

Three-Phase Z-Source Power Supply Design and Dynamic Modeling

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Abstract— Z-source converter configurations make possible to overcome intrinsic limits present in conventional both ac-dc and dc-ac converters. A typical three-phase inverter can not supply output voltages greater than the voltages at its input; at the same manner, a typical three-phase boost-rectifier can not supply output voltages lower than input voltages. Using Z-source topology permits to overcome both these limits. In fact, a Z-source boost-rectifier can theoretically step-down the output voltage to any desired value. Additionally, it presents intrinsic immunity to shoot-through states, relaying to improved reliability of the entire system. In this paper, attention is focused on the mathematical modeling of a three-phase Z-source boost-rectifier for PFC power supply applications; where, using of such a topology as first-stage converter allows to design the second-stage converters with the same voltage constraints of single-phase units.

I. INTRODUCTION

For the present generation of three phase power supply converters, the cost of the entire system is an important issue to be considered during the design process alongside the overall performance. The front-end converter for power supply applications must achieve high power factor, low harmonic distortion, high efficiency, high reliability and low electromagnetic interference (EMI) noise. One of the conventional practices, commonly used to obtain three phase power supply converters, is the use of a two-stage approach based upon single-phase power modules [1], the first stage of each module is used to perform the PFC function to meet harmonic current standards such as the IEC 61000-3-2, while the second-stage dc-dc converter regulates the dc output voltage of the system and guarantees system current sharing. Usually, for proper operation of a two stage power supply, the intermediate bus voltage must be slightly higher than twice the input phase peak voltage, which means that the voltage rating of the boost power switches must be at least 700V in applications for which the rated line-to-line input

voltage is 400V. Same requirement for the intermediate bus voltage is expected in three phase boost rectifiers. As a consequence, the switches of the second stage dc-dc converter will experience high voltage stress unless a three-level structure is used for the dc-dc converter [2-5]. A significant breakthrough in simplifying the single-phase modules was achieved by some rectifiers [6, 7]. The VIENNA rectifier can be seen as a simplified version of three single-phase PFCs connected to the same intermediate bus voltage.

The Z-source topology can be proposed as the first stage of a three-phase PFC in order to reduce the dc-link voltage down to 400V; as a consequence same design of single-phase PFC second stage can be used also for three-phase applications where parallel connection of two or more second stage units can be used at occurrence, thus reducing design, manufacturing and maintenance costs. Same benefits can be achieved when the proposed three-phase Z-source boost rectifier is applied to distributed generation systems where either wind or diesel generation units are considered [8]. The Z-source configuration has not cost advantages when compared to the conventional 3-phase boost rectifier and a simple control method is used; in fact, the additional Z-section components represent an additional cost whereas input filter as well switching components have the same size and cost of the conventional configuration [9]. However, the opportunity of 400Vdc as dc-link voltage even with 3-phase line-to-line 400Vac power supply grid is highly valued when second stage power electronic units are required as in telecom applications and in auxiliary dc power supply systems in general.

The paper presents the modeling of a 10kW rated three-phase Z-source boost rectifier which is intended to operate as first stage of a two-stage PFC power supply. Control transfer functions are derived in both steady state and dynamic state. Further, the influences of main circuital parameters on system dynamics are described. Main criteria for the Z-source boost rectifier input filter design are discussed as well a design algorithm is proposed for the Z-section LC

components The control transfer functions are then used to design regulators of the control loops, a prototype of the converter has been built and experimental results are discussed.

II. THREE-PHASE Z-SOURCE BOOST RECTIFIER MODELING

A. Steady State

A three-phase Z-source boost-rectifier presents the same circuitual configuration of the conventional three-phase boost-rectifier, with the addition of a particularly shaped impedance network (L_1, L_2, C_1, C_2) and an additional switch (S_7) as shown in Fig. 1. Proper synchronization of the additional switch gate command with the three-phase switching bridge driving pulses it is possible to achieve ideally whatever output voltage. In particular, this feature is achieved using functional states of the three-phase switching bridge, the shoot-through states, that in typical three-phase converters are potentially harmful. The presence of the particularly shaped impedance network, allows using these states without damages to the converter. Fig. 2 depicts the operating states of the additional switch; during typical three-phase bridge operating states, the additional switch S_7 being connected to the impedance network is turned on; whereas, during conventional zero state condition the shoot-through condition can occur and the switch S_7 is turned off.

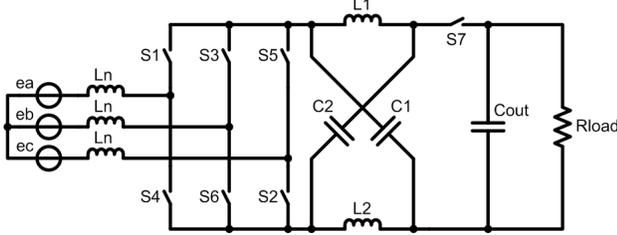


Figure 1. Three-Phase Z-source boost-rectifier

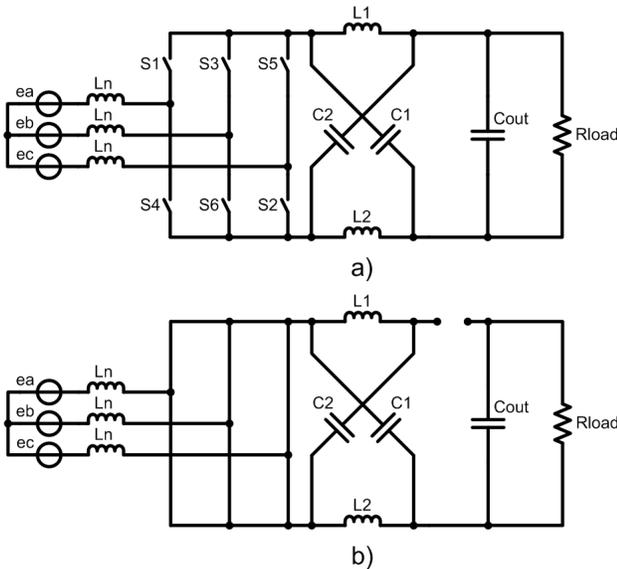


Figure 2. Z-source boost-rectifier additional switch operating states

Past literature [10, 11] well describes the circuit analysis and the steady state ideal ratio between ac voltage and dc voltage; as well voltage stress on Z-source converter both switches and diodes and current and voltage across on Z impedance devices have been already satisfactorily investigated. The peak phase voltage results $e_{pk} = M \cdot V_{dc} / 2 \cdot B$ where M is the modulation index and B is the buck factor in the ac-dc boost rectifier configuration. The B factor results from the shoot-through zero state and S_7

turning off. B is defined as $B = \left(2 \cdot \frac{T_7}{T} - 1 \right) \leq 1$ where T_7 is

the time on of the switch S_7 , corresponding to the sum of the time intervals the three-phase converter is in one of the eight non-shoot-through states during a switching cycle T. Appropriate values for T_7 allow 400V as dc link voltage with typical line-to-line grid voltage of $400V \pm 10\%$.

When it is used the simple control method, that employs equal to or greater than the peak value of the three phase references to control shoot-through duty ratio in traditional sinusoidal PWM, the Z-source boost rectifier maintains the 6 active states unchanged as the conventional carrier based PWM control. For this simple control, the achievable shoot-through duty ratio decreases with the increase of M. The maximum shoot-through duty ratio of the simple control is limited to $(1-M)$, thus reaching zero at the modulation index of one[11]. As a result, the voltage stress across switches and diodes is directly related to the line-to-line grid voltage and modulation index; for this reason, it is convenient to keep M as high as possible according to the acceptable values for the B factor and the desired output dc voltage. Suitable values for M index and B factor are further discussed in Section III for the specific proposed application.

Steady state modeling is achieved, assuming a symmetrical Z impedance network ($L_1=L_2, C_1=C_2$), by considering three equations for the a, b, c axes, two equations for the Z impedance network, and one equation for the output capacitance

$$\begin{cases} \frac{d\bar{i}_{ab}}{dt} = \frac{v_{ab}}{3L_N} - \frac{(2\bar{v}_C - \bar{v}_{Cout})d_{ab}}{3L_N} - \frac{\bar{i}_{ab}R_N}{L_N} \\ \frac{d\bar{i}_{bc}}{dt} = \frac{v_{bc}}{3L_N} - \frac{(2\bar{v}_C - \bar{v}_{Cout})d_{bc}}{3L_N} - \frac{\bar{i}_{bc}R_N}{L_N} \\ \frac{d\bar{i}_{ca}}{dt} = \frac{v_{ca}}{3L_N} - \frac{(2\bar{v}_C - \bar{v}_{Cout})d_{ca}}{3L_N} - \frac{\bar{i}_{ca}R_N}{L_N} \\ \frac{d\bar{i}_L}{dt} = \frac{\bar{v}_C(1-2d_{ST})}{L} - \frac{\bar{v}_{Cout}(1-d_{ST})}{L} \\ \frac{d\bar{v}_C}{dt} = \frac{(d_{ab}\bar{i}_{ab} + d_{bc}\bar{i}_{bc} + d_{ca}\bar{i}_{ca})(1-d_{ST})}{C} - \frac{\bar{i}_L(1-2d_{ST})}{C} \\ \frac{d\bar{v}_{Cout}}{dt} = \frac{2\bar{i}_L(1-d_{ST})}{C_{OUT}} - \frac{(d_{ab}\bar{i}_{ab} + d_{bc}\bar{i}_{bc} + d_{ca}\bar{i}_{ca})(1-d_{ST})}{C_{OUT}} - \frac{\bar{v}_{Cout}}{R_{LOAD}C_{OUT}} \end{cases} \quad (1)$$

where L_N, R_N and C_{OUT} are the boost rectifier respectively input phase inductance and series resistance and output dc-link capacitance, L and C are the Z impedance network elements, i_{xy} and v_{xy} (with $x=a, b, c$ and $y=a, b, c$) are the

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