Space-Vector-Modulated Three-Level Inverters With a Single Z-Source Network

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***Abstract*—The Z-source inverter is a relatively recent converter topology that exhibits both voltage-buck and voltage-boost capability. The Z-source concept can be applied to all dc-to-ac, ac-to-dc, ac-to-ac, and dc-to-dc power conversion whether two-level or multilevel. However, multilevel converters offer many benefits for higher power applications. Previous publications have shown the control of a Z-source neutral point clamped inverter using the carrier-based modulation technique. This paper presents the control of a Z-source neutral point clamped inverter using the space vector modulation technique. This gives a number of benefits, both in terms of implementation and harmonic performance. The adopted approach enables the operation of the Z-source arrangement to be optimized and implemented digitally without introducing any extra commutations. The proposed techniques are demonstrated both in simulation and through experimental results from a prototype converter.**

***Index Terms*—Buck–boost, neutral point clamped inverter, space vector modulation (SVM), Z-source inverter.**

I. Introduction

MANY industrial applications require higher power converters (inverters) which are now almost exclusively implemented using one of the multilevel types. Multilevel converters offer many benefits for higher power applications which include an ability to synthesize voltage waveforms with lower harmonic content than two-level converters and operation at higher dc voltages using series connection of a basic switching cell of one type or another [1]–[4].

Even though many different multilevel topologies have been proposed, the three most common topologies are the cascaded inverter [5]–[7], the diode clamped inverter [8]–[12], and the capacitor clamped inverter [13]–[15]. Among the three, the three-level diode clamped [also known as the neutral point clamped (NPC)] inverter has become an established topology in medium voltage drives and is arguably the most popular [16]–[19]—certainly for three-level circuits. However, the NPC inverter is constrained by its inability to produce an output line-to-line voltage greater than the dc source voltage. For applications where the dc source is not always constant, such as a fuel cell [20], [21], photovoltaic array [22], and during voltage sags, etc., a dc/dc boost converter is often needed to boost the dc voltage to meet the required output voltage or to allow the nominal operating point to be favorably located [23], [24]. This increases the system complexity and is desirable to eliminate if possible.

The Z-source inverter [25] topology was proposed to overcome the above limitations in traditional inverters. The Z-source concept can be applied to all dc-to-ac [26], ac-to-dc [27], ac-to-ac [28]–[31], and dc-to-dc [32], [33] power conversion whether two-level or multilevel. The Z-source concept was extended to the NPC inverter in [34], where two additional Z-source networks were connected between two isolated dc sources and a traditional NPC inverter. In spite of its effectiveness in achieving voltage buck–boost conversion, the Z-source NPC inverter proposed in [34] is expensive because it uses two Z-source networks, two isolated dc sources, and requires a complex modulator for balancing the boosting of each Z-source network. To overcome the cost and modulator complexity issues, the design and control of an NPC inverter using a single Z-source network was presented in [35]. The operational analysis and optimal control of the reduced element count (REC) Z-source NPC inverter was subsequently described in [36].

The REC Z-source NPC inverter is expected to find applications in grid connected distributed generation (DG) systems based on renewable energy sources such as photovoltaic systems, wind turbines, and fuel cell stacks [37]. Two DG systems can be connected to the grid with only one REC Z-source NPC inverter, thus reducing the volume and cost while increasing efficiency and facilitating control. The power quality of current injected to the grid is improved because of the three-level structure. It can also find use in adjustable speed drive systems in applications such as conveyor belts, fans, and water pumps [38].

In [36], the modulation of the REC Z-source NPC inverter was described using the carrier-based approach. However, the space vector modulation (SVM) approach offers better harmonic performance [11] (compared with carrier-based pulsewidth modulation (PWM) strategy without zero-sequence voltage injection) and can more conveniently handle overall switching patterns and constraints [39], [40], and it is simple to implement using a DSP [41]. The contribution of this paper is, therefore, the development of a modified SVM algorithm for controlling the REC Z-source NPC inverter. The theoretical development is discussed in detail, and simulations as well as experimental results are used to verify the operation of the circuit and proposed SVM-based modulation.

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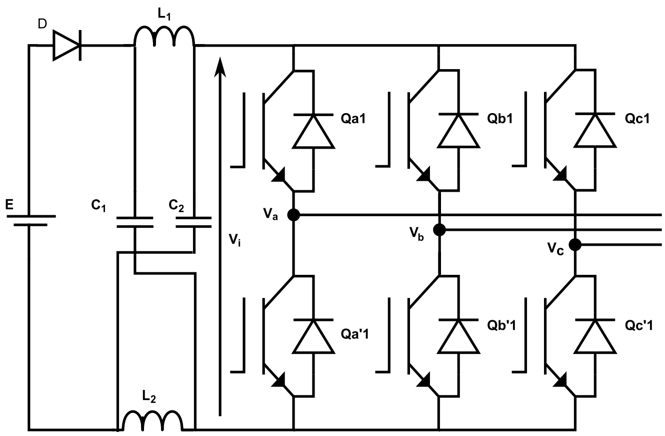

Fig. 1. Topology of two-level Z-source inverter.

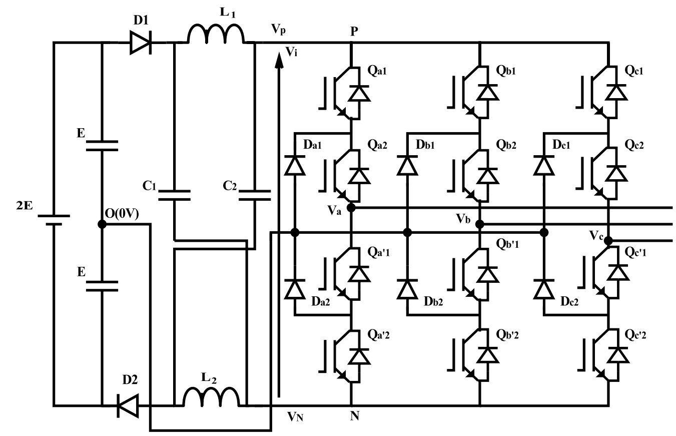

Fig. 2. Topology of an REC Z-source NPC inverter.

II. Review of Z-source Concept

The topology of a two-level Z-source inverter is shown in Fig. 1. The only difference between the Z-source inverter and a traditional voltage source inverter (VSI) is the presence of a Z-source network comprising a split-inductor (L_1 and L_2) and two capacitors (C_1 and C_2). The unique feature of the two-level Z-source inverter is that the output ac voltage fundamental can be controlled to be any value between zero and (theoretically) infinity regardless of the dc source voltage. Thus, the Z-source inverter is a buck–boost inverter that has a very wide range of obtainable output voltage. Traditional VSIs cannot provide such features.

In Fig. 1, the two-level Z-source inverter bridge has 15 permissible switching states unlike the traditional two-level VSI that has 8. The traditional three-phase VSI has six active states when the dc voltage is impressed across the load and two zero states when the load terminals are shorted through either the lower or upper three devices, respectively. However, the two-level Z-source inverter bridge has seven extra zero states (termed shoot-through states) when the load terminals are shorted through both upper and lower devices of any one phase leg (i.e., both devices are gated ON), any two phase legs, or all three phase legs. These shoot-through states are forbidden in a traditional VSI for obvious reasons. The Z-source network makes the shoot-through zero states possible and provides the means by which boosting operation can be obtained. Critically, any of the shoot-through states can be substituted for normal zero states without affecting the PWM pattern seen by the load.

Therefore, for a fixed switching cycle, insertion of shoot-through states within the zero intervals with the active state intervals maintained constant will not alter the normalized volt–second average per switching cycle seen by the ac load. Instead, with the shoot-through states inserted, the effective inverter dc link voltage V_i can be stepped up as given in (1) [25], [42]. Consequently, taking also the PWM modulation index M into account, the phase ac output voltage $V_x (x\epsilon\{a, b, c\})$ can be expressed by (2)

$$V_i = \frac{E}{(1 - 2 \cdot T_{\mathrm{ST}}/T)} = B \cdot E, \quad B \geq 1 \tag{1}$$

$$V_x = \frac{M \cdot V_i}{\sqrt{3}} = B \cdot \{ME/\sqrt{3}\} \tag{2}$$

where T_{ST} and T are the shoot-through interval and switching period, respectively, B is the boost factor and the term in parenthesis represents the phase ac output voltage of a traditional VSI. Equations (1) and (2) show that the ac output voltage of a Z-source inverter can be regulated from zero to the normal maximum by altering M and maintaining $B = 1$, or can be boosted above that obtainable with a traditional VSI by choosing $B > 1$. A similar analysis can be carried out for the current-type Z-source inverter [43]. However, since the focus of this paper is that of the voltage-type Z-source inverter, the analysis for the current-type Z-source inverter would not be discussed further due to space limitation.

III. Topology of REC Z-Source NPC Inverter

A. *Extension of The Z-Source Concept to the NPC Inverter*

To describe the operating principle of the REC Z-source NPC inverter shown in Fig. 2, we concentrate initially on the operation of one phase leg. The operation of each inverter phase leg of a traditional NPC inverter can be represented by three switching states P, O, and N. Switching state "P" denotes that the upper two switches in a phase leg are gated ON, "N" indicates that the lower two switches conduct, and "O" signifies that the inner two switches are gated ON.

However, each phase leg of the Z-source NPC inverter has three extra switching states which resemble the "O" state of the traditional NPC inverter. These extra switching states occur when all the four switches in any phase leg are gated ON [full-shoot-through (FST)], or the three upper switches in any phase leg are gated ON [upper-shoot-through (UST)] or the three bottom switches in any phase leg are gated ON [lower-shoot-through (LST)]. These shoot-through states are forbidden in the traditional NPC inverter because they would cause a short circuit of the dc-side capacitors. Again, the Z-source network makes these shoot-through states permissible and provides the means for boost operation.