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PHOTOVOLTAIC MODULE-INTEGRATED CONVERTER (MIC) BASED ON SEMI-Z-SOURCE INVERTERS (SZSI): A NEW SLIDING MODE CONTROL SCHEME

CONVERTIDORES FOTOVOLTAICOS EN MÓDULOS INTEGRADOS BASADOS EN INVERSORES DE FUENTE-SEMI-CUASI –Z: UN NUEVO ESQUEMA DE CONTROL POR MODOS DESLIZANTES

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Abstract: A control scheme for power conditioning in a photovoltaic (PV) system based on semi-quasi-z-source inverters (SqZSI) is proposed. The adopted inverter topology allows the independent control of each leg current, enabling the tracking of the maximum power point (MPP). The scheme is an implementation of a hysteretic current mode controller that controls quasi-z-source single-phase inverter. The good agreement between the analytical study and simulation results confirms the validity of the proposed control system.

Keywords: Module integrated converter (MIC), semi-quasi-Z-source inverter (SqZSI), sliding-mode control.

Resumen: Se propone un esquema de acondicionamiento de potencia para un sistema de generación fotovoltaica (FV) basado en un inversor de fuente-semi-cuasi -Z. La topología de control seleccionada facilita el control independiente de corriente por rama, a la vez que permite seguir el punto de máxima potencia. El esquema se basa en un control por histéresis en modo de corriente que actúa sobre el inversor de fuente-semi-cuasi –Z. Los buenos resultados obtenidos entre el estudio analítico y las simulaciones, confirman la valides del sistema de control propuesto.

Palabras clave: Módulos de convertidores integrados, inversor de fuente-semi-cuasi –Z, publicación, control en modo deslizante.

1. INTRODUCTION

The use of distributed generation systems (DGSs) has facilitated the development of module-integrated converter (MIC), which allow to optimize the extracted power from a grid connected photovoltaic generation system (PV). Additionally, the MICs have an excellent relationship between cost, reliability, flexibility and easy installation.

However, compared with the string inverters, MICs have lower efficiencies “The available commercial MICs have reached 96.3% peak efficiency” (Zhou *et al.*, 2013). In most existing MIC topologies, its low efficiency is due to the switching loss of the semiconductor devices and transformer loss. The research and development of MICs have resulted in inverters ranging from 100 to 300 W.

In recent year, MICs based on Z-source inverters have been applied in PV systems (Araque *et al.*, 2013; Cao *et al.*, 2011). The Z-source inverters, show in Fig. 1, which by employing five active switches (MOSFETs with their anti-parallel diodes) four of these converters can realize bidirectional and bipolar operation. This family owns both buck and boost characteristics depending on control of the duty cycle. With one polar input voltage source this converter can produce negative and positive voltage only by controlling duty cycle, which makes the inverter simpler and more economical than other inverters.

This paper presents a MIC based on semi-quasi-Z-source inverter proposed in (Cao *et al.*, 2011), as shown in Fig. 2. The reason of using sqZSI is to reduce the number of the semiconductor devices and thereby improve the inverter efficiency. However, compared with the H inverter, two control loops are necessary for the sqZS inverter. The control scheme proposed uses two sliding-mode control loops, which will be explained in detail in Section III. A control loop to track the grid voltage is used and another to extract the maximum power from the PV panels. The applied maximum power point tracker (MPPT) algorithm uses a type of current control by sliding-mode control, which in turn allowing the sqZSI inverter to extract maximum power from the PV array (Cabal *et al.*, 2013).

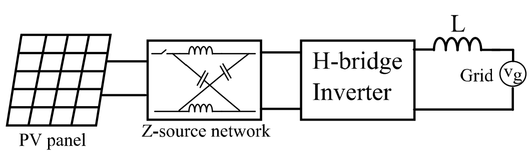


Fig. 1. Single-phase grid connected PV MIC based on ZSI.

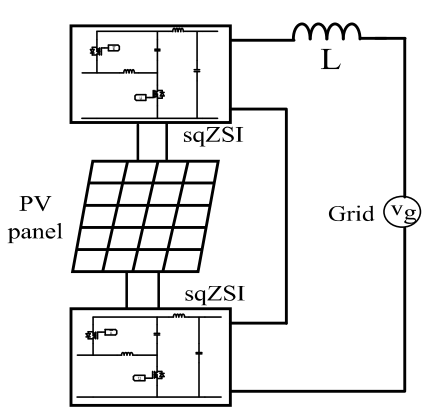


Fig. 2. Single-phase grid connected PV MIC based on sqZSI.

2. ANALYSIS OF SqZSI CONVERTER

The circuit diagram of a converter is show in Fig. 3. A semi-quasi-z-source is a DC-DC converter, whose output voltage can be controlled for synthesis of sinusoidal waveforms.

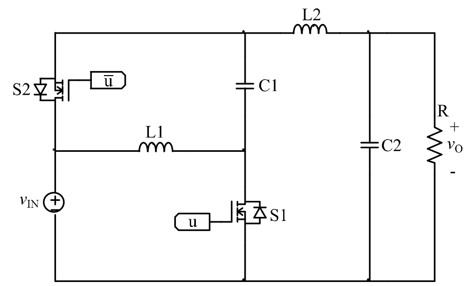


Fig. 3. Single-phase Semi-quasi-Z-source inverter.

2.1 State I (S1 is *ON*)

When the switch S1 is *ON* (S2 is *OFF*), the inductor L1 absorbs energy from the source and the energy stored in capacitor C1 is transferred to inductor L2. The stored energy in capacitor C2 is delivered to load R. The inductor currents i_{L1} and i_{L2} increase linearly during this mode and the input current i_{IN} is the sum of i_{L1} and i_{L2}. The dynamic equations during a State I operation are given by:

$$\begin{cases} \frac{di_{L1}}{dt} = \frac{v_{IN}}{L1} & \frac{di_{L2}}{dt} = \frac{v_{C1}}{L2} - \frac{v_{C2}}{L2} \\ \frac{dv_{C1}}{dt} = \frac{i_{L2}}{C1} & \frac{dv_{C2}}{dt} = \frac{i_{L2}}{C2} + \frac{i_{O}}{C2} \end{cases} \quad (1)$$

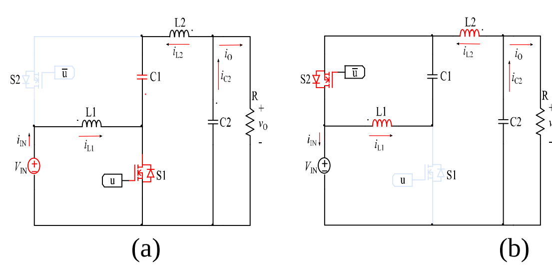


Fig. 4. Semi-quasi-Z-source inverter operation mode. (a) State I S1is ON. (b) State II S2 is ON.

2.2 State II (S2 is *ON*).

When switch S2 is turned *ON*. The inductor L1 transfers the energy to capacitor C1. At the same time, i_{L2} flows through C2–R. This energy supplies the load current and replenishes the charge drained away from the output capacitor C2 when it alone was supplying the load current during the *ON* time. Both currents iL1 and iL2 decrease during this mode of operation. The dynamic equations during this mode:

$$\begin{cases} \dfrac{di_{L1}}{dt} = \dfrac{v_{C1}}{L1} & \dfrac{di_{L2}}{dt} = \dfrac{v_{IN}}{L2} - \dfrac{v_{C2}}{L2} \\ \dfrac{dv_{C1}}{dt} = \dfrac{i_{L2}}{C1} & \dfrac{dv_{C2}}{dt} = \dfrac{i_{L2}}{C2} + \dfrac{i_{O}}{C2} \end{cases} \quad (2)$$

3. PROPOSED CONTROL SCHEME FOR MIC BASED ON Sqzsi INVERTER

In this section, we aim at designing a controller that will be able to ensure: (i) a perfect MPPT (whatever the power of the PV panel), (ii) synthesis of the grid voltage (Álvarez y Arango, 2013). A control scheme proposed for Single-phase grid connected PV MIC based on sqZSI is shown in Fig. 5. The structure is composed of two semi-quasi-Z-source inverter (sqZSI). Each sqZSI consists of two power switches with anti-parallel diodes and the same DC-bus (PV panel). Moreover, each sqZSI inverter has its own control loop.

3.1 MPPT based on sliding mode control for SqZSI converter

Due to its potential to significantly reduce the error signal and high performance in DC/DC converters for photovoltaic systems, the hysteretic current mode controllers has received an increasing attention recently (Alaa *et al.*, 2009; Fadil *et al.*, 2012; Farjah *et al.*, 2012; Kavitha & Uma, 2012).

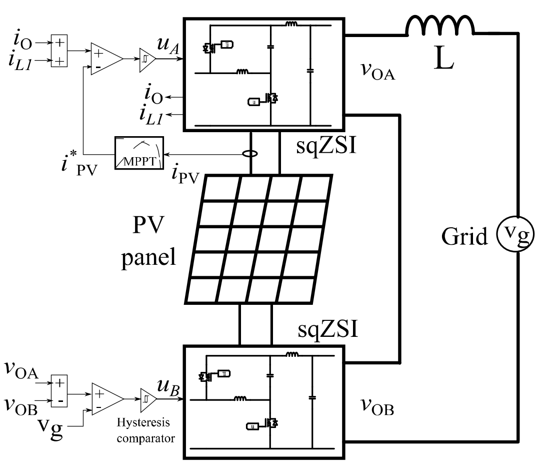


Fig. 5. Control scheme proposed for Single-phase grid connected PV MIC based on sqZSI.

In the continuous condition mode the SqZSI converter can be represented by the following set of differential equations:

$$\begin{cases} \dfrac{di_{L1}}{dt} = \dfrac{v_{C1}}{L1}(1-u) + \dfrac{v_{IN}}{L1}u \\ \dfrac{dv_{C1}}{dt} = -\dfrac{i_{L1}}{C1}(1-u) + \dfrac{i_{L2}}{C1}u \\ \dfrac{di_{L2}}{dt} = \dfrac{v_{C1}}{L2}u - \dfrac{v_{C2}}{L2}u + \dfrac{v_{IN}}{L2}(1-u) \\ \dfrac{dv_{C2}}{dt} = \dfrac{i_{L2}}{C2} + \dfrac{i_{O}}{C2} \end{cases} \quad (3)$$

Where u=1 during T_{ON} (i.e. S_1 *ON* and S_1 *OFF*)

Recall that the control objective is to enforce the current i_{PV} to track the optimal point $i^*_{PV} = I^*_{PV} + A\sin wt$.

To this end, current sliding-mode control design principles are invoked (Biel *et al.*, 2004; Cao *et al.*, 2011; Carpita & Marchesoni, 1996; Gupta & Ghosh, 2006; Lopez *et al.*, 2013).

Let us introduce the following tracking error: $x_e = i_{L1} - i_{L2} - i^*_{PV}$

The switching function selected is:

$$\begin{cases} S(x_e) = i_{L1} - i_{L2} - i^*_{PV} \\ \dot{S}(x_e) = \dot{i}_{L1} - \dot{i}_{L2} - \dot{i}^*_{PV} \end{cases} \quad (4)$$

The control law is:

$$\begin{cases} u(t) = 1 \quad \text{if} \quad i_{L1} < i^*_{PV} \quad \text{or equivalently} \quad u(t) = 1 \quad \text{if} \quad S(x_e)<0 \\ u(t) = 1 \quad \text{if} \quad i_{L1} > i^*_{PV} \quad \text{or equivalently} \quad u(t) = 0 \quad \text{if} \quad S(x_e)>0 \end{cases}$$

Achieving the tracking objective amounts to enforcing the error x_e to vanish. To this end, the invariance condition $S(x_e)=0$ and $\dot{S}(x_e)=0$ is imposed. It follows from (3) and (4) that, the expression of the equivalent control is:

$$u_{eq} = \frac{L2v_{C1} - L1v_{IN} + L1L2Aw\cos wt}{(L1\text{-}L2)v_{C1} + L1v_{C2} + (L2\text{-}L1)v_{IN}} \quad (5)$$

Assuming L1=L2=L, lead to the following expression of u_{eq}

$$u_{eq} = \frac{v_{C1} - v_{IN} + LAw\cos wt}{v_{C2}} \quad (6)$$

From (6) we conclude that a sliding regime will exist since $v_{C2} \neq 0$. The constraints imposed on the lower and upper bounds of the equivalent control $0 < u_{eq} < 1$ result in the condition:

$$\frac{LAw}{v_{C2}} < \min\left(1+\frac{v_{IN}-v_{C1}}{v_{C2}}, \frac{v_{IN}-v_{C1}}{v_{C2}}\right) \qquad (7)$$

3.2 Slide-mode control for synthesis of grid voltage, Vg

As in the preceding section, the control sliding-mode control strategy is designed. The selected sliding surface is:

$$\begin{cases} S(x_e) = v_g - v_{C2A} - v_{C2B} \\ \dot{S}(x_e) = \dot{v}_g - \dot{v}_{C2A} - \dot{v}_{C2B} \end{cases} \qquad (8)$$

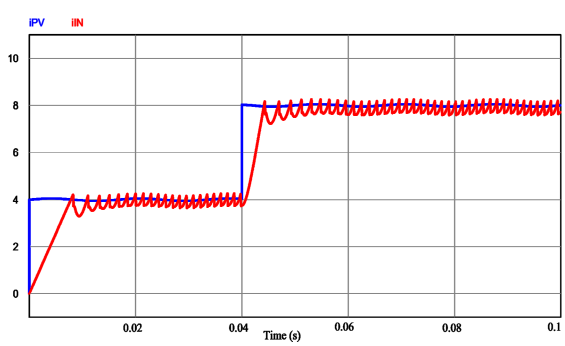
4. SIMULATION RESULTS

The proposed control scheme has been implemented in PSIM software for a PV grid connected system with parameters given in Table I.

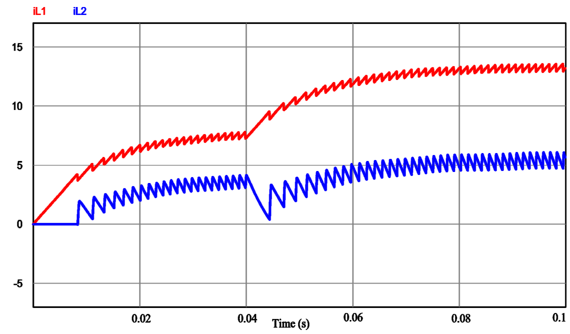
Table I: simulation parameters

Parameter	Value
C1	1 µF
C2	200 µF
L1=L2	47 mH
PV Panel	KC200GT

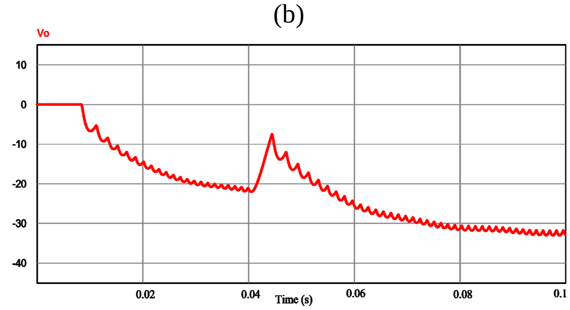
Fig. 6 depicts the transient behavior of the system input current and output voltage for positive sudden change of PV characteristics, which is carried out by the increase the input current reference.



(a)



(b)



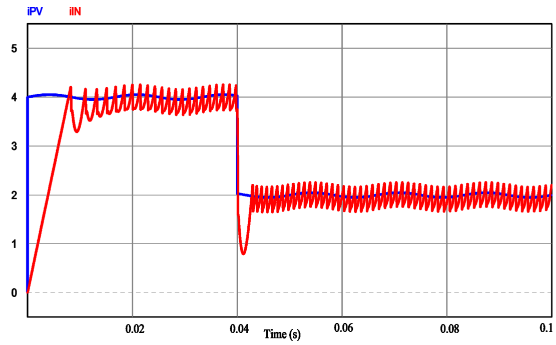
(c)

Fig. 6. Input currents, inductor current and output voltage waveforms for step load variations. (a) Input currents for positive variation of PV power, (b) inductor current for positive variation of PV power, (c) output voltage for positive variation of PV power.

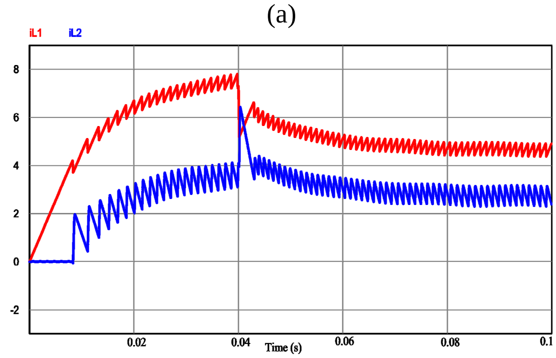
Note that there is a very small state-state error between current iPV and iIN (i^*_{PV} and i_{PV} respectively), showing the efficacy of the tracking by means of the sliding-mode control. As predicted by the theory, the sliding surface is a high-frequency signal of very small amplitude oscillating around zero.

A similar interpretation can be derived from Fig. 7 when the system undergoes a negative sudden change of PV power, which is conducted by a change of the radiation conditions. It can be observed that the new steady state is reached after 0.08 ms approximately, and that the current and power are in phase opposition during the transient-state.

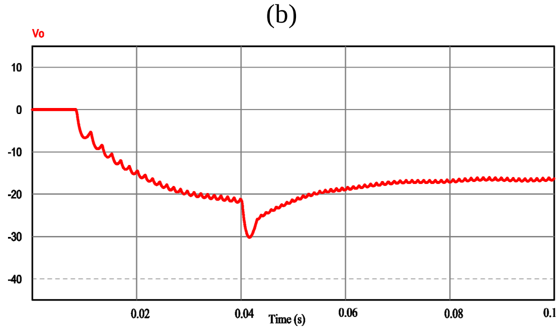
Hence, the search starts at the right of the MPP yielding a decrement of the inductor current reference and thus verifying the theoretical prediction of the MPPT algorithm.



(a)



(b)



(c)

Fig. 7. Input currents, inductor current and output voltage waveforms for step load variations. (a) Input currents for negative variation of PV power, (b) inductor current for negative variation of PV power, (c) output voltage for negative variation of PV power.

Fig. 8 depicts the Behaviour of u_{eq} for sqZSI inverter proposed. The voltages v_{C2A} and v_{C2B} of the system to be controlled is easily measured and compared with the grid voltage. The latter is only affected by the input quantity $|v_g|$ and provides the required trajectories that the controlled system will have to follow, independently of parameter variations or disturbances related to the load current.

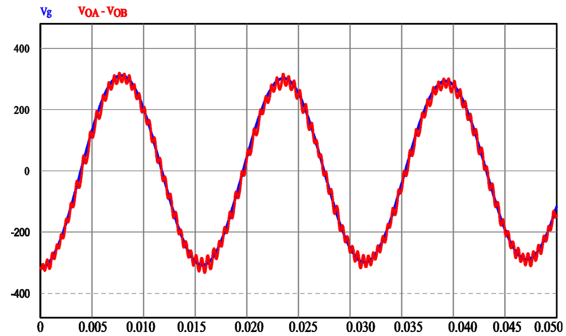


Fig. 8. Behaviour of u_{eq} for sqZSI inverter proposed.

5. CONCLUSIONS

A new sliding mode control design of SqZSI inverter was developed in this paper. A control scheme that improves the performances of the inverter PV system was proposed. The influence of the control parameters on the performances of the system was studied. An optimization algorithm was developed in order to calculate the optimal values of parameters based on a predefined specification. The importance of the application of this type of controllers for the high efficiency PV inverter is highlighted.

Results show excellent dynamic response of controller and robustness to load and input voltage with large variations around nominal values. Further research may focus to the study of the observation of load current, and on the stability of the controller-observer closed loop.

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