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Transformer-Based Z-Source Inverter with MVDC Link

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Abstract. Z-source inverters have attracted considerable attention in renewable energy systems like photovoltaic (PV) systems due to advantages such as buck–boost power conversion in single stage, shoot-through capability, and wide range of input voltage regulation. Transformer-Based Z-source inverters (Trans-ZSI) based on magnetically coupled inductors and reduced number of passive components can be used to improve the boost capacity of these inverters, and to increase the voltage levels. Medium voltage DC (MVDC) is being used more and more in distribution grids and renewable energy systems. This paper presents a trans-Z-source inverter with MVDC link where renewable energy systems and energy storage systems can be integrated. The active and reactive powers and DC voltage are controlled by acting on the modulation index and shoot-through duty cycle of the converter. The trans-Z-source inverter is evaluated under different operating conditions to illustrate its suitable operation.

Key words. Transformer-based Z-source converter, medium voltage direct current link, control, grid-connected.

1. Introduction

Since Z-source and quasi-Z-source inverters (ZSI and qZSI respectively) were first presented in 2002 by Fang Zheng [1], they have introduced remarkable improvements with respect to the traditionally employed voltage source inverter [2]. Thanks to the impedance network connected before the inverter, a large voltage boost can be achieved in a single stage by charging and discharging the capacitors and inductors with the continuous shift between shoot-through and non-shoot through states. The DC bus voltage (voltage between the impedance network and the inverter) can be adjusted by controlling the shoot-through state of the switches (D), while the modulation index (M) adapts the DC bus voltage to the AC grid voltage.

Nevertheless, ZSI have some important limitations. For instance, they have infinite gain, and the boost voltage is limited by the stress in the components of the impedance network. These drawbacks can be solved in part through the modulation technique implemented [3], [4], and through new converter topologies. One of the advances in ZSI topologies is the addition of magnetically coupled inductors in the impedance network, which improves the voltage boost capabilities and the modulation index, as well as reduces the number and the size of the passive elements in the impedance network [5].

Some of these improved configurations are the trans-ZSI [5], [6] and the improved trans-ZSI in [7]. The increase in the voltage boost of the converter achieved with the modulation techniques in [3], [8] is modest, while the configurations presented in [7], [9] have very high current and voltage levels. Other solutions use coupled inductors for DC-DC conversion [10] or replace the impedance network with switched-inductors [11]. Again, these solutions do not solve the problem of voltage stress and increase the number of components in the converters. An advanced configuration that benefits from the advantages of both concepts is the trans-ZSI presented in [12], which consists of an impedance network comprising two capacitors, three diodes and three magnetically coupled inductors, plus a traditional inverter. The trans-ZSI under study has a high voltage gain in a single-stage DC-AC conversion, and a low voltage stress in the passive elements.

The trans-ZSI is a very pertinent alternative to integrate renewable energy sources like PV generation into MVDC grids using a single conversion stage. Power distribution in MVDC grids has been receiving much attention for the last decade [13], and hybrid MVDC microgrids using different Z-source converters for the interconnection of several power sources into a common bus have already been presented in the literature [14][15].

This work focuses on implementing a grid-connected trans-ZCI with MVDC link, the control system for controlling the active and reactive powers and DC voltage and evaluating the dynamic performance under different operating conditions.

2. System under Study

Fig. 1 shows the configuration of the trans-ZSI under study in this work, which is connected to a three-phase MVAC grid. It is composed of an impedance source network with 2 capacitors, 3 diodes, and a double winding magnetically coupled transformer [16] to raise the gain and modulation ratio. The rest of the system is a 3-phase voltage source inverter (VSI), and a filter to reduce the harmonics injection into the grid.

In this configuration, the two capacitors of the impedance network could be used to extend the capabilities of the converter and the configuration under study: 1) capacitor C1 to create a MVDC link between its terminals, where DC sources (like energy storage systems, electric vehicles or DC loads, among others) with additional power converters to control them could be connected; and 2) capacitor C2 to connect an energy storage system like battery (trans-ZSI with integrated energy storage system), whose charging/discharging could be controlled from the inverter control. In this paper, the option based on controlling the voltage across the capacitor C1 to create a MVDC link is shown.

The operation principles are described in [12]. As a conventional ZSI, it has two operating states, the non-shoot-through state, NSTS, and the shoot-through state, STS, where both switches of any phase conduct at the same time. In NSTS, the Trans-ZSI works as a traditional VSI, with a zero state where the inverter is not connected to the impedance network (Din on, D1 and D2 off) and an active state where the inverter is connected to the impedance network (Din and D2 on and D1 off) and it works as a current source. In STS, the inverter is short-circuited, and the input source is disconnected from the impedance network (Din off, D1 and D2 on). In this state, the impedance network boosts the DC-link voltage while protecting the inverter from damage. Furthermore, the double winding transformer improves the gain of the converter compared to traditional ZSI.

The voltage boost ability of the converter (B) is at least double than a traditional ZSI [16]:

$$B = \frac{V_{dc}}{V_{in}} = \frac{2}{1-(n+1)\cdot D} \qquad (1)$$

where V_{dc} is the output voltage of the impedance network, V_{in} is the DC source voltage, n is the transformer turn ratio between the primary and secondary windings (n=N_1: N_2= N_1: N_3), and D is the shoot-through duty ratio.

The voltage gain of the whole system (G) is given by the boost factor (B) and the modulation index of the inverter (M):

$$G = B \cdot M \qquad (2)$$

Moreover, the maximum value of D depends on the modulation methods [8], as can be seen in Table I.

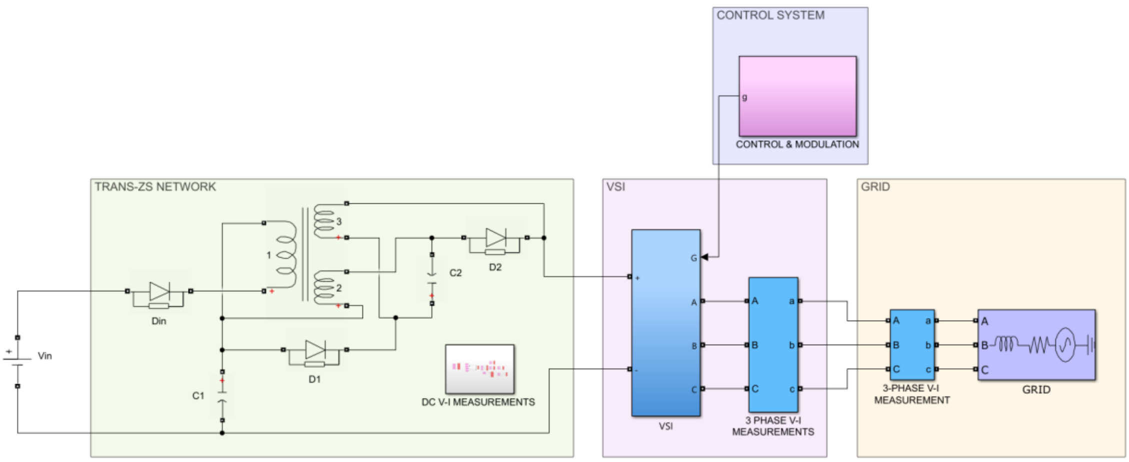

Fig. 1. Configuration of the system under study

Table I. – Comparison of modulation methods

Modulation Method	D	$G=B.M$ (M=0.8)
SBC	*1-M*	2.67
MCBC	*1-0.86M*	4
ZSVM1	*0.5(1-M)*	2
ZSVM4	*075(1-M)*	2.29
ZSVM6	*1-M*	2.67

Thus, two classical sinusoidal PWM methods are compared with three Z-Space Vector Modulation (ZSVM) to define maximum excursion of the Trans-ZSI. The PWM techniques, Simple Boost Control (SBC) [1], and Maximum Constant Boost Control (MCBC) [17] present gains equal to or higher than ZSVM methods, although these have relevant advantages of low voltage stress in the switches. Although some authors consider greater values of D [8], these values give rise to distortions when the ratio between the time of the zero state and the sampling period reaches the value of ($1-M$).

3. Control System

The proposed control system presents a ZSVM modulation technique to control the MVDC link voltage and both active and reactive power delivered to the grid.

A. Modulation Technique

In this work, ZSVM6 modulation method is used because it allows higher DC-link voltage utilisation and lower harmonics than SBC, and higher boost capability and lower switch voltage stress than others vectorial modulations [8]. Unlike traditional SVM modulation for inverters, ZSVM6 inserts six shoot-through time intervals in one switching period. The voltage vector reference is generated from the linear combination of non-zero, shoot-through and zero states in a switching period [18]. Thus, this technique uses D and M to generate the gating signals.

B. Control Strategy

The control strategy is designed to control the MVDC link voltage (voltage across capacitor C_1) and the active and reactive powers delivered to the grid. Hence, a PI controller is used to control D to maintain the MVDC link voltage at the desired value.

The control system has been carried out in a *dq* reference frame aligned with the grid voltage, to decouple the control of active and reactive powers (P and Q), and it is composed of two cascaded control loops. The outer loops are responsible for controlling P and Q to their references and generating the reference values for the *dq* components of the grid current, taking into account the following relationships among them given by Eq. (3) [5]:

$$\begin{aligned} P &= \frac{3}{2} \cdot u_{d,g} \cdot i_{d,g} \\ Q &= -\frac{3}{2} \cdot u_{d,g} \cdot i_{q,g} \end{aligned} \tag{3}$$

where $u_{d,g}$ and $i_{d,g}$, $i_{q,g}$ are the *dq* components of the grid voltage and current, respectively.

The inner loops control both components of the grid current to follow the references provided by the outer control loops and generate both components of the modulation index (m_d and m_q), and the gating pulses for the inverter from m_d and m_q and the modulation technique.

4. Results and Discussion

To validate the behaviour of the system, a model has been implemented in MATLAB/Simulink® and a case study is considered. The main parameters of the trans-ZSI are listed in Table II.

Table II. – Parameters of the trans-ZSI

Parameter	Value
DC input voltage, V_{in}	1300 V
Grid voltage, V_{grid}	1850 V
Inverter nominal power, P_n	200 kW
System Frequency, f	50 Hz
Nominal DC voltage, V_{dc}	3800 V
MVDC voltage, V_{c1}	1500 V
Switching frequency, f_c	10 kHz
Maximum ST duty ratio, $D = 1-M$	0.3
Transformer turn ratio, n	2
Transformer magnetising inductance, L_m	220 µH
Capacitors, $C_1 – C_2$	68.44 µF
Output filter, R_{filter} - L_{filter}	39mΩ, 39mH

The trans-ZSI with MVDC link under study and its control system are evaluated under changes in the active and reactive powers. Thus, during the first second, the system delivers the maximum active power to the grid (the inverter rated power, 200 kW) with unity power factor. Then, the active power reference is reduced to 175 kW to evaluate if the system can follow a limiting reference from the grid. At 1.5 s, the power references are changed to 150 kW and 30 kVAr so that the system works as a conventional power plant regulating both active and reactive powers. In the last part of the simulation, from 2 to 2.5 s, the system returns to rated power with zero reactive.

Fig. 2 shows that the trans-ZSI follows the active and reactive power references. The results are very close to the reference values, showing some small step delays. In Fig. 2b, a little disturbance in reactive power occurs at 1 s due the change of the active power reference.

The evolution of the control variables M (m_d and m_q components) and D is shown in Fig. 3. It can be seen that m_d, m_q and D vary to follow the required changes in P and Q references and keep constant the MVDC link voltage. Nevertheless, these changes in the references affect the outer loops of the control system, varying the grid current references, as depicted in Fig. 4. According to Eq. (3), i_d and i_q references follow the reference values of P and Q, respectively. The outputs of the outer loops are the inputs of the inner loops, which control the values of M components, m_d (Fig. 3a) and m_q (Fig. 3b).

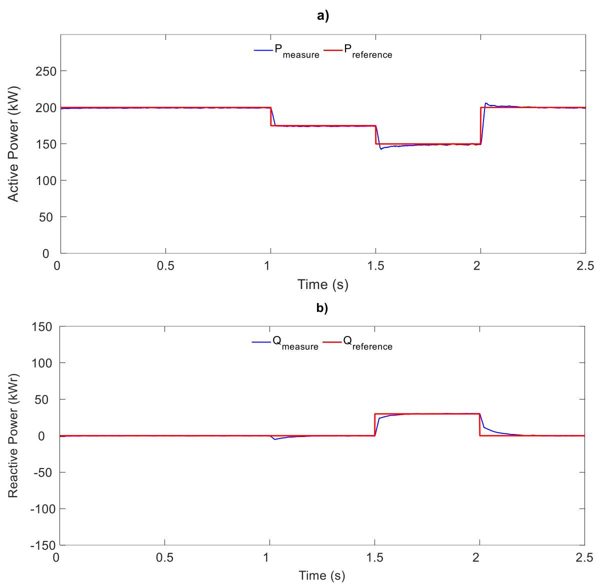

Fig. 2. a) Active power and b) reactive power developed to the grid.

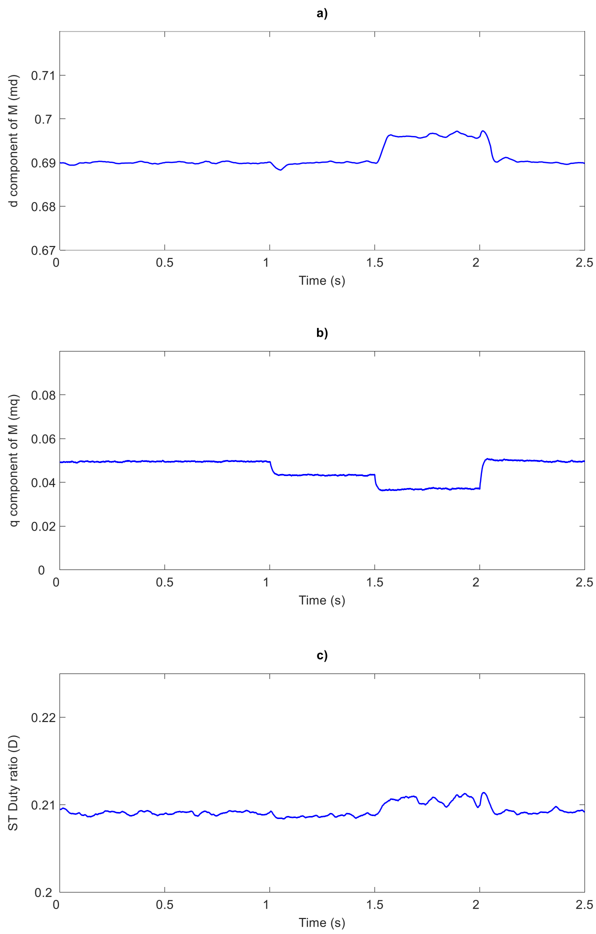

Fig. 3. *Dq* components of the Modulation index, a) md and b) mq, and c) Duty Cycle (D)

As can be observed, M (m_d and m_q) controls the power delivered to the grid, decoupling active and reactive power in a similar way as it can be done in a conventional power station. The other control variable, D, keeps constant the voltage across the capacitor C_1 at a value of 1500 V, as shown in Fig. 5, which allows to consider a MVDC link at this point.

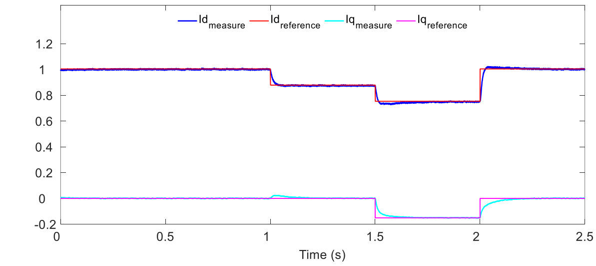

Fig. 4. *Dq* components of grid current and their references

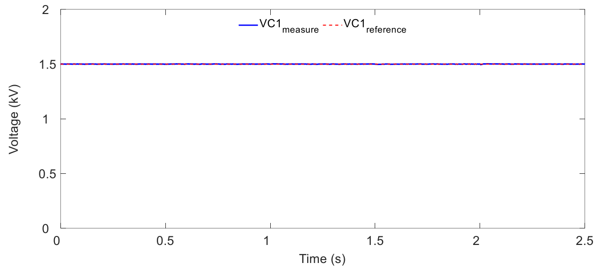

Fig. 5. Voltage across the capacitor C1 of the trans-ZSI (MVDC link).

5. Conclusion

This paper has presented a trans-ZSI based on three magnetically coupled inductors, two capacitors and two diodes that can be used to integrate an energy storage system and create a MVDC link where other renewable energy systems and energy storage systems can be connected.

A high power trans-ZSI was implemented: rated power of 200 kW, grid voltage of 1850 Vac, nominal DC voltage of 3800 Vdc. The MVDC link (1500 Vdc) was achieved at the capacitor C1 of the trans-ZSI. ZSVM6 modulation method was used to trigger the converter. The control of the active and reactive power delivered with the grid was performed by acting on the *dq* components of the modulation index and the MVDC link voltage was controlled by acting on the shoot-through duty cycle of the converter. The trans-ZSI with MVDC link under study and its control system were evaluated under changes in the active and reactive powers, and the results illustrated the right configuration and operation of the converter.

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