Decoupled Maximum Constant Boost Control for Quasi-Z-Source Inverter

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Abstract—**Maximum Constant Boost Control (MCBC) is one of the most suitable modulation techniques for Z-Source Inverters (ZSI) and quasi-ZSI (qZSI). Nevertheless, it cannot decouple the output voltage control and the fluctuations of the voltage source at the input of the inverter. This work proposes a new method based on this modulation technique that allows decoupling the control of these two variables, input and output voltages of a qZSI. The simulation results show that the Decoupled Maximum Constant Boost Control (DMCBC) has the same features and advantages than the one without decoupling.**

Keywords—Impedance Source Inverter, Modulation Technique, Maximum Constant Boost Control, Decoupling

I. INTRODUCTION

Since the appearance of the ZSI [1], they have shown better behaviour than conventional Voltage Source Inverters (VSI). The impedance network between the converter and the power source allows the converter to work in a single-stage, integrating DC-DC boost and inverter into the same element, which is an interesting alternative for renewable energy systems. At the same time, they avoid some problems of the VSI, such as: 1) buck or boost a voltage; 2) short-circuit of the input terminal when both switches of any phase leg are gated simultaneously (Shoot-Through State, STS); and 3) there is no need to add any dead time into the control schemes, which reduces the output distortion [2].

The impedance network has been profusely modified from the basic structure [3] in order to improve boost voltage in the converter [4] or reduce the sizing of the impedance network [5]. In this last objective, qZSI stands out for lower component ratings and drawing a continuous and constant DC current from the source to the inverter, which is easier to assemble and causes less EMI problems [6].

The main difference between ZSI and VSI modulations is based on a new state in the commutation, the STS, where both the upper and the lower switches of any leg conducts simultaneously. Thus, ZSI has two types of operational states: 1) Non-Shoot-Through states (NSTS), the same as the VSI, and 2) STS, where the impedance network boots the DC-link voltage [7].

Some three-phase ZSI modulation schemes and techniques have been proposed in the literature as modifications of VSI methods. In fact, they are classified in: 1) Pulse-Width-Modulation (PWM) methods and 2) Space-Vector (SV) methods [8]. PWM methods try to integrate the STS in classical PWM techniques to achieve maximal voltage boost, minimal harmonic distortion, low semiconductor stress, and a minimum number of devices commutation per switching cycle. There are some comparatives studies between different PWM methods in the literature [9][10][11][12]. In these studies, the modulation technique known as MCBC presents better global features than other classical techniques. For this reason, this technique has been used in energy systems with ZSI.

In [13] this technique was analysed for multiphase ZSI to overcome both limits and problems in three phase systems as well as quality of the outputs voltages and currents. A bidirectional qZSI was used in [14] for interlinking converter application in hybrid AC-DC microgrids for both grid-connected and islanded modes of operation in presence of unbalanced AC loads. Nevertheless, the proposed MCBC was a simple boost control with third-harmonic injected modulation. In most of the cases, the DC source was a photovoltaic generation system like in [15], where the photovoltaic system was controlled by means of Particle Swarm Optimization (PSO)-tuned PI controllers or by controllers based on PI and fuzzy logic in [16].

The main problem of the MCBC method is that both operation states, STS and NSTS, are related in order to obtain the maximum boost voltage. Only Ref. [17] presented a multilevel single-phase qZSI, where the authors reported on the decoupled control of the input and output voltages of the qZSI, but they did not show how to decouple both control signals.

This paper presents a new method based on MCBC for the decoupled control of the input and output voltages of qZSI, which considers a new control signal to modify the STS displacement.

II. TOPOLOGY OF QZSI

The topology of the proposed qZSI under study is shown in Fig. 1. As can be seen, the system considered in this work contains: a VSI; an impedance network connected to the DC side; an AC load connected to the AC side of the inverter; and a DC voltage source connected to the input of the impedance network.

The VSI has a control circuit to produce the firing signals of the power devices in accordance with the particular modulation technique.

The parameters of the load are R = 49.38 Ω, and L = 326 mH. The parameters of capacitors C1 and C2 of the impedance network are the same and equal to 2.139 mF. The parameters of the coils, L1 and L2, are the same and equal to 95.3 mH. The DC voltage source (V_{dc}) at the input of the impedance network has a value of 500 V.

III. MCBC AND DECOUPLING OF THE DUTY CYCLE

Simple Boost Control (SBC) was the first modulation techniques proposed for qZSI [1]. It is based on a modified PWM (SPWM) sinusoidal technique. One of the features of

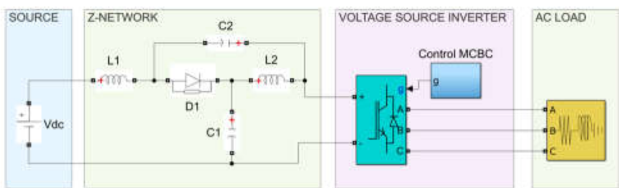

Fig. 1. Topology of the system under study

this technique is that the modulation index (M) and the duty cycle (D) of the STS are not related and can be controlled independently, which is very useful for certain applications of qZSI.

The second modulation technique proposed in the literature was Maximum Boost Control (MBC) [18]. This technique offers greater voltage gain than SBC using the positive and negative envelope curves of the modulating signals as levels of the STS. But the value of D is not independent of the value of M.

MCBC technique was proposed by [19] as an alternative to the MBC. It was designed to reduce the volume and cost of the impedance network. It also offers a low voltage ripple value in the capacitors, and low current ripple value in the inductors of the impedance network, and a low voltage stress in the inverter input. To achieve this, the ST duty ratio in MCBC remains constant.

As shown in Fig. 2, this modulation technique involves 6 signals:

- a triangular carrier signal of frequency f_c and unit amplitude (green signal in Fig. 2);
- three sinusoidal modulation signal of amplitude M (red, blue and yellow signals in Fig. 2), which is given by

$$\begin{aligned} v_a &= M \sin(\omega_1 t) \\ v_b &= M \sin(\omega_1 t - \tfrac{2\pi}{3}) \\ v_c &= M \sin(\omega_1 t + \tfrac{2\pi}{3}) \end{aligned} \quad (1)$$

where $\omega_1 = 2\pi f_m$;

- two reference signals for the STS, called v_p and v_n (violet and cyan signals in Fig. 2), which are expressed by

$$vp = \begin{cases} M\{\sqrt{3} + \sin(\omega_1 t - {}^{2\pi}/_{3})\} & \rightarrow \quad 0 \le \omega_1 t \le {}^{\pi}/_{3} \\ M \cdot \sin(\omega_1 t) & \rightarrow \quad {}^{\pi}/_{3} \le \omega_1 t \le {}^{2\pi}/_{3} \end{cases}$$
$$vn = \begin{cases} M \cdot \sin(\omega_1 t - {}^{2\pi}/_{3}) & \rightarrow \quad 0 \le \omega_1 t \le {}^{\pi}/_{3} \\ M\{\sin(\omega_1 t) - \sqrt{3}\} & \rightarrow \quad {}^{\pi}/_{3} \le \omega_1 t \le {}^{2\pi}/_{3} \end{cases} \quad (2)$$

These two signals are characterized because the distance between both of them remains constant and equal to $\sqrt{3}M$. For this reason, the ST duty ratio is constant and can be expressed by

$$D = \frac{T_0}{T} = 1 - \frac{\sqrt{3}M}{2} \quad (3)$$

The boost factor B and the voltage gain G are respectively given by

$$B = \frac{1}{\sqrt{3}M - 1} \quad (4)$$

$$G = M \cdot B = \frac{M}{\sqrt{3}M - 1} \quad (5)$$

A. Decoupling of the Duty Cycle

Compared to the other two techniques (MBC and SBC), MCBC control method offers the advantages described above. But both, MCBC and MBC, have a great drawback for certain applications of qZSI, that is, the dependence between D and M. This dependence offers maximum amplification, but it does not allow that D and M can be modified their values independently. This feature becomes necessary for certain applications, such as in photovoltaic systems, where the decoupling between D and M allows independent control of the voltage gain of the inverter and maximum power point tracking (MPPT) of photovoltaic panels. This can be done with the SBC technique, where the output voltage is controlled by M and the MPPT is achieved by the control of D.

In order to achieve the benefits offered by the MCBC technique, and also to use it in applications where the decoupled control of M and D is needed, this work proposes a new control technique based on MCBC, where the average values of the new reference signals for v_p and v_n can be shifted vertically a distance F, called offset. In this modified technique, the signals v_p and v_n can be determined by the following expressions:

$$vp' = \begin{cases} M\{\sqrt{3} + \sin(\omega_1 t - {}^{2\pi}/_{3})\} + F & \rightarrow \quad 0 \le \omega_1 t \le {}^{\pi}/_{3} \\ M \cdot \sin(\omega_1 t) + F & \rightarrow \quad {}^{\pi}/_{3} \le \omega_1 t \le {}^{2\pi}/_{3} \end{cases}$$
$$vn' = \begin{cases} M \cdot \sin(\omega_1 t - {}^{2\pi}/_{3}) - F & \rightarrow \quad 0 \le \omega_1 t \le {}^{\pi}/_{3} \\ M\{\sin(\omega_1 t) - \sqrt{3}\} - F & \rightarrow \quad {}^{\pi}/_{3} \le \omega_1 t \le {}^{2\pi}/_{3} \end{cases} \quad (6)$$

These signals are shown in Fig. 3. Given the above, in this new modified technique, the D still remains constant, but it takes the value (D')

$$D' = \frac{T_0}{T} = 1 - \frac{\sqrt{3}M + 2F}{2} \quad (7)$$

As can be seen in Eq. (7), D' is a function of M and F. A suitable choice of the offset value can allow M and D to be

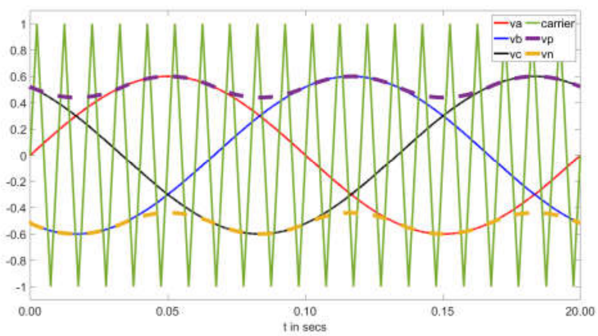

Fig. 2. MCBC signals

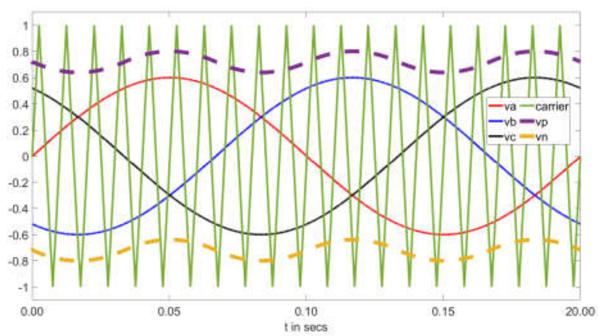

Fig. 3 MCBC signals with offset

independently modified. The values of the boost factor *B'* and the voltage gain *G*' can be expressed as follows:

$$B' = \frac{1}{\sqrt{3}M+2F-1} \tag{8}$$

$$G' = M \cdot B' = \frac{M}{\sqrt{3}M+2F-1} \tag{9}$$

With this new strategy, maximum amplification is not achieved, but the decoupling of *D* and *M* is achieved, maintaining the advantages of the MCBC over the SBC.

IV. Simulation Results and Disccussion

The behaviour of the system under study is analysed in this section when it is controlled with the new modulation technique proposed in this work. The aim of the study is to test how the offset level *F* affects the MCBC modulation and if it can work in a similar way than SBC technique, decoupling the modulation index and the ST duty cycle.

The proposed system with decoupled MCBC modulation technique has been simulated in MATLAB/Simulink. It is considered an output voltage frequency of 50 Hz, while the carrier frequency is twenty-one times higher, that is 1050 Hz. On the other side, the amplitude of the output voltage depends on the gain level of the specific case study.

Some case studies have been considered to verify the decoupled MCBC technique. Thus, the first case study considers how the voltage gain changes when the offset *F* is different from zero. The second case study analyses the devices voltage stress when the duty cycle is decoupled of *M*. The last case study examines the THD of the output voltage when *F* is modified while *M* remains constant. Additionally, a comparison between MCBC and SBC techniques has been implemented in order to verify that the proposed technique presents better behaviour than decoupled SBC.

A. Case 1: Voltage Gain (G) versus Modulation Index (M)

The decoupled MCBC modulation technique has been tested in open loop with a constant *F* and a variable *M* from zero to a value near its asymptote. The reference curve is the one with a null offset, that is, the curve shown in Fig. 6 of Ref. [19] with maximum gain and a asymptote value of $\sqrt{3}/3$. Furthermore, six curves with different *F* have been obtained, from 0.05 to 0.4. In these curves, the gains and the asymptote value decrease according to the expression $\sqrt{3}/3.(1-2F)$.

Fig. 4 depicts the different curves of *G* versus *M* for a constant *F*. The typical curve shown in the literature with null offset is depicted in blue color, including the theoretical limit obtained from Eq. (5). The rest of the curves are obtained by simulations with different *M* and constant *F*. As can be seen, the shapes of the curves are very similar, but with a left displacement to lower gains and asymptotes. As a result of the above, the system can work properly with offset greater than zero, with a decoupled ST duty cycle. Thus, the system works in a similar way as SBC modulation technique, but with greater voltage gain.

B. Case 2: Voltage Stress (Vs)

In the MCBC modulation technique, the voltage stress *Vs* across the power devices can be expressed as:

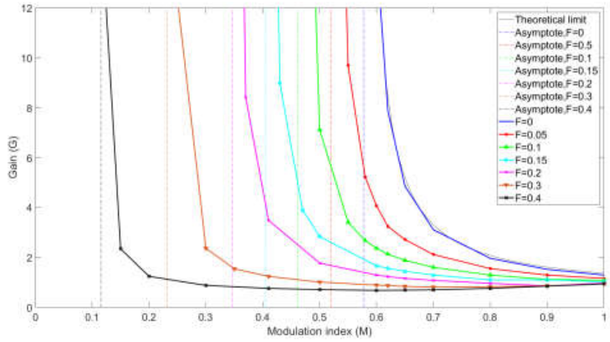

Fig. 4 Voltage Gain versus Modulation index, with variable offset

$$Vs = B'.Vdc = \frac{Vdc}{\sqrt{3}M+2F-1} \tag{10}$$

As proposed in [19], an equivalent DC voltage is considered $(G.Vdc)$ to analyze the voltage stress. This voltage includes the boost factor due to the impedance network as the DC voltage needed in the traditional VSI to produce the same output voltage. Thus, the ratio of the voltages stress is $Vs/(G.Vdc)$.

The first simulation proposed to test the *Vs* ratio is shown in Fig. 5, where a constant *M* is considered while *F* is changed from zero to a maximum, and the ST duty cycle is null. In this figure, the theoretical and simulated curves of *Vs*, in case of zero offset, are depicted as reference for the comparison with curves obtained by constant *M* and changes in *F* from zero to its maximum value. Thus, four different *M* have been simulated, from 0.6 to 0.9. As can be observed, in the *Vs* range from two to three, only an extra 40% *Vs* is needed to achieve a voltage gain of 3. Furthermore, the ratio of *Vs* remains constant when *F* changes. All the additional curves are flat, included the magenta curve when *M* is 0.6 and the maximum voltage gain increases near the asymptote value of the modulation index.

The second test tries to prove the *Vs* ratio when the decoupled MCBC modulation technique works with a constant *F*. As considered in Fig. 5, the reference curve is obtained with zero *F* and *M* varying from 1 to a minimum value near its asymptote. The rest of the simulations have been in a similar way, but with a *F* of 0.1 and 0.2, respectively. Fig. 6 shows the results of the three shapes considered in the test. The blue curve is the reference, which is same as shown in Fig. 9 of [19]. The others curves, with nonzero *F*, are very

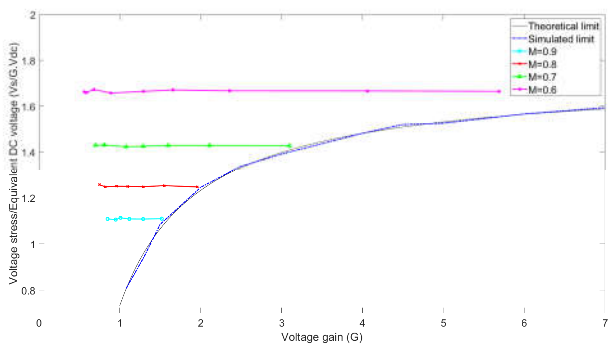

Fig. 5 Voltage stress ratio with variable offset

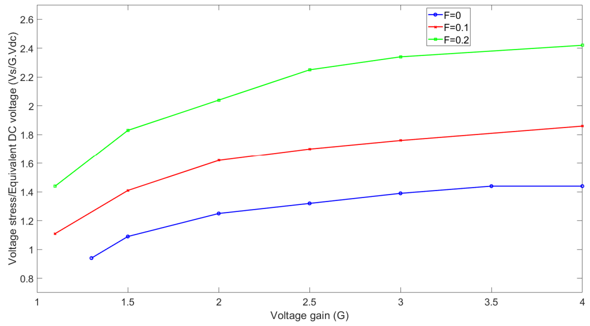

Fig. 6 Voltage stress ratio with constant offset

similar to the reference, but with a significant increase of the *Vs* ratio. Thus, for a voltage gain of 3, the *Vs* ratio doubles from zero *F* to 0.2. As a result, in the decoupled MCBC modulation technique, the main control signal must be *M*, while *F* controls the fluctuations over the output voltage setpoint due to the voltage source.

C. Case 3: Output voltage harmonics (THD)

In this study, voltage harmonics are analyzed because the proposed energy system works off-grid, and the output voltage is the main source of distortion.

To verify the decoupled MCBC modulation technique from the harmonic distortion point of view, Ref. [19] was considered as reference because the authors studied if this technique introduced any extra harmonic contents compared to the traditional VSI, working with the same *M* and same output voltage. They concluded that the harmonic contents in both cases were almost exactly the same, and STS does not increase harmonic levels.

To study how *F* affects the harmonic contents, any type of filter is omitted in the circuit, and thus, the harmonics are measured at the output of the inverter. Furthermore, Total Harmonic Distortion (THD) is selected to compare the harmonic profile when *M* is constant and *F* changes.

Table I illustrates the RMS values of the fundamental output voltage with their THD at a M of 0.8 and a F varying from 0 to 0.4. In the simulations, the maximum frequency for THD computation is 1050Hz.

The results of the proposed simulations show that the harmonic distortion is not affected by the *F*. Nevertheless, the harmonic contents are high, as in a traditional VSI, and suitable filters are needed to reduce them.

D. Decoupled SBC and MCBC comparison

The last simulation considered in this study is the comparison between the proposed decoupled MCBC and the traditional SBC. Both modulation techniques are applied to the system under study shown in Fig. 1 with the same *M* (0.8) and the same *F* (0.1). The results are shown in Table I. As can be noted, MCBC presents higher absolute values than SBC modulation technique. That is because MCBC voltage gain is 37% higher than SBC. Nevertheless, if relative values are considered, *Vs* ratio and THD are similar, but capacitor voltage ratio is about 14% lower.

V. Conclusions

This work analyzed the possibility of decoupling the STS from the *M* in the MCBC technique. Thus, this decoupled MCBC can boost the voltage output and adjust the gain to possible oscillations of the source. To achieve this goal, a new control signal was proposed to move both ST signals and, therefore, to decouple the ST duty cycle and *M*.

The decoupled MCBC was verified by simulations in order to prove that its behavior is the same as the MCBC without decoupling. Voltage gain, stress and harmonic distortion were studied and the results showed that the behavior was not modified, except the reduction of the boost factor. Additionally, a comparison between SBC and decoupled MCBC was performed to prove that, with a certain decoupling level, the proposed method achieves the same advantages that MCBC against SBC.

Table I. Harmonic distortion for different offsets

Offset	*RMS Output Voltage (V)*	*THD (%)*
0	345.4	29.16
0.1	227.8	29.15
0.2	169.7	29.15
0.3	145.0	29.15
0.4	133.7	29.16

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