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A Novel Space Vector Modulation Based Control Strategy for Z-Source Inverter

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Abstract: In this study, a novel control strategy based on Distributed Space Vector Modulation is proposed to improve dynamic performance of a Z Source Inverter (ZSI) while utilizing only capacitor voltage feedback. Distributed space vector modulation allows ZSI output voltage to be controlled by Z source capacitor voltage with a simple equation. Therefore, only one voltage feedback is enough to control inverter output voltage. Furthermore, zero state is not utilized in the proposed control strategy, so an additional control loop for the modulation index is no longer necessary. Flexible modulation index allows work with flexible dc line voltage and limits the voltage stresses in the inverter switches so ZSI has low cost switches and high efficiency. Moreover, the proposed control method was investigated for both resistive and inductive loads due to ZSI load power factor-dependent characteristics. The effectiveness of the suggested control method is verified by Matlab/Simulink simulations, considering the sudden changes in both the dc source and load level.

Keywords: dc-ac power converters; inverters; power conditioning; impedance source inverters ; power system dynamics; linear feedback control systems.

Kontrolna strategija inverterja na osnovi modulacije prostorskega vektorja

Izvleček: Predstavljena je nova kontrolna strategija na osnovi distribuirane modulacije prostorskega vektorja za izboljšanje dinamičnih lastnosti inverterja z Z virom (ZSI) le z uporabo kapacitivne napetostne povratne zanke. Distribuirana modulacija prostorskega vektorja omogoča nadzor izhodbe napetosti ZSI z napetostjo vhodnega kondenzatorja z eno preprosto enačbo. Za nadzor napetosti je tako potrebna le ena povratna zanka. V strategiji ni uporabljeno ničelno stanje. Kontrolna zanka za modulacijo prav tako ni več potrebna. Fleksibilen modulacijski indeks omogoča delo s fleksibilno dc napetost in omejuje napetostni stres v stikalih inverter, kar omogoča uporabo cenenih stikal z visokim izkoristkom. Predlagana kontrola je bila uporabljena na rezistivnih in induktivnih bremenih. Učinkovitost metode je bila preverjena v Matlab/Simulink okolju.

Ključne besede: dc-ac močnostni pretvornik; inverter; dinamika moči; linearna povratna zanka

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1 Introduction

Power conditioning units (PCU) are widely used in different areas like industry, energy plants, transportation, etc. Z Source Inverter (ZSI) is an emerging and promising topology for these units, having significant benefits such as buck-boost capability, low cost, reduced volume, and higher efficiency when compared to Voltage Source and Current Source Inverters [1]. Due to its advantages, ZSI has been widely investigated from various aspects; i.e., modulation methods, closed loop control methods, design, and novel topologies [2, 3].

Although ZSI has some significant superiorities, it has the drawback of poor dynamic performance. ZSI output voltage amplitude depends on both modulation index (M) and dc line voltage, so it is strictly connected with a shoot through duty ratio (D). ZSI has a buck-boost characteristic; similar to other buck-boost converters, the transfer function between shoot through duty ratio and ZSI output has a right half plane zero [4]. RHP zero causes an instability in the system. During step changes in shoot through the duty cycle, an initial collapse dip occurs in the capacitor voltage, followed by a damped oscillation. This causes a disturbance in the output voltage of the inverter [5],[6]. Therefore, proper controller design is needed for high dynamic performance. There are many researches dealing with this problem, and their suggestions can be classified under four groups: capacitor voltage control, direct DC line voltage control, indirect DC line voltage control, and unified control.

Using [7, 8] only capacitor voltage (Vc) has been suggested for controlling. In this method, Vc is kept constant; however, output voltage stability and voltage stress across switches have not been considered. In [9, 10] one model, predictive control has been proposed to keep Vc constant; however, it has four current sensors and a voltage sensor for feedbacks. Therefore, it is too complicated and too expensive. In direct dc line voltage control [6], an external sensing circuit has been given to measure dc line voltage (Vi) directly and stabilize it due to the pulsating nature of dc line voltage. However, the complex design of the external sensing circuit makes the control system expensive. In [6], [11-13], indirect dc line voltage control methods have been proposed to eliminate Vi measurement problems because of their pulsating nature. Nevertheless, they utilize zero state (Z) as a margin between D and M, because they use the constant modulation index as a result of constant Vi. Thus, they work with a low modulation index and a high dc line voltage. As a result, their voltage stress across bridge switches and switching losses are much higher than they could be. In [14] a unified control method is proposed, with an output voltage control loop getting feedback directly from ZSI output. Shoot through duty ratio and modulation index are controlled simultaneously. The main *drawback* of this method occurs in grid-tied applications, because output voltage feedback is fixed to network voltage.

Choosing the correct modulation technique is also an important factor for ZSI control design. There are different modulation techniques for ZSI in literature: Simple Boost Control, Maximum Boost Control, Maximum Constant Boost Control, Traditional Space Vector Modulation, and Modified Space Vector Modulation. A detailed comparison of these methods has been given in [15]. It is very important to choose the right modulation technique to achieve the lowest voltage stress on switches, highest efficiency, and the lowest THD.

In the majority of power conditioning units, the main goal of the control loops is to achieve a stable output at the desired level. When we consider ZSI in a PCU, the control loop should be focused on getting a stable output voltage. Nevertheless, most previous researches endeavored to be keep the capacitor voltage (Vc) or dc line voltage (Vi) constant. Moreover, in order to limit voltage stress across inverter bridge and switching losses, ZSI should operate with the lowest possible dc line voltage. None of the aforementioned methods have been taken into account, both in order to simultaneously obtain a stable output during transients and to limit switching losses. An indirect output voltage governed by controlling impedance network capacitor voltage is preferred to overcome the drawbacks listed above and to get a simple configuration [16].

ZSI behavior is affected by load power factor and has been investigated in some researches [17-18]. For this reason, the effectiveness of the controller used in ZSI for different power factor levels needs to be validated. In this paper, a PI control strategy has been given considering different power factor levels. Transfer function between shoot through duty ratio and inverter output voltage is needed to design a PI compensator. Thus, a dynamic model of ZSI is obtained by state space averaging and small signal analysis. There are some studies about dynamic modelling of ZSI in the literature, such as [8], [13], [19-21]. However, the modulation index is not considered as a control variable. Moreover, they do not consider input voltage as a perturbation source; in this case, the input voltage drop scenario would not be reflected in the model. The ZSI dynamic model, which is given in this research, considers all of these issues and is utilized to control output transfer function. The designed PI controller considering this dynamic model is tested with simulations.

a)

b)

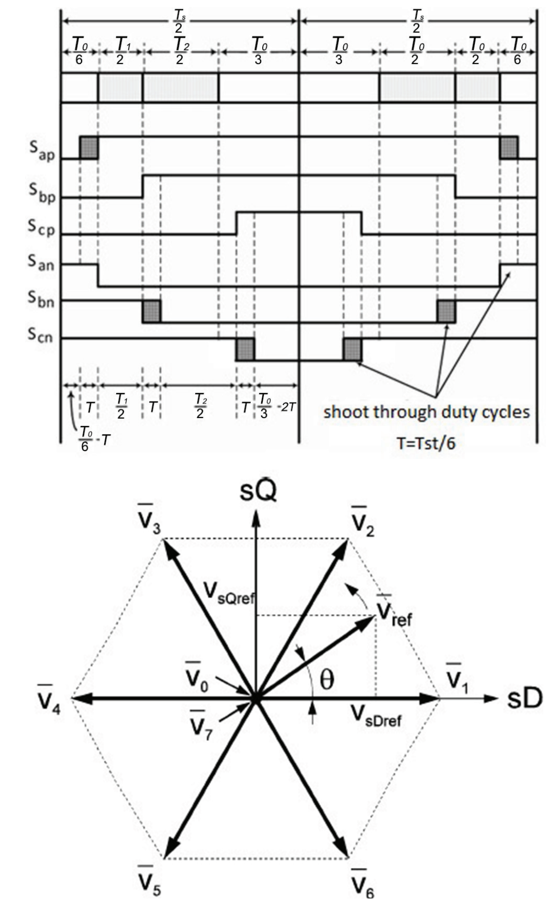


Figure 1: a) DSVM switching pattern; b) Voltage space vectors

2 Distributed Space Vector Modulation

The Distributed Space Vector Modulation (DSVM) switching pattern is given in Figure 1. Shoot through duty cycles are divided into six parts, which are settled not only into zero states but also between active states. This results in a well-balanced distribution of shoot through states and thus a better performance can be achieved.

DSVM gives the chance to get the highest DC bus utilization, and DSVM allows ZSI output voltage estimation with only z-source capacitor voltage feedback. The DSVM scheme can be seen in Figure 1. Related equations are given in (1)-(6).

$$V_k = \left(\frac{2}{3}\right) V_{in} \tag{1}$$

$$V_{ref\_max} = V_{out\_peak} = \left(\frac{\sqrt{3}}{2}\right) V_k \tag{2}$$

$$V_{outpeak} = \frac{V_{i_{peak}} M}{\sqrt{3}} \tag{3}$$

$$M = 1 - D \tag{4}$$

$$V_{i_{peak}} = \frac{V_c}{1-D} \tag{5}$$

$$V_{out_{peak}} = \frac{V_c}{\sqrt{3}} \tag{6}$$

The terms used in these equations are described below.
k: voltage space vector number (1,2...6)
V_i: ZSI dc line voltage
V_{in}: ZSI dc input voltage
$V_{ref,max}$: ZSI ac output voltage peak value (reference)
V_{out}: ZSI ac output voltage
M: modulation index
D: shoot through duty ratio
V_c: ZSI impedance network capacitor voltage

As can be seen from (4), no zero state is used in the proposed control method. Thus, it is guaranteed to get the minimum possible dc line voltage and the minimum voltage stress to get the desired output voltage level. According to (6), the ZSI output voltage can be estimated by a very simple calculation using only the capacitor voltage feedback. This is a very precious relationship because it allows ZSI output voltage control without output voltage feedback. So, it is possible to control ZSI output voltage indirectly by capacitor voltage control. It is necessary to achieve control to output transfer function to design a suitable controller. So, this is needed to get a dynamic model of ZSI.

3 Modelling of ZSI

It is essential to get a dynamic model of ZSI to analyze both steady state and transient operation; it is also essential to get a transfer function between shoot through duty ratio and z source capacitor voltage to design a proper controller. However, ZSI has a nonlinear characteristic, as can be seen in Figure 2.

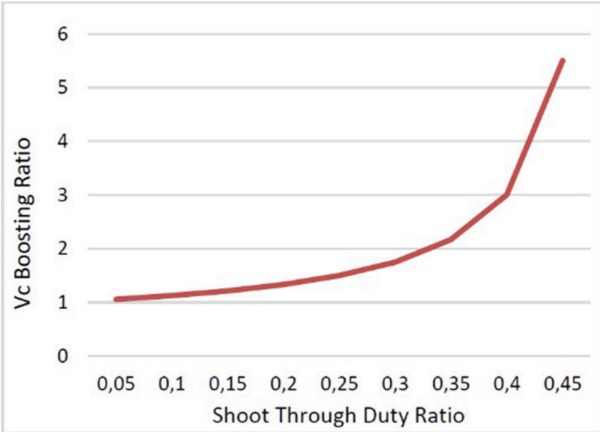


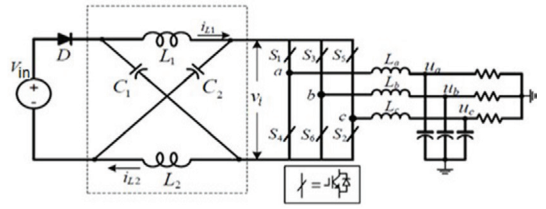
Figure 2: Nonlinear relationship between shoot through duty ratio and capacitor voltage boosting ratio

Because of the nonlinear characteristic of ZSI, the system shall be linearized around an equilibrium point due to utilizing a linear controller. Therefore, the state space averaging method is used to get the ZSI model, and small signal analysis is used to linearize the system around an equilibrium point. Although previous researches have ignored the modulation index as a control variable, in this research it is considered a control variable to determine the exact dynamic inverter model. Moreover, it is also essential to consider input voltage as a perturbation source to get a model for analyzing dynamic problems like inverter input voltage drop.

In order to simplify ZSI ac side as a dc load it has been considered ZSI has a balanced load. The circuit diagram can be seen in Figure 3.

Three states are considered while modelling ZSI: shoot through mode, zero voltage vector mode, and active voltage vector mode. These modes can be shown with the proper switch states in Table 1.

a)



b)

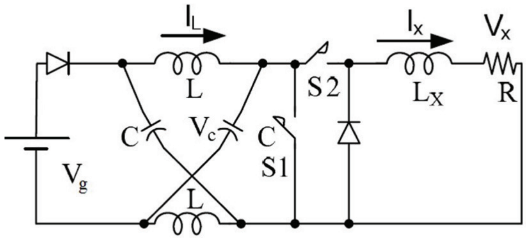


Figure 3: a) ZSI basic structure; b) DC equivalent ZSI circuit

Table 1: ZSI operatıng modes accordıng to swıtch modes

Item	S1 Position	S2 Position
ZERO STATE	OPEN	OPEN
SHOOT THROUGH	CLOSED	OPEN
ACTIVE STATE	OPEN	CLOSED

In this model the state variables are inductance current, capacitor voltage, and load current.

$$x(t)=\left[i_L(t)\ v_c(t)\ i_x(t)\right] \tag{7}$$

Considering three operating modes and using the state space averaging method, the state space average model can be written as in (8).

$$\frac{d}{dt}\begin{bmatrix} i_L(t) \\ v_c(t) \\ i_{Lx}(t) \end{bmatrix} = \begin{bmatrix} 0 & \frac{2d-1}{L} & 0 \\ \frac{1-2d}{C} & 0 & -\frac{m}{C} \\ 0 & \frac{2m}{L_x} & -\frac{R_x}{L_x} \end{bmatrix} \begin{bmatrix} i_L(t) \\ v_c(t) \\ i_{Lx}(t) \end{bmatrix} + \begin{bmatrix} \frac{V_{in}}{L}(1-d) \\ 0 \\ \frac{V_{in}}{L_x}m \end{bmatrix} \tag{8}$$

As can be seen in (8), i_L, v_c, and i_x are state variables, M and D are control variables, and v_c and v_x are the outputs to be controlled.

Steady state equations of state variables can be derived from the state space model, as in (9)-(11).

$$V_c=\frac{D'}{D'-D}V_{in} \tag{9}$$

$$I_L=\frac{D'}{D'-D}I_{Lx} \tag{10}$$

$$I_{Lx}=\frac{V_c}{R_x} \tag{11}$$

Small signal analysis was used to linearize the system around an equilibrium point. In this analysis, the general form for the variable is $x=X+\hat{x}(t)$, where *X* is the variable's component at the equilibrium point, *x* is the variable in the state space model (as in (7)), and is the perturbation signal. By using these formulas for all the variables, the state space model to be used for the dynamic model can be achieved as in (12).

$$\begin{bmatrix} s\hat{I}_L \\ s\hat{V}_c \\ s\hat{I}_X \end{bmatrix} = \begin{bmatrix} 0 & \frac{2D-1}{L} & 0 \\ \frac{1-2D}{C} & 0 & -\frac{M}{C} \\ 0 & \frac{2M}{L_X} & -\frac{R_X}{L_X} \end{bmatrix} \begin{bmatrix} \hat{I}_L \\ \hat{V}_c \\ \hat{I}_X \end{bmatrix} + \begin{bmatrix} \frac{1-D}{L} & \frac{2V_C-V_{in}}{L} & 0 \\ 0 & -\frac{2I_L}{C} & -\frac{I_X}{C} \\ -\frac{M}{L_X} & 0 & \frac{2V_C-V_{in}}{L_X} \end{bmatrix} \tag{12}$$

State equations of ZSI small signal analysis are given in (13)-(15).

$$sL\hat{i}_L=(2D-1)\hat{v}_c+(1-D)\hat{v}_{in}+\left(2V_c-V_g\right)\hat{d} \tag{13}$$

$$sC\hat{v}_c=(1-2D)\hat{i}_L-M\hat{i}_x-2I_L\hat{d}-I_x\hat{m} \tag{14}$$

$$sL_x\hat{i}_x=2M\hat{v}_c-R_x\hat{i}_x-M\hat{v}_{in}+\left(2V_c-V_{in}\right)\hat{m} \tag{15}$$

It is possible to control the output transfer function by using small signal equations and steady state equa-

$$G_{VcD}(s)=\frac{(-2I_LL_xL)s^2+(2L_xV_c-L_xV_{in}-4DL_xV_c+2DL_XV_{in}-2I_LLR_x)s}{(CL_xLs^3+CLR_xs^2+4L_xD^2-4L_xD+2LM^2+L_x)s+(4R_xD^2-4R_xD+R_x)}+ \\ +\frac{2R_xV_c-R_xV_{in}-4DR_xV_c+2DR_xV_c+2DR_xV_{in}}{CL_xLs^3+CLR_xs^2+(4L_xD^2-4L_xD+2LM^2+L_x)s+(4R_xD^2+4R_xD+R_x)} \tag{16}$$

tions. The output control transfer function (16) is provided as a third order transfer function.

The derived transfer function has a right half plane (RHP) zero that causes a non-minimum phase response.

As seen in Figure 4, a step change in shoot through duty ratio causes a high oscillation in capacitor voltage. Thus, ZSI output voltage would be oscillated, too. In order to prevent this unwanted oscillation a closed loop control is used.

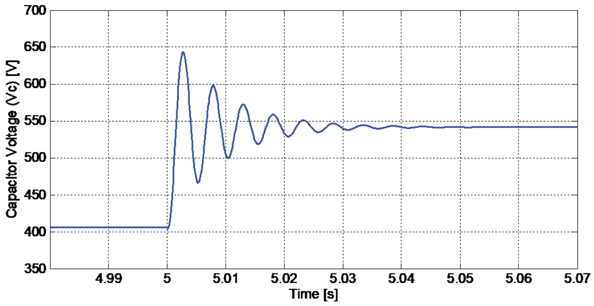


Figure 4: Vc oscillation during a step change in D

4 PI Control of ZSI

In the proposed method, shoot through duty cycle and modulation index are adjusted to track a reference sinusoidal output. As seen in Figure 5, just one control loop is utilized to control the variables M and D. PI controller is used to adjust shoot through duty ratio, and modulation index is calculated considering the shoot through duty ratio to eliminate an unnecessary control loop.

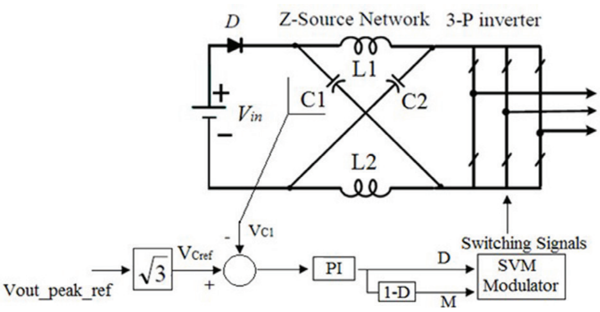


Figure 5: PI control schema

This is aimed to get high stability so only one control loop is utilized in the system. Inverter output voltage tracking is achieved with z source capacitor voltage reference and feedback. As seen in Figure 5, the M=1-D equation is used to adjust the modulation index considering dc line voltage. Therefore, an additional control loop is needed for the modulation index to be eliminated.

The circuit parameters used to investigate the performance of the proposed method are given in Table 2.

Table 2: ZSI Parameters

Circuit Parameter	Value
L1, L2	650 µH
C1, C2	500 µF
Input voltage	450 V
Switching Frequency	2 kHz
Load Resistance	12,5 Ω
Load Inductance	340 µH

Transfer function between shoot through duty ratio and Z source capacitor voltage is given in (17).

$$G_{VcD} = \frac{-2,346x10^{-5}s^2 - 0,7096s + 5625}{1,105x10^{-10}s^3 + 4,063x10^{-6}s^2 + 0,001106s + 6,125} \tag{17}$$

Compensated and uncompensated system bode diagrams can be seen in Figure 6.

(a)

(b)

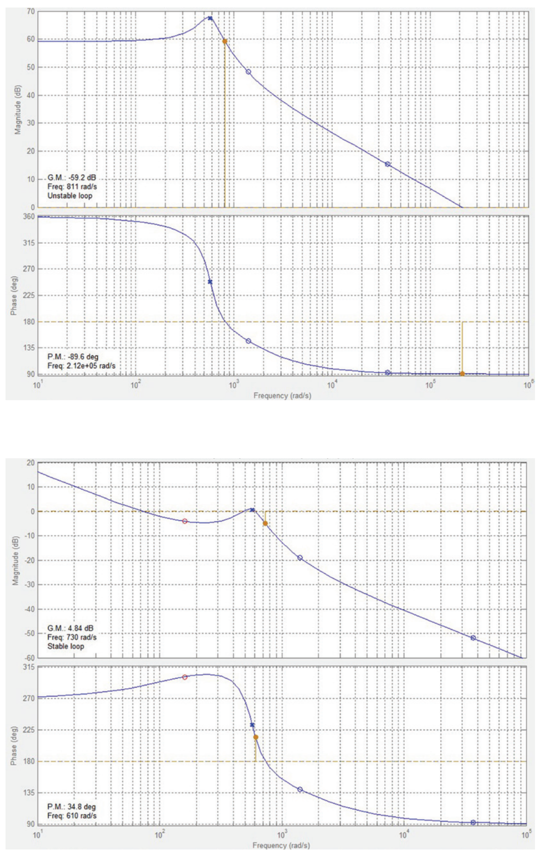


Figure 6: (a) Uncompensated and (b) compensated system bode diagram

5 Results

The proposed control method is tested with Matlab/Simulink simulations for two different power factor levels (PF = 1 and PF = 0,9) to investigate the performance of controller for different kinds of loads. The Simulink diagram of the control system can be seen in Figure 7.

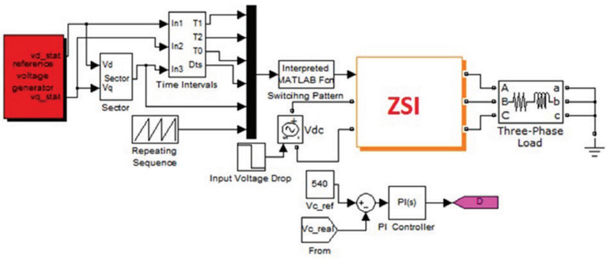


Figure 7: Simulink diagram of the control system

The proposed method is tested for two situations:

1. 11% input voltage drop (450 V to 400 V) at 0,5 seconds.
2. 75% load decrease at 0,4 seconds, and then a 75% load increase at 0,7 seconds.

The results are given in Figures 8-12. As seen in Figure 8, the proposed control method compensates overshoots and oscillations of the capacitor voltage, as given in Figure 4. Therefore, it contributes to the safety of the system.

Figure 9 (a) and (b) show that when the input voltage decreases, the shoot-through duty cycle D increases in order to obtain the desired ac output voltage, with a transient regulation. Figure 9 (c) and (d) show that when the load increases or decreases, the shoot-through duty cycle D respectively reduces or increases in order to obtain the desired ac output voltage. Moreover, as can be seen in Figure 10, dc line voltage is increased during input voltage step down so it is not kept constant, contrary to previous researches. Figure 11 shows the phase-A output voltage and current. Note that the current is scaled to ten times the actual value to be comparable with the voltage. Fig. 11(a) and (b) shows the output voltage and output current after the input voltage changes. Also, Figure 11(b) and (d) shows the ac voltage and current during the load variation.

The zoomed version of the inductor current and the dc line voltage are shown in Figure 12 to illustrate the impact of the shoot-through states. It can be observed from this figure that the inductor current is increasing during the shoot-through states, while dc line voltage is zero because of the short-circuit of the dc line.

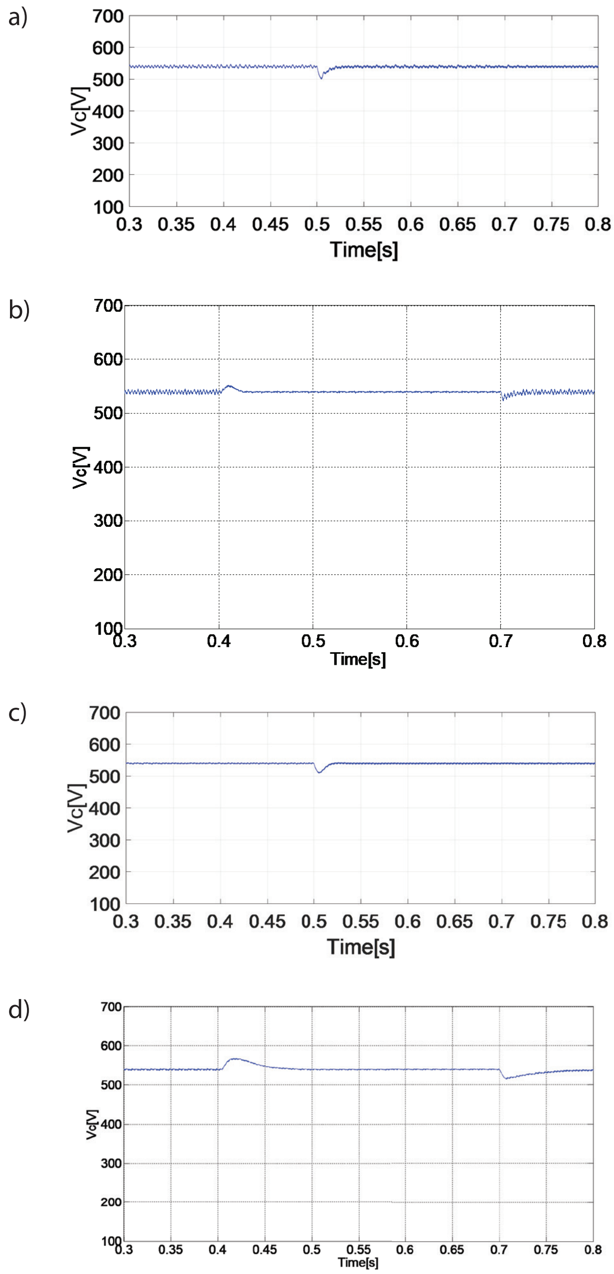


Figure 8: Capacitor voltage (Vc) response for a) 11% input voltage step down (PF=1); b) 75% load change (PF=1); c) 11% input voltage step down (PF=0,9); and d) 75% load change (PF=0,9)

As seen in the figures, the proposed PI control method has a good dynamic performance for both resistive and inductive loads. Control performance is nearly excellent for resistive load, and inverter output voltage becomes stable in half a period during a disturbance. Control performance is also very good for inductive load, and inverter output voltage becomes stable in the 2-3 period during a disturbance. Contrary to previous works, variable dc line voltage lets the ZSI work with a flexible

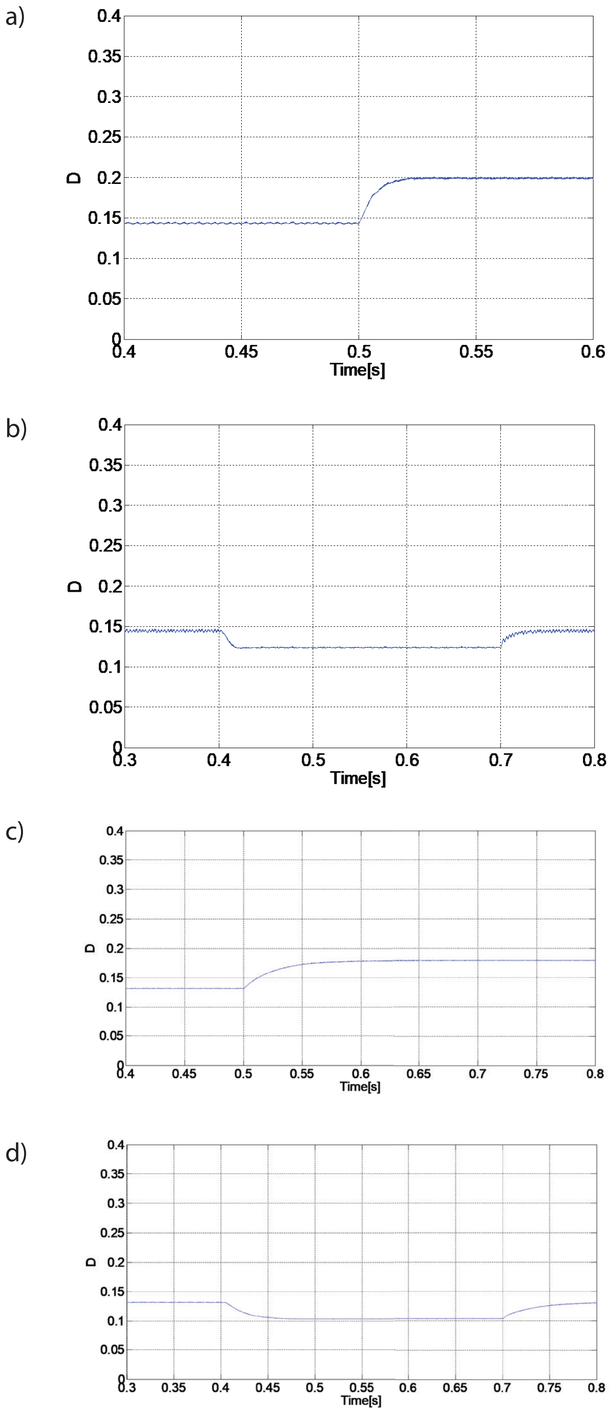


Figure 9: Shoot Through Duty Ratio (D) response for a) 11% input voltage step down (PF=1); b) 75% load change (PF=1); c) 11% input voltage step down (PF=0,9); and d) 75% load change (PF=0,9)

modulation index; therefore, ZSI becomes capable of working with lower voltage stress on switches. Flexible modulation index and SVM lets it work with minimum dc line voltage. Thus, voltage stress on switches is minimized.

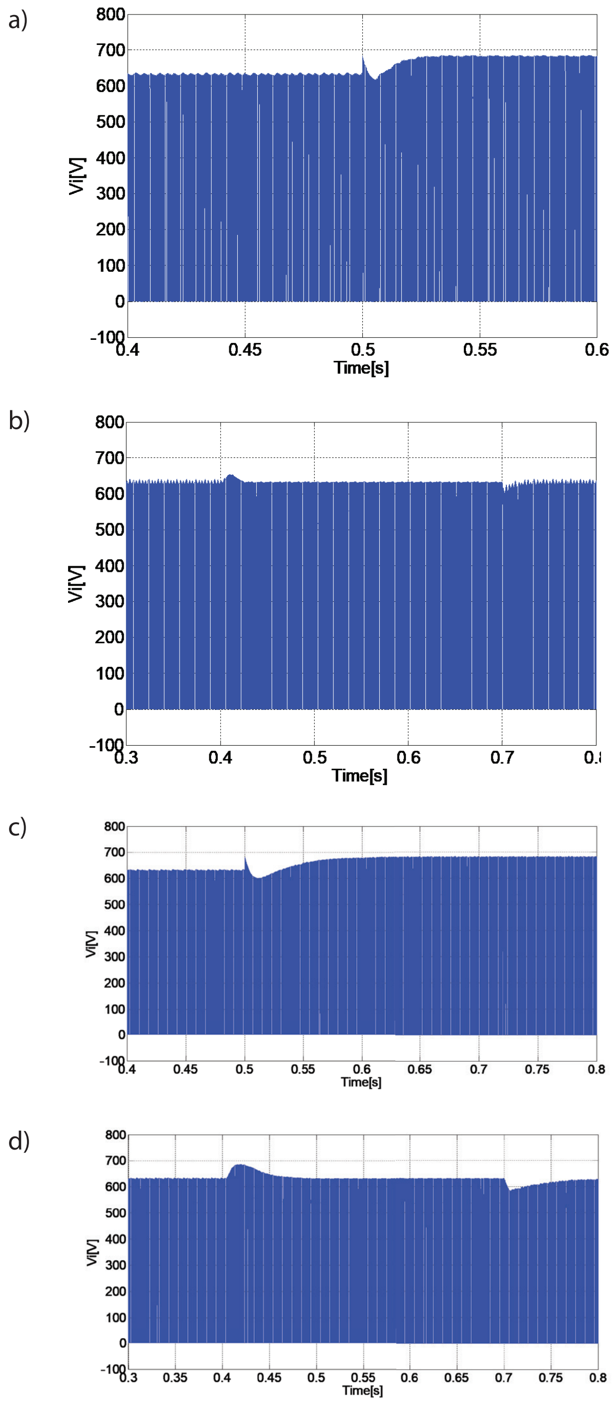


Figure 10: Dc line voltage (Vi) response for a) 11% input voltage step down (PF=1); b) 75% load change (PF=1); c) 11% input voltage step down (PF=0,9); and d) 75% load change (PF=0,9)

6 Conclusion

In this research, a dynamic model of ZSI is given. It considers both modulation index (*M*) and shoot through

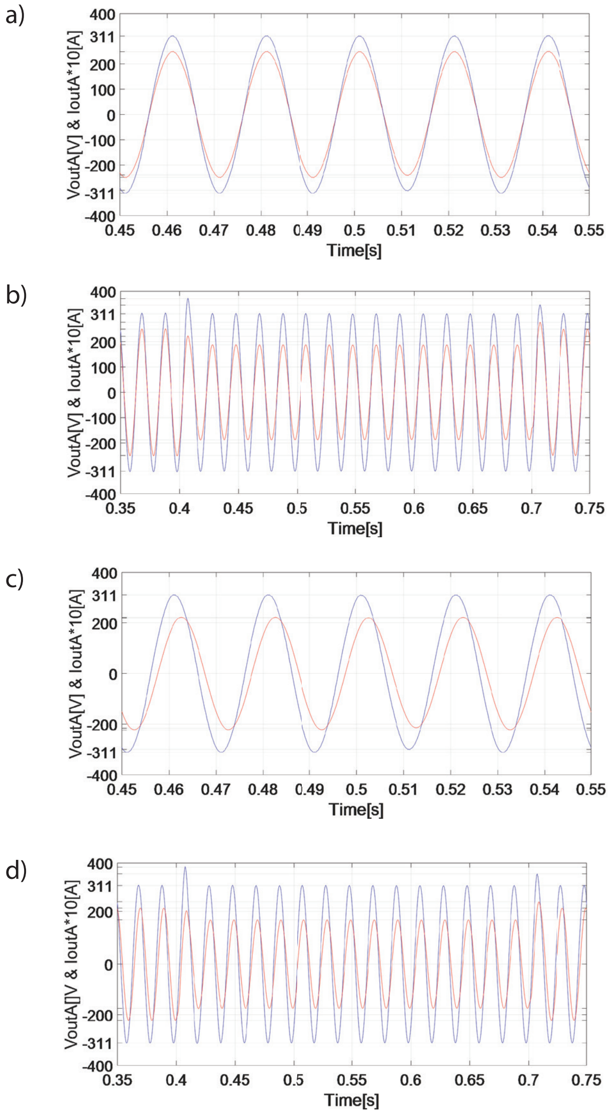


Figure 11: Phase-A output voltage (Vout) and Output current (Iout) response for a) 11% input voltage step down (PF=1); b) 75% load change (PF=1); c) 11% input voltage step down (PF=0,9); and d) 75% load change (PF=0,9)

duty ratio (*D*) as control variables; moreover, three operation states (active, zero, and shoot through) are considered for modelling to get a successful model. Considering this dynamic model, a control method based on distributed space vector modulation, which eliminates the drawbacks in the previous researches, is proposed for ZSI. In the proposed method, inverter output voltage is controlled via z source capacitor voltage feedback in order to achieve a high dynamic performance. Furthermore, the proposed method is investigated with a novel approach by considering different load power factor levels. Although the proposed method is effective for different loads, research results show that linear control methods are not enough for

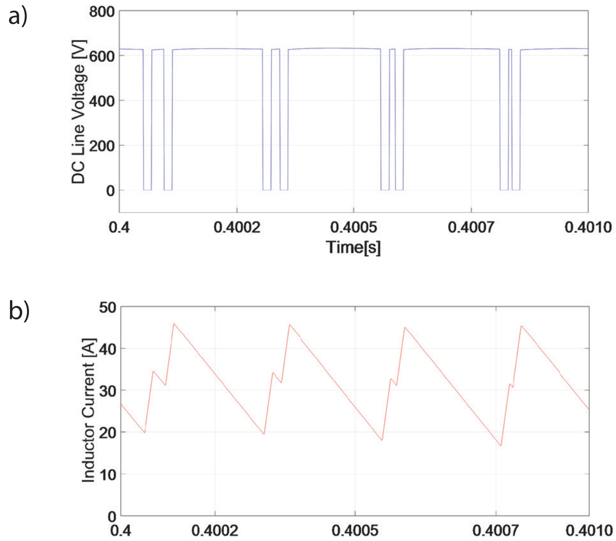


Figure 12: The zoomed version of a) the dc line voltage (V_i); b) the inductor current (I_l)

systems that have a load power factor range that is too wide. Moreover, very high input voltage oscillations make linear controllers useless because of the transfer function, which is obtained on an equilibrium point. Therefore, nonlinear control systems with a new approach shall be utilized for wide power factor ranges and wide input voltage oscillations variations.

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