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Sliding Mode Control of Single-Phase Grid-Connected Quasi-Z-Source Inverter

UMESH K. SHINDE[1], (Member, IEEE), SUMANT G. KADWANE[2], (Senior Member, IEEE), S. P. GAWANDE[2], (Member, IEEE), M. JAYA BHARATA REDDY[3], (Senior Member, IEEE), AND D. K. MOHANTA[4], (Senior Member, IEEE)
[1]Bhivarabai Sawant College of Engineering and Research, Pune, India
[2]Yeshwantrao Chavan College of Engineering, Nagpur, India
[3]National Institute of Technology, Trichy, India
[4]Birla Institute of Technology, Mesra, Ranchi, India

Corresponding author: Umesh K. Shinde (ukshinde@yahoo.com)

ABSTRACT Quasi-Z-source inverters (qZSIs) are nowadays increasingly used owing to advantages such as single-stage operation, lower component rating, and continuous input current and common dc rail. These benefits lead to investigate this converter for grid-connected applications. This paper presents a grid-connected qZSI with both ac and dc side control. Sliding mode control (SMC)-based controller for capacitor voltage regulation has been proposed to ensure a fast and dynamic response for wide variations in input voltage, output load, and reference controlled quantity. A detailed mathematical model of the system is presented. A stable and fast response of SMC has been demonstrated using simulation and is validated by experimental results.

INDEX TERMS Quasi-Z-source inverter, sliding mode control (SMC), grid connected system.

I. INTRODUCTION

Use of renewable energy sources has been increased over the last decade due to the deficit in fossil fuels. Among all renewable energy sources, Photovoltaic (PV) systems are getting more popularity, because they are clean, and help in direct conversion by nature. PV panels produce the DC voltage and currents, which depend on environmental conditions. For certain applications, there is a need to convert these DC quantities to AC using inverters. An additional DC-DC converter is required, to maintain the inverter input voltage within the required range. These two-stage conversion methods, require an additional active device and hence, increases the complexity, power loss, and cost of the entire system. Another approach is, connecting the inverter output to the step-up transformer for boosting the output voltage. But the size and the cost of the transformer are the major disadvantages of this approach.

An alternative solution for such applications is the use of the Z-source inverter (ZSI) [1]. The ZSI uses, the impedance network comprising of two inductors and two capacitors, which is connected to the input of the inverter. By using these passive components, ZSI is capable of bucking or boosting its output voltage with its single stage configuration. Many PWM control techniques for ZSI are also analyzed [2]–[4]. The application of ZSI in different areas like photovoltaic systems, drives, electric vehicles, etc. has been investigated by many researchers [5]–[7]. To reduce device stress and to optimize the component rating, different versions of ZSI have been studied recently [8], [9].

A more improved version of ZSI has also been investigated recently, called as the quasi-Z-source inverter (qZSI) [10]–[11]. The qZSI has many advantages, which make it more suitable for Distributed Generation (DG) applications. The qZSI draws continuous current from an input source, and it is also capable of handling a wide input voltage range. The continuous input current in qZSI is due to the presence of an input inductor, which reduces the input stress. In the case of ZSI, the voltage across both the capacitors is the same. Therefore, the voltage stresses on both the capacitors are the same. Whereas in the case of qZSI, voltage stresses on the capacitors are less, because both the capacitors have different voltages. The overall component ratings of qZSI are less as compared to the component ratings of ZSI [12]. And also, the performance of qZSI with the standalone configuration and the grid-connected configuration is excellent [13]. qZSI has a common DC rail between the source and the inverter, which decreases the complexity of the circuit. And therefore, Electromagnetic interference (EMI) problems are less.

The ZSI and qZSI use shoot-through states to boost the input voltage. During shoot-through states, the upper and lower devices of the inverter are ON. So, the primary control objective is to control capacitor voltage by varying the shoot-through duty time. Many different control topologies are proposed for the better dynamic response of capacitor voltage control [11]–[13].

SMC was initially, introduced for a variable structure system [14]. SMC is well known for robustness towards variations in input, variations in output, and parameter uncertainties. Because of the switching function, power converters are inherently variable structure systems. SMC is investigated in DC-DC converters to improve their dynamic response [15]. But because of the limitations of switching frequency of power converters, SMC cannot be applied ideally, [16], [17]. In [18], the authors have investigated SMC in ZSI. In [19], the authors have nicely, explored SMC in qZSI, with a control objective to control battery charging current. So far, none of the literature has addressed the investigation on SMC in qZSI for the purpose of capacitor voltage control. In this paper, SMC is employed for the control of capacitor voltage in qZSI. This paper presents the detailed analysis and demonstrates, the dynamics of the SMC based grid-connected single-phase qZSI.

This paper is organized as: Section II presents the mathematical model of qZSI. The proposed control methodology is described in Section III. Section IV explains the detailed procedure and analysis of SMC. Section V provides the simulation results of the proposed system. The experimental setup and hardware results are presented in section VI, followed by a summary, of the work presented in the last section VII.

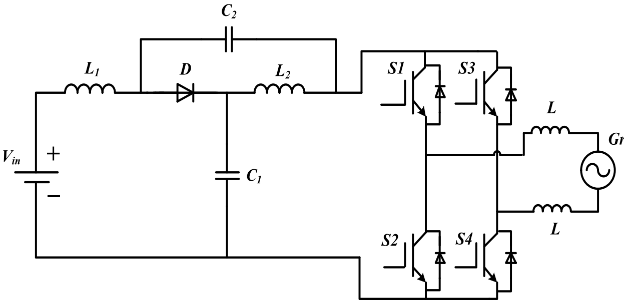


FIGURE 1. Single-phase grid connected qZSI.

II. MODELING OF QUASI-Z-SOURCE NETWORK

Fig. 1, shows the configuration of the existing single-phase grid connected qZSI. It consists of a quasi-Z-source (qZS) impedance network, connected to the grid connected inverter, which acts as a single stage conversion network. The qZS impedance network consists of two inductors L_1 and L_2, and two capacitors C_1 and C_2. The qZSI has two operational states in continuous conduction mode, shoot-through state, and non-shoot-through state.

Assuming that, the total switching cycle time is T, the shoot-through cycle time is T_o and the non-shoot-through cycle time is T_1. Therefore, the shoot-through duty ratio is expressed as $D=T_o/T$. Also, for the modeling, the system presumes a symmetrical qZS network, (which means identical values of inductors L_1 and L_2, and capacitors C_1 and C_2).

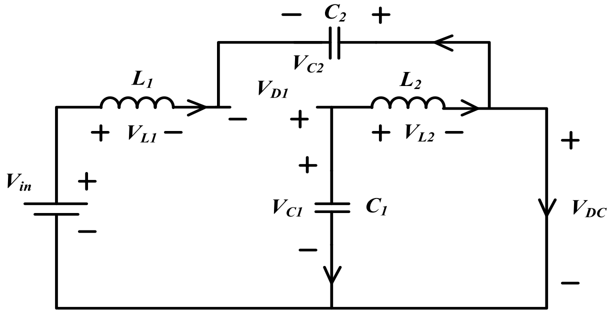


FIGURE 2. Equivalent circuit of qZSI in shoot-through state (u = 1).

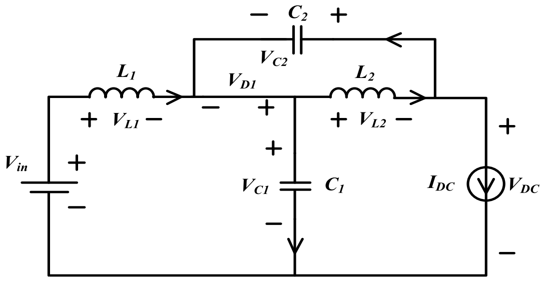


FIGURE 3. Equivalent circuit of qZSI in shoot-through state (u = 0).

During the shoot-through state, the DC link terminal of the inverter is short-circuited through the upper and lower switches of the inverter. Fig 2, shows the equivalent circuit of qZSI in the shoot-through state. The ON state of a single switch SH is represented as $u = 1$. From shoot-through equivalent circuit,

$$\begin{aligned} v_{L1} &= v_{C2} + v_{in} \\ v_{L2} &= v_{C1} \\ i_{C1} &= -i_{L2} \\ i_{C2} &= -i_{L1} \end{aligned} \tag{1}$$

During the non-shoot-through state (u = 0), and the inverter acts as a conventional voltage source inverter. Fig 3, shows the equivalent circuit of qZSI in a non-shoot-through state. The OFF state of single switch SH is represented as $u = 0$. From the non-shoot-through equivalent circuit,

$$\begin{aligned} v_{L1} &= -v_{C1} + v_{in} \\ v_{L2} &= -v_{C2} \\ i_{C1} &= i_{L1} - i_{DC} \\ i_{C2} &= i_{L2} - i_{DC} \end{aligned} \tag{2}$$

From (1) and (2),

$$\begin{aligned} v_{L1} &= (-v_{C1} + v_{in}) + (v_{C1} + v_{C2})u \\ v_{L2} &= (-v_{C2}) + (v_{C1} + v_{C2})u \\ i_{C1} &= (i_{L1} - i_{DC}) + (i_{DC} - i_{L1} - i_{L2})u \\ i_{C2} &= (i_{L2} - i_{DC}) + (i_{DC} - i_{L1} - i_{L2})u \end{aligned} \tag{3}$$

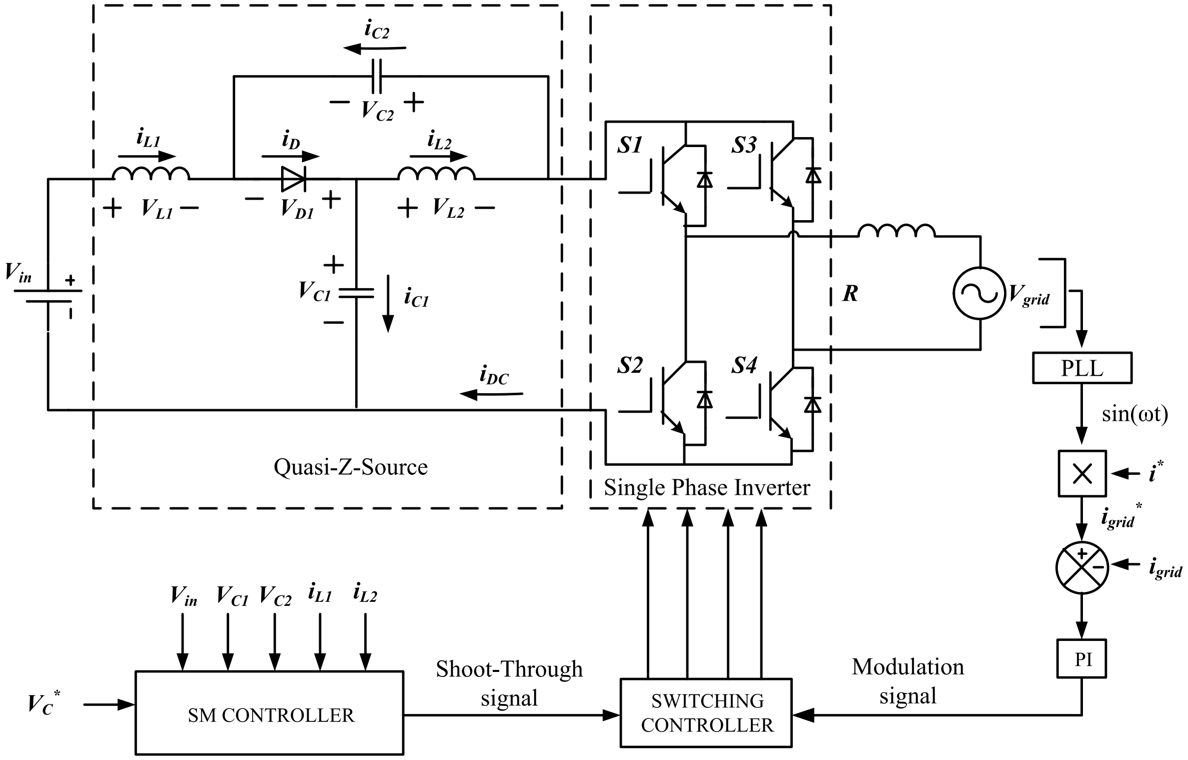


FIGURE 4. Proposed grid connected quasi-Z-Source Inverter with closed loop control.

Considering inductor currents i_{L1} and i_{L2}, and capacitor voltages v_{C1} and v_{C2} as state variables of the system,

$$X = [i_{L1}\ i_{L2}\ v_{C1}\ v_{C2}]^T \tag{4}$$

The state space averaged model of the qZSI is expressed as,

$$\dot{X} = A + Bu \tag{5}$$

where,

$$A = \begin{bmatrix} \frac{1}{L_1}(-v_{C1} + v_{in}) \\ \frac{-v_{C2}}{L_2} \\ \frac{1}{C_1}(i_{L1} - i_{DC}) \\ \frac{1}{C_2}(i_{L2} - i_{DC}) \end{bmatrix} \quad B = \begin{bmatrix} \frac{1}{L_1}(v_{C1} + v_{C2}) \\ \frac{1}{L_2}(v_{C1} + v_{C2}) \\ \frac{1}{C_1}(i_{DC} - i_{L1} - i_{L2}) \\ \frac{1}{C_2}(i_{DC} - i_{L1} - i_{L2}) \end{bmatrix}$$

III. CONTROL METHODOLOGY

For single stage control of qZSI two control loops are required. A first control loop, which is the DC side control loop, regulates the voltage across the capacitor in the qZS network through shoot-through duty ratio D. Second control loop, which is the AC side control loop, controls the AC side voltage or current through the modulation index M. The overall gain of the qZSI depends on the shoot-through duty ratio D and modulation index M. As indicated in Section I, many control strategies have been investigated for closed-loop control of the capacitor voltage.

The proposed closed loop control scheme of qZSI is shown in Fig. 4. The main aim of this paper is to investigate the closed-loop grid connected system with an improved dynamic response. As the system is grid-connected, dynamic response is imperative. Irrespective of the variations in input DC voltage, the output grid current should be well regulated so that it does not disturb the grid. For an improved dynamic response, SMC is adopted for DC side control. In the same way, the system should have a fast response to the local load change, and also, for the reference grid current change. For AC side, the current control method is implemented. PLL is used for synchronizing the inverter output with the grid.

IV. SLIDING MODE CONTROLLER

SMC is well known for stability and robustness towards system input, output variation, and parameters uncertainties. SMC cannot be applied ideally, due to the limited switching frequency of power converters. So, SMC is used for power converters that act as quasi-sliding mode controllers (qSMC). There are many literatures, which propose the application of SMC, to control the output voltage of DC-DC converters such as buck, boost, and cuk converters. This basically, concerns with the selection of sliding coefficients for the desired dynamic properties. In renewable applications, where the DC input voltage of the converter varies in different circumstances, or DC voltage, which is fed to the inverter varies due to the load, qSMC seems to be suitable. SMC is best suitable for such applications, because of robustness towards system input and output load variation. In this paper, SMC is employed to control and regulate the DC output voltage of the grid connected qZSI impedance network.

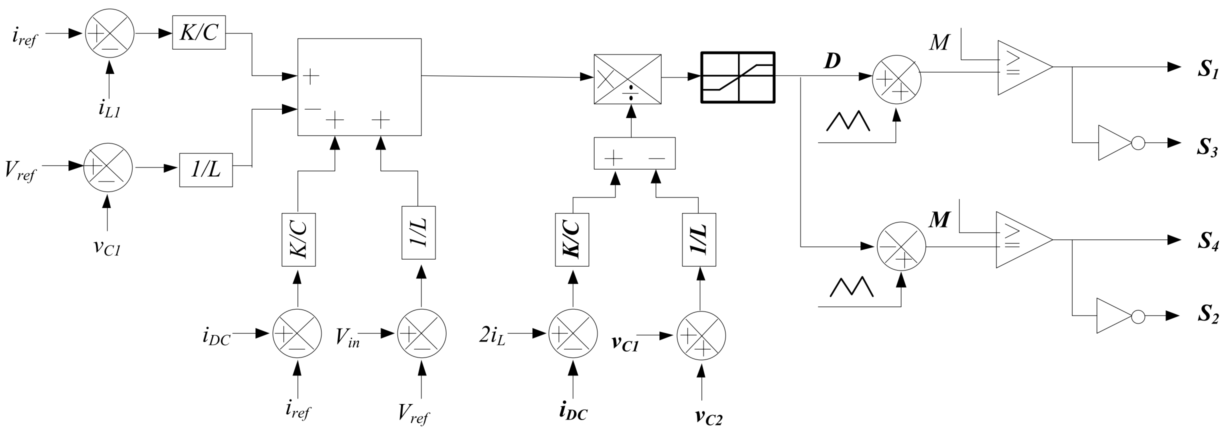


FIGURE 5. Control Logic for implementation of SMC.

The system must enter into SM operation, to achieve a dynamic and steady-state performance. For that, three necessary conditions, namely, the hitting condition, existence condition, and the stability condition, have to be abided. The hitting condition can be satisfied by, the appropriate choice of the switching function.

A. SLIDING SURFACE

Irrespective of the initial condition, the state trajectory should hit the sliding surface. The selection of the switching function is important to satisfy, the hitting condition. The logic states of power switches are represented by, the switching function,

$$u = \frac{1}{2}(1 + sign(S)) \tag{6}$$

where, S is the instantaneous state variable trajectory, and $S = 0$ is the sliding surface of the system.

The proposed SMC, uses the capacitor voltage error and the input inductor current error as controlled state variables, and are expressed as

$$\begin{aligned} x_1 &= v_{ref} - v_{C1} \\ x_2 &= i_{ref} - i_{L1} \end{aligned} \tag{7}$$

The sliding surface of the proposed controller is chosen as a linear combination of these state variables, which is expressed as

$$S = \alpha_1 x_1 + \alpha_2 x_2 = GX \tag{8}$$

where, α_1, α_2 are the sliding coefficients and G is the vector of the sliding coefficients.

Therefore, the state-space equation in the standard form can be given as

$$\dot{X} = AX + Bu + D \tag{9}$$

where,

$$A = \begin{bmatrix} 0 & \frac{1}{C} \\ -\frac{1}{L} & 0 \end{bmatrix}, B = \begin{bmatrix} \frac{2i_L - i_{DC}}{C} \\ -\left(\frac{v_{C1}+v_{C2}}{L}\right) \end{bmatrix}, D = \begin{bmatrix} \frac{i_{DC}-i_{ref}}{C} \\ \frac{v_{in}-v_{ref}}{L} \end{bmatrix}$$

B. EQUIVALENT CONTROL

To satisfy, the existence condition, the function should meet the following two conditions.

$$S(x, t) = GX = 0 \tag{10}$$

$$\dot{S}(x, t) = G\dot{X} = 0 \tag{11}$$

Combining (9) and (11),

$$\dot{S}(x, t) = G\dot{X} = GA + GBu_{eq} + D = 0 \tag{12}$$

Therefore, the equivalent control signal is obtained as,

$$\begin{aligned} u_{eq} &= -[GB]^{-1}[GAX + GD] \\ u_{eq} &= \frac{\left[k\frac{(i_{ref}-i_{L1})}{C} - \frac{(v_{ref}-v_{C1})}{L}\right] + \left[k\frac{(i_{DC}-i_{ref})}{C} + \frac{(v_{in}-v_{ref})}{L}\right]}{\left[k\frac{(2i_L-i_{DC})}{C} - \frac{(v_{C1}+v_{C2})}{L}\right]} \end{aligned} \tag{13}$$

Where, $k = \alpha_1/\alpha_2$ are constant gain parameters, and normally, u_{eq} lies between zero and one. But for qZSI, the shoot through duty ratio is *1-D*, so, the value of u_{eq} is limited to 0.4.

$$0 < u_{eq} < 0.4 \tag{14}$$

This gives the average sliding motion on the defined sliding surface.

C. EXISTENCE CONDITIONS

After hitting the sliding surface, the state trajectory should be confined to the sliding surface and the approach towards its equilibrium point. To ensure the existence of the SM operation, the local reachability, condition must be satisfied, which is given as

$$\lim_{S\to 0} S\,\dot{S} < 0 \tag{15}$$

The inequality can be given as

$$\begin{aligned} \dot{S}_{S\to 0+} &= GAX + GBu_{S\to 0+} + D < 0 \\ \dot{S}_{S\to 0-} &= GAX + GBu_{S\to 0-} + D > 0 \end{aligned} \tag{16}$$

Presuming constant values of inductors L_1 and L_2, and capacitors C_1 and C_2, two cases will be as follows.

Case I: $S \to 0^+, \dot{S} < 0$

Substituting $u = 1$ in inequality equation,

$$\dot{S}_{S\to 0+} = k\frac{i_{L1}}{C} - \frac{v_{C2}}{L} - \frac{2v_{ref}}{L} + \frac{v_{in}}{L} < 0 \tag{17}$$

Case II: $S \to 0^-, \dot{S} > 0$

Substituting $u = 0$ in inequality equation,

$$\dot{S}_{S\to 0-} = -k\frac{i_{L1}}{C} - \frac{v_{C1}}{L} + k\frac{i_{DC}}{C} - \frac{2v_{ref}}{L} + \frac{v_{in}}{L} > 0 \tag{18}$$

The actual values of the qZS network parameters L and C are used in the above equation of inequality, for verification. From the above equation, for a range of practical values of v_{in}, such that qZS is configured in boost mode, the inequality condition will be satisfied. The compliance of minimum value of input voltage is required for the abidance of the existence condition. The values of sliding coefficients are calculated from the above equations.

D. STABILITY CONDITION

The replacement of u by equivalent control u_{eq} into the large signal model of qZSI converts the discontinuous system, into an ideal sliding mode continuous system, which is expressed as (19).

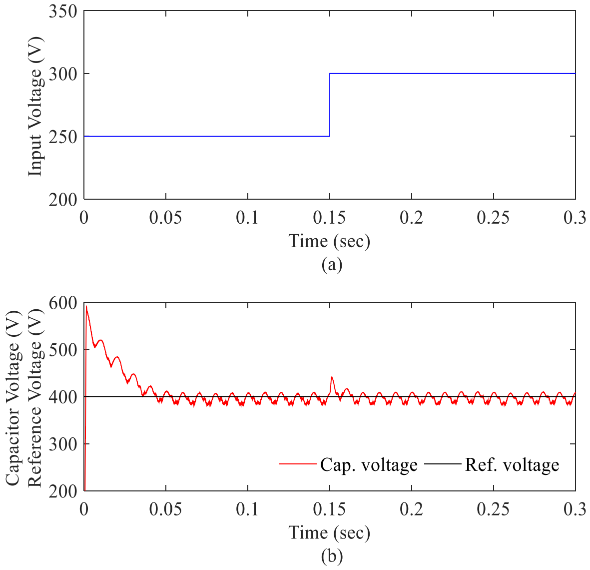
$$\frac{d}{dt}\begin{bmatrix} i_{L1} \\ i_{L2} \\ V_{C1} \\ V_{C2} \end{bmatrix} = \begin{bmatrix} \frac{1}{C_1}(-V_{C1} + V_{in}) \\ \frac{V_{C2}}{L_2} \\ \frac{1}{C_1}(i_{L1} - i_{DC}) \\ \frac{1}{C_2}(i_{L2} - i_{DC}) \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1}(V_{C1} + V_{C2}) \\ \frac{1}{L_2}(V_{C1} + V_{C2}) \\ \frac{1}{C_1}(i_{DC} - i_{L1} - i_{L2}) \\ \frac{1}{C_2}(i_{DC} - i_{L1} - i_{L2}) \end{bmatrix} u_{eq} \tag{19}$$

TABLE 1. Specifications of Simulation Model

Sr. No.	Parameters	Values
1	Grid Voltage	230V
2	Grid Frequency	50Hz
3	Inverter power rating	5kW
4	Switching Frequency	10kHz
5	qZSI inductors (L_1,L_2)	160μH
6	qZSI capacitors (C_1,C_2)	1000μF
7	AC Filter inductor	3mH
8	Local Load	R=40Ω

V. SIMULATION RESULTS

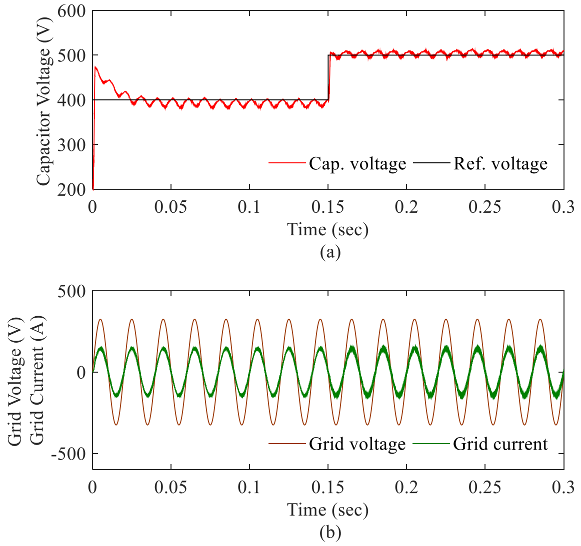
Simulation of the proposed system has been carried out in the MATLAB software. Diagram of control logic for implementation of SMC is shown in Fig. 5. Table 1, shows the specification of the simulation model. In order to observe the dynamic response of the SMC, the effect of a step change in input voltage, capacitor reference voltage, and grid feed current on controlled capacitor voltage has been observed. Also, the simulation results of the effect of a step change in capacitor reference voltage with SMC, are compared with the results of the PI controller.



(a)

(b)

FIGURE 6. Simulation results for step change in input voltage from 250V to 300V (a) Input voltage (b) Capacitor voltage.



(a)

(b)

FIGURE 7. Simulation results for step change in capacitor reference voltage from 400V to 500V (a) Capacitor voltage (b) Grid voltage and current.

Capacitor voltage regulation with a change in input DC voltage is represented in Fig. 6, where controller effectiveness has been demonstrated for change in input voltage from 250V to 300V. Here, the shoot through duty ratio is regulated by SMC, and the capacitor voltage is maintained at a constant level. Thus, it reflects that the input disturbances have not been transferred to the DC side.

Dynamic response of the controller, for a step change in capacitor reference voltage, is shown in Fig. 7.

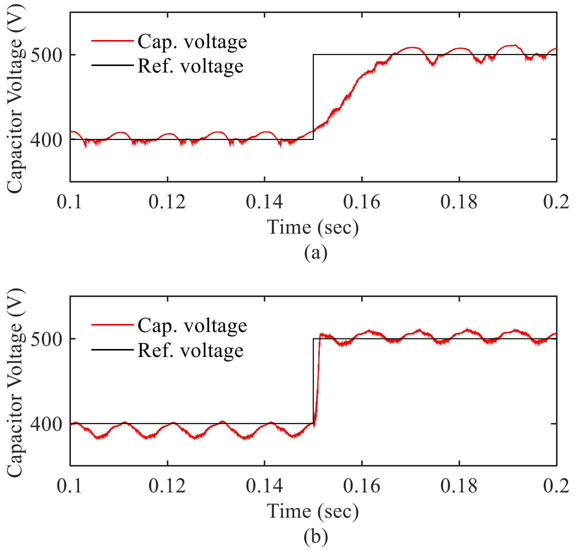


FIGURE 8. Comparison of Simulation results for step change in capacitor reference voltage (a) PI Controller (b) SM Controller.

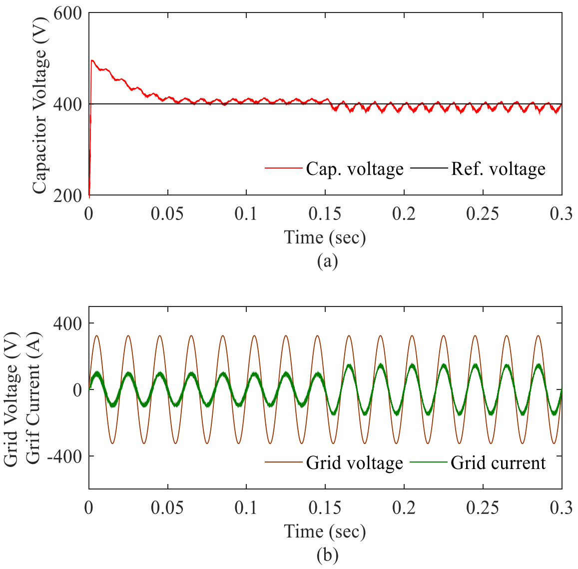


FIGURE 9. Simulation results for step change in grid feed current from 10A to 20A (MF=5) (a) Capacitor voltage (b) Grid voltage and current.

Here, a step change in reference capacitor voltage at 0.4sec from 400V to 500V is applied. The figure shows that SMC is fast enough to track this change in capacitor reference voltage. A comparison of the transient response of SMC and the PI controller for a step change in reference capacitor voltage is also shown in Fig. 8. The figure clearly indicates that the response of PI controller is far sluggish as compared to SMC.

Further, the response of the SMC for a step change in grid current is carried out. Fig. 9, shows that the capacitor voltage is unaffected by a step change in grid current from 10A to 20A.

The harmonic analysis of the system is carried out for different input and capacitor voltage conditions. THD under steady state conditions is calculated, and it is shown in Table 2, which is within an acceptable limit, satisfying the IEEE 519 harmonic standard.

TABLE 2. Harmonic analysis at different input voltage and capacitor voltage

		Inverter current		Grid current	
Input Volt (V)	*Cap. Volt. (V)*	Fundamental (A)	THD	Fundamental (A)	THD
250	400	29.04	1.41%	20.91	1.96%
300	400	29.09	1.37%	20.96	1.90%
250	500	29.22	1.65%	21.09	2.28%

TABLE 3. Specifications of Hardware Model

Sr. No.	Parameters	Values
1	Grid Voltage	230V
2	Grid Frequency	50Hz
3	Inverter power rating	500W
4	Switching Frequency	10kHz
5	qZSI inductors (L_1,L_2)	500µH
6	qZSI capacitors (C_1,C_2)	1000µF
7	AC Filter inductor	5mH

Therefore, the proposed SMC gives a very fast and dynamic response for a change in input, output, and the reference control parameter. This is also proved by, a comparison of the transient response of SMC with the PI controller.

VI. HARDWARE STUDY

A scaled down prototype of 500W, is developed to validate the simulation results. The specifications of the hardware prototype are shown in Table 3. The steady-state and transient response of the system, are demonstrated in the hardware results. Fig. 10 shows the photograph of the hardware prototype. It consists of the qZS network, inverter, control board, gate driver circuit, PC interface, PCC, and other measuring instruments.

Fig. 11, shows the waveforms of the input voltage, capacitor voltage, grid voltage, and current under steady state conditions. At a steady state, the input voltage is set at 250V, Capacitor reference voltage is set at 400V, and grid feed current is set at 2A rms. The transient response of the system, for different conditions like a step change in input voltage, a step change in capacitor reference voltage, and a step change in grid feed current are carried out, and the effect of this change in the regulated capacitor voltage has been observed.

The response of the controller, for a step change in input voltage from 250V to 300V, is presented in Fig. 12. The controller is fast enough to maintain the capacitor voltage at 400V, without any disturbance of step change in the input voltage. The nature of the applied step input is sluggish, which is because of the limitations of the power supply.

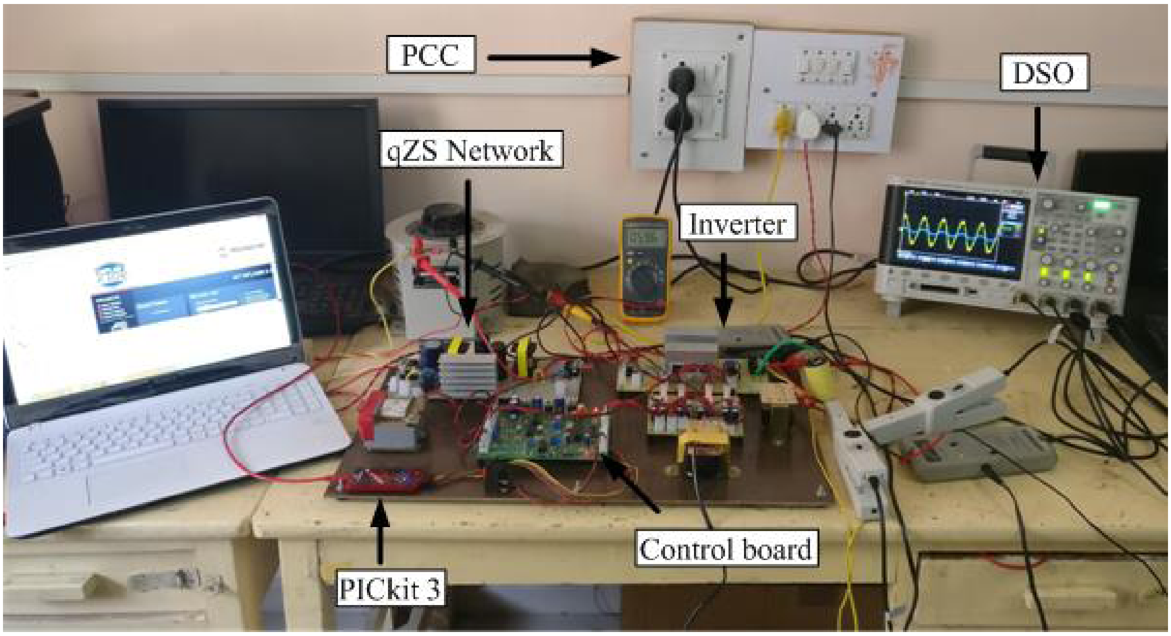


FIGURE 10. Hardware prototype of the proposed system.

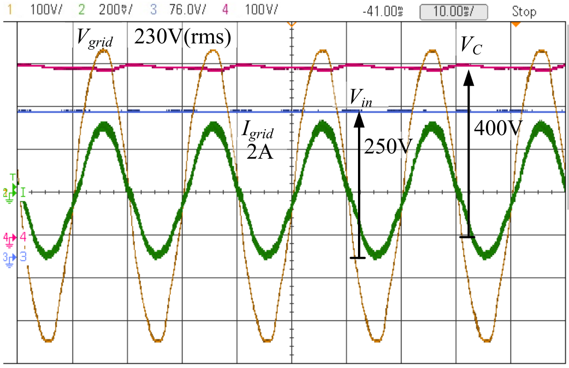


FIGURE 11. Hardware results for steady state condition: Input voltage = 250V, Capacitor voltage = 400V, Grid voltage = 230V, Grid current = 2.5A.

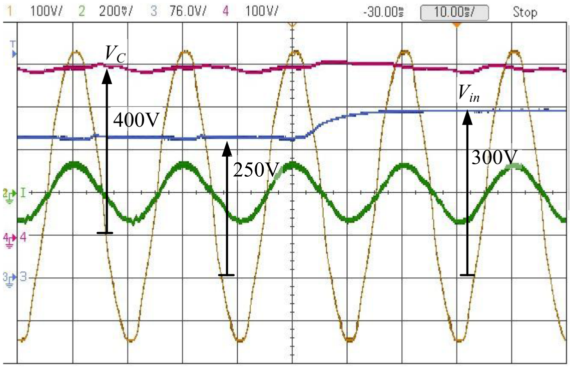


FIGURE 12. Hardware results for step change in input voltage from 250V to 300V.

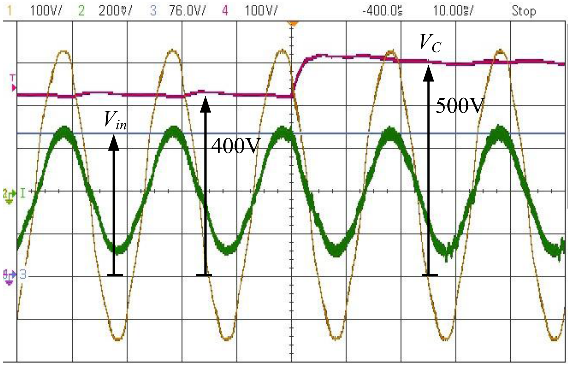


FIGURE 13. Hardware results for step change in capacitor voltage from 400V to 500V.

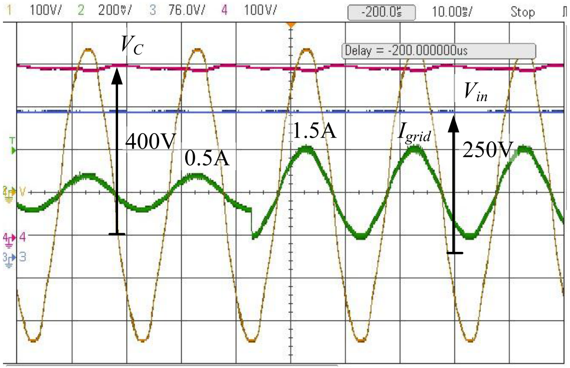


FIGURE 14. Hardware results for step change in grid feed current from 0.5A to 1.5A.

Thereafter, the input voltage is maintained constant at 250V, and the step change in reference capacitor voltage is applied from 400V to 500V as shown in Fig. 13. The controller tracks this change in reference value within less than 5msec.

Finally, to observe, the effect of output variations are observed by applying a step change in grid feed current from 0.5A to 1.5A. This change in current is carried out by, changing the AC reference current of the AC side controller. Fig. 14, shows that the capacitor voltage is unaffected by, this change in grid feed current.

Thus, it is seen that the experimental results for all three step changes are in line with the simulation results and are proved to be satisfactory.

VII. CONCLUSION

In this paper, SMC is used for controlling the dynamic response of the grid connected qZSI system. The detailed mathematical analysis of the SMC is done. Various aspects of the controller, are discussed in the paper, which include the selection method of the sliding surface, and the existence condition. The simulation and experimental result shows that the capacitor voltage controller gives a very fast response to a step change in reference value. Also, the controller is stable and robust for wide variations in input and output. A comparison of the proposed controller, with the PI controller, also clearly, proves the superiority, of the SMC based controller, over the classical controller.

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UMESH K. SHINDE (M'16) received the B.E. degree in electrical engineering from Shivaji University, Kolhapur, Government College of Engineering, Karad, the M.E. degree in control systems from Pune University, Government College of Engineering, Pune. He is currently pursuing the Ph.D. degree at YCCE, Nagpur. He has 13 years of teaching experience and three years of industrial experience. He is also an Assistant Professor with the Department of Electrical Engineering, Bhivarabai Sawant College of Engineering and Research, Pune. His areas of interest are power electronic converters and renewable energy.

SUMANT G. KADWANE (SM'16) received the B.E. degree in electrical engineering from Nagpur University at YCCE, Nagpur, India, the M.E. degree in control systems from Pune University, Government College of Engineering, Pune, India, and the Ph.D. degree in engineering from the Birla Institute of Technology (BIT), Mesra, India. He was a Faculty Member with the Department of EEE, BIT, for seven years. He is currently a Professor with the Department of Electrical Engineering, YCCE, teaching both undergraduate and postgraduate students. He has guided over 25 postgraduate students with various control and DSP-based projects. His areas of interest are control system design, power electronic converters, and renewable energy. He is a member of IE(I) and ISTE. He is the Editor-in-Chief of the *Journal for Research in Engineering and Applied Sciences*.

S. P. GAWANDE (M'16) received the B.E. degree in electrical engineering and the M.Tech. degree in integrated power system from Nagpur University, Nagpur, India, and the Ph.D. degree from VNIT, Nagpur. He has 13 years of teaching experience. He is currently an Assistant Professor with the Department of Electrical Engineering, Yeshwantrao Chavan College of Engineering, Nagpur. He has authored over 50 papers in reputed peer-reviewed journals and the IEEE conferences, such as PEDES, IECON, PESC, and INDICON. His research interest includes power electronics, facts, power quality, and power electronics applications to renewable energy systems. He is a Life Member of ISTE and IACSIT and a member of the Institution of Engineers, India. He is an Editor of the *Journal of Electrical and Power System Engineering*, the *Journal of Advances in Electrical Drives*, the *Journal of Controller and Converter*. He is a regular reviewer for the IEEE the IET, Elsevier, and Taylor and Francis and for various reputed IEEE conferences, such as PEDES, IECON, CIGRE, and PES Winter meetings.

M. JAYA BHARATA REDDY (SM'13) was born in India in 1980. He received the B.E. degree in electrical and electronics engineering from Nagarjuna University, Guntur, India, in 2002, and the M.E. degree in electrical engineering and the Ph.D. degree from the Birla Institute of Technology, Ranchi, India, in 2004 and 2008, respectively. He has 13 years of experience in teaching and research. He is currently an Associate Professor with the Department of Electrical and Electronics Engineering, National Institute of Technology, Trichy. His current research interests include smart grid, substation automation, wide-area protection, digital relaying, soft computing applications in power system, power quality analysis, and power system protection. In 2010, he received the prestigious national level IEI Young Engineer's Award in the field of electrical engineering. He is an Associate Editor and an Editorial Board Member of the *Electric Power Components and Systems Journal*.

D. K. MOHANTA received the B.Sc. degree in engineering from the College of Engineering and Technology, Bhubaneswar, India, the M.E. degree from the Birla Institute of Technology (BIT), Ranchi, India, and the Ph.D. degree from Jadavpur University, Kolkata, India. He has 27 years of experience in teaching and in industry. He was an Electrical Engineer with the Captive Power Plant, National Aluminium Company, Angul, India. He is currently a Professor with the Department of Electrical and Electronics Engineering, BIT. He is an Editor of the *Electric Power Components and Systems Journal*.

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