Control of Grid Connected Three-Phase Inverter for Hybrid Renewable Systems using Sliding Mode Controller

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Abstract—**This paper presents a power control approach of a grid connected 3-phase inverter for hybrid renewable energy systems that consists of wind generator, flywheel energy storage system and diesel generator. A sliding controller is developed around the grid connected inverter to control the injected currents which leads to control the active and reactive powers requested by grid and/or isolated loads. In series with the controller, a Space Vector Pulse width Modulation method is used to drive the six inverter switches to generate 3-phase voltages and currents for transferring the desired powers requested by the alternative side. Simulations under Matlab-Simulink software of the hybrid renewable energy systems are made to show performances given by the developed sliding mode controller.**

Keywords—*Grid connected systems; sliding controller; hybrid renewable systems; SVPWM*

I. INTRODUCTION

The international renewable energy program is a strategic initiative for the world that aims to substantially increase the share of renewable energy in the total energy mix. In 2017, worldwide, renewable power capacity had a 31% share of total power capacity, edging out coal [1]. In terms of total power output, renewable energy is predicted to make 28% of global electricity output by 2021[1]. This strategy is followed after the reduction of fossil fuel sources such as oil and gas. There are many renewable sources of energy such us wind energy, solar energy, and biomass. They appear clearly to complete the used energy. Their production fluctuates and it is not predictable [2,3,4]. These problems affect directly the quality of the active and reactive power transferred to the grid which are very fluctuating and which pose unbalances consumption-production. This limits their rate of penetration into the grid [5,6].

These problems of the grid connection and the quality of the energy transmitted can be solved by the good control of the active and reactive powers transferred from the renewable sources. This control is possible by the action on the inverter which is the principle element of connection between renewable sources and the grid. There are many researches who worked on the control of active and reactive powers generated by renewable wind, solar and hybrid energy systems and they have used various methods [7,8].

In this paper we present the active and reactive powers control for a 3-phase grid connected inverter of hybrid renewable energy system (HRES) that consist of wind system, flywheel energy storage system and diesel generator. A sliding mode controller is developed from the mathematic line model to control the injected currents which leads to control the active and reactive powers requested by grid and/or isolated loads. This method has been used in many works with wind and solar renewable energy systems generally to extract the maximum power (MPPT)[9], to control the grid connected photovoltaic system [10] and to control the electrical machines in wind energy systems[2,3,11]. In series with the sliding controller a Space Vector Pulse Width Modulation (SVPWM) method is used to drive the six inverter switches which generate consequently the necessary 3-phases voltages and currents for transferring the powers requested by the grid. This method is developed in this paper because it is easy to implement on the calculator and it can eliminate the low order harmonics generated by the inverter. The experiment results of the SVPWM show the high reliability of this method. Simulations under Matlab-Simulink software are made to show the results given by the developed sliding mode controller. These results show the advantages of this controller that offers a compromise between good speed of system response and reliability, especially since the system is very fluctuating in very short time depending on the wind speed.

This paper is organized as follows. Section II describes the HRES configuration. Section III presents the control approach within the sliding controller. Section IV presents the simulation results and discussions.

II. SYSTEM COMPONENTS AND DESCRIPTION

The simplest structure of the hybrid renewable energy system that studied is shown on figure 1. It consists of power electronic converters which increase the system efficiency and simplify the control methods. This configuration based on permanent magnetic synchronous machine (PMSM) offers a good efficiency for low power [2,3,4]. The AC/DC converters are used to connect hybrid system with the DC-link. It is a bi-directional converter, to allow the energy transfer between the DC-link and the flywheel in the two directions. The DC-link and the AC grid are connected by capacitor and 3 phase

inverter. An RL filter can be also added to smooth the current. Salient parameters of the system are presented in table 1.
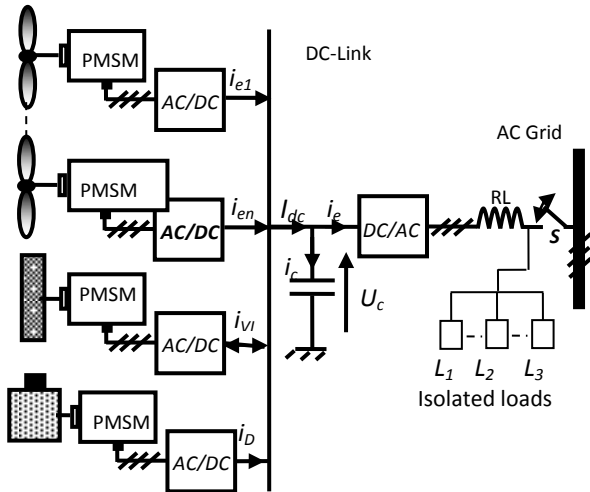

Fig. 1. The Grid Connected Hybrid System Configuration.

III. CONTROL STRATEGY

In our previous works [2,3] we have developed local methods to control subsystems of the overall HRES and a global supervisor able to generate the reference powers requested by the grid. The aim of this paper is to control, by sliding controller, the 3-phase inverter which connects the DC-link bus to the grid.

The control of active and reactive powers transferred to the grid is carried out by the control of grid injected currents. The control vector $U = \begin{bmatrix} V_{od\_ref} & V_{oq\_ref} \end{bmatrix}^T$ that represents the output reference voltages of the inverter in Park-dq axis is calculated by sliding mode method for current control. The reference values of currents are calculated by using the active and reactive powers reference values P_{req_ref} and Q_{req_ref} that requested by grid and/or isolated loads. These reference powers are calculated by using the powers generated by hybrid renewable energy system and by considering the power in the capacitor for regulation of DC link voltage U_c and losses in the electronic converters.

The PWM signals are determined by using SVM method to drive the six inverter IGBT`s of inverter. They generate the real inverter output voltages from their reference values calculated by the sliding mode controller and transfer the necessary active and reactive powers to the alternative side. Figure 2 shows the control strategy of a three-phase-inverter for HRES.

A. DC- Link Voltage Control

The main aim of the voltage control loop is to regulate the DC-link voltage at a specified value and to provide the reference current. The DC-link voltage is set to 515V while the grid line voltage (V_{rms}) is set to 220V. The closed loop control of the DC-bus voltage is needed because the output power of the renewable sources is variable with climatic conditions. The inverter input reference current $i_{e\text{-}ref}$ is described by the following relation:

$$i_{e-ref} = i_{dc} - PI(U_{c-ref} - U_c) \tag{1}$$

For the control of the DC-link voltage, a proportional integral corrector (PI) has been used. It is parameterized according to the capacitor and the dynamic of the regulation loop. By neglecting losses in the inverter switcher, the power balancing yields:

$$P_{req} \approx i_e . U_c \tag{2}$$

The reference active power injected into the grid is given by:

$$P_{req\_ref} \approx i_{e-ref} . U_c \tag{3}$$

B. Sliding Mode Control of 3-Phase Inverter

The sliding controller requires the knowing of the sliding surface, the condition of convergence and the control law. The general form of the sliding surface is given in[12]:

$$S(x) = (\frac{\partial}{\partial t} + \lambda_x)^{r-1} e(x) \tag{4}$$

With:

$e(x) = x_{ref} - x$, is the error of the variable to be regulated

λ_x is a positive constant which interprets the band-width of the desired control.

r: is a number of times that it is necessary to derive the output variables to reveal the command.

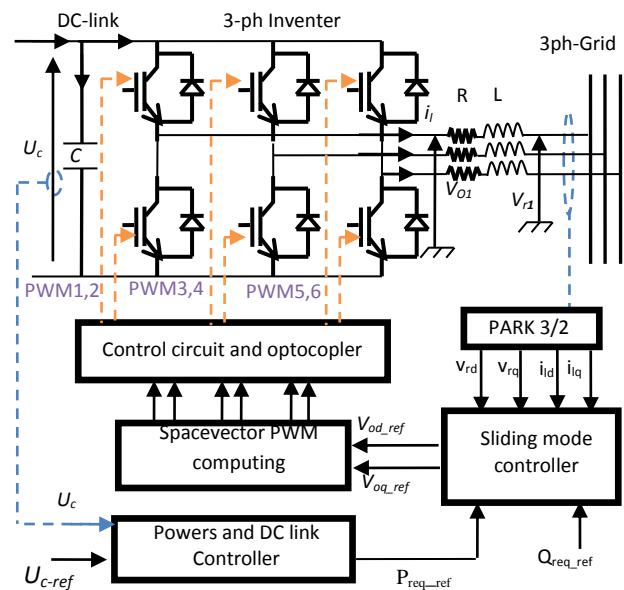S(X)=0: A linear differential equation whose single solution is $e(x) = 0$.

Fig. 2. Control Strategy Diagram.

The general form of the sliding controller is $U = U_{eq} + U_{nl}$. U_{eq} and U_{nl} are respectively the equivalent controller that is the solution of the equation $\dot{S}(X) = 0$ and the nonlinear part

that can be interpreted as the overage value of the controller which permits to maintain the state of the system on the sliding surface [13,14]. The nonlinear command (U_{nl}) is given to guarantee the attractively of the variable to be controlled towards the sliding surface and to satisfy the condition of convergence. The simplest function is in the form of relay. It is given by $U_{nl} = K.sign\ (S(X))$ with K is a positive constant [13,14].

C. Application to the inverter

The control vector is carried out by the model of the RL-line filter. This model is given, in Park dq- axis, by:

$$\begin{cases} V_{Od} = Ri_{ld} + L\dfrac{di_{ld}}{i_{ld}} - L\omega_s i_{lq} + V_{rd} \\ V_{Oq} = Ri_{lq} + L\dfrac{di_{lq}}{i_{lq}} + L\omega_s i_{ld} + V_{rq} \end{cases} \tag{5}$$

With V_{od} and V_{oq} are the inverter output voltages in dq-axis ; V_{rd} and V_{rq} are the grid voltages in dq-axis ; R and L are respectively the resistance and the inductance of the filter; ω_s is the frequency of injected currents. The control vector $U = \begin{bmatrix} V_{od\_ref} & V_{oq\_ref} \end{bmatrix}^T$ is given by the direct inversing of Eq. 5. It's expressed as follows:

$$\begin{cases} V_{od\_ref} = V_{ld\_ref} - L\omega_s i_{lq} + V_{rd} \\ V_{oq\_ref} = V_{lq\_ref} + L\ \omega_s i_{ld} + V_{rq} \end{cases} \tag{6}$$

The output is the currents vector $I_l = \begin{bmatrix} i_{ld} & i_{lq} \end{bmatrix}^T$. S_1 and S_2 constitute respectively the sliding surfaces of the exit variables i_{ld} and i_{lq}. They represent the errors of the direct and quadratic currents. They are expressed as follows:

$$\begin{cases} S_1 = I_{ld\_ref} - i_{ld} \\ S_2 = I_{lq\_ref} - i_{lq} \end{cases} \tag{7}$$

By using the equations of system (6), the first derivation of Eq. 7 gives:

$$\begin{cases} \dot{S}_1 = \dot{I}_{ld\_ref} + \dfrac{1}{L}\left[Ri_{ld} - L\omega_s i_{lq} + V_{rd} \right] - \dfrac{1}{L} V_{od} \\ \dot{S}2 = \dot{I}_{lq\_ref} + \dfrac{1}{L}\left[Ri_{lq} + L\omega_s i_{ld} + V_{rq} \right] - \dfrac{1}{L} V_{oq} \end{cases} \tag{8}$$

The relative degree of the system is equal to 1 because the command appears in the first derivation of the variables to be controlled. Equation 8 can be replaced by:

$$\begin{cases} \dot{S}_1 = B_1 + A_1 V_{ld} \\ \dot{S}_2 = B_2 + A_2 V_{lq} \end{cases} \tag{9}$$

With :

$$\begin{cases} B_1 = \dot{I}_{ld\_ref} + \dfrac{1}{L}\left[Ri_{ld} - L\omega_s i_{lq} + V_{rd} \right] \\ A_1 = -\dfrac{1}{L} \\ B_2 = \dot{I}_{lq\_ref} + \dfrac{1}{L}\left[Ri_{lq} + L\omega_s i_{ld} + V_{rq} \right] \\ A_2 = -\dfrac{1}{L} \end{cases} \tag{10}$$

The solution of equation $\dot{S} = 0$ leads to the equivalent controller (U_{eq}). Its expression is given by:

$$\begin{cases} V_{ld\_eq} = -\dfrac{B_1}{A_1} \\ V_{lq\_eq} = -\dfrac{B_2}{A_2} \end{cases} \tag{11}$$

The nonlinear part of the sliding controller is given by:

$$\begin{cases} V_{ld\_nl} = K_d signS_1 \\ V_{lq\_nl} = K_q signS_2 \end{cases} \tag{12}$$

With:

$K_d = K_q = K = |V_{max}|$.

The global command $U = \begin{bmatrix} V_{od\_ref} & V_{oq\_ref} \end{bmatrix}^T$ is the sum of the equivalent and the nonlinear parts given by equations 11 and 12. It's expressed as follows:

$$\begin{cases} V_{od\_ref} = L\ \dot{I}_{ld\_ref} + R\ i_{ld} - Lw_s i_{lq} + V_{rd} + K_d signS_1 \\ V_{oq\_ref} = L\dot{I}_{lq\_ref} + Ri_{lq} + Lw_s i_{ld} + V_{rq} + K_q signS_2 \end{cases} \tag{13}$$

The reference currents, given in 13, are expressed as functions of the active and reactive reference powers requested by the grid and / or isolated loads. They are given by:

$$\begin{cases} I_{ld\_ref} = \dfrac{P_{req\_ref}.V_{rd} + Q_{req\_ref}.V_{rq}}{V_{rd}^2 + V_{rq}^2} \\ I_{lq\_ref} = \dfrac{P_{req\_ref}.V_{rq} - Q_{req\_ref}.V_{rd}}{V_{rd}^2 + V_{rq}^2} \end{cases} \tag{14}$$

D. Three-Phase Inverter SVPWM

The SVPWM (Fig.3) is a technique used to drive the inverter switches to generate equilibrate three-phase voltages with desired amplitude and frequency; V_{oa}, V_{ob} and V_{oc}, from the reference voltages V_{oa_ref}, V_{ob_ref} and V_{oc_ref}. These voltages are calculated by the Park transformation (dq-abc) of the inverter voltages V_{od_ref}, V_{oq_ref} provided by the sliding controller bloc [15,16].

As indicated by figure 4, the algorithm of SVPWM is based on the knowledge of the reference vector $\overrightarrow{V_{ref}}$ which rotates in six sectors in the switching hexagon. Its coordinates are the components $V_{\alpha ref}$ and $V_{\beta ref}$, and the change values for each angle θ_s which allowing the calculation of the switching times.
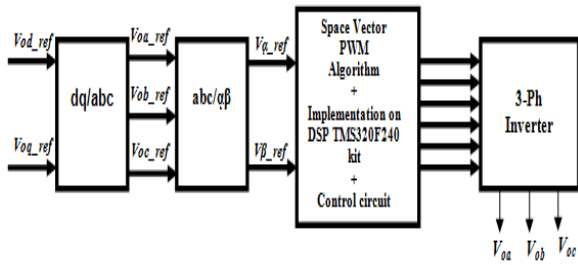
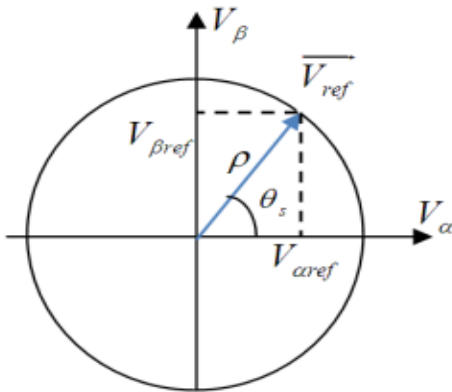Fig. 3.   SVPWM Signals Generation.

Fig. 4.   Reference Vector Variation in αβ-axis.

- Amplitude Variation of Output Voltages

The components $V_{\alpha ref}$ and $V_{\beta ref}$ are expressed as follows:

$$\begin{cases} V_{\alpha ref} = \rho \cos\theta_s \\ V_{\beta ref} = \rho \sin\theta_s \end{cases} \tag{15}$$

The maximum radius of the circle within the switching polygon is $\rho_{max} = \sqrt{\frac{3}{2}} V_{max} = \frac{1}{\sqrt{2}} U_c$.

The 3-phase inverter controlled by SVPWM can generate three phase- voltages with maximum value equal to $\frac{U_c}{\sqrt{3}}$. Therefore, by selecting the variable ρ, we can set the amplitude of the inverter output signals.

- Frequency Variation of Output Voltages

The discretization of the reference vector requires a good choice of the number of samples per revolution, and therefore the sampling period on which to build it. The maximum number of samples per period is limited by the speed of calculation of the DSP TMS320F240.In general, for a number faster than 72 (5 ° for a sample) the reference vector is continuously variable over time. To fix the period of the reference vector and the period of the inverter output voltages, it is necessary to fix the modulation period given by [17]:

$$T_m = 2.T_e . \frac{n}{F_h} \tag{16}$$

With

- Te is the period corresponds to the count number of the (T1CNT) of DSP (TMS320F240). It is used to compare the corresponding values to the inverter switching times.

- F_h is the clock frequency of the DSP fixed at 20 MHz.

- n is the clock frequency of the DSP divider.

- The period of the inverter output variables is given by:

$$T = kT_m = 2kT_e \frac{n}{F_h} \tag{17}$$

The frequency of the inverter three-phase output voltages is 50Hz (T=0.02s). To set this frequency value the following parameters are selected:

- k = 360.

- T_e= 138.

- n = 4.

Figure5 shows the IGBT driving signals PWM$_i$ for i={1, 2…6}.

IV. SIMULATION STUDY

Simulations by Matlab-Simulink software were performed to test and verify the 3-phase inverter control presented and developed in the previous section and to study the output inverter voltages, the injected currents, and the active and reactive powers transferred from the hybrid renewable energy system to the grid.
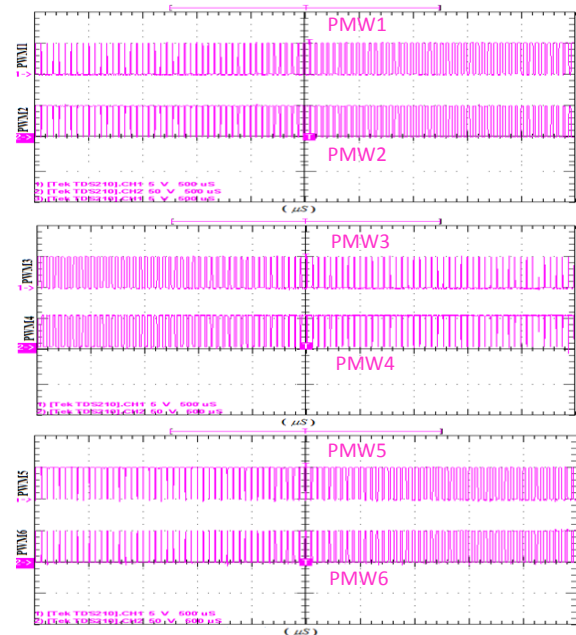

Fig. 5.   Driving Signals.

These simulations have been obtained under various values of power requested by grid and/or loads. They are selected to demonstrate the most significant performances of the control approach. The reference and measure are respectively represented by dotted and continuous line. The interaction between the renewable energy sources is not

discussed in this paper. Only the inverter control is considered in this paper.

value	symbols	Parameters
0.01H	L	Inductance of the filter
0.92µF	C	Capacitance of the DC-link
0.05Ω	R	Resistance of the filter
314rd/s	w_s	Pulsation of the grid voltage
311V	$K_d = K_q$	Constant of the sliding control
515V	U_{cref}	DC-link voltage reference

A variable wind signal, shown on figure 6, is applied to the turbines. It varied between 7 and 11m/s regarding the maximal power point tracking zone.

Fig. 6.   Wind Speed Variation.

As indicated by figure 7, the reference active power requested by the grid and/or loads (P_{req_ref}) is considered variable within the time while the reference reactive power should be zero in order to obtain the line current in phase with the grid voltage. On figure 7a, it is shown that the active power generated by the hybrid system satisfies the requested power however the reactive power transferred to the grid oscillates around its reference fixed at zero (Fig. 7b). According to those figures, the inverter output reactive power remains equal to zero while the active power varied with the demand of the load in the alternative side.
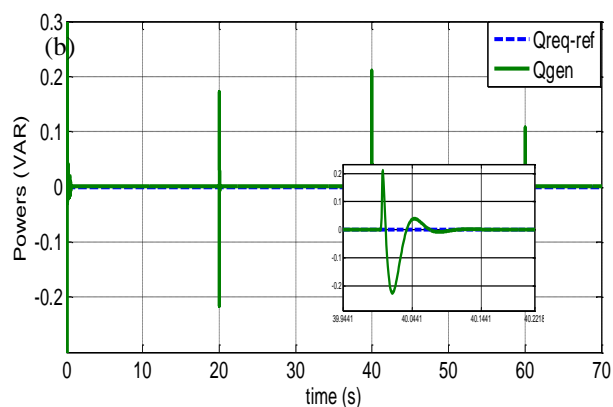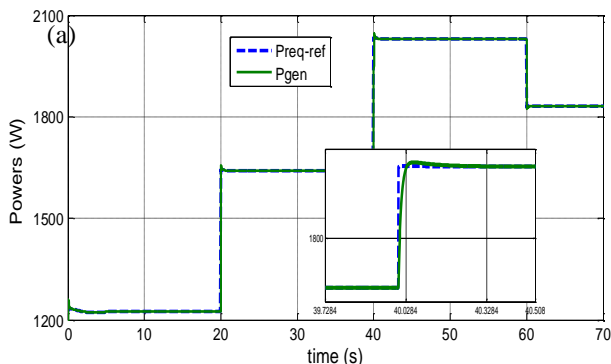

Fig. 7.   Inverter output powers (measure and reference): (a): active powers, (b): reactive powers.

Figure 8a presents the DC-current provided by the renewable energy system to satisfy the power requested by the load. The current varied proportionally with the power values injected into the alternative side while the DC-link voltage is constant and follows its reference (U_{c_ref}) fixed at 515V. The DC-link voltage presents some instantaneously overshoots in each change of requested power load (Fig. 8b).
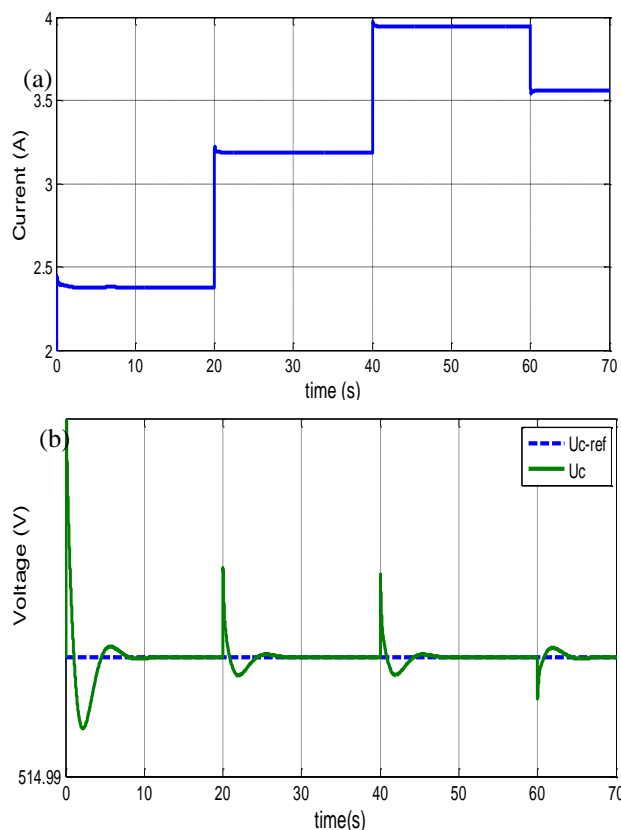

Fig. 8.   Input characteristics of the inverter; (a): DC-current provided by the renewable energy system, (b): DC-link voltage (measure and reference).
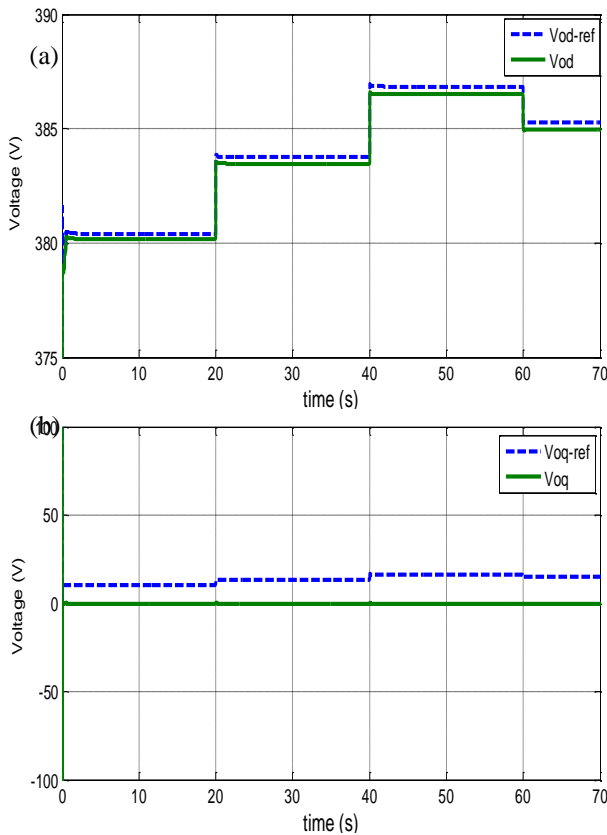
Fig. 9. Inverter output voltage (measures and references); (a): direct components; (b): quadratic components.

Fig. 10. Iinverter output current (measures and references); (a): direct components; (b): quadratic components.

Finally, the control unit composed by the sliding controller, the DC-link voltage regulator and the SVPWM block, achieves the control of the 3-phase grid connected inverter of hybrid renewable energy system. It permits to regulate instantaneously, the DC-link voltage, the inverter output powers (active and reactive powers) and the currents injected into the grid. The previously figures show the reliability and the short time response of the global system with the developed controller, even with the wind system that is very fluctuating and the diesel generator which has a very slow dynamics since it is a mechanical system.

V. Conclusion

In this paper, a control strategy based sliding mode controller, has been proposed. The command approach ensures the control of the 3-phase inverter output currents which leads the control of the active and reactive powers transferred into the grid and/or the isolated loads. In series with the sliding controller a SVPWM was developed to drive the six inverter switches to generate 3-phase voltages necessary to transfer the desired powers. This command approach (sliding controller with SVPWM) has given very acceptable results in terms of response time and accuracy of the controlled variables, especially since this system is very variable and has disturbances according to the wind speed.

Figure 9 illustrates the dq-components of the inverter output voltage under variable load powers. As it can be seen by this figure, the sliding mode controller presents good performances in terms of stability and response time. The inverter output voltages reach instantaneously their reference values provided by the controller within the changes of the requested load power. The direct and the quadratic components of the inverter output current i_{ldq} are represented respectively by figures 10a and 10b. As it can be seen by those figures, the inverter output currents reach instantaneously their reference values provided by the sliding controller.
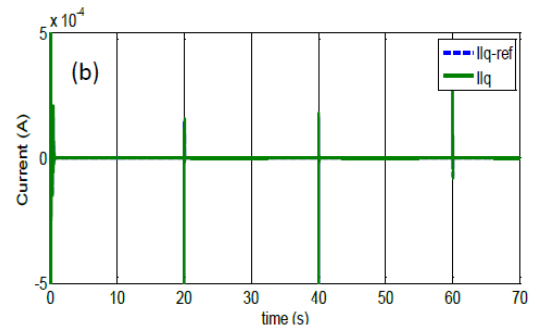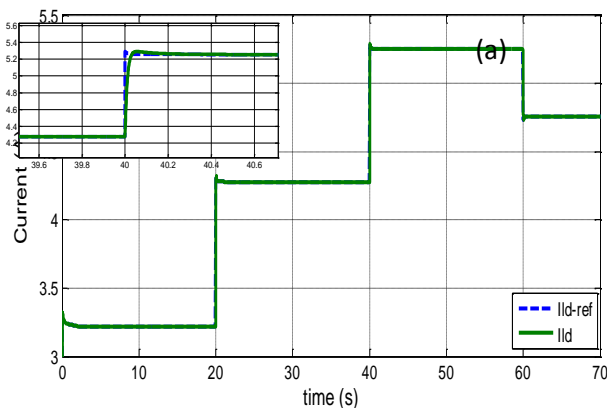
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