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Small signal modeling and transient analysis of a Trans quasi-Z-source inverter

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ABSTRACT

This paper proposes, analyses and validates, both computationally and experimentally, an AC small signal model for a Trans quasi-Z-source inverter working in continuous conduction mode (CCM). For the implementation of the small-signal model, the dynamics of the particular Trans-qZSI network components have been considered. The presented AC small signal model is used for a detailed analysis of the performance of the Trans-qZSI topology, involving various aspects; a parametric study of the influence of the passive components on the dynamic response of the Z network, as well as the influence of their associated losses. Duty cycle and load variations are studied too, for Z topology operating point performance analysis. The AC small-signal model is then used to design a compensator for a closed-loop control scheme. Computer simulation results are presented to validate the model and the control method, comparing PSIM Trans-qZSI detailed simulations to the MATLAB derived results. Finally, experimental validation is achieved for the AC model in a low-medium power Trans-qZSI design, both in time and frequency domain. According to experimental results analysis, a snubber circuit is designed too, for the converter.

1. Introduction

Recently, a great deal of effort has been put into developing converters that meet the DC–AC conversion requirements of the electric vehicle (EV) applications. So, VSIs are widely used, as they increase the overall efficiency of traction drive systems [1] by properly regulating the DC-link voltage. It is known that the VSI voltage gain is DC-link dependent and always less than unity (if over modulation is avoided). Depending on the AC load requirements, the DC–AC converter could be demanded to perform in boost mode, which is not achievable with a standard VSI. For that purpose, an additional DC–DC boost stage could be implemented and attached to the VSI input side, so a regulated and higher DC-link voltage can be obtained. This solution brings additional cost to the overall conversion device. In this context, more direct buck-boost DC–AC topologies emerged.

The Z-source inverter (ZSI), which was first proposed in 2002, is a power converter with both buck and boost capabilities in a single conversion stage [2], so it can overcome the aforementioned limitations. Since then, researchers have proposed alternative topologies of ZSI [3–14], some focused on reducing the component count maintaining the boost factor [3,7], some focused on achieving higher boost factors, regardless of the component count [5,6,9]. Transformer-based quasi Z-source inverters (Trans-qZSI), are focused in improving the boost factor with lower component count; Transformer-based quasi Z-source inverters (Trans-qZSI), first presented in 2011 [8], and further developed [15], introduced magnetic coupling inductors into the original quasi-Z-source inverter, as shown in Fig. 1(a) [14].

The first studies of the control for Z-source inverters were focused on modifying the existing pulse width modulation (PWM) switching algorithms [16–19]. These modified PWM strategies, apply a proper shoot-through duty ratio, consisting of short-circuiting the upper and lower switches of the same branch (e.g. by turning on S1 and S4 in Fig. 1(a)), in order to produce a flexible and regulated AC output voltage. The PWM methods developed for traditional ZSIs, are also applicable to other Z source inverters like the Trans-qZSI.

In order to design controllers for Trans-qZSIs, proper dynamic modelling and analysis are needed. In the case of EV motors, a fixed DC-link voltage (v_i) is usually required, so small perturbations must also be considered. This paper will develop a small signal model that

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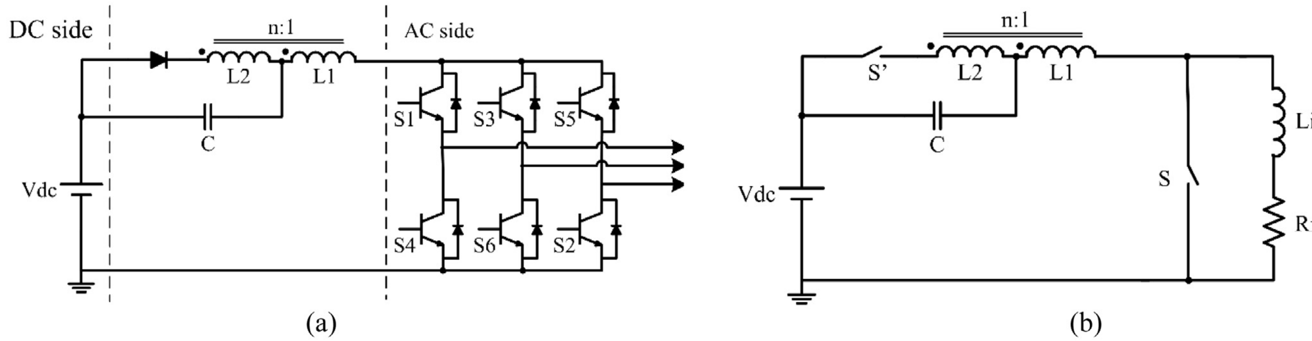

Fig. 1. Trans-qZSI. (a) Tras-qZSI original model and (b) simplified model.

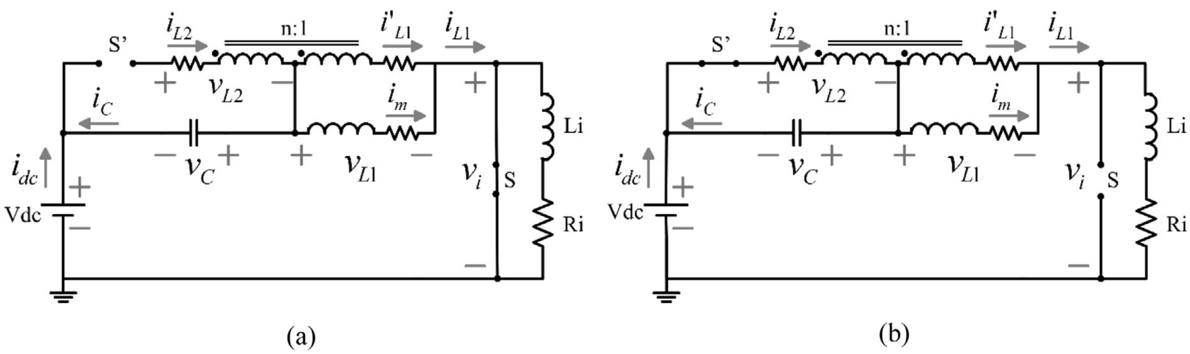

Fig. 2. Operating states of the Trans-qZSI. (a) Equivalent circuit during shoot-through zero state and (b) during non-shoot-through zero state.

provides both global and a detailed analysis of system dynamics to be used in control algorithms, identifying several phenomena on the DC and AC sides of the inverter.

A number of publications [20–22] have contributed to the dynamic modelling and transient analysis of the Z network. This paper will build upon those, but considering the coupled inductor to be non-ideal, in order to develop a more accurate model for the Trans-qZSI topology, as the losses in the inductor will greatly influence the performance of the system.

The main contribution of this paper is the AC small signal modelling, which takes into account the internal losses of the coupled inductor, and, thus, the analysis of a Trans-qZSI in continuous conduction mode (CCM) subjected to small perturbations. The conducted analysis and methodology are meant to provide guidelines for the dimensional design of these inverters as well as to assist the design of the controller's closed loop.

In Section 2 the AC small signal models for the Trans-qZSI in CCM are derived based on the state space averaging method. From there, the most relevant transfer functions for the voltages and currents in the circuit are obtained in Section 3. According to these functions, a design-oriented analysis is conducted in Section 4. In Section 5, the proposed model is validated through computer simulations, and a compensator is designed for the closed-loop control. In Section 6 the proposed model and methodology are validated experimentally, and finally conclusions are drawn in Section 7.

2. Derivation of AC small signal model

Some studies [20,22–24], confirm that the operation of Trans-qZSIs can be illustrated by simplifying the AC side circuit to an equivalent DC load (or source). The model used for the analysis is shown in Fig. 1(b), it is the simplified circuit where the load, consisting of an inductor (L_i) in series with a resistor (R_i), in the end, represents the current i_i that will be demanded to the converter. This load is in parallel with an active switch S, which performs the aforementioned shoot-through. Using this representation, the PWM modulation is not considered so the analysis can focus on the dynamics of the Trans-qZ network.

The proposed small signal modelling and analysis begins with the following assumptions.

1. The Trans-qZSI is operating in CCM.
2. The capacitor, C, is lossless, nevertheless, the internal resistances associated to the inductances, L_m, L_1 and L_2 will also be considered, to analyze their effect on the response.
3. The input voltage V_{dc} is an independent voltage source.
4. The on-resistance (R_{on}) of switch S is much smaller than the load impedance, the R_{on} effect is neglected in the derivation.

Two states involving two different circuit topologies can be identified in Trans-qZSI operation [8], Fig. 2(a) and (b). During the shoot-through state (ST), no energy is transferred from the source to the load because the load side and source side are decoupled and the S' is off (Fig. 2(a)). The shoot-through duty ratio, D, of S is equal to T_0/T_S, where T_0 is the time-interval of the shoot-through state during one switching period T_S. During the non-shoot-through state (NST), energy is transferred between source and load, Fig. 2(b), S' is on and its duty ratio is $D' = (1 - D)$.