Control and simulation of a standalone photovoltaic-wind with a fuel cell and battery storage

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Abstract— This paper proposes a control strategy of a standalone hybrid energy conversion system. The hybrid renewable energy system is the combination of wind, solar, battery, fuel cell and dump load are connected to the common dc bus. In the proposed hybrid system, control of the generator side converter is used to achieve maximum power extraction from the available wind power by the indirect field orientation control (FOC). Moreover the PV array is integrated with an Incremental Conductance (IncCond) control algorithm to track the maximum power. Control of the bidirectional buck-boost DC-DC converter is used to maintain the constant dc-link voltage by charging or discharging the battery and compensating the power differences between the wind source and loads. The potential excess of power is dissipated in the damp resistor with the chopper and buck converter. The load side voltage source inverter (VSI) is used to control the output load side voltage in terms of the frequency and voltage amplitude. In order to reduce harmonic currents injected to the AC load, a passive LCL filter is integrated. Extensive simulation results using Matlab/SIMULINK to establish that the performance of the controllers is quite satisfactory under variations in wind speed, solar irradiance and load condition.

Keywords—component; ***Stand-alone; hybrid system; Variable speed wind turbine; PMSG; PV; LCL Filter***

I. INTRODUCTION

The proposed standalone hybrid system considered as case study a combination of wind and photovoltaic subsystems as shown in Fig.1. Consists of a permanent magnet synchronous generator (PMSG) based variable speed wind energy conversion, PV array, battery, fuel cell and dump load. The PV array of maximum power of 7.46 kW is connected through a boost converter. Similarly, the dump load is connected through a buck converter which is used to consume the excess power in the load during fully charged battery condition. Furthermore, the voltage rating of dump load is considered at 68V. The Wind turbine with its PMSG is connected to DC bus through four-quadrant converter when the rating power is 10 kW. The lead acid battery is used as a storage device which is connected to the DC-link voltage through a DC-DC bidirectional buck-boost converter and the operating voltage is about 220 V while 650V. The fuel cell (FC) is connected to the DC bus through a boost DC /DC converter when the rating power 10 kW and the operating voltage is considered at 300 V [9]. Hence the FC is activated only during low battery storage to charge the battery and meet the load demand. Finally a LCL filter is connected after the VSI to eliminate the high frequency harmonics from output AC current and voltage were are injected to the AC load.

The similar hybrid energy system is study by some researchers [3-4, 6–8]. In [4] authors present a power management of a stand-alone system using different sources, however, authors have not discussed about the control of ac load side and the voltage and frequency which is not mentioned. In [6] authors present a standalone hybrid generation systems to the supply only the dc load. In [5-8] authors, the control of dump load is not presented. Similarly, in [6], the dumping load and battery storage is not considered which to maintain the balance of system unreliable. In [1] authors present a standalone wind turbine with a PMSG, the VSI connected to the AC load through L filter. However, the L filter causes high harmonic attenuation is generated to load. The LCL filter which is more efficient than L and LC filters. In addition, authors in [12-14] demonstrate the performance to control VSI with LCL filters in grid connected and standalone. In the reference [4], the wind turbine with its PMSG is connected to DC bus through diode rectifier and boost converter to achieve the maximum power. However, the diode rectifier causes high distortion of the current and voltage in the machine. In [1-3-4], the AC loads are connected to the DC bus through PWM based inverter. However, the inverter can be generating high frequency harmonics in the output voltage. In [2-3-9] authors present a modified hysteresis-control strategy which was applied in the battery converter. However, this technique improves the power quality (Harmonic mitigation).

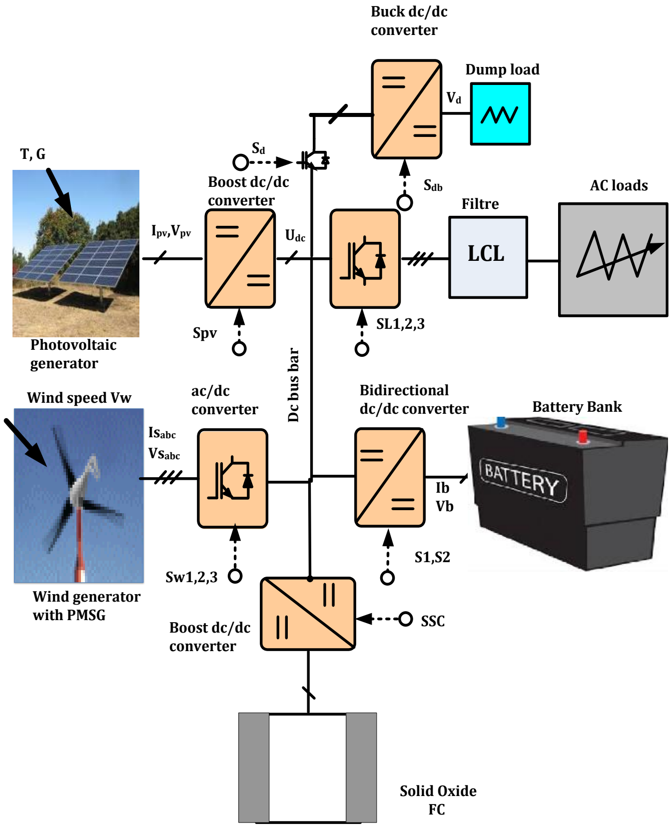

Fig. 1.The proposed standalone hybrid system

II. Control of Power converters

Four different type of power converter are used to control the system as shown in Fig.1. The boost dc/dc converter, is used the control the PV and FC. While the bidirectional dc/dc converter for the battery which is used to regulate the DC link voltage. The buck converter is used to control the dump load. The bidirectional inverter or converter which is used as the generator side or load to control the PMSG to achieve MPPT and the output load side voltage.

A. *Control of PV*

Several techniques of maximum power tracking have been considered in PV array application: In [8-9] presented as a MPPT based on P&O. However, the IncCond algorithm has advantages compared to P&O. In addition, the IncCond method also offers good performance under rapidly changing atmospheric conditions. The algorithm of this method is presented in [2].

B. *Control of Generator side converter*

The control objectives for the wind system is to obtain the maximum power from varying wind speed and minimize the rating of the wind converter by regulating reactive power generation at zero , in order to attaining the unity power factor operate .The power of PMSG are controlled by the d-q axis current respectively. The control of the stator side with PI controller system is presented in the block diagram shown in

Fig 2. The rotor angle position (θ_r) used in the transformation between abc and dq variables is obtained from the rotor speed of generator. Finally, V_{sd}* and V_{sq}* are voltage reference of current controller transformed to α-β plan to be used by the SVPWM method. The value of the speed reference (ω_{ref}) is determined by MPPT method of the wind turbine and is calculated as [1-12]

$$\omega_m = \frac{\lambda_{opt} V_\omega}{R} \qquad (1)$$

Where λ_{opt} is the maximum torque coefficient, R is the blade radius, and V_ω is the wind speed.

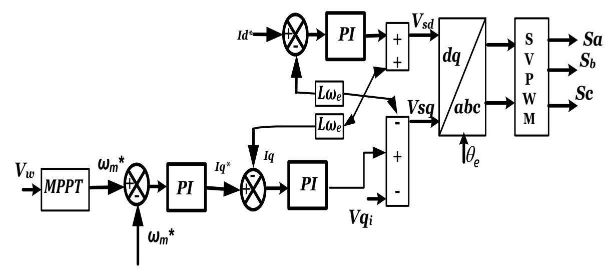

Fig. 2 . Control of generator side converter

C. *Control of the battery*

The battery storage system is important to regulate the DC bus voltage constant at 650V to maintain the balance between the generated power from the sources (photovoltaic, wind) and required loads power through charge/discharge energy from this storage system by triggering the switches S_1 and S_2. The controller technique is shown in Fig.3 includes two loops; external voltage control and internal current control. In this paper the charge/discharge of the battery is considered with above mentioned rang of SOC between 20% and 80% [3-9].

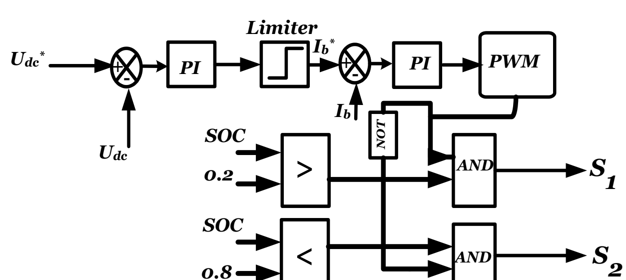

Fig. 3 . Control of battery bidirectional converter

D. Dump load control

The dump load is absorbing the surplus power form the wind and solar when the dc bus voltage matches the reference dc voltage and the state of charge of battery SOC are above upper limit of SOC 0.8 via the chopper control S_d in Fig.4. The control of buck converter control can maintain the voltage of dump load at constant value as a reference value (switch S_e) when the SOC is at the maximum limit 0.8 and switching is ON of S_d.

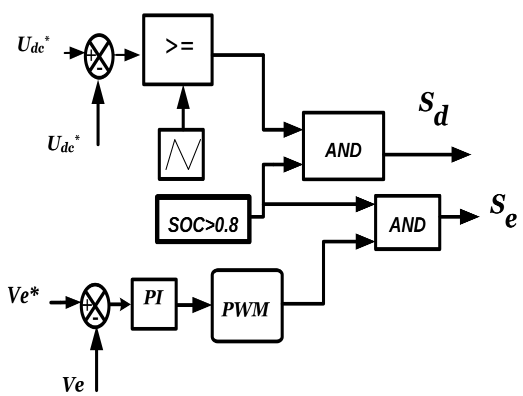

Fig. 4. Dump load controller

E. Control the current of FC source

The fuel cell source is connected to DC bus through a boost DC/DC converter. The FC is used to meet the deficit load demand when the SOC of the battery is less than 0.2. The control of the boost converter is illustrated, as in Fig. The controller includes two loop, voltage control and current control.

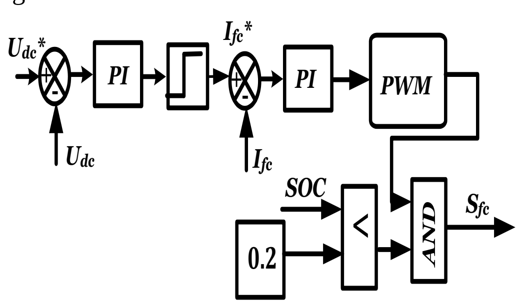

Fig. 4. Fuel cell controller

F. The load side VSI control strategy

The load side VSI control is responsible to regulate the amplitude and frequency at the consumer load. The simplified dynamic diagram control of the load is connected to the LCL filter, in the d-q rotating reference frame can be derived as shown in Fig.5, include the cross couplings $C_f\omega$, $L\omega$, where L is total series inductances $L = L_i + L_z$, in order to improve tracking capability of the control system. In this control technique, the load output current in the internal control loops and the load output voltages in the external control loops are regulated by PI controllers.

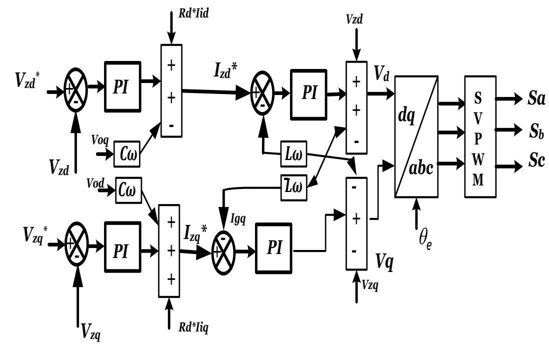

Fig. 5 . The load side VSI control strategy

In this paper, the specified root-mean-square (RMS) value of the output phase voltage and the load voltage frequency are 230V and 50HZ. The u_d reference voltage value of resistive load can be directed by [1-8-11]:

$$u_d = \sqrt{2}V_{RMS} \qquad (2)$$

Where $V_{RMS}$is the *RMS* reference value of the output phase voltage.

III. RESULTS AND DISCUSSION

To evaluate the controller's performance of hybrid system, simulations were carried using MATLAB\Simulink. The wind turbine is a three-phase PMSG with rated power of 10 kW at rated wind speed of 14 m/s. The PV array with rated power of 7.46 kW at STC. The common dc voltage is maintained above 650V. The performance of the proposed hybrid energy system is tested by considering the following cases.

A. Dump load and battery controller

In this case, the irradiance (G) and temperature (T) are stable respectively at 1kW/m^2 and 25°C, the wind speed (V_w) is fixed at 14m/s. the power load demand (P_L) is fixed at 14kW. The initialization of state of charge of battery storage SOC of the battery is carried out near about 0.8 and assuming that surplus power is a violable from sources the battery is fully charged then the excess power is deviated to dump load. So it could be clear from Fig. 6 when SOC becomes more that 0.8 at t = 2.7 s, the dump load is consuming excess energy and battery stops charging which makes its power zero. The figure also shows that the sum power from PV and Wind system (Ppv+Pw) is around 17.5 kW. Fig. 7 demonstrates the performance control of proposed system, the control of buck converter regulate the voltage of dump load at 68V at the period (t>2.7s); the control of battery regulates the commune bus voltage Udc at 650V. Furthermore, the battery start charging (P_L<P_{pv}+P_w), the current I_b is negative (-16.15 A). At moment of SOC more that 0.8 at t = 2.7 s, the current state very face zero. It is clear from Fig.6 and Fig.7 that MPPT control of wind turbine the indirect FOC efficiently controls PMSG speed and MPPT InCond makes the output power of PV.

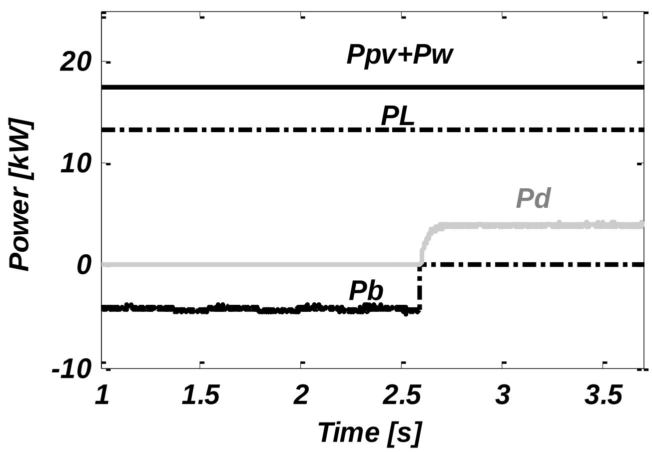

Fig. 6. Power generation of the hybrid system (Case 1)

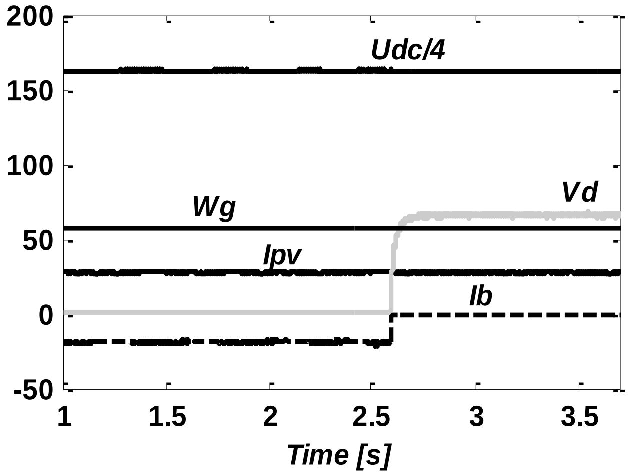

Fig. 7 . Performance of the hybrid system (Case 1)

depicted that the DC bus voltage constant at a reference value of 650V. The indirect FOC and IncCond controllers make the out power at a maximum value.

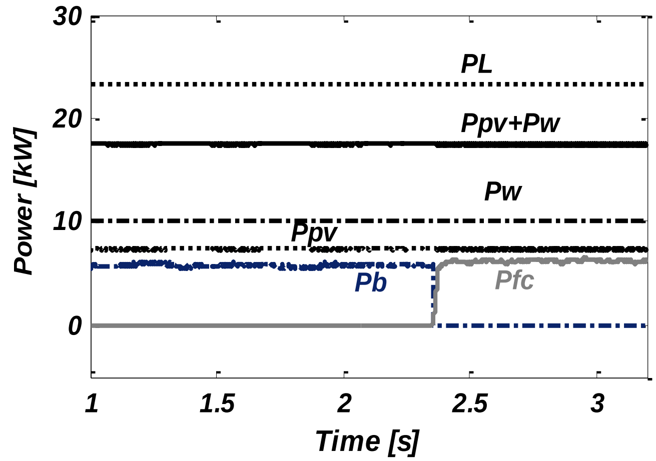

Fig. 8 . Power generation of the hybrid system (Case 2)

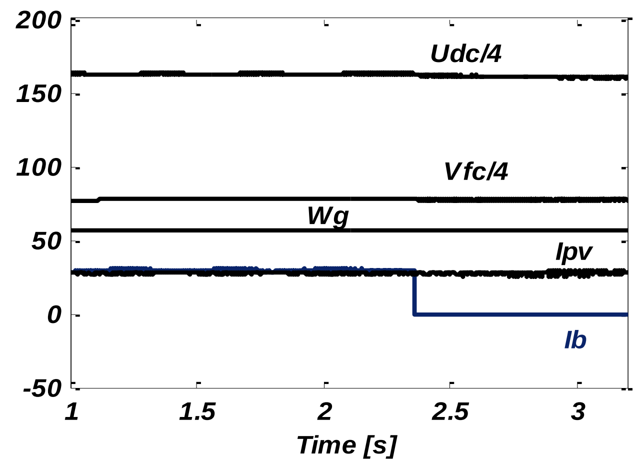

Fig. 9 . Performance of the hybrid system (Case 2)

A. Fuel Cell and battery controller

In this case, the irradiance (G) and temperature (T) is stable respectively at 1kW/m^2 and 25°C, the wind speed (V_w) is fixed at 14m/s. the power load demand (PL) is fixed at 23.2kW The initialization of state of charge of battery storage SOC of the battery is carried out near about 0.2 and is becomes less that 0.2 at t = 2.35 s. At t=(1-2.35) s, the load demand is more than the wind power production, therefore the required energy is supplied by the battery as shown in Fig.9 and the current I_b is positive. At moment of SOC less that 0.2 at t = 2.35 s, the battery is floating with zero output current. Furthermore the FC source is energizing to regulate the DC link voltage as the battery is at low SOC. Moreover, it is seen that the battery and FC are maintaining the power balance between the power production and load demand. The corresponding response of dc bus voltage is shown in Fig.9 from which it is

B. *Meteorological changes, with constant load*

Consider the step changes in irradiance from 1 kW/m^2 to 0.5 kW/m^{2}at t=1.5 s in wind speed from 14m/s to 10 m/s at t = 1.5 s. consider the power load demand (P_L) is fixed from 14kW. For the first period (t<1.5 s), the sun power of PV and Wind is around 17.5Kw (P_{pv}+P_w<P_L), while the battery is charging with a negative current as shown in Fig.10. Stepping to second period (t>1.5s), the load demand is more than the PV and Wind power production, therefore the required discharging the battery with a negative current as shown in Fig.11. The figure also shows that the DC bus voltage U_{dc} is regulated to 650V. The MPPT InCond and the indirect FOC controller make the output power of Wind and PV at a maximum value.

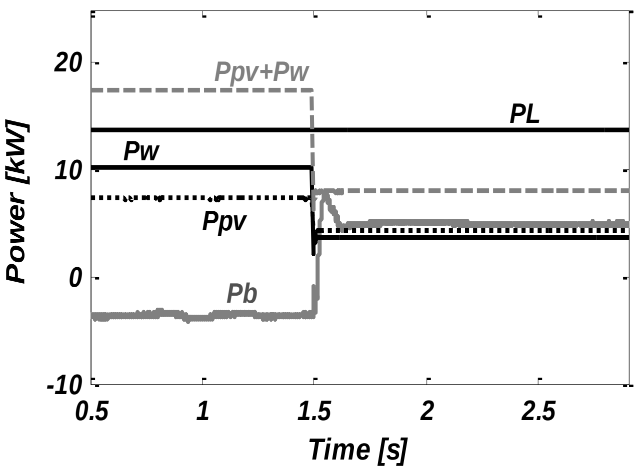

Fig. 10 . Power generation of the hybrid system (Case 3)

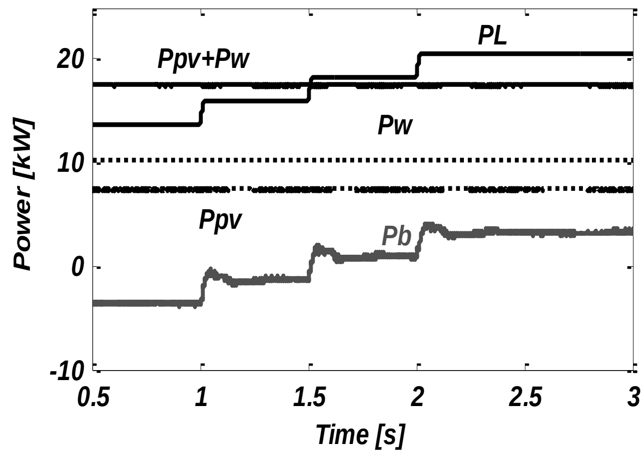

Fig. 12 . Power generation of the hybrid system (Case 4)

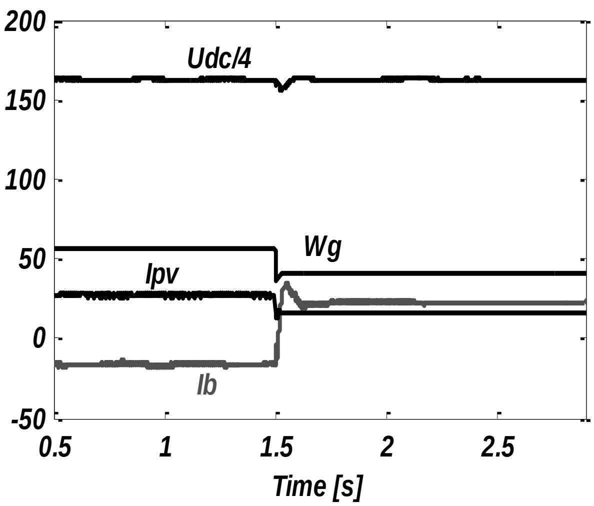

Fig. 11 . Performance of the hybrid system (Case 3)

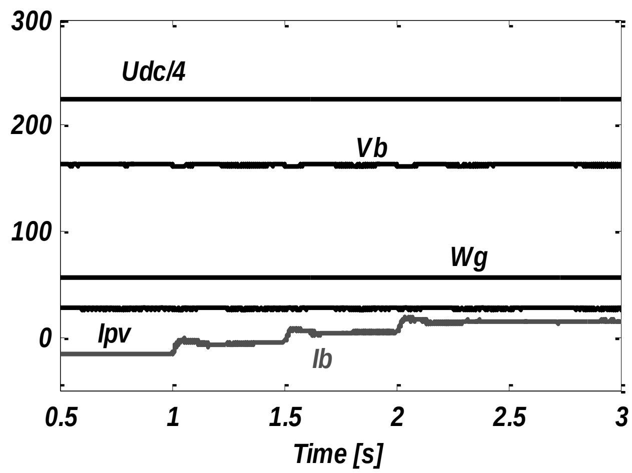

Fig. 13. Performance of the hybrid system (Case 4)

C. *Meteorological constants, and varying load*

Now consider the step change in required load power but the G, T and V_w is fixed respectively 1kW/m^2, 25°C and 14m/s. Then the load is suddenly increased the battery will act instantly and supply the required load demand as shown in Fig.12. The battery becomes negative (t<1.5s) and positive (t>1.5s) according to discharge or charge state. It is clear from in Fig.11. The figure also shows that DC bus voltage which is maintained at constant value at 650V. The voltage V_b battery change according of power. Since when P_b becomes positive the V_b start to decrease and vice versa. Applying InCond MPPT and FOC controls keeps I_{pv} and W_g at a reference value respectively 27.5A and 56.7 rad/s.

D. *Meteorological and load changes*

The proposed system is tested for the variations in solar irradiance, wind speed and in required load power demand. The performance of the system in this case is similar to cases 2 and 3. The load demand is more than the sum power production by wind and PV solar, therefore the required energy is supplied by the battery as shown in Fig. 14. In this situation the battery with a positive current the keep the DC bus voltage constant. The RMS voltage of AC load is plotted as shown in Fig.15. Where it is keep up 230V as reference value. The phase voltage V_{La} and I_{La} of AC load are Fig.16. So it could be clear that the waveforms are sinusoidal and unity power factor operation. The measured voltage THD current and voltage is less than 1% it can be established that with the help of SV-PWM switching and a passive LCL filter.

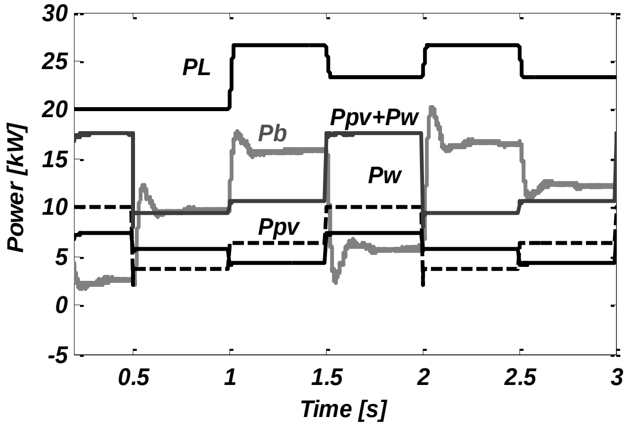

Fig. 14 . Power generation of the hybrid system (Case 5)

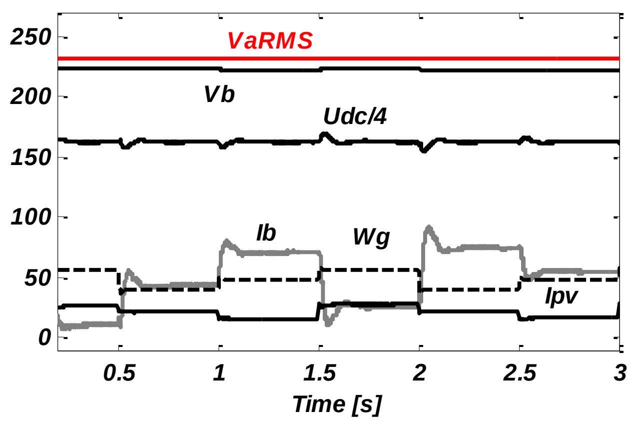

Fig. 15 . Performance of the hybrid system (Case 5)

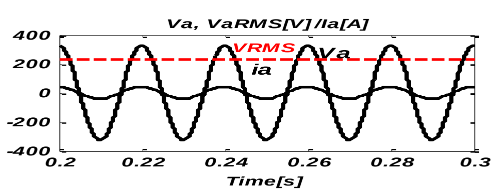

Fig. 16 . Output phase load: current I_a, voltage V_a and RMS value response

IV. Conclusion

Control strategies to regulate the amplitude and frequency of a standalone hybrid system consisting of variable speed wind turbine with PMSG, solar, battery and dump load are presented in this paper. The SV-PWM technique is then employed to achieve constant switching frequency and to ensure the sinusoidal current injected in to the resistive load. The total harmonic distortion (THD) in voltages and currents is a less 1%, which illustrates the good quality of voltage generated at AC resistive load. From both simulation results, we verified in all operating conditions the following: the wind and PV is operated at maximum power, the dc bus voltage U_{dc} and the output of inverter maintained at reference value, the battery and FC are maintaining the power balance between the power production and load demand The simulation results show that the performance of the proposed is satisfactory under the steady-state power as well as transient solar, wind speed and load power conditions.

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