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Analysis and Comparison of Control Methods of Z-Source Inverters Used in Photovoltaic Systems

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Abstract **-**One of the most important parts of photovoltaic system is inverter. In recent years; impedance source inverter (ZSI), which is a buck-boost inverter without the need of a dc-dc converter, has been presented to overcome disadvantages of voltage source and current source inverters, and a lot of papers about ZSIs have been published in international literature. ZSIs should have high efficiency and low cost and sustain a high quality output voltage to be an economic alternative to conventional inverters. Meeting these requirements basically depends on the used control method. Since there are very few works about ZSI control methods comparison, both all the sinusoidal pulse width modulation (PWM) control methods that are presented in the literature up to now, and space vector modulation control methods that are used recently with different switching schemes are analysed in this study, and all these methods are simulated via Matlab/Simulink. The results are compared, and it has been seen that space vector PWM can be applied to ZSIs without any problem, and it has superior performance than sinusoidal PWM control methods.

Keywords**:** Photovoltaic systems, impedance source inverter(ZSI), space vector modulation(SVPWM), simulink

1. Introduction

Distributed generation and renewable energy sourced systems have involved increasing number of industrial and academic research. Among these studies photovoltaic systems emerge as an important renewable energy source. Due to decreased expense and cost of photovoltaic panels, photovoltaic energy generation has found a very good penetration in Turkey and in the world market. Inverters are one of the most important components of photovoltaic systems. Inverters used in the conventional power electronic applications in various fields are categorized to voltage-source and current-source inverters. Both structures have some drawbacks.

Voltage-source inverters' disadvantages can be mentioned as (Peng, F. Z., 2003), (Stocklosa, O. et al., 2010):

- They have buck structure. In case of insufficient DC bus voltage level, the system must be upgraded using dc-dc converter boosting DC bus voltage.
- The switches which have taken part in the same leg of inverters cannot be switched on simultaneously. Under unwanted conditions such as Electromagnetic Interference (EMI), the switches may take place in such situation and cause a risk to the system.
- Dead time between the commutation of switches, causes the output voltage harmonics.

Current-source inverters' disadvantages can be mentioned as (Peng, F. Z., 2003), (Stocklosa, O. et al., 2010):

- They have boost structure. It needs dc-dc converter for wide range operating voltage applications.
- They require a series diode in IGBT applications, which limits the use of intelligent power module (IPM).
- Depending on the switch position, the source can be open circuit and cause a risk for system.
- The necessity of commutation time overlap for safe commutation causes harmonics in output voltage.

To eliminate disadvantages of voltage- and current-source inverters, as shown in Fig. 1 impedance-source inverter structure has been developed. There exists an impedance network at input of this structure. Inverter can be operated buck-boost and thereby eliminates the need for dc-dc converter for applications requiring operation over a wide voltage range. Thus, by using less semiconductor switches in the system, the total volume and cost of the system have been reduced. In addition, due to the reliable nature of the circuit, a short circuit or open circuit of the DC source through the inverter legs would not cause a risk to the system.

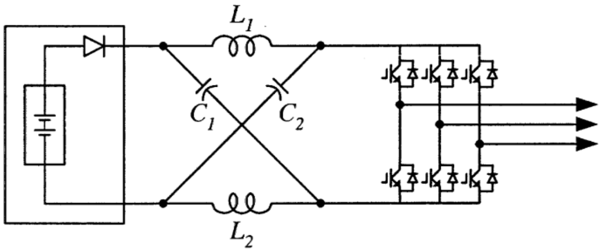


Fig. 1. Z-Source Inverter

The output voltage of the photovoltaic panel varies over a wide range depending on the weather conditions. Therefore in conventional photovoltaic applications the use of dc-dc converter together with voltage source inverter is required. This situation causes a negative impact in terms of cost, efficiency and volume(Huang, Y., 2006). It is important to choose the right control technique for achieving all of the advantages of ZSI. There are some papers in literature which have proposed different control techniques. In this paper, the most advantageous control techniques are analysed and simulated to compare them. It is a new approach to compare all of them with the same circuit parameters to get a certain comparison.

2. Control Methods Using Sinusoidal Pulse Width Modulation(SPWM)

In impedance source inverters, unlike conventional approaches, to boost the inverter voltage the legs should be operated as short-circuit. At a certain part of switching period which is determined by the rate of voltage boost, the short circuit operation is carried out, and it is called as shoot through state. In impedance source inverters, sinusoidal PWM applications can be investigated under three separate headings. These are: simple boost control (SBC), maximum boost control (MBC) and the maximum constant boost control (MCBC).

2. 1. Simple Boost Control

This method is the first proposed control method for the impedance source inverters (Peng, F. Z., 2003). Switching logic is shown in Fig. 2. In practice inductance and capacitance values used in impedance network are selected equal, hence the impedance network is symmetrical and therefore the following equations are valid.

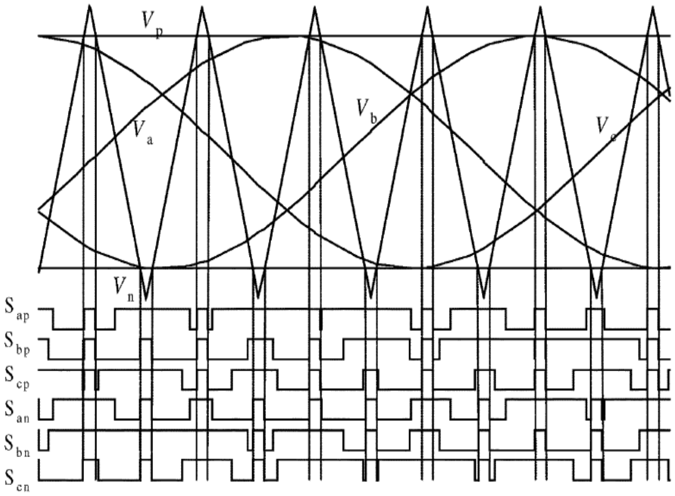


Fig. 2. Simple Boost PWM Control

$$v_{C1} = v_{C2} = v_C \tag{1}$$

$$v_{L1} = v_{L2} = v_L \tag{2}$$

Equivalent circuit of ZSI during shoot through state can be seen in Fig. 3. During this state, equations (3) and (4) are valid (Peng, F. Z., 2003).

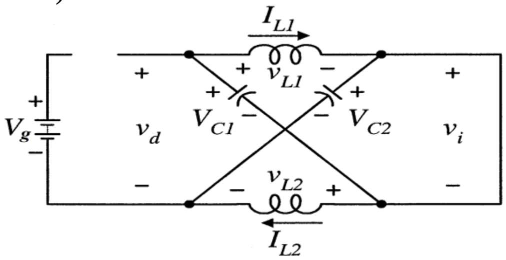


Fig. 3. The equivalent circuit under short-circuit operation

$$v_L = v_C = v_d/2 \tag{3}$$

$$v_i = 0 \tag{4}$$

Equivalent circuit of ZSI during non-shoot through state can be seen in Fig. 4. During this state, equations (5)-(7) are valid[1].

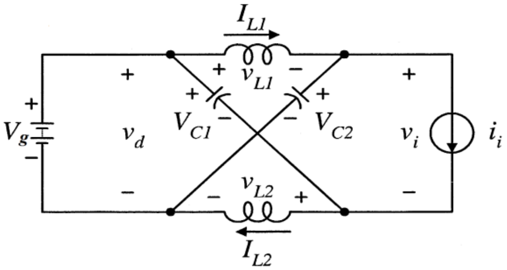


Fig. 4. The equivalent circuit of the inverter operating

$$V_L = V_g - V_C \tag{5}$$

$$V_d = V_g \tag{6}$$

$$V_i = V_C - V_L = 2V_C - V_g \tag{7}$$

In the steady state the average value of the voltage on the inductor will be zero and the following equations can be obtained.

$$V_L = \overline{v_L} = \frac{T_{kd} \cdot V_C + T_n (V_g - V_C)}{T_s} = 0 \tag{8}$$

$$D = \frac{T_{kd}}{T_s} \tag{9}$$

$$\frac{V_C}{V_g} = \frac{1 - D}{1 - 2D} \tag{10}$$

$$V_i = \overline{v_i} = \frac{T_{kd} \cdot 0 + T_n \cdot (2V_C - V_g)}{T_s} = \frac{T_n}{T_n - T_{kd}} V_g \tag{11}$$

$$\hat{v}_i = V_C - v_L = 2V_C - V_0 = \frac{T_s}{T_n - T_{kd}} V_g = B . V_g \tag{12}$$

$$B = \frac{1}{1 - 2D} \geq 1 \tag{13}$$

In these expressions D, B and V_i, represent shoot through duty ratio, boosting factor and the DC line voltage, respectively. The inverter output phase voltage (V_{ac}) can be defined with following equations. In these formulas M describes sinusoidal PWM modulation index:

$$\hat{v}_{ac} = M.B.\frac{V_g}{2} \tag{14}$$

$$M + D \leq 1 \tag{15}$$

Modulation index and boostingfactor are interdependent as will be understood from equation (15). For boosting the voltage by using shoot through operation, the boosting factor has a value greater than zero, so the modulation index falls naturally. Multiplication of the modulation index and the boosting factor gives the value of the gain (G) and the following expressions can be written.

$$G = MB = \frac{\hat{V}_f}{V_g / 2} = \frac{M}{2M - 1} \tag{16}$$

$$B = \frac{1}{2M - 1} \tag{17}$$

$$M = \frac{G}{2G-1} \tag{18}$$

$$V_s = BV_g = (2G-1)V_g \tag{19}$$

Here, V_s represents the voltage stress exerted on the semiconductor switches. This voltage causes switching losses, and thus has a direct impact on the efficiency. While developing different control techniques for Impedance source inverters, the quest mainly comes for working with the aim to provide the lowest possible voltage stress.

2. 2. Maximum Boost Control

The relationship between the amplification factor and the modulation index for simple boost control is given in Eq. (17). Here as it can be seen, in the applications requiring high output voltage, the need for large-value of amplification ratio decreases the modulation index value. The overgrowing of DC-link voltage to high values increases voltage stress on the semiconductor switches and cause a decrease in the overall efficiency of the system by increasing the switching loss. Switching structure for maximum boost control is presented in Fig. 5 (Peng, F. Z. et al., 2005). There is not a separate signal for controlling the shoot through operation, in the moments that the carrier wave amplitude is higher than the sinusoidal reference signal the inverter runs in shoot through mode. This prevents the shoot through operating rate to remain constant. As it can be seen from equations (20) and (21), when $\theta = \pi/3$, the shoot through operating rate is at its maximum value, and when $\theta = \pi/6$ or $\theta = \pi/2$, it is at its minimum value.

$$\frac{T_{kd}(\theta)}{T_s} = \frac{2-(M\sin\theta - M\sin(\theta - \frac{2\pi}{3}))}{2} \tag{20}$$

$$\frac{\overline{T_{kd}}}{T_s} = \int_{\frac{\pi}{6}}^{\frac{\pi}{2}} \frac{2-(M\sin\theta - M\sin(\theta - \frac{2\pi}{3}))}{2} d\theta \tag{21}$$

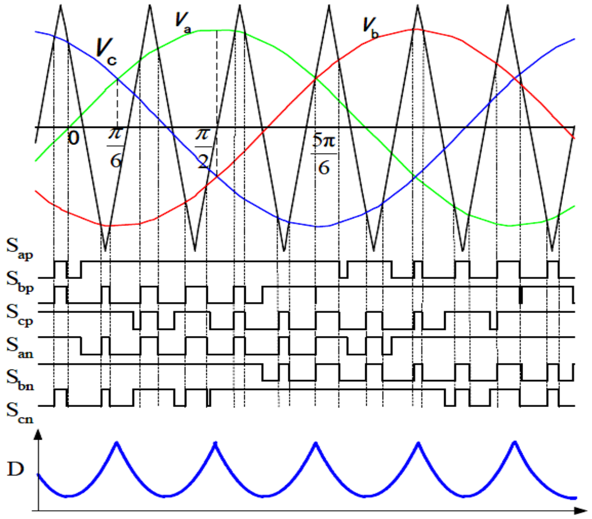


Fig. 5. Maximum Boost PWM Control

Boosting factor, modulation index and voltage stress expressions for the maximum boost control technique, are given in the equations (22) - (24).

$$B = \frac{1}{1-2D} = \frac{\pi}{3\sqrt{3}M - \pi} \tag{22}$$

$$M = \frac{\pi G}{3\sqrt{3}G - \pi} \tag{23}$$

$$V_s = BV_g = \frac{\pi V_g}{3\sqrt{3}M - \pi} = \frac{3\sqrt{3}G - \pi}{\pi} V_g \tag{24}$$

As shown in the following (25) to (27) equations, in low frequencies inductor ripple current is increased, which reveals the need to use a larger inductance and this decreases efficiency, thus the costs caused by an increase.

$$\Delta V_L = V_{imax} - V_{imin} \tag{25}$$

$$\Delta V_L = \left(\frac{\sqrt{3}}{2}M - \frac{\sqrt{3}}{2}M\cos\left(\frac{\pi}{6}\right)\right)BV_g \tag{26}$$

$$\Delta V_L = \frac{\left(\frac{\sqrt{3}}{2} - \frac{3}{4}\right)MV_g}{12(3\sqrt{3}M - \pi)fL} \tag{27}$$

Ultimately although it is driven by a decrease in the voltage stress with this method, the increase in inductance size led to the search for new control methods.

2. 3. Maximum Constant Boost Control

High voltage stress caused by constant boost control and on the other hand variable short circuit operating rate caused by maximum boost control have brought both control techniques to be disadvantageous. Therefore, a novel control technique has been proposed by (Shen, M. et al., 2004), (Shen, M. et al., 2006) to sustain low voltage stress and constant shoot through duty ratio (Shen, M. et al., 2004), (Shen, M. et al., 2006). Switching structure for this method is shown in Fig. 6. Short-circuit operation rate is determined by upper and lower control curves (V_p, V_n) shown in Fig. 6. The amplitude values in different time zones of the upper and lower control curve, the shoot through duty ratio, boosting factor, sinusoidal PWM modulation index and voltage stress expressions relating to the method, are provided with equations number (29) - (36), respectively.

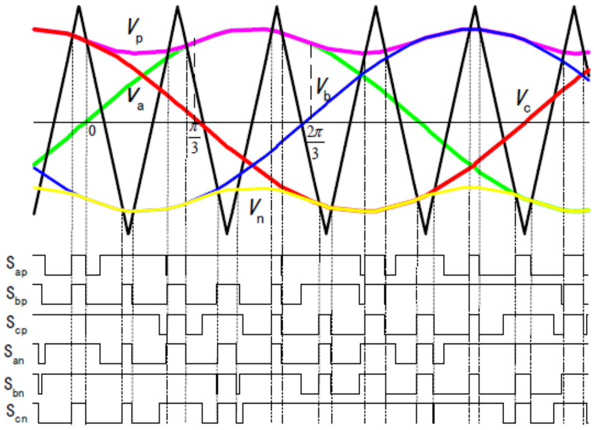


Fig. 6. Maximum Constant Boost PWM Control

$$V_{p1} = \sqrt{3}M + \sin(\theta - \frac{2\pi}{3})M \qquad 0 < \theta < \frac{\pi}{3} \tag{28}$$

$$V_{n1} = \sin(\theta - \frac{2\pi}{3})M \qquad 0 < \theta < \frac{\pi}{3} \tag{29}$$

$$V_{p2} = \sin(\theta)M \qquad \frac{\pi}{3} < \theta < \frac{2\pi}{3} \tag{30}$$

$$V_{n2} = \sin(\theta)M - \sqrt{3}M \qquad \frac{\pi}{3} < \theta < \frac{2\pi}{3} \tag{31}$$

$$D = 1 - \frac{\sqrt{3}M}{2} \tag{32}$$

$$B = \frac{1}{\sqrt{3}M - 1} \tag{33}$$

$$M = \frac{G}{3\sqrt{3}G - 1} \tag{34}$$

$$V_s = BV_g = \frac{V_g}{\sqrt{3}M - 1} = (\sqrt{3}G - 1)V_g \tag{35}$$

This method is the most preferred method among the sinusoidal PWM control techniques. The main problem is the same with the sinusoidal PWM method which is low utilization rate of dc bus.

3. Control Methods within Space Vector Modulation

Space vector modulation applications in voltage-source inverters are discussed in a very broad way in the literature. The higher DC link utilization rate than sinusoidal PWM techniques makes this method preferable. Impedance source inverter also provides an even greater advantage of this situation. Thanks to this method in the variation value of the supply voltage, the minimum dc supply voltage level required for increasing the DC line voltage located between impedance network and inverter circuit rises and thus increase in the efficiency of the system is ensured thanks to the need for less voltage amplification. The applications of space vector modulation in impedance source inverter is similar to the applications in voltage-source inverters, likely active vector must be placed without causing any changes into a switching period during the shoot through state interval (Thangaprakash, S. & Krishnan, A., 2010), (Thangaprakash, S. & Krishnan, A., 2009). The equations expressing space vector modulation is given below.

$$m = \frac{V_{ref}\sqrt{3}}{V_{dc}} \tag{36}$$

$$D = 1 - m \tag{37}$$

$$B = \frac{1}{1 - 2D} \tag{38}$$

$$V_s = BV_g \tag{39}$$

$$\hat{V}_{ac} = \frac{2}{\sqrt{3}} m.B.\frac{V_g}{2} \tag{40}$$

m symbol mentioned in the above equations, unlike the sinusoidal PWM modulation index M, represents the space vector modulation index. Fig. 7 shows the voltage space vectors and operation sectors. . As can be seen from the figure the voltage need of load can be higher than maximum reference voltage amplitude which equals to (√3/2)*Vk (k=1,2,…,6). In this situation dc line voltage is boosted by shoot through operation of the inverter, thus desired output voltage can be achieved (Liu, Y., 2011).

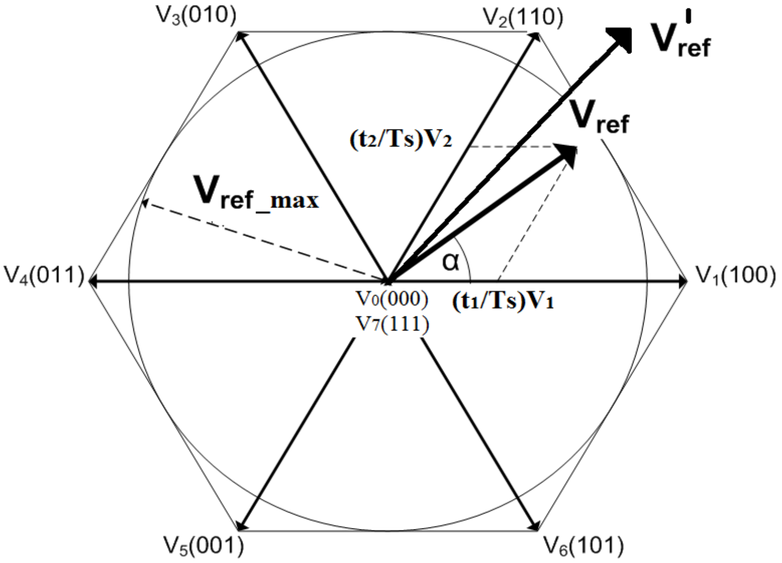


Fig. 7. Voltage Space Vectors and Operation Sectors

Fig. 8 and Fig. 9 shows two separate switching structure of the space vector modulation (Shajith, U. A. & Kamaraj, V., 2011), (Chun, T.W. et al., 2011). In Fig. 8 Conventional SVM (CSVM) switching pattern is given. Shoot through duty cycle are divided in four separate part (T_{kd}), and these parts settled into zero states. In Fig. 9. distributed SVM (DSVM) switching pattern is given. Shoot through duty cycle are divided in 6 parts, and these parts are settled not only into zero states but also between active states. It causes a well balanced distribution of shoot through states and thus a better performance can be achieved as it will be given in simulation results. It can be clearly seen from the figures there is no change in active voltage vector time durations, shoot through states use only zero voltage vector time durations. SVM satisfies different approaches for switching pattern. It could be possible to develop new switching patterns except given ones in this paper.

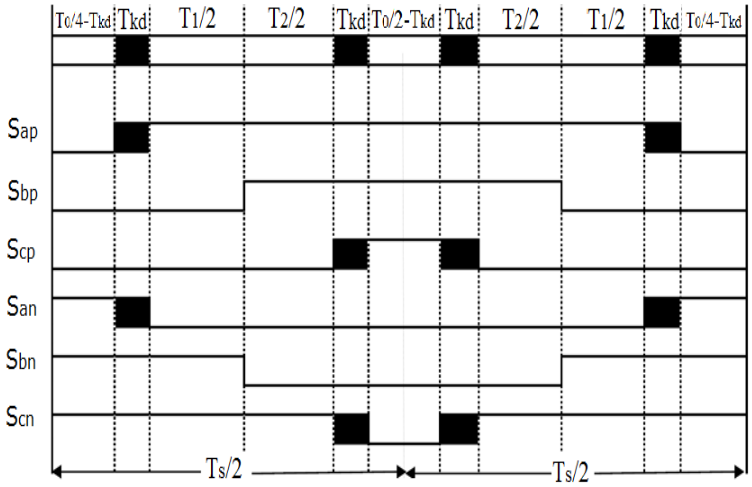


Fig. 8. Switching Structure of Traditional Space Vector Modulation

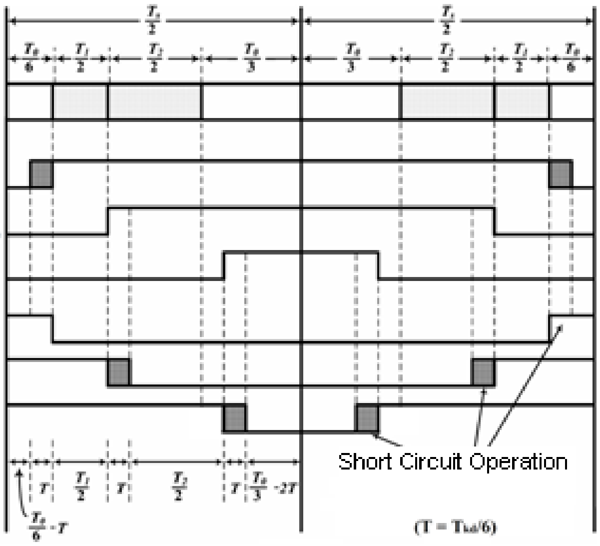
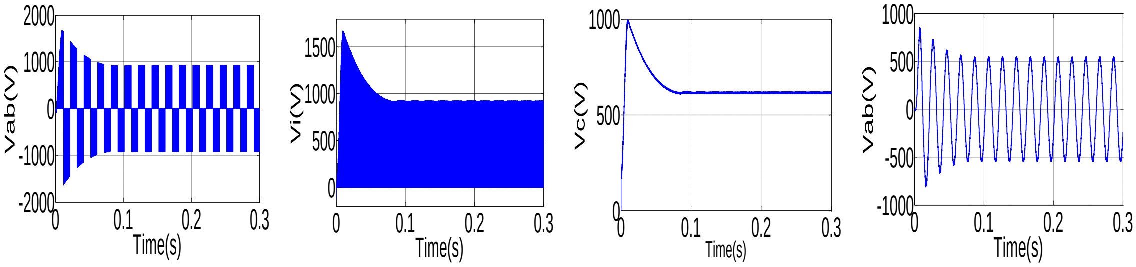


Fig. 9. Switching Structure of Distributed Space Vector Modulation

4. Simulation Results

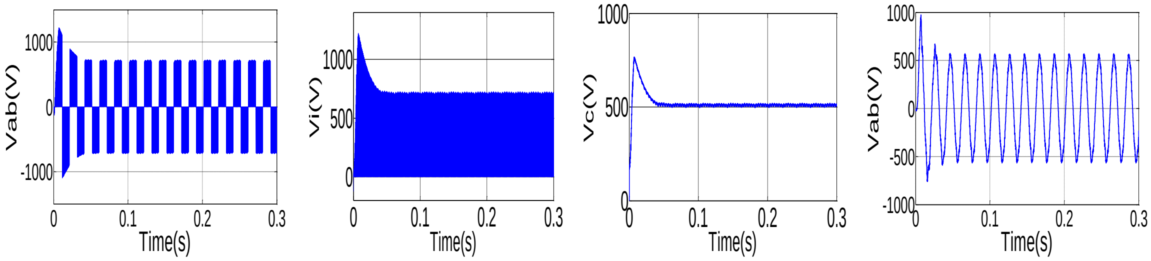
Simulations of all control methods discussed in this work were made separately and the results for comparison are given in the following figures. The simulations of impedance source inverter made with 311 V dc source and in each case the value of the gain (G) was controlled at 2 ensuring to obtain 220 V rms phase voltage. The simulated circuit parameters are as follows:

- $V_i = 311$ V , $V_{phase, rms} = 220$ V
- $L_1 = L_2 = 1$ mH , $C_1 = C_2 = 1{,}1$ mF
- G = 2
- $f_s = 2$ kHz , $R_{load} = 9\ \Omega$



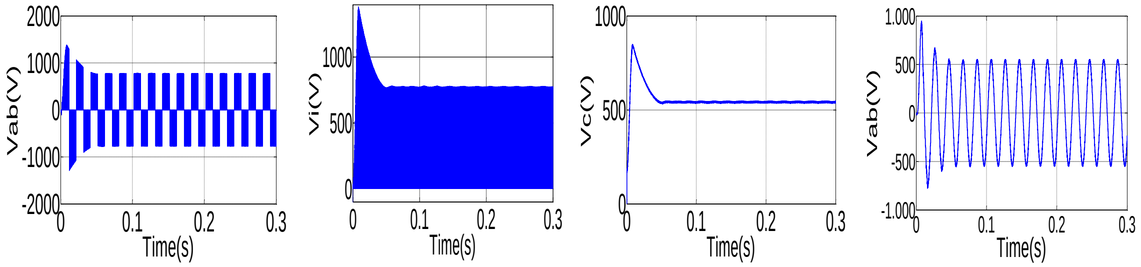
a) b) c) d)

Fig. 10. Simulation Results of Simple Boost Control - a) Inverter Output Voltage, b) DC Bus Voltage, c) Capacitor Voltage, d) Filtered Output Voltage of Inverter



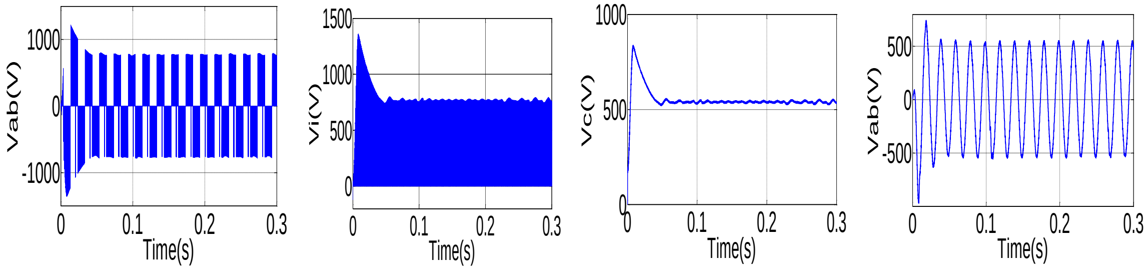
a) b) c) d)

Fig. 11. Simulation Results of Maximum Boost Control - a) Inverter Output Voltage, b) DC Bus Voltage, c) Capacitor Voltage, d) Filtered Output Voltage of Inverter



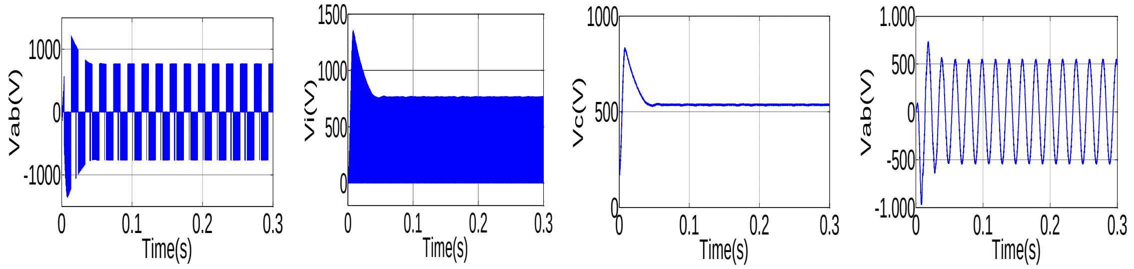
a) b) c) d)

Fig. 12. Simulation Results of Maximum Constant Boost Control - a) Inverter Output Voltage, b) DC Bus Voltage, c) Capacitor Voltage, d) Filtered Output Voltage of Inverter



a) b) c) d)

Fig. 13. Simulation Results of Traditional Space Vector Modulation Control - a) Inverter Output Voltage, b) DC Bus Voltage, c) Capacitor Voltage, d) Filtered Output Voltage of Inverter



a) b) c) d)

Fig. 14. Simulation Results of Distributed Space Vector Modulation Control - a) Inverter Output Voltage, b) DC Bus Voltage, c) Capacitor Voltage, d) Filtered Output Voltage of Inverter

Table. 1. Voltage Stress and Total Harmonic Distortion of Unfiltered Phase Current For Each Control Method.

	I_{thd} (%)	V_i (V)
Simple Boost	37,71	925
Maximum Boost	36,55	725
Maximum Constant Boost	35,52	780
Traditional Space Vector	32,01	783
Distributed Space Vector	34	769

As can be seen from the results all the theoritical data is in compliance with simulation results. SBC has a high voltage stress which would cause higher switching losses, and it also requires switches which have higher voltage values. MBC has the lowest voltage stress; however, there is a ripple in inductance current and capacitor voltage because of variable shoot through duty cycle, therefore the inductance in impedance network should be chosen with a higher value and it would cause extra cost and extra loss for the system. MCBC is a good choice for ZSI. However, it can be possible to work with a lower voltage stress and lower THD by utilizing SVM, without an extra cost. DSVM gives a stable output with a low output current harmonic, and it has a low voltage stress. Thus, DSVM seems as the best choice for ZSI applications.

4. Conclusion

In this paper the most important control techniques for ZSI used in photovoltaic systems have been presented. All of these techniques are investigated with both mathematical analysis and simulations, and they are compared with the same circuit parameters for a certain comparison.

As can be seen from the results DSVM seems as the best choice for ZSI applications because of its low voltage stress and low output current harmonic distortion.

Considering CSVM and DSVM results it is obvious that different switching patterns of SVM gives different results. SVM has a chance to vary switching pattern easily. Thus, in the future developing novel SVM switching patterns for ZSI would be an important research topic to get better results.

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