Improved Responses of Grid Connected Quadratic Boost Inverter Based on Super-Twisting Sliding Mode Control

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Abstract—This paper proposes a new method for improving the performance of grid-connected single-stage Quadratic Boost Inverters (QBIs). Compared to the other single-stage boosting inverters, such as ZSI, qZSI, and the basic SSI, QBI has several advantages. It combines the features of a quadratic dc-dc boost converter and Split-Source Inverter (SSI) to give a high voltage gain. As a result, it offers superior benefits in reducing the overall system's complexity, size, and cost. The grid-connected QBI is traditionally controlled via two control loops. The first loop regulates the dc-link voltage using a PI controller, while the second controls the current injected into a grid using the decoupled control approach. In this paper, a sliding mode controller (SMC) is proposed for the grid-side controller to achieve accurate and quick responses instead of using the decoupled approach that is based on PI controllers. The basic principles and detailed analysis of the proposed method are introduced. Moreover, comprehensive simulation results based on the actual parameters of a prototype have verified the overall control system and the advantages of the proposed SMC compared to the PI controller.

Keywords—Grid-connected systems, Single-stage, quadratic boost inverter (QBI), sliding mode control (SMC).

I. INTRODUCTION

Both research and industry have put much focus on renewable energy sources (RESs) in the last two decades in order not only to overcome the problems associated with conventional sources but also to meet the energy demands. As a result, many types of RESs exist, including photovoltaic (PV), wind energy conversion systems (WECSs), biomass, fuel cells (FCs), etc. Among these types, their penetration is continuously increasing [1], [2]. Nevertheless, the generated power from the PV panels is primarily affected by the weather conditions. Furthermore, power converters play an important role in renewable energy and different applications such as electric vehicles, energy backup architectures, etc.

Regarding the RESs, the power electronics are used to ensure minimum energy consumption under weather conditions and supply this energy to the grid or an isolated load. For PV and FC, the dc-ac boost converters are essential, especially when low voltage modules of 20–40 V are connected with a higher ac voltage grid of 200–400 V [3], [4].

Therefore, a two-stage converter, shown in Fig. 1(a), which is composed of a dc-dc boost converter and a dc-ac voltage source inverter, has been presented [5], [6]. The first stage boosts the dc-input voltage to a high value and extracts the maximum power from the PV module. Meanwhile, the second stage converts the dc voltage to the required ac value by controlling the injected active and reactive powers to the grid and hence obtaining a unity power factor (UPF) operation. In addition, its control can meet the requirements of low current harmonic distortion and other power quality issues [7]. However, these two-stage topologies solve the problem of low input dc voltage but add to the complexity and cost of the system. Furthermore, to adjust the entire converter voltage gain, there are additional active switches with their control. These switches limit the overall system efficiency [8],[9]. Due to the problem mentioned above with the two-stage dc-ac converters, power electronics researchers presented new topologies of dc-ac converters known as single-stage [9]–[11].

Z-source inverter (ZSI) is considered one of these single-stage converters. It consists of an impedance network followed by the conventional VSI [10]. This impedance network comprises two capacitors, two inductors, and a single diode. Even though the ZSI solves the demerits of the two-stage converters, it draws a discontinuous input current and has a pulsed dc-link voltage. It also operates in the narrow range of modulation regions from 0.5 to one. This leads to higher output voltage harmonics, especially at low modulation. Moreover, the ZSI has an inverse relationship between the output voltage and the modulation index. Thus, quasi-ZSI (qZSI) topology, shown in Fig. 1(b), is developed to overcome the problem of discontinuity in the input current and is hence used for PV, EV, and FC applications [12], [13]. However, the qZSI cope with the discontinuity of the input current, but the remaining problems of the conventional ZSI have still existed.

Consequently, the split source inverter (SSI), shown in Fig. 1(c), has been proposed to defeat the ZSIs problems where it has [14]–[17]

- continuous input current and dc-link voltage waveforms,
- a lower number of passive components,
- lower voltage stresses on the switches, and
- similar switching states of the standard VSI, unlike ZSI.

In comparison to the two-stage topology, the SSI has the following features:

- higher THD of the output voltage at low voltage gain,
- higher voltage stresses across the switches, and
- lower switches of the SSI have higher current stresses.
In general, the parasitic elements of the passive components affect the boosting factor; hence, the output voltage gain in practice does not reach infinity. As a result, extensive research focuses from the researchers to increase the voltage gain of the SSI [18]–[20]. One of these developments is the split-Y-source inverter [18], [19]. But its problems are more passive elements and complex in implementation. For further improvements, the authors proposed a new topology called by Quadratic-Boost Inverter (QBI), shown in Fig. 2(a), which combines the features of ZSI, quadratic dc–dc boost converter, and SSI in a single circuit [21]. The main features of these topologies are

- retain the basic structure of split-source inverter,
- use the conventional modulation schemes of SSI,
- obtain higher boosting and voltage gains, and
- achieve both boost and buck operations. However, it corresponds to the following demerits: Due to the previous features, the QBI can be used in different applications such as PV systems, FC systems, EVs, isolated loads, grid-connected systems, etc.

The controller plays an important role in any application where the overall system efficiency can be increased based on the selected type of control. For the grid-connected system, many control strategies are presented to control the inverter and guarantee some objectives such as achieving the unity power factor, regulating the dc-link voltage, extracting the maximum power, reducing the total harmonic distortion, regulating the boosting voltage, and so on. Therefore, the controller's selection and design procedure are essential to simultaneously achieve some of these objectives. The control approaches can be divided into linear and nonlinear control based on the literature. Linear control methods, such as proportional-integral (PI) and proportional resonance (PR) controllers, are proposed to control the active and reactive power [22]. Meanwhile, a cascaded PI controller indirectly regulates the dc-link voltage to control the input currents. Due to the dependence on the system parameters, the controller performance is sensitive to parameter disturbances. Further, the grid-converter is multiple variables. Hence strong coupling nonlinear system is existed [23]. Therefore, nonlinear control methods are proposed to overcome the problem of nonlinearities and improve the performance of the system. Without ignoring the nonlinearities and parasitic effects of the system, these nonlinear control strategies can achieve better performance (i.e., static, and dynamic). There are different nonlinear control methods, such as backstepping, feedback linearization, fuzzy control, sliding mode, and so on [24]–[30]. Among these different control techniques, sliding mode control (SMC) is considered one of the most robust strategies for controlling the uncertain nonlinear systems where it can offer many advantages such as high reliability, a low sensitivity against a parameter variation, fast dynamic response, and its easy design and implementation [31]–[33]. There are many types of SMC such as conventional SMC, terminal sliding mode control, continuous terminal SMC, etc. [23],[29],[31],[34]. Super twisting sliding mode controller (STSMC) overcomes most of the problems that exist in other types [35].

Therefore, this work focuses on applying the QBI to the grid-connected system. A closed-loop control system should be employed to achieve the grid requirements. The dc-link voltage is regulated via decoupled voltage-oriented control (VOC). Most of the used controllers are based on the proportional-integral (PI) controller, but the problem is the inadequate response. Therefore, super twisting sliding mode controllers (STSMC) are used in the inner control loop instead of the PI controller to achieve a faster and good dynamic response. Moreover, a modified space vector modulation (MSVM) scheme is used, and the input current is regulated to control the power required to supply.

II. DESCRIPTION OF THE PROPOSED SYSTEM

The proposed grid-connected system is based on the QBI topology, which consists of an impedance cell and the standard SSI semiconductor bridge, as shown in Fig. 2(a). The impedance cell is composed of two inductors, \( L_1 \), \( L_2 \), two capacitors, \( C_1 \), \( C_2 \) and two diodes, \( D_1 \), \( D_2 \). This combination gives a cascaded boost. The analyzed QBI has a continuous input current due to the presence of the input inductance \( L_1 \) in series with the supply. As a result, the supply is less stressed. Additionally, the QBI topology utilizes a common dc-circuit between the inverter bridge and the supply rail. This minimizes the effects of common-mode noise.

There are many PWM schemes of the QBI. Although, the modified space vector modulation (MSPWM) introduced in [21] ensures no low-order current ripples of the supply current. It uses a flat bottom modulating signal like that shown in Fig. 2(b), but it is lifted to the upper limit of the carrier waveform. It has only one manipulating parameter (which is the modulation index, \( M_{ac} \)) to control both the dc and ac sides of QBI. To decouple the control of the ac and dc side from each other, two independent manipulating variables must exist so that one of them is used in the control. The regulated MSVM which is firstly proposed by [37] for the basic SSI and developed in [21] for the QBI, is more suitable for the grid-connected applications. In this modulation scheme, the minimum envelopes of the per phase duty cycles \( (d_a, d_b, d_c) \) are kept constant to \( (1 - M_{dc}) \) as shown in Fig. 2(b). Therefore, the dc side can be controlled with \( M_{dc} \) while the ac side can be controlled with \( M_{ac} \), where the dc modulation index should be less than one, (i.e., \( M_{dc} < 1 \)). Thus, the boosting factor, \( B \) of the QBI, which depends only on \( M_{dc} \) can be expressed by

\[
B = \frac{1}{(1 - D)^2} = \frac{1}{(1 - M_{dc})^2},
\]

and the peak output phase voltage \( \hat{v}_{\phi_1} \) can be obtained by

\[
\hat{v}_{\phi_1} = BE \frac{M_{ac}}{\sqrt{3}}.
\]
It should be noticed that $M_{dc}$ should be higher than $M_{ac}$ otherwise, high harmonic distortion will appear on the ac side due to overmodulation.

III. CONTROL SCHEME FOR THE PROPOSED SYSTEM

In the following subsection, the detailed control schemes of the grid-connected QBI, shown in Fig. 2, are presented. Based on the decoupled voltage-oriented control (VOC), the dc-link voltage is controlled through output current controllers. Meanwhile, the input power required for the supply is controlled and superimposed as an outer control loop on the input current controller with the duty cycle of the boost converter. Thus, a modified modulation technique is required on the duty cycle and modulation index are independently controlled. More details about every control part are as follows.

A. DC-link voltage controller

The dc-link voltage is kept constant by controlling the d-axis output current. This is illustrated based on the input-output power balance and considering the system is lossless, as given by

$$
\frac{3}{2} (v_{dg}i_d + v_{aq}i_q) = -v_{dc}C \frac{dv_{dc}}{dt} - i_L \frac{di_L}{dt} + e.i_L 
$$

(3)

Based on the principle of the VOC, $v_{aq} = 0$ and $v_{dg} = \hat{V}_{d1}$

$$
\frac{3}{2} v_{dg} i_d = -v_{dc}C \frac{dv_{dc}}{dt} - i_L \frac{di_L}{dt} + e.i_L 
$$

(4)

After linearization around the equilibrium point and neglecting the higher-order terms results, (2) is as follows

$$
\frac{3}{2} \hat{v}_{dg} i_d = -v_{dc}C \frac{dv_{dc}}{dt} - i_L \frac{di_L}{dt} + e.i_L 
$$

(5)

$$
\frac{3}{2} \hat{v}_{dq} i_q = -v_{dc}C \frac{dv_{dc}}{dt} + V_{dc}i_L - i_L \frac{di_L}{dt} + I_L \hat{e} 
$$

(6)

where $v_{diff}$, $\hat{v}_d$, $\hat{v}_q$, $\hat{e}$, and $\hat{i}_L$ are the perturbation in the dc-link voltage, d-axis current, input voltage, and input current, respectively. Meanwhile, the corresponding steady-state values are $V_{inv}, i_d$, $E$, and $I_L$. As the source is a constant voltage source and the input current is controlled by controlling $M_{dc}$, their perturbations can be neglected, and hence (29) is rewritten by

$$
\frac{3}{2} \hat{v}_{dg} i_d = -v_{dc}C \frac{dv_{dc}}{dt} 
$$

(7)

It can be noticed that the dc-link voltage is affected by the value of the d-axis current; hence a PI controller can be used to adjust this value.

B. Output current controllers

The dq-axis output voltages from the inverter can be expressed by

$$
\begin{align*}
\hat{v}_d &= v_{dg} + i_d R_L + L_i i_d - w_q L_f i_q \\
\hat{v}_q &= v_{hq} + i_q R_L + L_q i_q + w_L L_f i_d 
\end{align*}
$$

(8)

(9)

where $w_q$ is the grid angular frequency, and $R_f, L_f$ are the filter resistance and inductance between QBI and grid.

From these relations, it is illustrated that the d- and q-axis currents are controlled by controlling the inverter d- and q-axis voltages $\hat{v}_d$ and $\hat{v}_q$. As mentioned before, the reference value of the d-axis current is obtained from the dc-link voltage control loop. Meanwhile, the q-axis reference current is set to zero to achieve a unity power factor. To remove the coupling between the d- and q-axis voltage compensation is used.

C. Phase-locked loop (PLL)

The main target of the PLL is to extract the grid voltage vector angle for proper alignment of the d-axis with the voltage vector in the VOC [36]. Based on the VOC where $v_q = 0$, the operation of PLL aligns the d-axis with the voltage vector and hence the q-axis voltage is expressed by

$$
\hat{v}_q = \hat{V}_{q1} \sin (\omega t_\alpha - \omega t) 
$$

(10)

where $\omega t_\alpha$ is the voltage vector angle with respect to $\alpha$-axis, and $\omega t$ is the angle of the d-axis concerns the $\alpha$-axis.
D. Input current controller

The input current relation can be obtained during charging and discharging by

\[ \frac{di_{d}}{dt} = ED_{ch} + (E - v_{c1})D_{dis} \]  

(11)

Based on the volt-second balance concept, the inductor \( L \) is charged with

\[ D_{ch} = M_{dc} \]  

(12)

Hence, by controlling \( M_{dc} \) the input dc current can be regulated by controlling the value of the modulation index.

IV. SLIDING MODE CONTROL FOR DC-LINK VOLTAGE CONTROLLER

The super twisting sliding mode control technique (STSMCT) is used to regulate the grid injection power by controlling the dq-axis output voltages from the inverter. The \( d \)-axis and \( q \)-axis of the output current are represented by the variables of STSMMC, as shown in (13), where \( i_{d} \) and \( i_{q} \) are the desired values of the output current. Meanwhile, the STSMCT output is \( v \).

\[ x = \begin{bmatrix} e_{d} \\ e_{q} \end{bmatrix} = \begin{bmatrix} i_{d} - i_{d} \\ i_{q} - i_{q} \end{bmatrix} \quad \text{and} \quad v = \begin{bmatrix} v_{q} \\ v_{d} \end{bmatrix} \]  

(13)

From these relations, it is illustrated that the \( d \)- and \( q \)-axis of inverter voltage is controlled by controlling the inverter \( d \)- and \( q \)-axis voltages \( v_{d} \) and \( v_{q} \).

The state-space of the STSMCT is denoted as a function of the \( d \)- and \( q \)-axis errors of output current, \( e_{d} \) and \( e_{q} \), respectively, as shown in (14):

\[ s = \begin{bmatrix} s_{d} \\ s_{q} \end{bmatrix} = \begin{bmatrix} e_{d} + w_{d} \int e_{d} \\ e_{q} \end{bmatrix} \]  

(14)

The \( q \)-axis voltage can be obtained by adopting the dynamic \( q \)-axis current error as the control input. So, the \( q \)-axis voltage based on the STSMCT technique can be defined by

\[ v_{q} = e_{q}\left| e_{q} \right|^{m}sgn(e_{q}) + z_{q} \]

\[ \dot{z}_{d} = -k_{d}sgn(e_{d}) \]

\[ \dot{z}_{q} = -k_{q}sgn(e_{q}) \]  

(15)

where \( e_{d}, k_{d}, k_{q}, \) and \( r \) are the selected positive gains. The STSMCT output variable has a nonlinear term that is modified by adjusting the performer, \( m \), which in this study is indicated to be 0.5 [35]. The dynamic current equation can be used as the control input to achieve the \( dq \)-axis output voltages. The STSMCT is represented as states in (16).

\[ \begin{bmatrix} v_{d} \\ v_{q} \end{bmatrix} = \begin{bmatrix} e_{d} \left| e_{d} \right|^{m}sgn(e_{d}) + k_{d} \int sgn(e_{d}) \\ e_{q} \left| e_{q} \right|^{m}sgn(e_{q}) + k_{q} \int sgn(e_{q}) \end{bmatrix} \]  

(17)

The STSMCT can make the variable states of the grid-connected quarter boost inverter system approach the sliding mode variable with a smoother operation, improving the dynamic characteristics of the grid-connected system. Figure 3 shows the schematic diagram of the \( dq \)-axis inverter output voltage control loops based on the STSMCT.

V. SIMULATION RESULTS

This section discusses the simulation results using the MATLAB/Simulink to illustrate the superiority of the proposed STSMCT technique. The simulation parameters are listed in Tables I and II. The performance of the grid-connected system using the proposed STSMCT was investigated and compared to that of the PI controller. In this investigation, the input current is dropped from 10A to 7.5A at 0.3 seconds, as illustrated in Fig. 4. Figures 5 and 6 show the dynamic response of the \( q \)-axis and \( d \)-axis currents, respectively. The \( q \)-axis current is kept constant at zero according to the control technique. As demonstrated in fig. 7, the control technique successfully regulates the DC-inverter voltage at the desired value. Compared to the PI controller, The suggested STSMCT outperforms the PI controller, as seen in Figs. 5-7. Figs. 8 and 9 demonstrate the three-phase current responses of the grid-connected system based on the PI controller and the proposed STSMCT, respectively. It can be observed that phase-A of the QBI input current using the proposed algorithm has a better response rather than that of the PI controller, as shown in Figure 10. The output phase voltage and input current of the QBI using the PI controller and the proposed STSMCT are shown in Figs. 11 and 12. The voltage and current angle is almost zero, indicating that the controlled system has a unity power factor.

The grid-connected system using the proposed STSMCT has a faster and smoother dynamic response. Furthermore, compared to the PI controller, the STSMCT is more effective in regulating DC-inverter voltage with a smaller steady-state error than the PI controller, as shown in Figs. 5-12.

<table>
<thead>
<tr>
<th>Table I: PI controller gains</th>
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<tr>
<td>( K_{p} )</td>
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<tr>
<td>DC-link voltage controller</td>
</tr>
<tr>
<td>SSI input current controller</td>
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<tr>
<td>PV voltage controller</td>
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<th>Table II: Parameters of the proposed system</th>
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<tr>
<td>Parameter</td>
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<tr>
<td>( L_{dc} = L_{f} )</td>
</tr>
<tr>
<td>( L )</td>
</tr>
<tr>
<td>( C_{r} )</td>
</tr>
<tr>
<td>( f_{1} )</td>
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<tr>
<td>( L_{c} )</td>
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</table>
In this paper, the utilization of QBI in a grid-connected system is proposed. This QBI has many advantages in reducing the overall system's complexity, size, and cost compared to other topologies. Moreover, the STSMC is proposed for controlling the active and reactive power supplied to the grid. The STSMC is used for the inner current loops, where it achieves better performance than the PI. Faster
dynamic responses and lower distortions in the output current are removed. The basic principles and detailed analysis of the proposed method are introduced. Finally, the system is simulated in MATLAB/Simulink to validate the control scheme.

REFERENCES


