A Novel Hybrid Wind Generation Scheme Suitable for Varied Speed Grid Isolated Installations

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***Abstract*—Generation of electrical power from wind is much advantageous due to its clean nature and abundance. This paper presents a wind generation scheme which uses two wind generation sources. The first source is a permanent magnet synchronous generator (PMSG) operating in maximum power tracking mode. The other source is a single-phase dual stator winding induction generator (DWIG). The two machines are connected together with the help of rectifier and a common DC bus. The hybrid wind generation configuration thus obtained can harness wide range of wind speeds for generation purpose and can sustain single-phase isolated domestic loads. Provision of storage is kept using a suitable storage battery during surplus energy available. Additionally, photovoltaic (PV) panel can be added across the DC bus for generation and sustaining loads during no wind. The control of the two generators with PV panel is studied in the paper. The simulation results obtained, backed by the experimental findings validates the proposed concept.**

Keywords—permanent magnet synchronous generator (PMSG); dual stator winding induction generator (DWIG); wind energy; grid isolated operation

I. Introduction

Renewable energy schemes especially wind and solar-Photovoltaic (PV) are becoming popular choices for driving grid isolated domestic and critical loads [1]-[3]. Both wind and solar are intermittent in nature [4] and thus require control strategies which are at times very complex to setup for steady generation. Induction generators have been widely used to harness wind energy for grid-connected [5]-[7] as well as grid-isolated installations [7]-[9] due to obvious advantages of ruggedness and no need for separate excitation. An induction generator has a disadvantage of need for a source of a reactive power for generation and sustaining loads [4], [7]. Moreover, these generators often suffer from the problem of voltage regulation with changing wind speeds or with changing loads and hence proper control is necessary. Permanent magnet synchronous generators (PMSG) are also advantageous as they do not require reactive power for excitation unlike induction generators [10]. Also a PMSG can be driven at almost any speed to generate electricity although for supplying customers, the need for a fixed frequency inverter is necessary [11], [12]. For supplying single phase loads, single-phase induction machines as generators have been extensively studied in literatures [13]-[15]. Use of inverters for providing variable excitation has been shown to increase the operating range for such machines improving the voltage regulation [16]. The single-phase induction generators are also sometimes used with PV-panels for sustaining loads in hybrid installations [17]-[19]. These generators can be designed for higher number of poles for harnessing wide range of wind speeds. The single-phase induction machines have two distinct sets of stator windings viz. the auxiliary winding and the main winding. These two stator windings can be separated and used as dual stator winding induction generator. One winding can be used for controlling the generation purpose and the other winding can be used for generation. PMSGs require an inverter and storage for sustaining consumer loads. PMSG-DFIG based generation is proposed in [20]. A PMSG can be operated with a single-phase dual stator winding induction generator with sharing the fixed frequency inverter requirement with the later. The PMSG can generate from lower ranges of wind speeds and thus can also provide the initial reactive power support for the single-phase DWIG. A storage battery with controller switch can also be used with the two generators when generation is surplus when load is low.

In the proposed generation scheme, a 3-phase, 200W, 240V, 50Hz, PMSG with bride rectifier at the stator terminals is used with a DC-DC converter which is connected with the DC bus of the rectifier connected 500W, 240V, 50 Hz, single-phase DWIG. The DWIG is controlled using a single-phase variable frequency inverter supplied via this common DC bus and an optional storage battery. A PV panel can be used across the bus for augmenting power. The DC bus output is connected to a single-phase fixed-frequency inverter to cater single-phase domestic isolated AC loads. The proposed generator is capable for supplying isolated domestic loads with wide range of wind speeds. The simulations backed with proper experiments on a prototype validates the viability for the generation scheme especially for isolated and critical loads.

II. Description of the Proposed Scheme

A single-phase DWIG is used with the main winding is used as generating winding. The output of which is connected to a single-phase bridge rectifier. The generated voltage is rectified from the PMSG using another single-phase bridge rectifier and is connected to the output of the single-phase

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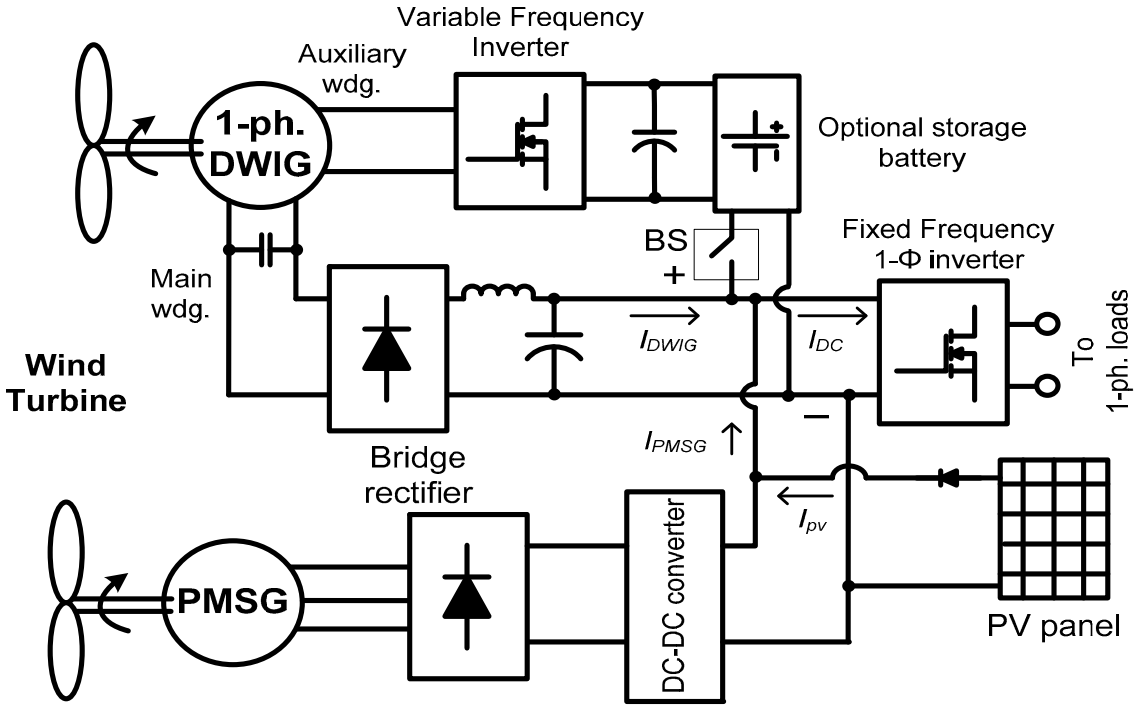


Fig. 1. Block diagram of the proposed generation scheme.

DWIG. To supply single-phase domestic loads, the output of the common DC bus is then connected to a fixed frequency single-phase inverter which is operated at 50 Hz constant frequency. The block diagram of the setup is shown in Fig.1. A battery may be used as optional storage device across the DC bus and the same can be used for providing the variable excitation of the DWIG via a single-phase variable frequency inverter.

The proposed scheme is advantageous as a PMSG invariably requires an inverter and a battery to supply domestic loads, which it can share with the DWIG. The DWIG can be used when wind speeds is sufficient to generate, below critical speeds, PMSG can generate. Moreover, a PV panel used across the DC bus can supply loads during periods of no winds. The proposed scheme is a hybrid generation scheme and thus costly initially but it is expected to incur the money spent on its installation during its working period. The reliability of the system is also increased which is especially advantageous for supporting critical loads and loads isolated from the grid.

III. Modeling and Control of the Proposed Scheme

The PMSG works on maximum power point tracked (MPPT) from the wind turbine, where the turbine model [21] can be given as,

$$P_w = \frac{1}{2}\rho\pi R^2 V^3 C_P \tag{1}$$

where, ρ is the air density in kg/m^3, R is the radius of turbine rotor in metres, V is the air velocity in m/sec and C_P is the turbine power coefficient which is a function of the tip speed ratio and the pitch angle of the turbine. A horizontal axis turbine is considered in the proposed scheme having a pitch angle β, where C_P is defined as [22],

$$C_P(\lambda,\beta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)e^{\frac{-c_5}{\lambda_i}} + c_6\lambda \tag{2}$$

Where, values of c_1, c_2, c_3, c_4, c_5 and c_6 for the turbine are, 0.52, 105, 0.4, 5, 21 and 0.007 respectively. The tip speed ratio (TSR) is given as,

$$\lambda = \frac{R\omega_r}{V} \tag{3}$$

Where, ω_r is the rotor angular velocity (rad/s). λ_i is the ideal tip speed ratio and is given as,

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{4}$$

Putting the value of V from (3) in the power equation (1) and putting the maximum conditions of λ, C_P and angular speed, the maximum power obtainable from the turbine is given as [],

$$P_{w\max} = \frac{1}{2}\rho\pi R^5 \frac{\omega_{r\max}^3}{\lambda_{\max}^3} C_{P\max} \tag{5}$$

In the proposed scheme, the MPPT used is reference curve based and is obtained from simulated results using *MATLAB/Simulink*. This data is fed to a microcontroller memory for simulating the wind turbine characteristics. The power from the curve is compared with the actual power as

calculated from the output of the rectifier of PMSG via a proportional-integral (PI) controller to generate the PWM pulses for switching the DC-DC converter. The control scheme is shown in Fig.2.

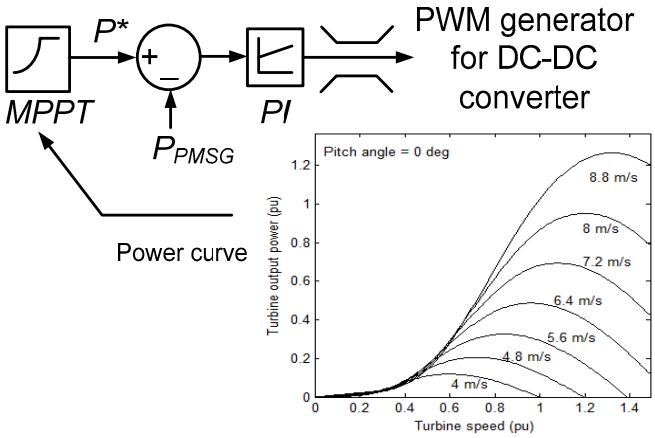


Fig. 2. Block diagram for control of PMSG based generation unit.

The single-phase induction generator with dual stator windings is modeled in stationary *ds-qs* axes reference frame using voltage equations as,

$$v_{ds} = R_{ds} i_{ds} + p\psi_{ds} \tag{6}$$

$$v_{qs} = R_{qs} i_{qs} + p\psi_{qs} \tag{7}$$

$$0 = R_{dr} i_{dr} + p\psi_{dr} + \omega_r \psi_{qr} \tag{8}$$

$$0 = R_{qr} i_{qr} + p\psi_{qr} - \omega_r \psi_{dr} \tag{9}$$

where, R, i, ψ and p are the winding resistance, current, flux linkage and differential operator respectively with *ds* and *qs* suffixes denoting the stationary *ds-qs* axes components. The flux linkages are denoted as,

$$\psi_{ds} = L_{lds} i_{ds} + L_{dm}(i_{ds} + i_{dr}) \tag{10}$$

$$\psi_{qs} = L_{lqs} i_{qs} + L_{qm}(i_{qs} + i_{qr}) \tag{11}$$

$$\psi_{dr} = L_{ldr} i_{dr} + L_{dm}(i_{ds} + i_{dr}) \tag{12}$$

$$\psi_{qr} = L_{lqr} i_{qr} + L_{qm}(i_{qs} + i_{qr}) \tag{13}$$

where, L_l represents the leakage inductance with L_m as the magnetizing inductance. The induction generator uses a direct voltage loop based control scheme for switching the single-phase variable frequency inverter. For the switching of the inverter, the DC bus voltage of the rectifier output is sensed and is compared with a set reference voltage. The error is passed through a PI controller and the output is taken as the DC bus current reference i_{dc}*. This current reference is compared with the actual sensed current of the DC bus i_{dc} and the error is passed through another PI controller. This current reference is compared with the actual sensed current of the DC bus i_{dc} and the error is passed through another PI controller. The output from which is compared with a triangular carrier to generate the PWM pulses for the inverter as shown in Fig.3.

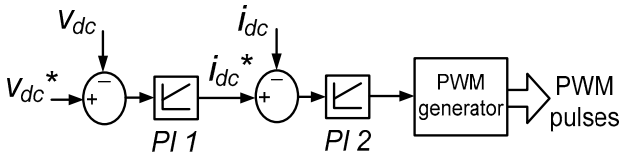


Fig. 3. Scheme for single-phase inverter control.

The PV panel is always connected to the DC bus and is not operated in MPPT mode to avoid complexity. The PV panel augments the generated power at low or no wind conditions. During surplus generation, the same can be stored in batteries. It is modeled using a simplified *I-V* relation [23], [24] which can be given neglecting the shunt resistance effect as it is very high as compared to series resistance of panel as,

$$I_{pv} = N_P I_{PH} - N_P I_S [\exp((qV_{pv} + I_{pv}) / N_S V_a) - 1] \tag{14}$$

where, N_P and N_S are parallel and series connected cells with I_{PH} and I_S as diode photocurrent generated and the saturation current. V_a is the thermal voltage generated. q is the charge of electron. The DC bus current for the proposed model when battery is not connected can be given as,

$$I_{DC} = I_{pv} + I_{PMSG} + I_{DWIG} \tag{15}$$

The scheme uses an optional battery storage which can be used as a storage unit when the generated voltage becomes surplus after meeting the load demand. The battery is connected across the DC bus of the variable frequency inverter of the DWIG across its auxiliary winding. The same can be connected across the main DC bus using a bidirectional switch (BS) as shown in Fig.1. Thus for battery charging and discharging control, the bidirectional switch with configuration shown in Fig.4 is used. It consists of two MOSFETS S1 and S2 connected in anti-parallel mode with series connected diodes D1 and D2. For charging, S1 and D1 can be on. The gate pulses are controlled depending on *SOC* values and other operating conditions through microcontroller. During discharging, S2 is on and D2 conducts and the current flow is from battery to DC bus.

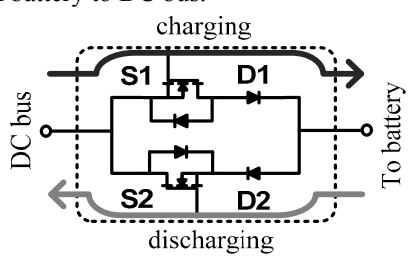


Fig. 4. Bidirectional switch (BS) for connecting/disconnecting storage battery to the DC bus.

An energy management scheme is also necessary as the proposed scheme uses various renewable energy sources. An energy management scheme will consider all the physical conditions of operation for the proposed system. The energy management scheme considering different operating modes for the generation scheme is also proposed. The energy management considers factors like solar insolation, wind

speed and battery state-of-charge (*SOC*) as key factors for operation. During operation of both PV panel and wind based generation in parallel, various conditions can occur. This can lead to different operating modes as regards sharing of power to load.

Case 1: Both solar insolation and wind speed are high

The excitation requirement for the DWIG through auxiliary winding and the real power demand by the load both are supplied from the power generated through the main winding and PMSG also by the PV panel. The storage battery is in charging mode if battery *SOC* < 0.8.

Case 2: Solar insolation is high but wind speed is low

The excitation requirement for the generator and the real power demand by the load both are supplied mainly by the PV panel and PMSG generated power. The wind generated power is low and adds up to the PV generated power to meet the load demand. The storage battery can supply load until battery *SOC* = 0.4.

Case 3: Solar insolation is low and wind speed is high

The excitation requirement for the DWIG and the load power demand are both supplied by the wind generated power through main winding. PMSG also generates power. The storage battery can be in charging mode if battery *SOC* < 0.8 if wind power is excess after supplying the load.

Case 4: Both solar insolation and wind speed are low

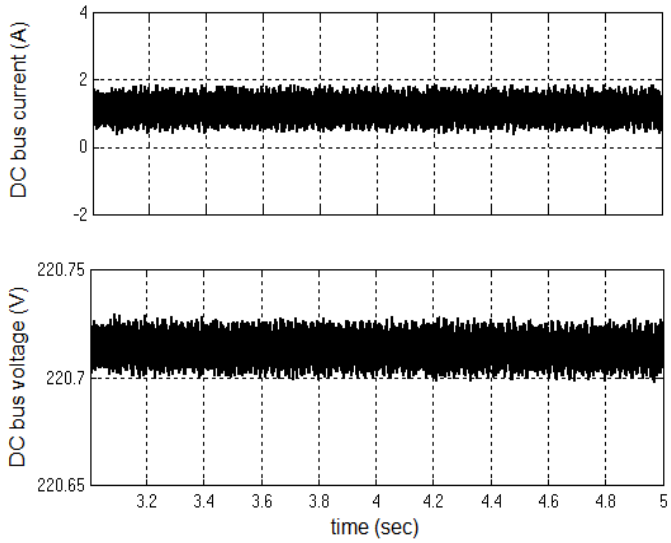
The excitation requirement for the DWIG and the load demand both are supplied by the storage battery which can be in discharging mode until battery *SOC* = 0.2. PMSG also generates power if wind speed is sufficient.

Insolation is taken as a function of PV panel open circuit voltage and the *SOC* is measured according to battery open circuit voltage and the data is fed to a microcontroller for experimental purpose. The practicability of development and installation of the proposed generation scheme is validated using suitable simulations which are verified through experimental results obtained using a laboratory prototype.

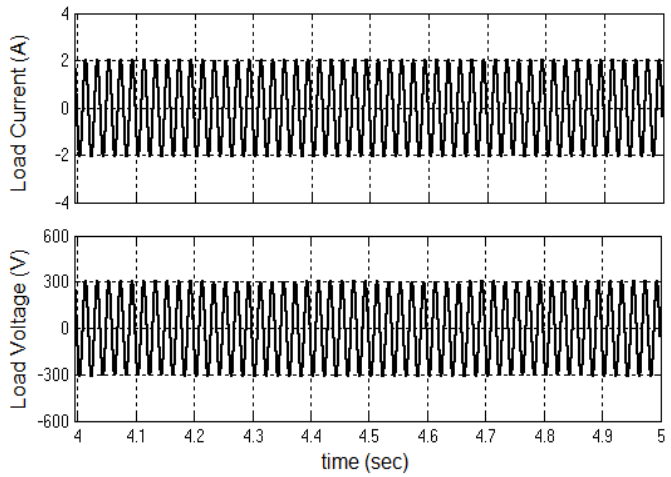
IV. Simulation and Experimental Results

The proposed generation scheme is first simulated using *MATLAB/Simulink* ver. *R2014b*. The single-phase induction machine operated as DWIG is rated at 500W, 240V, 50Hz and designed for 4-stator poles. The PMSG is rated for three-phase, 200W, 240V, 50Hz. The PV panel is mainly used as a backup for the proposed scheme and the wind sources are designed as to supply the bulk energy for the system. When renewable sources are sufficient to meet the load demand, the surplus power will charge the battery bank.

The simulated steady state DC bus voltage and current with load side voltage and current is shown in Fig.5 (a) and Fig.5 (b) respectively, when DWIG and PMSG are both generating power in steady conditions of load and speed.



(a)

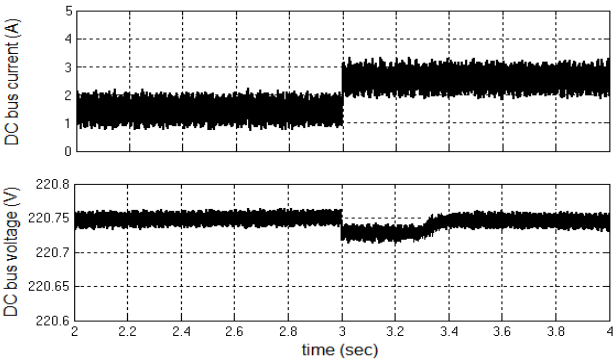


(b)

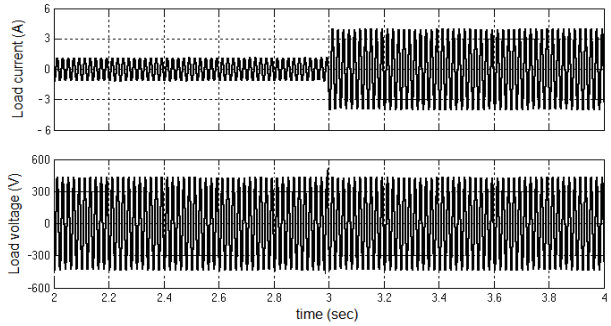
Fig. 5. Simulation waveforms for (a) DC bus current and voltage and (b) load current and voltage at steady state.

The generation scheme is now tested for change in load. The simulation study is carried out in the *MATLAB/Simulink* based model. With a step increase in load current from 1A to 2.5A, the change in DC bus current and voltage is shown in Fig.6 (a), the corresponding change in load current and voltage terminals are shown in Fig.6 (b). The load voltage is maintained at constant as shown in the figure with step change in load with the proposed control scheme from the DWIG.

The experiments are conducted on a laboratory setup consisting of a 500W, 240V, 50Hz single-phase induction machine configured as DWIG and a 200W, 240V, 50Hz PMSG. The inverters and DC-DC converter uses MOSFETS K2611 with 900V, 11A rating. PIC microcontroller PIC18F452 is used for implementing the control scheme and providing the PWM pulses for the gate driver to operate the inverter and converter switches. The same is used for fabricating the bidirectional switch. The experimental hardware setup is shown in Fig.7.



(a)



(b)

Fig. 6. Simulation waveforms for (a) DC bus current and voltage and (b) load current and voltage with step change in load.

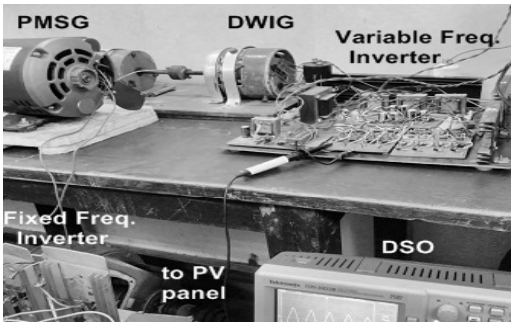


Fig. 7. The experimental laboratory hardware setup.

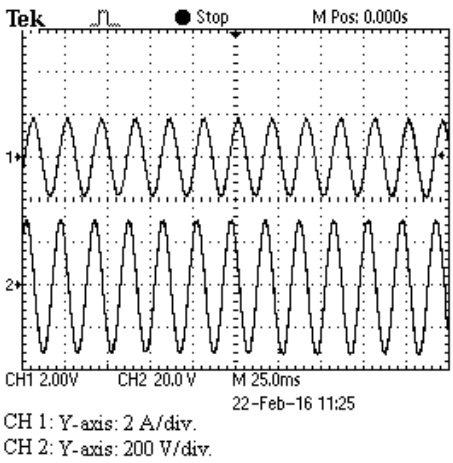


Fig. 8. Experimental waveforms of load current (CH 1) and load voltage (CH 2) in steady state.

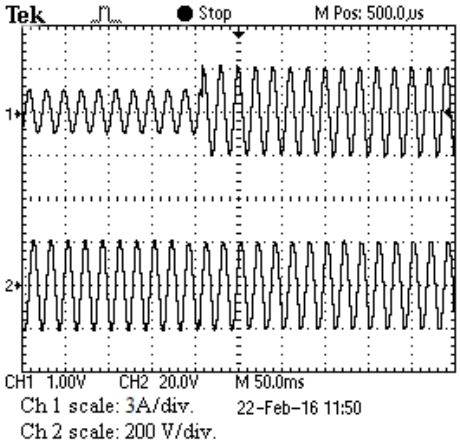


Fig. 9. Experimental waveforms of load current (CH 1) and load voltage (CH 2) with step change in load.

The experimental waveforms for the steady state load current and voltage is shown in Fig.8. Fig.9 shows the experimental waveforms for the change in load current with increase in load similar to the simulation result with change in load voltage. The load voltage is shown to be remaining almost constant as the DWIG with the controlled voltage and the MPPT operated DC-DC converter maintains the current for the DC bus by reducing the duty cycle and maintaining the voltage. Fig.10 shows the simulated power sharing status with change in speed and variable load.

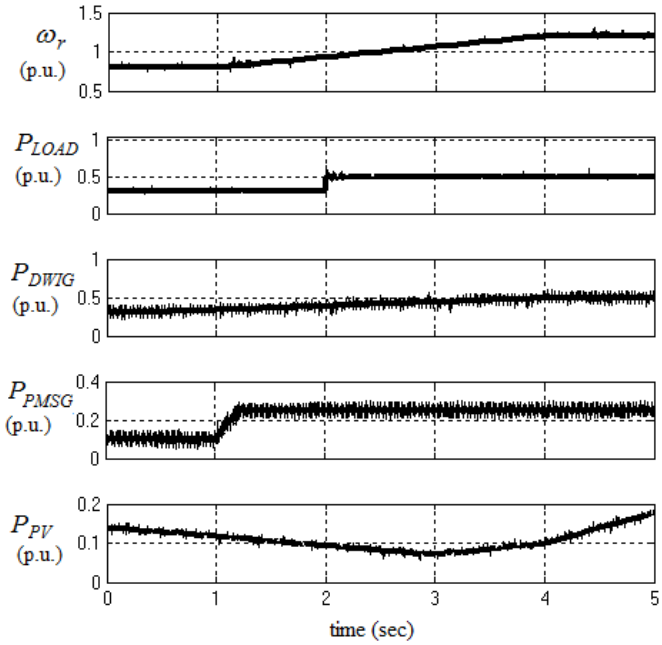


Fig. 10. Power sharing status between different sources with change in load and wind speed.

With the load changing at t = 2 sec from 0.3 p.u. to 0.5 p.u., the sharing of different powers for the renewable generation sources is depicted in Fig.9. It can be seen that with increase in rotor speed, the DWIG available power increases and the PMSG supplies almost constant power until there is change in speed. The generation becomes more reliable with the addition

of a PV panel and as observed, there is considerable energy that can be stored in the storage battery after meeting the constant load. Fig.10 thus demonstrates all the operating conditions that may arise as described in Section III.

The proposed scheme uses different sources of renewable power and similar schemes related to use of two or more types of wind turbines can be set up in critical locations, although the scheme can be initially costly to implement. The reliability as regards to the available power is much improved and can be suitable option in critical demanding remote load centers as hospitals, universities or markets. The reliability is of foremost importance in critical isolated systems.

V. Conclusions

A hybrid generation scheme is proposed in the paper wherein a PMSG based wind turbine generator is used for generation support from low wind speeds and a DWIG based single-phase generator for higher wind speeds. During low or absolutely no wind speeds a PV panel is used to support isolated loads. Otherwise during surplus, the excess energy can be stored in batteries. Battery storage can also provide the reactive power support for the DWIG. The proposed scheme is suitable to be used in remote areas as a stand-alone source of power. Thus the proposed scheme can be a suitable option as a microgrid structure in grid-isolated areas with its easy control and maintenance. Simulation studies backed by experimental results sum-up the suitability of the proposed scheme.

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