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Dynamic modeling and control system design of the buck-boost-based three-state three-phase Z-source inverter

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A B S T R A C T

In order to deliver power from low voltage sources to the distribution level loads, the key element is the interfacing stage, traditionally formed by a dc-ac power converter, an output filter and a step-up transformer. However, transformerless converter topologies naturally present lower cost and size when compared with conventional solutions. As counterpart, transformerless systems need a boost conversion stage to compensate the absence of the step-up transformer. The two-stage converter (dc-dc boost converter plus voltage source inverter) has the step-up stage necessary to connect the low voltage source to the load, at a cost of more complexity and high leakage currents circulating in the system. The complexity issue can be overcome by using one-stage step-up plus inversion configuration such as the Z-source inverter, although the leakage current problem will persist. In order to solve both issues, this paper proposes a three-state three-phase Z-source inverter (TS3ph-ZSI) that presents an intrinsic buck-boost plus inverter characteristic, featuring a common ground between source and load (dual ground configuration), responsible to eliminate the leakage currents in the system. This topology is especially useful for transformerless photovoltaic systems. The theoretical analysis of this topology, including its modeling and control system design, is carried out and validated by the simulation and experimental results.

1. Introduction

It is worth noting that transformerless inverters, when processing power from low voltage sources, require a voltage boost stage in order to maintain the dc bus voltage level suitable for transferring power from the source to the load or grid. This problem can be solved using configurations in which the required voltage step-up is obtained by a two-stage converter, consisting of a dc-dc boost converter cascaded with a voltage source inverter (VSI) [1].

The issue of the voltage step-up can also be solved using single-stage configurations, such as the Z-source inverter (ZSI) [2,3] that presents an intrinsic boost plus inverter characteristic. Some authors have shown that the number of switches and the volume of the converter can be reduced, decreasing the total cost of the system [4]. Despite its clear advantages, the ZSI originally proposed in [2] presents relatively low efficiency and high circulating leakage currents [5].

In order to solve the issue of high leakage currents, especially useful for transformerless photovoltaic systems [6], a family of transformerless single-phase converters with dual-grounding configuration (common ground between the input dc source and the output ac load) has been proposed in literature. Berkovich et al. proposed in 2007 a family of converters, in which some of them presented dual-grounding, eliminating the circulation of leakage currents [7]. An interesting feature of those converters is the use of the semi-Z impedance, a block formed by a switch, two inductors and two capacitors, capable of generating an output voltage in both polarities, similar to a half-bridge inverter. Nevertheless, the boost capability of those topologies was limited only to the negative polarity of the output voltage. Huang et al. proposed in 2013 a similar dual-grounding topology using also the semi-Z impedance, in which the boost capability was limited only to the positive polarity of the output voltage [8]. In the same paper, Huang et al. modified this topology, generating a family of three-switch three-state inverters (TSTS-ZSI) [8], presenting higher efficiency than the single-phase ZSI and the two-stage converter, dual-grounding and capability of boosting the ac output voltage in both polarities.

A three-phase topology based on the TSTS-ZSI, called TS3ph-ZSI, re-

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quiring only one additional switch when compared with the original three-phase ZSI has been proposed in [9]. Although promising, the converter was not modeled and no control strategy was presented. The authors only applied the converter in a three-phase transformerless photovoltaic system, with simplified open-loop simulation results. Since single-stage, high efficiency and dual-grounding are positive features of transformerless systems, it is clear the potential of the TSTS-ZSI-based topologies, justifying further studies. Based on a careful literature review, it was not found any work related to the converter model and its closed-loop control for both single-phase and three-phase TSTS-ZSI configurations.

This paper aims to provide the mathematical modeling and the control system design of the buck-boost-based three-state three-phase Z-source inverter (TS3ph-ZSI). The paper is organized as follows. In Section 2, the dynamic model of the single-phase TSTS-ZSI is deduced with the objective of designing a closed-loop control for the output voltage and its boost gain. Two three-phase topologies, derived from the single-phase TSTS-ZSI, are presented in Section 3, including their dynamic model. The first topology is deduced from the association of three single-phase TSTS-ZSI, one for each phase, presenting nine switches. In order to obtain a cost reduction and simplification of the inverter, it was observed that two of the switches can be eliminated, leading to the second topology with seven switches (TS3ph-ZSI). The TS3ph-ZSI components are defined by pole-zero maps analysis for different operation points. Thus, the control system design is presented in Section 4 and validated by experimental results in Section 5. Finally, Section 6 presents the conclusions of this work.

2. Dynamic modeling of the three-state single-phase ZSI

In order to design the proposed TS3ph-ZSI it is necessary to develop dynamic models [10,11] that can support the design of the control strategy. The single-phase TSTS-ZSI presented in Fig. 1(a) was proposed in [8] and it is the basis for the TS3ph-ZSI. However, the previous publications only developed steady-state models for both single-phase and three-phase converters, unsuitable for designing the control system [8,9]. It is possible to note in Fig. 1(a) the semi-Z impedance, a common structure in those dual-grounding topologies, formed by the semi-Z inductors L_1 and L_2, the semi-Z capacitors C_1 and C_2 and the semi-Z switch S_2.

In order to select the best controller for the single-phase TSTS-ZSI, first it is necessary to develop a mathematical model that reproduces its dynamic behavior. For this, a set of state-space equations are carried out by observing the equivalent circuits in Fig. 1(b)–(d). In these figures, the operation of the TSTS-ZSI is divided into three states [8]: State

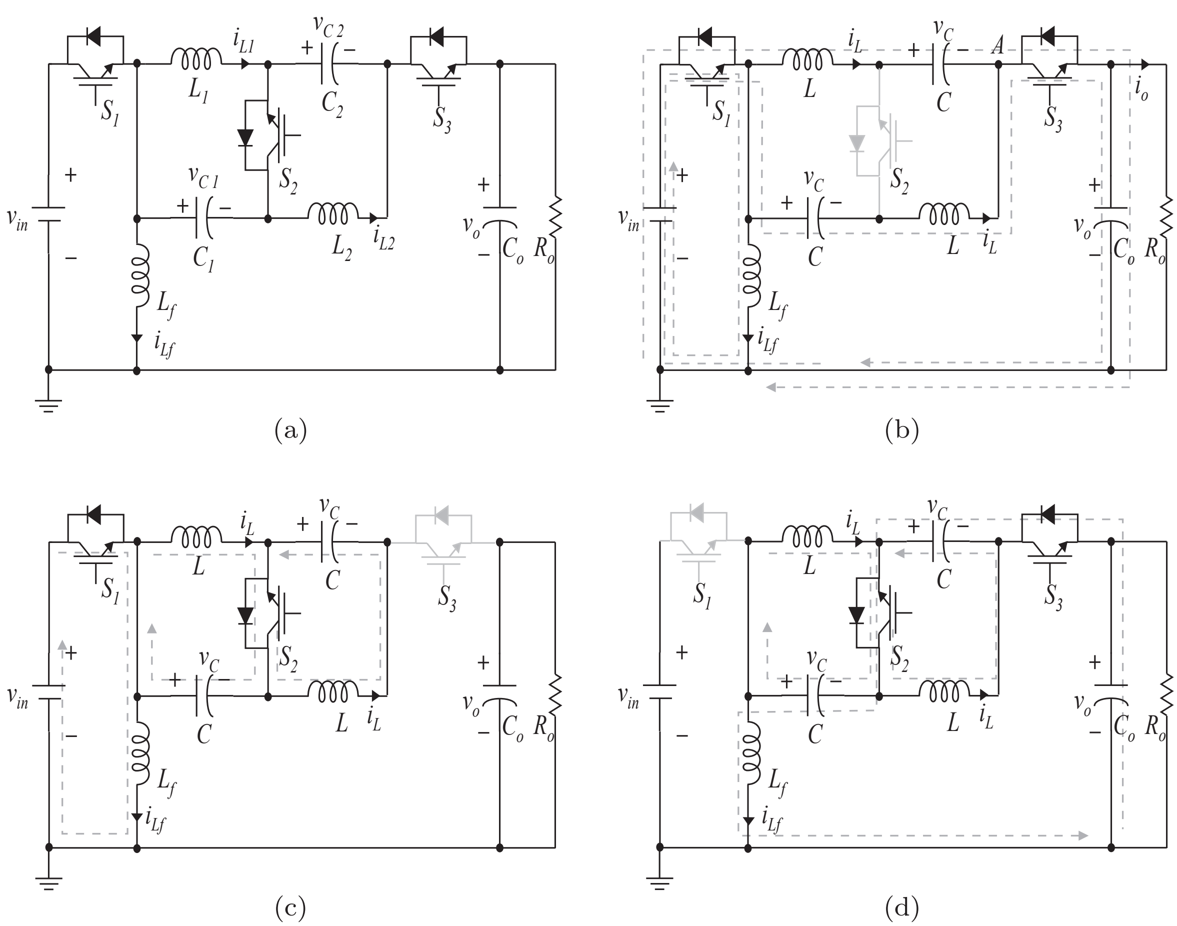

Fig. 1. (a) Buck-boost-based TSTS-ZSI proposed in [8]; (b)–(d) three possible states for the TSTS-ZSI: (b) State 1: S1 and S3 are on, S2 is off; (c) State 2: S1 and S2 are on, S3 is off; (d) State 3: S2 and S3 are on, S1 is off.