Impact of the Modulation Strategy on the Dimensioning of Three-Phase Z-Source Inverters

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***Abstract*—In Z-Source Inverters (ZSI), the modulation strategy determines the size of the inductors and capacitors as well as the system losses. In this paper the impact of the modulation method on the design of the passive components is examined in detail with an Interior Permanent Magnet Synchronous Machine as load. Specific features of several modulation methods are presented for steady state operation and guidelines for the design procedure are developed. It will be shown, that a large number of Shoot-Through states does not necessarily lead to small ripples in the passive components. From these considerations, a method for minimizing the required inductance and ZSI losses is established. Simulations and experimental results, including the measurement of the system losses support the analysis.**

***Keywords*—Z-Source Inverter, modulation, inductor design, capacitor design, semiconductor losses, Interior Permanent Synchronous Machine**

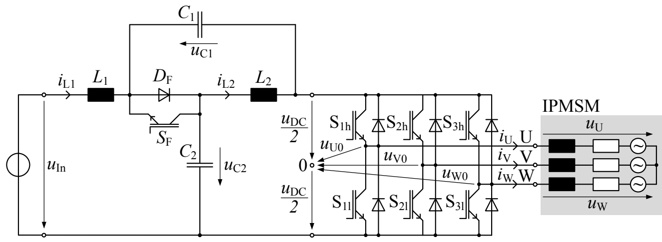

Fig. 1. Lossless QZSI with IPMSM

I. Introduction

Three-phase Z-Source Inverters (ZSI) are generally composed of a common inverter bridge and an impedance network, the so called Z-network. Differences in the topology are found in the arrangement of the inductors, capacitors and the input diode in the Z-network [1]. One variant of these one-stage topologies with buck- and boost functionality and the capability of regenerating energy is the widely used Quasi-Z-Source Inverter (QZSI) [2] according to fig. 1, on which the following investigations are based. However, the derived results are also applicable to other three-phase ZSI types.

The Z-network enables the integration of inverter phase-arm short circuits in the modulation scheme of the conventional inverter bridge [3], which provides the boost functionality. Key to the design of a ZSI is the way of allocating the Shoot-Through (S) states in the modulation scheme.

Originally, two continuous modulation (CM) schemes have been proposed, which either comprise two S-states in the middle of the two conventional Freewheeling (F) states [4] (fig. 3, CM2) or the insertion of six S-states in the transition between F- and Active (A) states (fig. 3, CM6) [1]. The latter modulation method has been discussed contradictory. On the one hand it is supposed to have high losses compared to other schemes [5] and on the other hand good loss properties are stated in [6]. With regard to the size of the inductors, also opposing results can be found [6]–[8]. Nevertheless, it is one of the most common modulation strategies. For reduction of the losses in comparison to method CM6, a modulation method with four S-states between the F- and A-states has been developed [9] (fig. 3, CM4). Moreover, in [10] advanced discontinuous modulation (DM) methods have been introduced, reducing the number of switching transitions and by that improving system efficiency. The most efficient variant features an unsymmetrical distribution of the switching states in relation to a symmetrical carrier signal. A similar scheme is implemented in [11].

Recently the authors of [12] have suggested two continuous loss-optimized modulation methods. In case of the first method, the S-states are allocated between the two A-states (fig. 3, CM2a). The other one involves an unsymmetrical S-arrangement (fig. 3, CM2b), similar to the discontinuous scheme from [10].

Except for the recent publications [7], [8], the focus of ZSI-modulation has been mainly on the minimization of semiconductor losses. A comprehensive analysis dealing with the influence of the modulation strategies on the dimensioning of the passive components has not yet been accomplished. Especially the modeling approach for the design of the capacitors has always been simplified, although the model complexity varies with the operating parameters.

This paper contributes to the impact of the modulation strategy on the dimensioning of the inductors and capacitors of three-phase ZSI topologies. For this purpose, a comparative analysis of the inductor current- and the capacitor voltage ripples is carried out, taking the load characteristic of an anisotropic Interior Permanent Magnet Synchronous Machine (IPMSM) into account. From the derived equations for the maximum current and voltage ripples, the inductance and capacitance values are calculated. Besides simulation results for the occurring ripples,

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also experimental results are presented in order to verify the loss performance of the regarded modulation schemes.
Detailed analysis is provided for a wide variety of modulation methods and an explicit recommendation is given for the operation of high power ZSIs.

II. Fundamentals

In this section the fundamentals of the QZSI are described for steady state operation, which are necessary for the dimensioning of the passive components. As usual, both inductors and both capacitors each have the same size [2], that is $L_1 = L_2 = L$ and $C_1 = C_2 = C$. Consequently, only one inductor current $i_{\mathrm{L1}} = i_{\mathrm{L2}} = i_{\mathrm{L}}$ and one capacitor voltage $u_{\mathrm{C1}} = u_{\mathrm{C2}} = u_{\mathrm{C}}$ has to be considered. For simplicity, linear curves are assumed for the currents and voltages. This is valid as long as the switching frequency is sufficiently high [13].

A. Inductor currents and capacitor voltages

The basic operation of the QZSI implies the use of the S-state, two freewheeling states F1 and F2 and two active states A1 and A2 in an arbitrary, periodical pulse pattern.
During the S-state the inverter is decoupled from the Z-network and energy is transferred from the input voltage source and the capacitors to the inductors:

$$\dot{i}_{\mathrm{L}} = \frac{U_{\mathrm{In}} + U_{\mathrm{C1}}}{L} = \frac{U_{\mathrm{C2}}}{L} \tag{1}$$

Here, the assumption of constant capacitor voltages $u_{\mathrm{C1}} = U_{\mathrm{C1}}$, $u_{\mathrm{In}} = U_{\mathrm{In}}$, $u_{\mathrm{C2}} = U_{\mathrm{C2}}$ is made. The capacitors are discharged with a constantly assumed inductor current $i_{\mathrm{L}} = I_{\mathrm{L}}$:

$$\dot{u}_{\mathrm{C}} = -\frac{I_{\mathrm{L}}}{C} \tag{2}$$

In both active states, A1 and A2, the inductor currents decrease:

$$\dot{i}_{\mathrm{L}} = \frac{U_{\mathrm{In}} - U_{\mathrm{C2}}}{L} = -\frac{U_{\mathrm{C1}}}{L} \tag{3}$$

As the DC-link current varies with the A-state, two equations are obtained for the capacitor voltages changes in the considered angle-sector $\omega t \in \left[0..\frac{\pi}{3}\right]$:

$$\dot{u}_{\mathrm{C,A1}} = \frac{I_{\mathrm{L}} - i_{\mathrm{U}}\left(\omega t\right)}{C} = \frac{I_{\mathrm{L}} - \hat{I}_{\mathrm{S}} \cos\left(\omega t - \varphi\right)}{C} \tag{4}$$

$$\dot{u}_{\mathrm{C,A2}} = \frac{I_{\mathrm{L}} + i_{\mathrm{W}}\left(\omega t\right)}{C} = \frac{I_{\mathrm{L}} + \hat{I}_{\mathrm{S}} \cos\left(\omega t - \frac{4}{3}\pi - \varphi\right)}{C} \tag{5}$$

where i_{U} and i_{W} are the time-varying phase currents. Furthermore, the differential equations for the inductor currents in the F1- and F2 state are equal to (3), whereas the capacitor voltage rise is stated as

$$\dot{u}_{\mathrm{C}} = \frac{I_{\mathrm{L}}}{C} \tag{6}$$

Applying volt-sec balance, the steady state relationships for the DC voltages of the Z-network are expressed by [2]:

$$U_{\mathrm{C2}} = \frac{1 - D}{1 - 2D} U_{\mathrm{In}} \tag{7}$$

$$\hat{U}_{\mathrm{DC}} = U_{\mathrm{C2}} + U_{\mathrm{C1}} = 2U_{\mathrm{C2}} - U_{\mathrm{In}} = \frac{1}{1 - 2D} U_{\mathrm{In}} \tag{8}$$

B. Modulation of the inverter bridge

For the generation of the basic pulse-width modulated inverter output voltages with sinusoidal first harmonic, two carrier based modulation methods from [3] are applied to the QZSI. One method comprises continuous three-phase reference voltages with an additional triangular alike zero component. The other one includes discontinuous reference voltages.

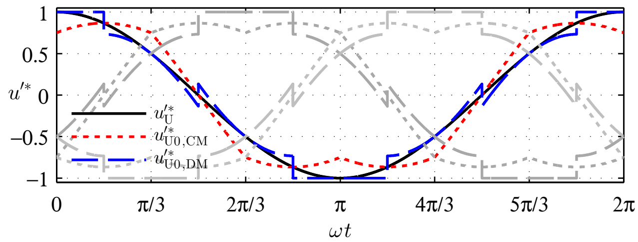

Fig. 2. Modulation functions for continuous (CM) and discontinuous (DM) modulation

Fig. 2 shows an example for the according waveforms of phase U, normalized with respect to $\hat{U}_{\mathrm{DC}}/2$ and without any S-states. u'^*_{U} is the phase voltage, $u'^*_{\mathrm{U0,CM}}$ the continuous (CM) reference voltage and $u'^*_{\mathrm{U0,DM}}$ the discontinuous (DM) one. The reference voltages are sampled by means of regular sampling and compared to a symmetric triangular carrier signal, which delivers the necessary pulses. Accordingly, the remaining phase voltages are generated in the same manner, each with a phase shift of $\frac{2}{3}\pi$. If the conventional modulation schemes are extended to the boost functionality, the A-states have to remain unchanged and only the F-states can be filled with S-states.

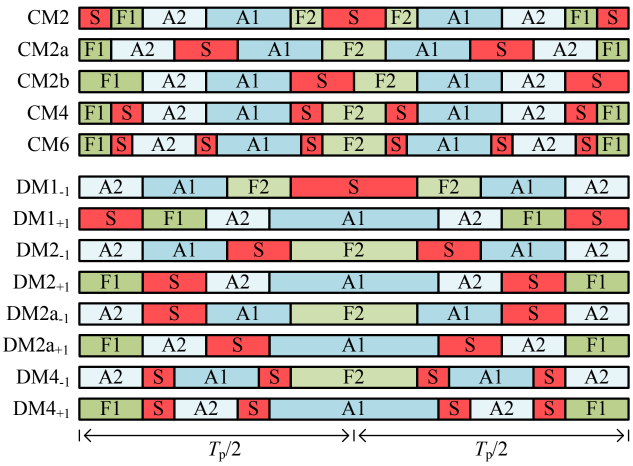

Fig. 3. Pulse pattern of the implemented modulation methods, S = Shoot-Through state, A1, A2 = Active states, F1, F2 = Freewheeling states

Fig. 3 displays the implemented modulation schemes, all featuring the voltage gain of the Constant Boost Control method [4]. In case of DM, the reference voltages are alternately clamped to +1 and −1. Hence, the semiconductors are evenly stressed in contrast to [10]. Nevertheless, this approach causes a sudden variation of the average values of the inductor currents and capacitor voltages when a clamped reference