unsatisfactory voltage regulation and frequency variation. To overcome these limitations, instead of providing reactive power using a three-phase capacitor bank, inverter assisted induction generators were proposed. [7] proposed IG schemes with PWM inverters, where the excess energy was sent to the utility grid to maintain the stator voltage and frequency constant or a speed governor to control the amount of the generated energy was employed. However, these schemes are unsuitable for wind-driven isolated operations. A PWM-VSI scheme with a battery bank or a dc charged capacitor has been proposed in [8]. In this scheme, there is a possibility of a voltage collapse in the event of the battery or the capacitor being deeply discharged due to persistent low wind speeds during a particular period of the year.

Hybrid wind-solar grid integrated schemes employing wind-driven PM alternator and PV resources were attempted earlier [9]. In these schemes, the PV array output and the rectifier output fed from wind-driven permanent magnet generator were connected in parallel. Separate controllers were incorporated to regulate the DC bus voltage before feeding it to a pulse width modulation (PWM) inverter. Thus more number of power electronic interfaces is required for these hybrid grid-connected generator schemes. Subsequently, a grid-connected hybrid
wind-PV scheme with AC-DC thyristor converter, a DC-AC thyristor inverter and an energy storage controlled by PLC containing a fuzzy logic module has been proposed [10]. Similarly, steady state performance of hybrid system based on PV and wind with battery storage connected to grid is investigated by [11]. In this scheme also, two stage conversions for grid integration is employed, since the wind turbine is coupled to a PM alternator. In order to overcome these difficulties in operating an induction generator in isolation in a otherwise grid connected scheme, a scheme integrating PV array with IG with or without battery storage is proposed in this paper. Earlier, a hybrid scheme employing PV array and induction generator supplying isolated load has been investigated [12-15]. However, the operation of the scheme in a non-autonomous grid connected mode requires a different control strategy for the inverter and this has been attempted in this paper. However, the scheme proposed in this paper has only an inverter for integrating the hybrid scheme with the utility network as compared to the earlier grid-connected hybrid schemes. Further, investigations on grid-connected hybrid wind-driven IG and PV scheme have not taken up so far and one such scheme is investigated in this paper.

2 DESCRIPTION OF THE SCHEME

The block schematic of the proposed scheme is shown in Fig. 1, where the PV array voltage is fed to a three-phase, six step Current-Controlled Voltage Source Inverter (CC-VSI). This CC-VSI is connected to the grid through an inductor. The controller for the inverter varies the inverter current to follow a reference current. The wind-driven induction generator is integrated with the grid when the wind-speed is greater than cut-in wind speed. The three-phase currents of the inverter are detected and compared with the corresponding phase-current references individually. The resulting current errors are directly used to generate the desired firing pulses for the inverter through an Average Current Mode Controller (ACMC). This is a current control technique that has fast response time and is capable of supporting wide range of power circuit topologies. The wind and PV generators can individually supply power to the grid and the control of the inverter meets the reactive power requirement of the induction generator. It should be noted that in the absence of the grid, the proposed scheme can supply power to a consumer by altering the current control of the inverter to simple SPWM operation. In such operation a three-phase fixed amplitude, fixed frequency supply obtained from the simple SPWM inverter forms the local grid to which the IG is kept integrated.

![Fig. 1. Block schematic of grid connected hybrid scheme: 1 – Wind turbine, 2 – Induction generator, 3 – PV Array, 4 – Three-phase VSI, 5 – Grid](image1.png)

2.1 Development of the controller for the inverter

The block schematic of three phase current control VSI for the (phase A) is shown in Fig. 2. The inverter currents of other two phases are also detected and similarly compared with the corresponding phase current references.

![Fig. 2. representation PWM current controlled VSI (phase A)](image2.png)

At the first stage, the inverter output current is compared with a reference to produce error current signal \( \varepsilon \). The ACMC takes this error current \( \varepsilon \), as an input and it produces an average current error signal which is compared with a triangular waveform. The output of this comparator gives the required pulse width modulated signal for the inverter. Thus by varying the gating pulses applied to the CC-VSI the inverter current is made to follow the reference current value. The schematic representation of an integrator employed in the ACMC controller is indicated in Fig. 3.

![Fig. 3. Integrator circuit for VSI](image3.png)
The ACMC uses an integrating filter to produce an average current error signal and the transfer function of the integrator circuit is given in (1)

\[
\frac{V_o}{V_{error}} = \frac{s R_f C_f z + 1}{s R_f (s R_f C_f z + C_f z + C_f z + C_f z)}
\]

where \( V_{error} = V_{ref} - V_{inv} \) and \( V_o \) is the output voltage of the ACMC. The filter component values are taken as given in [16]. The transfer function of the ACMC controller is given in (2).

\[
\frac{V_o}{V_{error}} = \frac{(s + 6250)}{1.3 \times 10^{-6}s(s + 62795)}.
\]

The integrated error signal is given to a PWM generator for generating firing pulses of the inverter.

### 3 Modeling and Analysis of the Scheme

The synchronously rotating reference frame equivalent circuit of the induction machine with stepped stator voltages caused by the inverter operation is well established and is available in [17–18]. Nevertheless, in order to represent the proposed hybrid scheme in the synchronously rotating reference frame, the equivalent circuit of the induction generator is extended to include the current controlled VSI fed by PV array and the grid. The \( q \) axis and \( d \) axis equivalent circuit of the hybrid system thus obtained is shown in Fig. 4 (a) and (b) respectively.

The equations of the induction machine in the time domain can be written as in [19]

\[
[v_{qs} \ v_{ds} \ 0 \ 0]^T =
\begin{bmatrix}
R_s + L_s p & \omega_s L_s & L_m p & \omega_s L_m \\
-\omega_s L_s & R_s + L_s p & -\omega_s L_m & L_m p \\
L_m p & \omega_s L_m & R_c + L_c p & (\omega_s - \omega_r)L_r' \\
-(\omega_s - \omega_r)L_m & L_m p & -(\omega_s - \omega_r)L_r' & R_c + L_c p \\
\end{bmatrix}
\times
\begin{bmatrix} i_{qs} \\ i_{ds} \\ i'_{qr} \\ i'_{dr} \end{bmatrix}.
\]

(3)

where \( p \) is simply an abbreviation of \( d/dt \) operator. The mechanical system is represented by equations (4) and (5)

\[
\frac{d}{dt} \omega_r = \frac{1}{2H} (T_\epsilon - F \omega_r - T_m),
\]

(4)

\[
T_\epsilon = -\frac{3}{2} \frac{P}{2} L_m (i_{qr} i'_{dr} - i_{ds} i'_{qr})
\]

(5)

where \( T_\epsilon \) is the electromagnetic torque, \( T_m \) is the mechanical shaft torque and \( P \) is the number of poles.

The machine voltages can be related with the grid voltage [20] as

\[
v_{qs} = \sqrt{2} V_\infty \cos(\theta_{cf}(0)) + R_L i_{q,grid} \\
+ L_L \frac{d}{dt}(i_{q,grid}) + \omega_s L_i d_{grid},
\]

(6)

\[
v_{ds} = \sqrt{2} V_\infty \sin(\theta_{cf}(0)) + R_L i_{d,grid}
\]

\[
+ L_L \frac{d}{dt}(i_{q,grid}) + \omega_s L_i d_{grid}(7)
\]

where \( R_L \) and \( L_L \) are equivalent resistance and inductance of the transmission line and \( V_\infty \) is the rms value of the grid voltage and \( \theta_{cf}(0) \) is its phase with respect to \( q \)-axis.

The output of PV array is connected to CC-VSI and is integrated to the grid and the equivalent inverter currents controlled by PV array is as follows

\[
i_{q,pv} = \frac{2}{3} \left( i_{q,pv} \cos(\omega_c t) + i_{b,pv} \cos(\omega_c t - \frac{2\pi}{3}) + i_{c,pv} \cos(\omega_c t + \frac{2\pi}{3}) \right)
\]

(8)

\[
i_{d,pv} = \frac{2}{3} \left( i_{a,pv} \sin(\omega_c t) + i_{b,pv} \sin(\omega_c t - \frac{2\pi}{3}) + i_{c,pv} \sin(\omega_c t + \frac{2\pi}{3}) \right)
\]

(9)

Equations (3)–(9) has been utilized to study the dynamic behavior of the proposed system.

### 3.2 PV array model

The classical equation of a PV cell is quite well established and it describes the relationship between current \( I \) and voltage \( V \) of the cell as [21]

\[
I_p = I_L - I_0 \left[ \exp \left( \frac{V_{pv} + R_{sh} I_{pv}}{V_T} \right) - 1 \right] - \frac{V_{pv} + R_{sc} I_{pv}}{R_{sh}}
\]

(10)
3.3 Variation of model parameters with temperature and irradiation [23]

As a matter of fact, the short-circuit current of the PV array $I_{SC}(Q,T)$ at given irradiation $Q$ and temperature $T$ is strongly dependent on $Q$ than on $T$ and is given as

$$I_{SC}(Q,T) \approx I_{sc}(1 + \alpha \Delta T).$$ (14)

On the other hand, $V_{OC}(Q,T)$ is a logarithmic function of $Q$ and decreases with $T$ and is given in (15)

$$V_{OC}(Q,T) \approx V_{oc}(1 - \gamma \Delta T) \ln(l + \beta \Delta Q).$$ (15)

Further, the peak power $P_m(Q,T)$ is found by assuming that the form of the $V-I$ characteristic remains the same with variation in $Q$ and $T$ and is given as

$$P_m(Q,T) \approx P_m \frac{I_{sc}(Q,T)V_{oc}(Q,T)}{V_{oc}I_{sc}}.$$ (16)

Since, at $I_{pv} = I_m$, $\delta V_{pv}/\delta I_{pv} = P_m/I_{m}$, from (1) $R_{sc}(Q,T)$ and $I_m(Q,T)$ are obtained as follows

$$R_{sc}(Q,T) \approx \frac{P_m(Q,T)I_{m}(Q,T)}{20.7[I_{sc}(Q,T) - I_m(Q,T)]},$$ (17)

$$I_m(Q,T)[1 + \frac{1}{20.7} \left(\frac{I_m(Q,T)}{I_{sc}(Q,T)} - \frac{I_m(Q,T)}{I_{sc}(Q,T)}\right) + \ln \left(\frac{I_{sc}(Q,T) - I_m(Q,T)}{I_{sc}(Q,T)}\right)] = \frac{2P_m(Q,T)}{V_{oc}}.$$ (18)

The variation of parameters of the developed PV model with respect to temperature and irradiation can be obtained from (14)-(18) using the basic parameters of $V_{oc}$, $I_{sc}$, and $P_m$ at standard temperature and irradiation as supplied by the manufacturers and assuming typical values of $\alpha$, $\beta$, $\gamma$ as 0.0025 per °C, 0.5 per Sun, 0.00288 V per °C correspondingly.

4 ANALYSIS OF THE SCHEME

The proposed hybrid grid connected scheme is simulated in Simpower of MATLAB. The PV array is made up of 40 panels connected in series with four such strings in parallel. Each panel is rated 80 W, 22 V and 4.7 A. The array is thus capable of supplying 9.8 kWp. The wind-driven squirrel cage induction machine is rated 7.5 kW, 400 V, Y connected, 4 poles, 1500 rpm. The output of the PV array is inverted by means of a three-phase 6-pulse IGBT inverter and the inverter feeds the grid at a phase-voltage of 230V. The switching frequency of the inverter is taken as 10 kHz. The measured current at each phase
Fig. 7. Three-phase grid connected waveforms subjected to varying reference currents at $t = 0.3$ s and at $t = 0.6$ s (0.1 s/div; 5 A/div)

The injected grid current for irradiation of 0.8 kWm$^{-2}$ and shaft torque of 40 N-m. is shown in Fig. 6. The entire CC-VSI fed by PV array is subjected to rapid variations in the reference current to the current controller to ascertain the ability of the controller to adapt to varying irradiation conditions. The simulated dynamic response of the controller as shown in Fig. 7, demonstrates the ability of the controller to rapidly switch to the varying references instantaneously.

The feasibility of the hybrid generator to inject current to the grid at different power factors is illustrated by means of phasor diagrams.

Case i: When the wind speed increases, the shaft torque of induction generator increases and reactive power consumed by the induction generator increases. However, in the proposed scheme, when there is sufficient irradiation and the phase angle $\theta$ of the reference current $I_{inv}$ is made greater than $\phi$, (where $\phi$ is the angle between the induction generator current $I_{ig}$ and the grid voltage $V_{grid}$), then leading current is injected into the grid. In this case, the PV array meets the reactive power requirements of the induction generator and supplies excess reactive power to the grid for any
wind speed and the phasor representation is indicated in Fig. 8(a).

Case ii: By appropriately varying the phase angle $\theta$ of reference current such that it is same as $\phi$, it is possible to deliver current with unity power factor to the grid as indicated in Fig. 8(b). This condition has also been ascertained for varying torque and irradiation conditions.

Case iii: Even when the irradiation and wind speed is high, it is observed that if the reference phase lead is less than $\phi$, then grid current lags the grid voltage as illustrated in Fig. 8(c). The leading VARs supplied by the PV array is decreased and consequently the reactive power requirements of the induction generator are met partly by the grid and PV.

4.1 Power flow variations for maximum irradiation and torque

The grid connected scheme is simulated and tested under the condition of maximum irradiation (0.8 kW$m^{-2}$) and wind speed (torque of 40 N·m). The maximum irradiation under standard conditions is 1 kW$m^{-2}$ and the maximum torque is computed from the machine rating. The real power supplied by the PV array $P_{pv}$ and the wind-generator $P_{wind}$ to the grid is presented in Fig. 9(a). The real power fed to the grid $P_{grid}$ and the residential load $P_R$ is supplied by PV and wind generators. Hence,

$$P_{pv} + P_{wind} = P_{grid} + P_R,$$

(19)

$$3V_{grid}I_{PV}\cos\theta + 3V_{grid}I_{ig}\cos\phi = P_{grid} + P_R.$$  

(20)

The reactive power flow variation for the same condition of torque is indicated in Eq. (12) and the simulation results in Fig. 9(b)

$$3V_{grid}I_{PV}\sin\theta + 3V_{grid}I_{ig}\sin\phi \leftrightarrow Q_{grid} \pm Q_R.$$  

(21)

As the phase lead advances, the reactive power requirement of the induction generator $Q_{wind}$ and the residential load $Q_R$ is completely supplied by PV array $Q_{pv}$ and excess reactive power is fed to the grid $Q_{grid}$ as evident in Fig. 9(b).

4.2 Variation in real and reactive power flow of PV array

The real power supplied by the PV array for varying irradiation and a shaft torque of 40 N·m is simulated for varying phase angle and amplitude of reference current of the controller. Maximum real power is supplied by the PV array when the power factor and irradiation is maximum and reduces as the power factor of operation is reduced as indicated in Fig. 10(a). Similarly the reactive power flow for varying irradiation is plotted in Fig. 10(b).

![Fig. 9. Power flow variations for maximum irradiation and torque: (a) – Real power flow variation, (b) – Reactive power flow variation](image1)

![Fig. 10. Power flow variations for varying irradiation: (a) – Real power flow variation, (b) – Reactive power flow variation](image2)
4.3 Real and Reactive power flow variations of grid for varying irradiation and torque

A three dimensional plot to study the variation of real power fed when the hybrid scheme is operated at different power factors is shown in Fig. 11a. The reduction in the real power from the array at low power factor operation can be compensated by the induction generator. This is true for any wind speed above the cut-in speed, but irradiation must be greater than the threshold value (0.4 kWm\(^{-2}\)). The reactive power flow variation for \(\theta = 90^\circ\) for varying conditions of torque and irradiation is indicated in Fig. 11b. The grid supplies the reactive power when the irradiation and wind speed are minimum and when the irradiation increases, the PV array meets the reactive power requirement of the induction generator and excess reactive power is supplied to the grid.

5 CONCLUSION

A hybrid dispersed generator employing a PV array and wind driven induction generator has been investigated. The hybrid generator is integrated to a three phase grid using a simple three-phase inverter. The PV array in the scheme is controlled to act as VAR compensator for the wind-driven induction generator and also as a source of real power to the grid. The \(dq\) axis model of the grid connected hybrid scheme has been developed and exhaustive simulations have brought out the capability of the controller to deliver currents at varying power factor. The operation of the hybrid generator to supply real and reactive power under varying torque and irradiation has been simulated and the results presented. Further, the range of irradiation and wind speeds for which reactive power could be fed into the grid is identified for a given rating of the hybrid generator. Furthermore, the real and reactive power limits for varying phase angle of the reference current of the controller for a given irradiation and wind-speed are identified. The Simpower model can be utilized to investigate the operation of a hybrid generator of any rating.

6 NOMENCLATURE

- \(I_{grid}\) RMS value of grid current (A)
- \(I_{ig}\) RMS value of Induction generator current (A)
- \(I_{PV}\) RMS value of Inverter current (A)
- \(R_s, R'_r, R_L\) resistances of stator, rotor (referred to the stator winding) and transmission line (\(\Omega\))
- \(I_s, L'_r\) per phase inductances of stator, rotor (H)
- \(L_L\) Equivalent reactance of transmission line
- \(L_m\) per phase magnetizing inductance (H)
- \(\Psi_{ds}\) \(d\)-axis stator flux linkage (Wb)
- \(\Psi_{qs}\) \(q\)-axis stator flux linkage (Wb)
- \(\Psi_{dr}\) \(d\)-axis rotor flux linkage (refered to stator winding) (Wb)
- \(\Psi_{qr}\) \(q\)-axis rotor flux linkage (refered to stator winding) (Wb)
- \(V_{\infty}\) RMS value of grid voltage (V)
- \(i_q, i_d\) quadrature and direct-axis machine currents (A)
- \(v_q, v_d\) quadrature and direct-axis machine voltages (V)
- \(H\) inertia constant of rotor (s)
- \(\omega_e, \omega_r\) angular speeds of reference-frame and rotor (1/sec)
- \(P_{PV}, P_{wind}\) Real power delivered by PV array and IG pu
- \(P_{grid}\) Real power fed to the grid pu
- \(P_R\) Real power fed to the residential load pu
- \(Q_{PV}\) Reactive power supplied by PV array pu
- \(Q_{wind}\) Reactive power of Induction generator pu
- \(Q_{grid}\) Grid reactive power fed to the grid pu
- \(Q_U\) Reactive power consumed by the load pu

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