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Modelling and simulation of A Low-harmonic Control Method of Bi-directional Three-phase Z-source Converters for Vehicle-to-Grid Applications

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Abstract—
Three-phase Z-source inverters provide a solution of voltage boosting by a single-stage topology. They are also capable of bi-directional operation as rectifiers, thus have great potential for applications in the field of transportation electrification such as Vehicle-to-Grid (V2G) chargers. In this paper, three new modulation schemes for three-phase Z-source converters are proposed and investigated. The best performed one is further developed to a closed-loop PI control method. While the voltage conversion ratio is flexible, the output voltage Total Harmonics Distortion (THD) is below 3% within the voltage ratio range of 0.5 to 2.5. The effectiveness of the proposed method has been fully validated in MATLAB/Simulink simulations and RT- LAB Hardware-In-Loop (HIL) experiments based on the real- time simulator OPAL-RT OP4510. Compared to existing control methods, the proposed one performs better with reduced harmonics, flexible voltage gain, and simpler control algorithm.

Index Terms—Z-source converter, Bi-directional converter, shoot-through states, voltage harmonics, closed-loop control.

I.INTRODUCTION

HERE is an increasing demand for advanced power converters and their corresponding control algorithms in the field of transportation electrification in general, and railway electrification in specific [1]. Traditional full-bridge three- phase inverter is a fundamental topology for energy transformation between Direct Current (DC) voltage sources such as vehicle batteries and three-phase Alternating Current (AC) power grids, microgrids or loads. However, in the control and operation of traditional full-bridge inverters, dead time between the two switches in the same bridge is required to avoid short-circuit failures [2]. The existence of dead time unavoidably brings AC output waveform distortions. Moreover, when there is a large difference in voltage level between the output AC side and the input DC side, one more DC-DC converter is often added in the inverter to regulate output voltage level. This two-stage system configuration not only decreases the efficiency but also weakens the dynamic response of the system with regard to both disturbances in environmental conditions and grid perturbations [3].

A Z-source inverter [4] and a quasi-Z-source inverter [5] were proposed to overcome the above barriers of traditional two-stage voltage-source inverters. As shown in Fig. 1, an X-shape impedance network composed of two inductors LZ1, LZ2 and two capacitors CZ1, CZ2 is combined in a traditional three- phase full-bridge inverter [6]. Because of the existence of the X-shape impedance network, it is possible to turn on the two switches in one bridge simultaneously without short-circuited the input voltage source [4]. Moreover, the Z-source inverters take advantage of the shoot-through states ingeniously to achieve voltage boosting without any additional switches or control circuitry [7]. Therefore, the Z-source inverters could achieve voltage buck and boosting by a single-stage topology with high robust. The voltage level of different microgrids could vary considerably, which makes the Z-source converters more advantageous in the process of EV batteries' feeding to the grids. The Z-source inverter could also operate bi-directionally, which is essential in V2G applications. The input diode Dr is connected in parallel with a switch S1. When switch S1 is turned on, the Z-source inverter could operate as a conventional three-phase PWM rectifier.

Because of the above-mentioned features, Z-source converters have been widely investigated in areas of not only EV charging [8] [9], but also EV motor drive [10] [11], PV solar energy system [12] [13], wireless energy transfer [14] [15] and integration of microgrid [16] [17]. The increasing voltage gain capability and modulation indexes of both rectifier and inverter stages are advantages of three-phase Z-source converters [18].

Different approaches of applying bi-directional Z-source inverters in V2G applications have been investigated [19] [20]. Paper [21] provided an overall introduction and comparison of space vector modulation schemes for three-phase Z-source inverters. Besides the basic Z-source impedance topology, many modified Z-source topologies have been developed [22]-[24] to reduce switching loss and improve power density. Though these proposed converters based on Z-source topology could generally achieve smaller size and wider voltage conversion ratio, they have issues in complicated structure, instability, voltage stress of switches, power level limitation[24] and output harmonics [7]

[25]. Therefore, this paper aims to improve the performance of converter by designing and optimizing the control method of a basic three-phase Z-source converter, rather than adding more devices or complicated circuits.

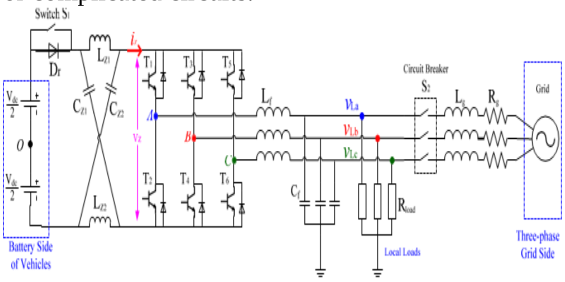


Fig.1 Topology of a bi-directional three-phase Z-source converter

Some advanced control logic for three-phase Z-source converters has been proposed to achieve better dynamic performance [26]-[28], realize ZVS rectifying [29], reduce grid current distortion [30], decouple active and reactive power [3] and increase voltage conversion ratio [31]. However, these control methods require tremendous and complicated calculations to meet the special requirements of designated applications with more passive devices added. Those control schemes are often complicated [32]. In this paper, three new modulation schemes of inserting shoot-through states are proposed. Among them, sine variable modulation shows better performance over harmonic suppression and is therefore further developed into a closedloop control method. The converter could be connected to the grid or a three-phase load. The switch S1 and circuit breaker S2 determine the working mode. To simplify the calculation, the input DC voltage source is divided into two voltage sources, each has the magnitude of Vdc/2, and the middle point is labelled as O. Compared to conventional control schemes, the proposed method in this paper has the following advantages: low harmonics in output voltage and current; support of bidirectional operation; easy to implement without complicated algorithm or computation burden; easy to modify for the control in grid-connected mode.

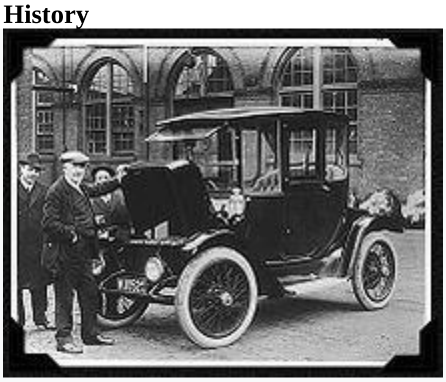
II.ELECTRIC VEHICLE

An **electric vehicle**, also called an **EV**, uses one or more electric motors or traction motors for propulsion. An electric vehicle may be powered through a collector system by electricity from off-vehicle sources, or may be self-contained with a battery, solar panels or an electric generator to convert fuel to electricity.[1] EVs include, but are not limited to, road and rail vehicles, surface and underwater vessels, electric aircraft and electric spacecraft.

EVs first came into existence in the mid-19th century, when electricity was among the preferred methods for motor vehicle propulsion, providing a level of comfort and ease of operation that could not be achieved by the gasoline cars of the time. Modern internal combustion engines have been the dominant propulsion method for motor vehicles for almost 100 years, but electric power has remained commonplace in other vehicle types, such as trains and smaller vehicles of all types.

In the 21st century, EVs saw a resurgence due to technological developments, and an increased focus on renewable energy. A great deal of demand for electric vehicles developed and a small core of do-it-yourself (DIY) engineers began sharing technical details for doing electric vehicle conversions. Government incentives to increase adoptions were introduced, including in the United States and the European Union

History



Edison and a 1914 Detroit Electricmodel 47 (courtesy of the National Museum of American History)

An EV and an antique car on display at a 1912 auto show

III. PULSE WIDTH MODULATION

What is PWM?

Pulse Width Modulation (PWM) is the most effective means to achieve constant voltage battery charging by switching the solar system controller’s power devices. When in PWM regulation, the current from the solar array tapers according to the battery’s condition and recharging needs Consider a waveform such as this: it is a voltage switching between 0v and 12v. It is fairly obvious that, since the voltage is at 12v for exactly as long as it is at 0v, then a 'suitable device' connected to its output will see the average voltage and think it is being fed 6v - exactly half of 12v. So by varying the width of the positive pulse - we can vary the 'average' voltage.

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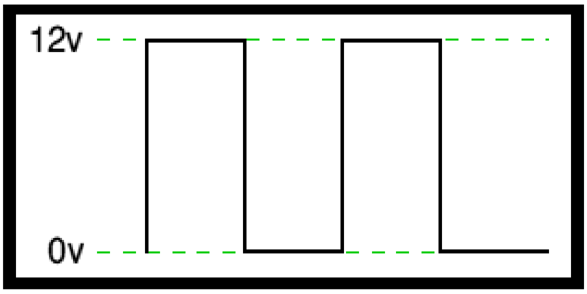
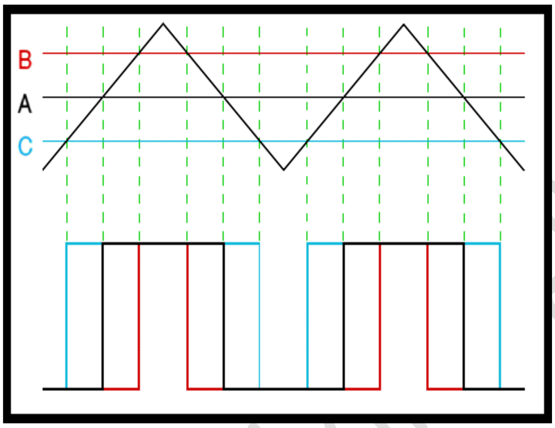


Similarly, if the switches keep the voltage at 12 for 3 times as long as at 0v, the average will be 3/4 of 12v - or 9v, as shown below.

Pulse Width modulator

So, how do we generate a PWM waveform? It's actually very easy, there are circuits available in the TEC site. First you generate a triangle waveform as shown in the diagram below. You compare this with a d.c voltage, which you adjust to control the ratio of on to off time that you require. When the triangle is above the 'demand' voltage, the output goes high. When the triangle is below the demand voltage, the



When the demand speed it in the middle (A) you get a 50:50 output, as in black. Half the time the output is high and half the time it is low. Fortunately, there is an IC (Integrated circuit) called a comparator: these come usually 4 sections in a single package. One can be used as the oscillator to produce the triangular waveform and another to do the comparing, so a complete oscillator and modulator can be done with half an IC and maybe 7 other bits.

IV.PROPOSED SYSTEM AND CONTROL DESIGN

PROPOSAL OF CONTROL METHODS AND ANALYSIS

A. Basic Principle of Three-phase Z-source inverters

Fig. 1 shows the three-phase Z-source inverter which consists of a Z-source topology, a diode Dr and a traditional three-phase full-bridge inverter. The Z-source topology is composed of two inductors LZ1, LZ2 and two capacitors CZ1, CZ2. To achieve the symmetrical characteristic, the two inductors usually would have the same inductance, i.e. LZ1=LZ2=LZ, while the two capacitors also would have the same capacitance, i.e. CZ1=CZ2=CZ. Otherwise, an asymmetric topology would lead to unbalanced operation as well as difference in voltage and current stress of devices [33]. The output side of the Z-source topology is connected to a classical three-phase full-bridge inverter with six switches. The diode Dr is placed in series with the DC voltage source to block any reverse current from the Zsource topology in order to achieve voltage boosting [33].

When circuit breaker S1 is turned on, the converter operates bi-directionally as a rectifier and power transfers from the grid to the DC side of the converter. The Z-source network acts as a special LC filter of the three-phase rectifier. Traditional SPWM control method of three-phase full bridge rectifiers is applicable. When circuit breaker S1 is turned off, the converter operates as an inverter and power transfers from the DC side to the threephase loads or the grid. Circuit breaker S2 determines whether the converter operates in grid-connected mode or resistive load mode. The voltage-boosting principle of three-phase Z-source inverters is similar to the one of single-phase ones as described in [33], and therefore the detailed analysis and equivalent circuits in each state are not repeated here. In short, the voltage VZ is boosted higher than the input voltage Vdc because of shootthrough states. In steady state, the operation of Z-source inverter is divided into two periods: shoot-through states and non-shoot-through states [33]. It is assumed that the total time of shoot-through states in one switching cycle is Ts, and the period of one cycle is T, then the shoot-through duty ratio D of shoot-through states is:

$$D=\frac{T_s}{T} \tag{1}$$

Equation (2) shows the state space equation:

$$\frac{d}{dt}\begin{bmatrix} i_{LZ1}(t) \\ i_{LZ2}(t) \\ v_{CZ1}(t) \\ v_{CZ2}(t) \end{bmatrix} = \begin{bmatrix} 0 & 0 & \frac{2D-1}{L_Z} & 0 \\ 0 & 0 & 0 & \frac{2D-1}{L_Z} \\ \frac{-D}{C_Z} & \frac{1-D}{C_Z} & 0 & 0 \\ \frac{1-D}{C_Z} & \frac{-D}{C_Z} & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} i_{LZ1}(t) \\ i_{LZ2}(t) \\ v_{CZ1}(t) \\ v_{CZ2}(t) \end{bmatrix} + \begin{bmatrix} \frac{1-D}{L_Z} \\ \frac{1-D}{L_Z} \\ 0 \\ 0 \end{bmatrix} \cdot V_{dc} + \begin{bmatrix} 0 \\ 0 \\ \frac{D-1}{C_Z} \\ \frac{D-1}{C_Z} \end{bmatrix} \cdot i_Z \tag{2}$$

The steady-state parameters could be obtained by setting (2) to zero, as shown in (3):

$$\begin{cases} \overline{i_{LZ_1}} = \overline{i_{LZ_2}} = \dfrac{1-D}{1-2D}\cdot\overline{i_Z} \\ \overline{v_{CZ_1}} = \overline{v_{CZ_2}} = \dfrac{1-D}{1-2D}\cdot V_{dc} = \overline{V_Z} \\ v_{Z-peak} = \dfrac{1}{1-2D}\cdot V_{dc} \end{cases} \qquad (3)$$

Since D must be greater than 0 and smaller than 1, the average magnitude of the output voltage across the Z-source topology VZ is boosted higher than input DC voltage Vdc as shown in (3). When more shoot-through states are inserted, the output voltage gain will become higher [34]. The voltage gain of Z-source inverters could be infinite theoretically, whereas the effect of parasitic components and harmonics requirement limit the maximum practical gain. The core concept of Z-source converter's control is to boost voltage by inserting shoot-through states while reducing output harmonics and power loss [33]. Three shoot-through states inserting methods are proposed below for three-phase Z-source converters. B. Proposed Modulation Schemes A study of inverters connected to resistive loads is presented here. Control methods of three-phase Z-source inverters could be classified into two categories: shoot-through of three-phaseleg modulation schemes and shoot-through of single-phase-leg modulation schemes [35]. Each subcategory could be further divided by continuous modulation methods and discontinuous modulation methods. If only one bridge is inserted with shootthrough states, then the high current during shoot-through states would all flow into the two switches of this bridge. Switches of the other two bridges do not share the same current stress, which leads to the asymmetry of the topology and the operation. Therefore, the three-phase-leg modulation scheme is selected for the proposed methods. In non-shoot-through states, its operation is divided by zero states and non-zero states [35]. Based on this, there are three primary subcategories of inserting shoot-through states: (1) Simple boost control: part of zero states are converted into shoot-through states; (2) Maximum boost control: all zero states areas are converted into shoot-through states; (3) Constant boost control: most of zero states areas are converted into shootthrough states [35] [36]. The proposed methods of inserting shoot-through states are based on conventional SPWM scheme of three-phase full-bridge inverters and belong to constant boost control. Three sinusoidal modulating signals at the frequency of the desired output but displaced from each other by 2π/3 phase are generated. The triangular carrier wave is compared with the modulation waves to generate six gate signals. The concept is modifying the magnitude of three modulation waves to create overlaps. In Fig. 2(a), the sine modulation waves of generating signals for switch T1 and T2 in phase A bridge are presented. The black solid curve represents a standard sine wave whose magnitude ranges from –M to M, where 0 < M < 1. Two more modulation waveforms are derived by adding a variable b(t) which varies with time respectively. The red dashed modulation wave is used for generating gate signals for upper switch T1, which is marked as wT1. The blue dotted modulation wave is used for generating gate signals for lower switch T2, which is marked as wT2. Fig. 2(b) is a zoomed view of the circled part of Fig. 2(a). It shows the overlap of switching signals GT1 and GT2 by two different modulation waves. For simplicity, b(t) is set as a constant in Fig. 2.

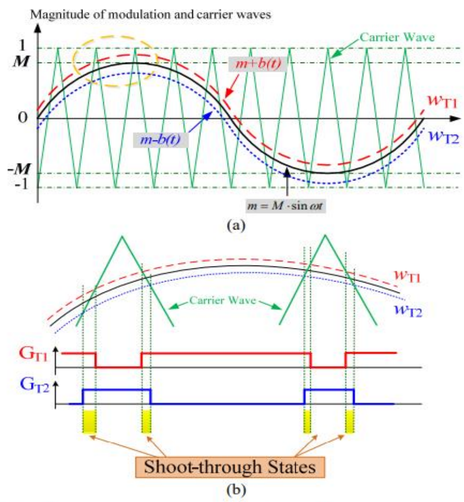


Fig.2 Shoot-through states inserting by overlap: (a) Modulation waves in one cycle; (b) Zoomed view

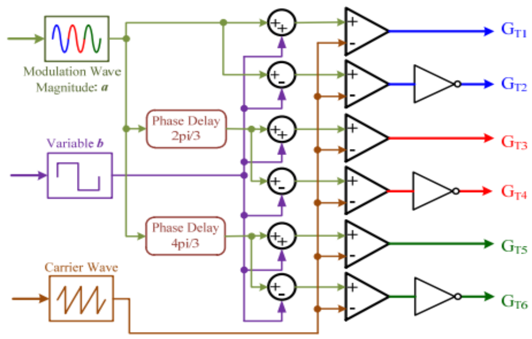


Fig.3 Generation of switching signals to insert shoot-through states

The magnitude variation of each modulation wave is marked as a function bn(t), where n represents the serial number of switches. The modified magnitudes of modulation waves are given in (5), where mAu, mBu and mCu represent the instantaneous magnitudes of modulation waves used for generating pulse signals for the upper switches of phase A, B and C, and mAl, mBl and mCl represent the instantaneous magnitude of modulation waves used for generating pulse signals for the lower switches of phase A, B and C. Fig. 4 shows the modified diagram of space vector modulation. In traditional SVPWM, there are eight vectors and only one switch in a bridge could be turned on. When the state of the upper switch is ON,

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the state is marked as 1; otherwise, marked as 0. Therefore, there are eight possible combinations of the three bridges' states, i.e. S0 to S7. Instead, shoot-through states are feasible for three-phase Z-source inverters. No matter which bridges are inserted with shoot-through states, the voltage VZ drops to zero, and all the three bridges share the same voltage VZ. Thus one more vector S8 is added, which represents the case that shoot-through state is inserted into at least one of the three bridges. The proposed control method belongs to shoot-through of three-phase-leg modulation scheme and continuous modulation method as previously mentioned.

V.SIMULATION RESULTS:

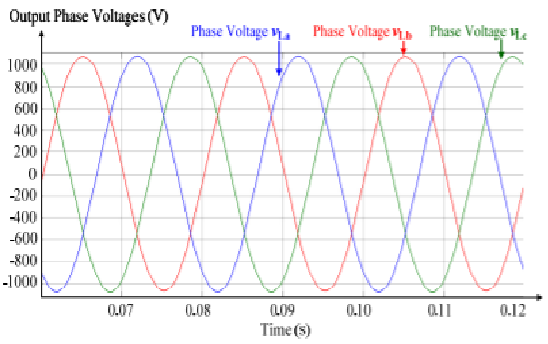

Fig4: Output phase voltages of sine variable method at rated output voltage

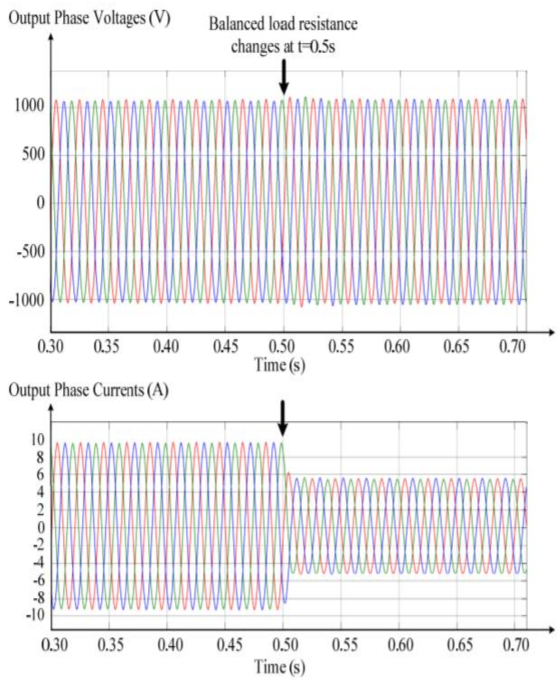

Fig5: Simulation waveforms of output phase voltages and currents when Rload changes

VI.CONCLUSION

The theoretical analysis, simulation and experimental results in the paper proved the good performance of the proposed methods for bi-directional three-phase Z-source converters. Shoot-through states are inserted sinusoidally, and the output three-phase voltages could be boosted while the harmonics are maintained within a low level. Constant variable method, sine variable method and cosine variable method are introduced and compared. Sine variable method produces least harmonics, and hence is further developed into a closed-loop PI control method. Steady-state waveforms in experiment results proved the capability of voltage boosting with all circuitry waveforms matched the theoretical analysis. Transient waveforms showed the dynamic response with the disturbance of input voltage and load resistance. The output phase voltages could catch the reference quickly and smoothly. Compared to existing control methods, the proposed one has better performance on harmonics suppression with an uncomplicated control algorithm, thus would be suitable for its application in vehicle chargers with bi-directional power flow between the vehicle batteries and the three-phase AC bus of a microgrid. The future work mainly includes the implementation of an EV charger prototype to testify the charging performance and conversion efficiency in a Power Hardware-In-Loop (PHIL) testing platform, suppression of the input current spikes and the advanced control in unbalanced load cases.

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