New Shoot Through Control Methods for qZSI with Voltage Stress Reduction-Based DC/DC Converterer

Nisy. P. Satheesh
PG Scholar, Department of EEE
Hindusthan College of Engineering and Technology,
Coimbatore, Tamilnadu, India

B. Nandhini
Assistant Professor, Department of EEE,
Hindusthan College of Engineering and Technology,
Coimbatore,TamilNadu, India.

Abstract*— Shoot-through control methods for qZSI-based dc/dc converters are presented and studied. This paper discusses three different shoot through PWM control methods suitable for this topology. For the verification of theoretical assumptions the converter prototype was assembled and tested. Experimental waveforms of the converter operated with different shoot-through PWM control methods are compared and discussed. Design considerations for converter and different control signal generators are provided. A new modulation technique, pulse width modulation (PWM) with shifted shoot-through, is compared with the conventional PWM shoot-through control method. The new method reduces switching frequency of bottom side transistors and inherently features partial soft switching. Previous studies have shown that the biggest drawback of PWM control with shoot-through is unequal switching frequencies of transistors. One solution to that problem could be signal swapping that has been proposed by this paper. The proposed converter is designed to be a power conditioning unit for a fuel cell powered systems. It is characterized by low voltage and high current values, which normally results in high losses of the system. Thus, serious attention should be paid to loss reduction not only in conductors but also in the semiconductor switches of the inverter. Losses in IGBT switches can be significantly reduced by proper control methods. One of the benefits that the qZS topology offers is soft switching without additional components. The number of soft switching transients achievable depends mostly on the modulation method. In some cases both zero current switching (ZCS) and zero voltage switching (ZVS) are possible over full operation range; The main advantage of the proposed system is the voltage stress across the switch is reduced. All control methods are first simulated and then experimentally verified on a test prototype.

Keywords*— DC/DC converter, quasi-Z-source inverter, shoot through control methods, signal swapping, switching losses.

I. INTRODUCTION

A QUASI-Z-SOURCE inverter (qZSI), as a sine wave inverter for ac loads, has been widely studied. In 2009, researchers of the Department of Electrical Drives and Power Electronics, Tallinn University of Technology proposed a new application field for the qZSI as an isolated step-up dc/dc converter .The qZSI inherits all the advantages of the Z-source inverter, which can realize buck/boost, inversion and power conditioning in a single stage with improved reliability. In addition, the qZSI has the unique advantages of lower component ratings and constant dc current from the source [2]. All these features make qZSI an attractive converter for renewable and alternative energy source.

It deals with a new family of single-phase ac– ac converters called single-phase quasi-Z-source ac–ac converters. This converter inherits all the advantages of the traditional single-phase Z-source ac–ac converter, which can realize buck–boost, reversing, or maintaining the phase angle. In addition, the proposed converter has the unique features that the input voltage and output voltage share the same ground and the operation is in the continuous current mode. The operating principles of the proposed converter are described, and a circuit analysis is provided. In order to verify the performance of the proposed converter, a laboratory prototype was constructed with a voltage of 84 Vrms /60 Hz. The simulation and experimental results verified that the converter has a lower input current total harmonic distortion and higher input power factor in comparison with the conventional single-phase Z-source ac–ac converter.

Voltage and current-source inverters find wide use in industry for ac motor drives, uninterruptible power supplies, distributed power systems, and hybrid electric vehicles. However, the traditional voltage- and current-source inverters have major problems. A traditional voltage-source inverter cannot have an ac output voltage higher than the dc source voltage and can only provide buck dc–ac power conversion [4]. Shoot through, generated by both power switches in a leg, is forbidden in a voltage-source inverter. A current-source inverter cannot have an ac output voltage lower than the dc source voltage; therefore, it provides only voltage boost dc–ac power conversion and it cannot tolerate an open circuit. For applications, where both buck and boost voltage are demanded, an additional dc–dc converter that acts as both a voltage- and current-source inverter, performs two-stage power conversion with high cost and low efficiency[8] .

Over the recent years, many researchers have given their focus in many directions to develop Z-source inverters (ZSI) to achieve different objectives. Some have worked on developing different kinds of topological variations, while others have worked on developing ZSI into different applications, where component sizing, modeling, analysis, controller design, and modulation method are addressed. Theoretically, ZSI can produce infinite gain, like many other dc–dc boost topologies; however, it is well known that this cannot be achieved due to effects of parasitic components where the gain tends to drop drastically[9].This also imposes limitation on variability, and thereby, the boosting of output voltage. In other words, increase in boost factor would compromise the modulation index and result in lower modulation index[6]. Also, the voltage and current stress on the switches would be high due to pulsating nature of the output voltage and current where the switches have to bear higher voltage in active states and high current during the shoot-through.

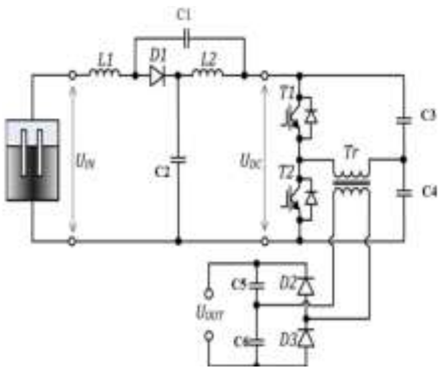

Fig. 1. Simplified power circuit diagram of the proposed converter.

Unlike the dc–dc converters, researchers of ZSIs have not given their focus to improve the gain of the converter so far. This opens a significant research gap in the field of ZSI development, particularly, in applications, like solar and fuel cells that may require high voltage gain to match the voltage difference and also to compensate the variations in output voltage. Need of high boost is significant when such energy sources are connected to 415-V three-phase systems.

In the case of fuel and solar cells, although it is possible to increase the number of cells to increase the voltage, there are other influencing factors that need to be taken into account. Sometimes the available number of cells is limited or environmental factors could come into play due to shading of light on some cells that could result in poor overall energy catchments. In the case of fuel cells, some manufactures produce them as lower voltage system to achieve a faster response. Such factors could demand power converters with larger boost ratio. This cannot be realized with a single ZSI. Hence, this paper focuses on developing new family of ZSIs that would realize extended-boost capability.

II. METHODOLOGY

Two basic shoot-through control techniques for the qZS-based dc/dc converter were recently proposed: pulse width modulation (PWM) and phase shift modulation (PSM). In both cases, shoot-through is generated during zero states. The zero and shoot-through states are spread over the switching period so that the number of higher harmonics in the transformer primary could be reduced[1].To reduce switching losses of the transistors, the number of shoot-through states per period is limited by two. Moreover, to decrease the conduction losses of the transistors, shoot-through current is evenly distributed between both inverter legs .

According to both methods (PWM, PSM) are fairly identical in terms of conduction losses since the number of conduction states and their duration remain unchanged. However, due to an increased number of hard-switched commutations in the case of the PSM shoot-through control method, switching losses were increased by more than 20%. Moreover, PSM injects noticeably higher over voltages into the system compared to the PWM control. Taking all that into account, PWM control seems to be the best control method for the qZS-based dc/dc converter. The only problem with the PWM shoot-through control is that it imposes unequal operating frequencies of the transistors, which results in unequal switching losses. Today's major trend in power electronics is to increase efficiency [7]. It is only achievable by optimizing operation parameters and components of a converter. One should avoid over- or under- loaded components. That is the reason why in the current research focus is on equalizing switching losses in the qzs inverter. This paper discusses the PWM shoot-through control method in detail. The authors have also proposed several new improved PWM control methods such as shifted shoot-through control and swapped PWM control, which allow us to achieve better performance of the converter.

A. PWM control principle

Pulse-width modulation (PWM), as it applies to motor control, is a way of delivering energy through a succession of pulses rather than a continuously varying (analog) signal. By increasing or decreasing pulse width, the controller regulates energy flow to the motor shaft. The motor's own inductance acts like a filter, storing energy during the "on" cycle while releasing it at a rate corresponding to the input or reference signal. In other words, energy flows into the load not so much the switching frequency, but at the reference frequency[1]. PWM is somewhat like pushing a playground-style merry-go-round.

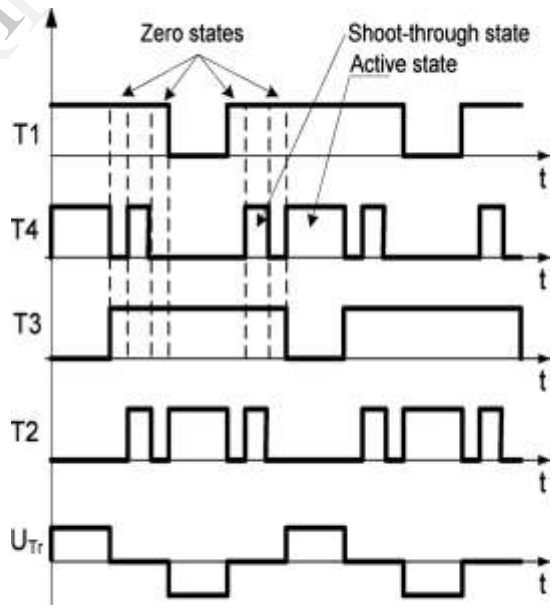

Fig. 2. Generation of PWM signals with shoot-through during zero states.

The PWM control principle of a qZS-based dc/dc converter is shown in Fig. 2. Shoot-through states should be placed so that they would not disturb the shape of the primary voltage of the isolation transformer. This enables us to keep the number of higher harmonics to a minimum. One way to accomplish that is to generate shoot-through inside zero states, as shown in Fig. 2. It must be pointed out that zero states are always generated by the same pair of switches: either the top (T1andT3) or the bottom (T2andT4) transistors. Currently the top side transistors were used. The minimum number of shoot-through states per period of the isolation transformer is two. One shoot-through state per period would cause discontinuous mode input current and the qZSI starts to behave abnormally.

In general, the maximum number of shoot-through states is not limited. However, one should bear in mind that every additional shoot-through state automatically increases the switching frequency of the transistors and switching losses. Thus, the number of shoot-through states should be kept to a minimum[3]. During shoot-through the current through the inverter switches reaches its maximum. The voltage in the dc-link (U_{DC})drops to zero. The voltage of the isolation transformer (U_{Tr}) remains unchanged, as indicated in Fig. 2

B. PWM control with shifted shoot-through

This modulation technique was proposed by the authors as an alternative to the conventional PWM control that was explained previously. To equalize transistor switching losses, the shoot-through states are shifted towards active states, as shown in Fig. 3. As a result, there is one switching transient less for bottom side transistors unchanged.

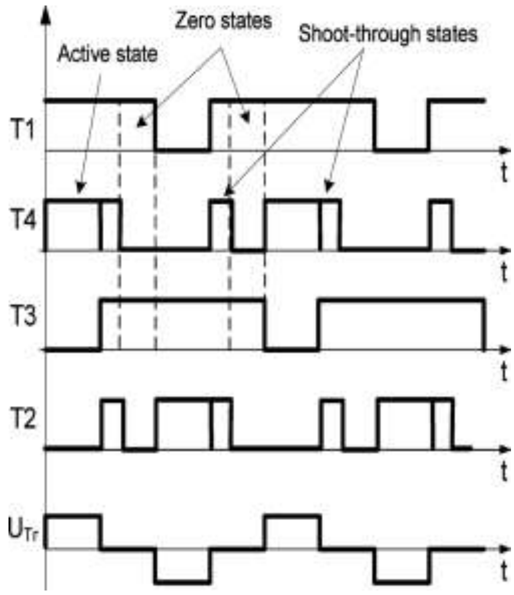

Fig. 3. Generation of PWM signals with shifted shoot-through during zero states

The states are shown for one period of the isolation transformer. As it can be seen, bottom side transistors have now two times higher operating frequency compared to the top side transistors. However, shoot-through states remain inside zero states, which is the condition required to keep the transformer voltage.

By shifting shoot-through states towards active states the switching losses of transistors could be balanced to some degree[5]. However, the switching frequency of top and bottom side transistors is still different, thus also switching losses. Since, the main target was to completely equalize transistor switching losses, we developed a further improvement method.

III. SIMULATION RESULTS

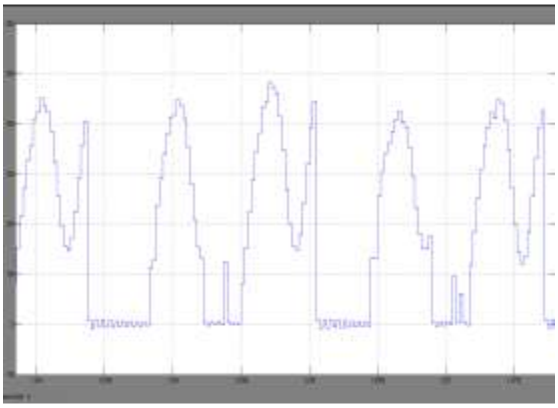

Fig. 4. impure DC output

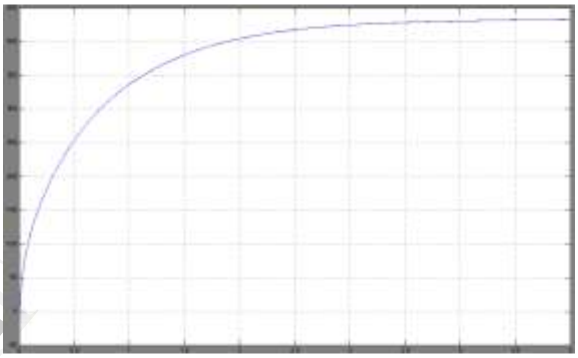

Fig. 5. pure DC output

The proposed new PWM control method together with two swapping techniques was simulated within PSIM simulation software. To predict the behavior of the real converter accurately, also some losses were taken into account: input inductors have internal resistance, diodes, and transistors have forward voltage drop. Operation parameters of the investigated converter were selected for the case of maximal voltage boost when the maximal current in the input side of the converter appears. The converter was loaded by the 300 resistor and the system power was around 1 kW. In the case of the conventional PWM control with shoot through, full soft switching (i.e., ZVS and ZCS) is possible for top side transistors. Moreover, soft switching is achieved for both: shoot-through and active states, Bottom side transistors are hard switched.

IV. EXPERIMENTAL VERIFICATION

Microcontrollers generate PWM using timers and compare values. As a rule, conventional microcontrollers have only one or two compare values per timer, which is enough in most cases. Currently, the situation is more complicated due to shoot-through states. To generate PWM with shoot-through states up to five compare values (cp1–cp5) are needed.. In other words, this means that PWM with shoot-through is impossible to be implemented on most of microcontrollers. Three methods can be considered as a solution to the problem:

1) Using a FPGA;

2) Using a microcontroller combined with a FPGA;

3) Using a microcontroller combined with an external logic circuitry.

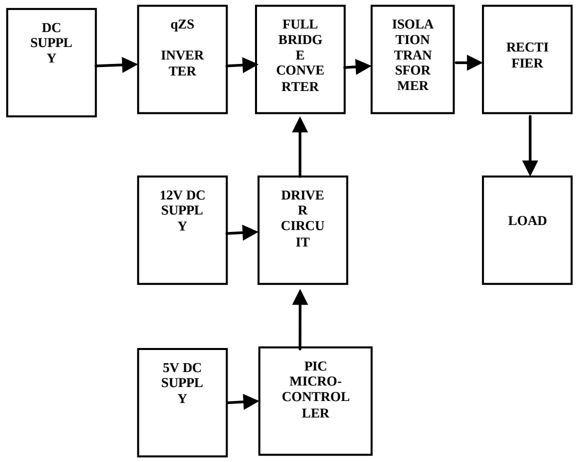

Fig. 6. Block diagram of the proposed system

A FPGA, as a highly configurable hardware that contains thousands of programmable logic blocks, could perfectly take the role of a modulator. At the same time, relatively poor performance in handling sequential algorithms and floating point calculations makes it an impractical solution as a regulator. The second option has higher prospects from that point of view. A FPGA could be used as a modulator while the microcontroller could handle all the needed calculations and measurements in the converter. The third option should be considered when the price and the development time are dominant parameters. The main idea here is to generate the shoot-through vector separately from PWM and mix signals by the help of an external logic.

Swapping can occur at any time instant but should not affect the transformer voltage. As mentioned before, this is only possible with diagonal swapping, i.e., diagonally placed transistors of a full-bridge will be swapped. Two control signals and the transformer primary voltage. As expected, no disturbances can be recognized in the transformer voltage despite swapping and the converter is working normally.

V. CONCLUSIONS

A new modulation method, PWM with shifted shoot-through for qZS-based dc/dc converters, was proposed and analyzed by this paper. Transistors are replaced by capacitors and thus the voltage stress is reduced across the switch. Thus the component rating of qzsi is very low compared to existing inverters and high efficiency is achieved.

ACKNOWLEDGMENT

Author is thankful to the Electrical department in Hindusthan college of Engineering and Technology for providing required experimental setup.

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