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Modified Z-Source Single-Phase Inverter for Single-Phase Pm Synchronous Motor Drives

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Abstract: *The Z-Source network, as a DC-link energy storage sub-circuit, was proposed to be used in DC-AC power conversion circuits (inverters) due to its advantages compared to the traditional LC DC-link. In this paper a new modified Z-source (MZS) network is proposed in order to reduce the number of switches in a single-phase inverter, from four switches, in a full-bridge converter, to only two switches, as well as to maintain the desired average voltage level in the DC-link. This paper presents the novel topology and the operating principle of the new MZS single-phase inverter with two switches, and an application of this converter in a motor drive system to a single-phase PM synchronous motor. The proposed system topologies are validated by digital simulations of the circuits in PSIM and SIMULINK, with tests due soon.*

I. Introduction

One of the major problems in single-phase voltage source inverters, having in the input stage batteries, photovoltaic, and fuel cells or a diode rectifier fed by the 230 V ac line, is the DC link voltage level, which could be smaller than the desired level, imposed by the application. Single phase voltage source inverters are used in photovoltaic or fuel cell grid-connected inverter systems as well as in inverter based motor drive systems. A growing interest is also shown in the field of hybrid electric vehicles. Some of the solutions to boost the DC link voltage are transformer-less boost circuits or circuits with high frequency transformers which are introduced between the DC voltage source and the inverter.

The main reasons why the Z-source network seems to be a good choice for the intermediate circuit between the DC link voltage and the inverter are the following: it provides a greater voltage than the DC link voltage if it is necessary, it makes the inverter immune to short circuits produced by the conduction of both transistors on the same phase leg (caused by EMI or bugs in the control software of the transistors), it reduces the inrush current and harmonics in the current thanks to the two inductors in the Z-source network, and it forms a second order filter and handles the undesirable voltage sags of the DC voltage source [1-7]. In this paper , the Z-source network is modified and a two power switch single phase PWM inverter, , which self boosts the input voltage twice to keep the output voltage at input level (and mitigate for voltage sags), is proposed. Fig. 1 presents the electrical circuit of the Z-source network connected to a single-phase full bridge inverter. The diode D at the front end of the Z-source network makes the circuit unidirectional. The electrical energy flows from the DC voltage source to the load. The two equivalent schemes for the two possible operating modes of the Z-source network are shown in Fig. 2. [3]

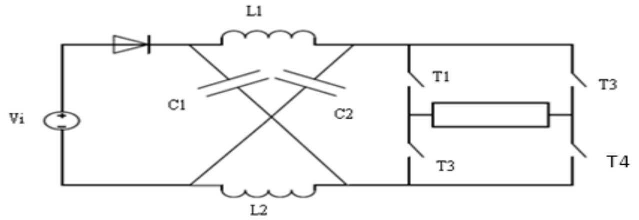
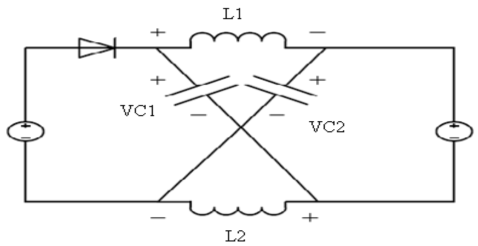


Fig.1. Z-source network with 4 switch single-phase inverter.

In the non-shoot through mode, in case of a single-phase inverter, two of the four transistors are switching: T1 and T4 or T2 and T3. With T4 on if T1 is on the output voltage is positive. Turning off T1 and turning on T3 (with T4 conducting) a through short circuit is produced to charge the inductances L1 and L2 and thus produce voltage boost.



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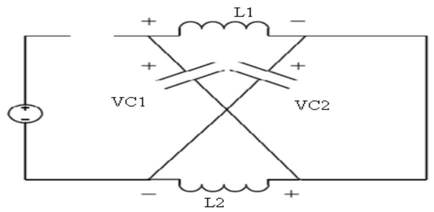

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Fig.2. Equivalent schemes of the Z-source network in (a) non-shoot through state (b) shoot-through modeL

In the shoot-through state:

$V_{L1}=V_{C1}$ $V_{L2}=V_{C2}$ $V_i=0$

In the non shoot-through state:

$V_{L1}=V_{DC}-V_{C1}$ $V_i=2V_{C1}-V_{DC}$.

If L1=L2 and C1=C2 then the voltage drops across the inductors are equal and the voltage drops on the capacitors are equal as well.

To control the voltage at the input of the single-phase inverter we need to control the voltage of one capacitor, because the average voltage across the inductors in steady state is zero [1].

$$V_C = \frac{1-\frac{T_{ST}}{T_S}}{1-2\frac{T_{ST}}{T_S}} V_{DC}$$

where TST is the shoot-through time. To obtain the required TST/TS a PI controller can be used [1].

II. Modified Z-Source Single-Phase Inverter With 2 Switches

The proposed modified Z-source network (MZS) is presented in Fig. 3. In many electrical circuits, instead of a high voltage rated electrolytic capacitor, series smaller voltage rated capacitors are used. It can be noticed that this change in the Z-source network reduces the number of transistors. The load is connected between the common node of the two series capacitors and the common node of the two switches (Fig. 3).

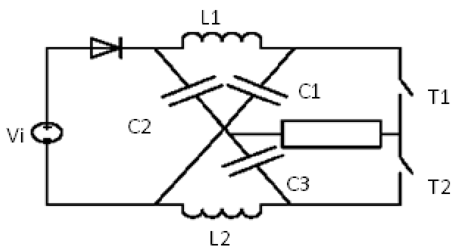


Fig. 3 .MZS single-phase inverter with two switches.

III. Operating Principle

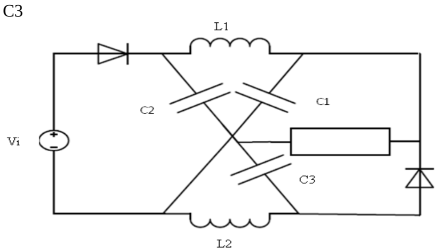
The introduced MZS single-phase inverter with two switches has three different states, two active and one shoot-through. The three equivalent circuits for the three states are illustrated in Fig. 4.

[State 1]: The converter is in one of the two active states. The upper transistor is conducting and the lower transistor is substituted by its freewheeling diode.

The voltage on the load is:

$V_{LOAD}=V_{C2}-V_{L1}=V_{C1}/2-V_{L1}$

If $V_{C2}=V_{C3}$



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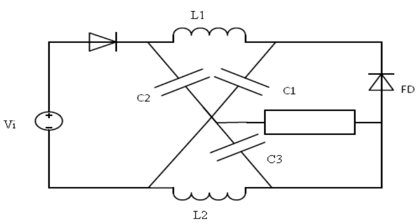

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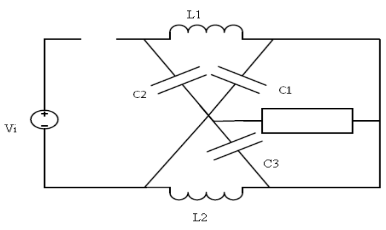


c)

Fig.4. Equivalent circuits of MZS single-phase inverter for (a) State 1 (b) state 2 (c) state 3.

[State 2]: The converter is in the other non-shoot-through state. The lower transistor is conducting and the upper transistor is acting like a diode.

The voltage on the load is:

$V_{LOAD}=-V_{C3}=-V_{C1}/2$

If $V_{C2}=V_{C3.}$

[State 3]: In this operating mode the demanded load voltage boost is realized. Both the upper and the lower switches are conducting; therefore an energy transfer is realized from the capacitors to the inductors. It can be seen that the circuit is asymmetrical (because the load is connected in parallel with the capacitor C3), so that the energy transfer from the capacitors to the inductors is not the same on the upper and on the lower side.

IV. Modified Z-Source Single-Phase Inverter With Single Phase Pm Synchronous Machine

Because of the complexity of the equations for each state of the MZS, the converter was modeled with discrete elements in PSIM. The single phase synchronous machine was modeled as a series connection of the following elements: the stator resistance R, the stator inductance L and a programmable voltage source which is the EMF, calculated in "Simulink" based on the motor equations at every sample time. We used three sensors in total: one load current sensor, one motor speed transducer and one voltage sensor for the measurement of C1 capacitor voltage (which is the average DC link voltage in steady state). So we have three control loops. For speed regulation a PI controller was used, for the load current control a hysteresis current controller. The hysteresis current controller commands one of the two transistors all the time. This means that there are no "inactive states" (e.g. the time duration for zero state vectors in case of a three phase inverter) during which the shoot-through states could be generated. In conclusion the shoot through states will take place during the active states. By connecting the motor between the common node of the two transistors T1 and T2 and the common node of the capacitors C2 and C3 the maximum voltage which can be delivered to the motor in our case study is 150 V if the voltages on the two capacitors C2 and C3 are equal to each other. In order to be able to supply the motor from 300 V with the block V* we prescribe 600 V average DC link voltage. To reduce the inrush current spikes in the inductors the V* voltage was increased from 300 V to 600 V in 300 ms. The output of the PI regulator in the DC link voltage control loop in Fig. 5a gives the ratio of the input DC voltage and the average DC link voltage. Based on equation (3) the block after the PI regulator calculates the shoot through time.

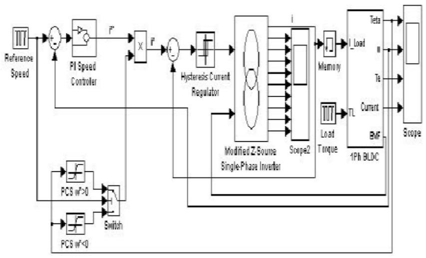
The shoot through time generation can be seen in Fig.6. It should be noticed that the shoot through time is calculated with a 10 kHz sampling rate and the shoot through pulses are distributed equally over the 100 ìs period at the beginning and at the end of the sampling period. The shoot-through pulses override the pulses generated by the hysteresis current controller thanks to the two or gates at the gate of each transistor.

$V_S = I_S.R_S + L_S.\frac{dI_S}{dt} + \omega_r.\lambda_{PM}(\theta_{er})$

$\frac{J}{p}.\frac{d\omega_r}{dt} = T_e + T_{cog} - T_{load}$

$T_e = P\lambda_{PM}(\theta_{er})I_S(t)$

$$\frac{d\theta_{er}}{dt} = \omega_r$$



a)

To demonstrate that the proposed MZS single phase inverter is suitable for motor drives with single phase PM synchronous machines, different perturbations on the drive were simulated. For example, it can be seen in Fig. 7 that for a 10% voltage sag of the nominal DC voltage source (fall from 300V to 270V) the C1 capacitor voltage remains unchanged. At the start of the converter one of the two series capacitors (C2) is discharged and the second (C3) is charged with electrostatic energy. The C1 capacitor voltage smoothly follows the prescribed average DC link voltage; it has a very small overshoot. Even if the prescribed average DC link voltage is raised gradually from 300V to 600V in 300ms, we do have some inrush current spikes in the inductors L1 and L2 (Fig. 8.). A longer ramping time could reduce these inrush current spikes.

Fig. 8 shows that the inductors peak currents are about two times greater than the peak load current. The difference between the two currents instantaneous values is the effect of the converter's asymmetry (see Fig. 4 state 2 and state3).

In Fig.8 b) can be seen that the instantaneous voltage across the load is asymmetrical, the positive part is two times greater than the negative part.

Fig. 9 shows the motor reference and measured speed while the motor accelerates to the nominal speed 3000 rpm in about 1.5 seconds. A breakpoint in the speed ramping is visible at 300 ms the moment when the C1 capacitor voltage reaches 600V. From this moment the motor has a steeper acceleration ramp, until it reaches 3000 rpm. A step load torque of 0.35 Nm is applied to the motor at t = 2 seconds until t = 8 seconds. This load torque is not reflected in the capacitor voltages and the speed does not suffer a speed drop, which indicates that the speed and current loops work well. At t = 3 seconds, the motor is decelerated to 33% of its nominal speed for 3 seconds. A voltage boost is visible in the capacitor voltages during the deceleration process.

At t = 6 seconds the motor speed increases again to the nominal speed. This time the acceleration time duration is longer than the deceleration time duration because we have a torque load which goes to zero at t = 8 seconds and the acceleration ramp gets steeper, again.

In Fig. 10 shows the variation in time of the load torque, electromagnetic torque and the cogging torque of the motor.

The transistors voltage and current stresses are illustrated in Fig. 11. The collector peak current is twice the inductor peak current. The peak instantaneous voltage across the transistor is two times bigger than the voltage across C1.

Table I presents the peak currents and voltages in the transistors for the following converter topologies: full bridge single-phase inverter with 4 transistors (A) and modified Z-source single-phase inverter with 2 transistors (B) for single-phase PM synchronous motor drives. The 2 transistor topology is payed for in addition V and A ratings.

The motor parameters:

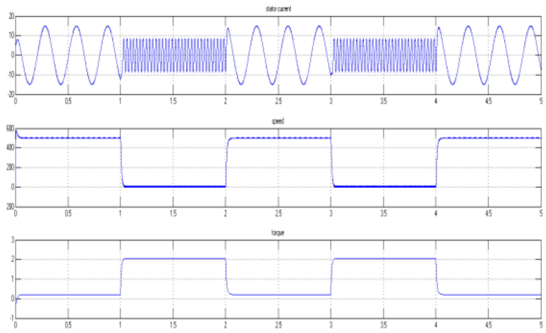
Stator resistance RS [ohm]: 40
Stator inductance LS [H]: 0.2913
Total inertia J [kg/m2]: 0.004
Viscous friction coefficient B[Nm s] : 0.001
Number of pole pairs: 1
Nominal voltage [V]: 300 .
The MZS converter parameters:
L1=L2=6mH;
C1=C2=C3=470ìF.
The PI speed controller parameters:
KP=2; Ki=20.

The PI controller parameters in the shoot-through-time control block:

Gain: 0.009;
Time Constant: 2.5 ms.

Simulation results:

Stator current, speed & torque with respective to time are shown as follows:



Voltages across inductors and capacitors are as follows:

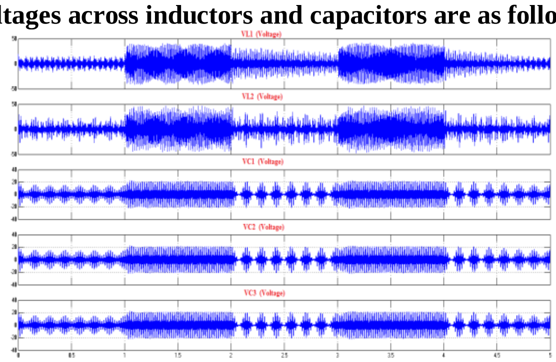


TABLE I

Topologies	No. of transistors	Peak transistor current	peak transistor voltage[v]
A	4	2	300
B	2	6	900

V. Conclusions And Discussions:

The proposed modified Z-source single phase inverter is a possible solution for motor drives with single phase permanent magnet synchronous machines. The converter is able to override the DC voltage sags. The inductors peak currents are approximately twice the load peak current.

The voltage boost of the intermediate DC link it can be produced even if there are no "inactive states".

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