A Digital Current Control of Quasi-Z-Source Inverter With Battery

Jianfeng Liu, *Member, IEEE*, Shuai Jiang, *Student Member, IEEE*, Dong Cao, *Student Member, IEEE*, and Fang Zheng Peng, *Fellow, IEEE*

***Abstract*—This paper presents a fixed frequency operating sliding mode (SM) current control method with fast response and improved stability. Different from the conventional SM control with variable switching frequency, the fixed-frequency SM controller is proposed to control the modulation index and shoot-through duty ratio of the voltage-fed quasi-Z-source inverter (qZSI), which will not increase the passive components and filter design difficulty. A large-signal dynamic model of the system has been established, which can be used for the system stability control in a wide operating range. By using linear approximation, the system small-signal model is also obtained to analyze the control system stability and transient response. Compared with the conventional current mode controller, the proposed SM controller can achieve faster response, lower current ripple and better stability for qZSI when the supply and load variation is large. Experimental results are presented to demonstrate the validity of the theoretical design and the effectiveness of the proposed controller.**

***Index Terms*—Large signal model, sliding mode control, small signal model, Z-source inverter.**

I. INTRODUCTION

THE Z-source inverter employs an unique impedance network to couple the inverter main circuit to the power source, which provides a novel power conversion concept [1]. By controlling the shoot-through duty ratio and modulation index, the Z-source inverter can step up and down the input voltage using passive components with improved reliability and reduced cost, thus providing unique features, such as ride-through capability during voltage sags, reduced line harmonics, improved power factor and reliability, and extended output voltage range [2]–[5]. The recent proposed quasi-Z-source inverter (qZSI) inherits all the advantages of the traditional ZSI and has several more advantages, including reduced passive component stress and continuous input current features [6]–[9]. Due to the above-mentioned features, the qZSI topology is very attractive for renewable energy sources interface application, such as photovoltaic panel, wind turbine and fuel cell [10], [11].

Usually, those renewable energy power systems require a battery to store the extra energy when the load is light or the source is abundant, and to supply the load power during the period without or shortage of the source [12]. So the inverter should have the function not only to charge the battery with the extra power, but also to feed the load from the battery when the energy is insufficient. Z-source inverters with energy storage battery have been applied to fuel cell battery hybrid electric vehicles (FCHEV) [13]. By replacing one of the capacitors in the Z-source network with a high voltage battery, one is able to control the fuel cell power, output power, and state of charge (SOC) of the battery at the same time by controlling the shoot-through duty ratio and modulation index.

The introduction of the battery makes it more complex to control the qZSI. And in order to prolong the lifetime of battery, the accurate control of the battery charging current should be brought to the forefront. However, most of the existing papers focused on system engineering, such as energy production [14], [15], energy management [16], system reliability, unit size, and cost analysis [17]. The battery charging current control methodology for the ZSI/qZSI with battery for energy storage was seldom discussed in detail.

For the battery charging current control of the qZSI, there are several challenges for the controller design as follows.

1) Both output voltage and the battery charging current of the qZSI system with battery have to be controlled by the shoot-through state, which makes the design of a stable and fast controller more difficult [18].
2) Similar to the boost converter, the qZSI operating in the continuous-condition mode (CCM) has a right-half-plane-zero (RHPZ) in its control transfer function [19], which limits the bandwidth of the controller and makes the dynamic response of the system sluggish.
3) The qZSI with battery is a fifth-order nonlinear system and the battery charging current will be very sensitive to the input and output variation [20]. If the controller is not well designed, the system may become unstable easily.

Numerous control methods to achieve fast response and small overshoot have been proposed for the nonlinear system control. Among them, nonlinear-carrier control and one-cycle control have been found practical in some applications. However, either method has some limitations. Nonlinear carrier control method requires two integrators to generate the nonlinear carrier signal [21]. The parameters of the integrator also vary with

---

Manuscript received November 26, 2011; revised April 18, 2012 and June 11, 2012; accepted September 24, 2012. Date of publication October 04, 2012; date of current version January 09, 2013. This work was supported in part by the National Natural Science Foundation of China under Grant 61203063, Grant 61071096, and Grant 61073103.. Paper no. TII-11-795.

J. Liu is with the School of Information Science and Engineering, Central South University, Changsha 410075, China (e-mail: ljf@csu.edu.cn).

S. Jiang, D. Cao, and F. Z. Peng are with Michigan State University, Lansing, MI 48864 USA (e-mail: jiangshu@msu.edu; caodong@msu.edu; fzpeng@msu.edu).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TII.2012.2222653

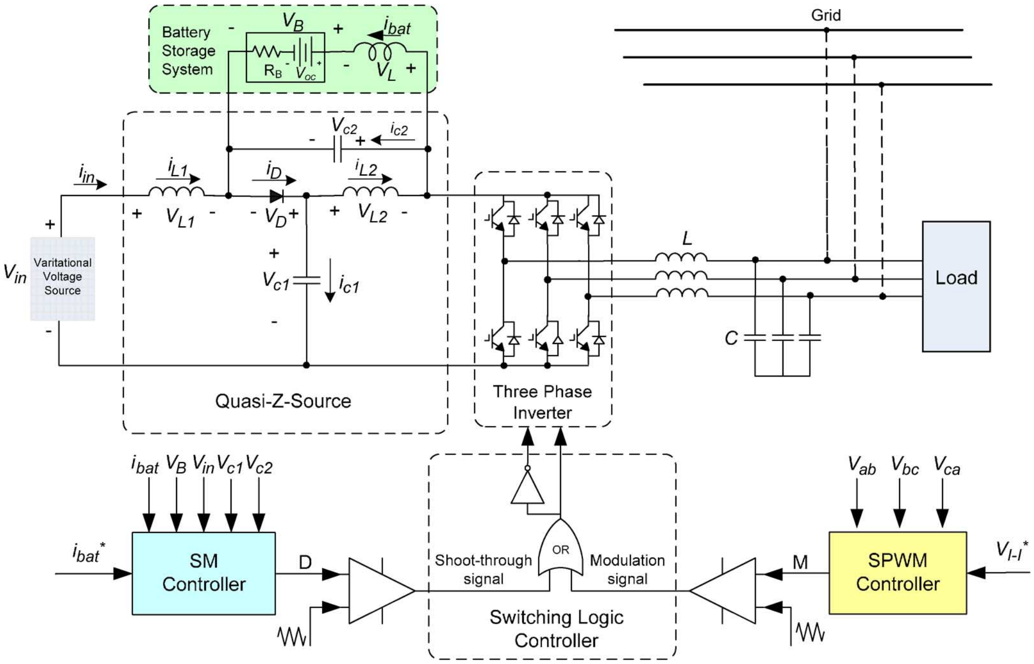

Fig. 1. Proposed qZSI with battery energy storage system configuration.

the switching frequency. These features make the integrated implementation of this method difficult. One-cycle control is actually a peak-current method, which is designed under a linearized small-signal model that is only optimal for a specific operating condition. Hence, it may lead to high harmonic current distortion, particularly under light load conditions and/or when the line voltage is high [22]. Concurrently, the SM control has been used to control the ?uk converter and other nonlinear power electronics converters by many researchers [23]–[27]. It is deemed to be a better candidate than the other nonlinear control methods for its relative ease of implementation, its excellent robustness and stability properties in handling large-signal perturbations and component's uncertainty, and its ability to provide highly consistent dynamic response as predesigned [28], [29].

Given that the battery current control method was seldom investigated in the literature [30], this paper is trying to cover the research gap. It presents a constant frequency SM current control method for battery charging current control in voltage-fed qZSI with battery storage system. And the use of the proposed current controller can obtain well stability performance and fast transient response of the qZSI with the variable input source for renewable energy applications.

The paper is organized as follows: the large-signal dynamic model of the system is introduced in section two; the designing of SM controller based on the equivalent control theory is presented in section three; section four is devoted to the description of the small-signal model near steady-state operating point by using the linearization method for the stable working conditions of the control system; simulation and experimental results are presented in section five to demonstrate the validity of the proposed SM controller. Finally, the conclusions of this work are pointed out in section six.

II. SYSTEM CONFIGURATION AND ANALYSIS

Fig. 1 shows the system configuration of the proposed voltage-fed qZSI with battery [31]. It consists of a voltage-fed quasi Z-source network, a battery energy storage unit, a three phase inverter, a variable input voltage source, a SM controller, a sinusoidal pulse-width modulator (SPWM) controller, and a switching logic controller. The battery energy storage system is connected in parallel with the capacitor C_2. Since the voltage stress of the capacitor C_2 is smaller, a relatively low-voltage battery with higher reliability, lower cost, and longer lifetime can be used in the system.

A. Dynamic Large-Signal Model of qZSI With Battery

The three-phase inverter bridge and external AC load can be represented by a single switch and current source connected in parallel [32]. Considering the asymmetric quasi-Z-source network, there are two switching states of the qZSI:

1) *During shoot-through state* $(u = 1)$, the ac load terminals will get a shoot-through in both upper and lower devices of any phase leg(s); meanwhile, the single switch is ON and the shoot-though ratio u equals to 1. The equivalent circuit of the qZSI is shown as Fig. 2(a). One can get

$$\begin{cases} v_{l_1} = v_{c_2} + v_{\text{in}} \\ v_{l_2} = v_{c_1} \\ i_{c_1} = -i_{l_2} \\ i_{c_2} = -i_{l_1} - i_{\text{bat}} \\ v_l = v_{c_2} - v_b. \end{cases} \tag{1}$$

2) *When operating at nonshoot-through states* $(u = 0)$, the single switch is OFF and the shoot-though ratio u equals to