Simulation of Modified Simple Boost Control for Z-Source Inverter

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Abstract

In this paper, a simple boost control with independence relation between modulation index and shoot-through duty ratio (modified simple boost) for z-source inverter is simulated and analysed using MATLAB/Simulink, as well as the simple boost and the maximum boost control methods. The simulation shows that the modified simple boost control, as well as the maximum boost control could utilize high modulation index to generate output voltage that requires high voltage gain. In turn, this may suppress the voltage stress on the devices of z-source inverter.

Keywords

Z-source Inverter; PWM; Control; Fuel Cell.

Introduction

Z-source inverter can boost dc input voltage without requirement of dc-dc boost converter or step up transformer, hence overcoming output voltage limitation of traditional voltage source inverter as well as lowering its cost. A comparison among conventional PWM inverter, dc-dc boosted PWM inverter, and Z-source inverter shows that Z-source inverter employs the lowest semiconductors and control circuit costwhich are the main costs of a power electronics system (Olzwesky, M., 2005). These advantages result in increasing attention on Z-source inverter, especially for the application where the input DC source has a wide voltage variation range, such as the photovoltaic (PV) grid-tied generation and fuel cell motor drive system (Li, J., Liu, J., and Liu, Z., 2009). Moreover, for Z-source inverter, EMI influence is free from concern since shoot through is welcome and even exploited, which in turn enhances the inverter reliability. There are various methods that can be used to control Z-source inverter (Peng, F. Z., Shen, M., and Qiang, Z., 2004; Loh, P. C., Vilathgamuwa, D. M., Lai, Y. S., Chua, G. T., and Li, Y., 2004; Muntean, N., Tutelea, L., and Boldea, I., 2007; Tran, Q. V., Chun, T. W., Ahn, J. R., and Lee H. H., 2007; Peng, F. Z., 2003; Liu, J. B., Hu, J. G., and Xu, L. Y., 2005; Shen M. S., Wang, J., Joseph, A., Peng, F. Z., Tolbert, L. M., and Adams, D. J., 2006). These can be classified into two categories according to the different shoot-through (ST) states insertion methods. The first category has the principle that ST states are generated by properly level shifting the modulation signals of voltage source inverter. ST states are inserted at every states transition, six ST state insertions in one switching cycle. The second category, in the other hand, directly replaces the null states (111 and 000) by ST states. There are two ST states insertion in one switching cycle of the second category. The comparison of these two categories shows that the efficiency of the second category is higher than that of the first category (Li, J., Liu, J., and Liu, Z., 2009).

Simple boost control, the basic method of the second categories, is simple and easy to be implemented. However, the obtainable shoot-through duty ratio, D_0 decreases with the increase of modulation index, M. The maximum shoot-through duty ratio of the simple boost control is limited to $1 - M$ for a particular operation, thus reaching zero at a modulation index of one. Consequently, the operation with high modulation index for simple boost control leads to low output voltage. In order to generate an output voltage that requires a high voltage gain, a small modulation

index has to be used. However, small modulation indices result in high voltage stress on the devices of the inverter. To overcome this problem, maximum boost control has been introduced. With maximum boost control, the minimum voltage gain can be increased to 1.5 (Peng, F. Z., Shen, M., and Qiang, Z., 2004). In this paper, a modulation strategy to produce high voltage gain with high modulation index which is fully independent of shoot-through duty ratio will be examined through simulation by MATLAB/ Simulink.

Z-Source Inverter

The configuration of 3-phase Z-source inverter shown in Fig. 1, consists of 2 identical inductors and 2 identical capacitors which are composed to form a unique impedance network to avoid short circuit when the devices are in shoot through mode, a diode to block reverse current, and a three phase bridge as in traditional inverter. In 3-phase Z-source inverter, one additional control parameter is introduced, namely the Boost Factor (*B*), which modifies the AC output voltage equation of traditional 3-phase PWM inverter as following.

$$\hat{v}_{out} = BM\frac{V_o}{2} \tag{1}$$

Where in equation (1), $\hat{v}_{out}$ is the inverter output voltage peak value, B is Boost factor, M is the modulation index and Vo is the DC input voltage. If BM is replaced with G, (1) may be rewritten as

$$\hat{v}_{out} = G\frac{V_o}{2} \tag{2}$$

In equation (2), G is the inverter gain, which can be expressed as

$$G = BM \tag{3}$$

It can be seen that (2) has the same form with that of the traditional voltage source inverter, i.e.

$$\hat{v}_{out} = M\frac{V_o}{2} \tag{4}$$

Boost Factor is obtained by introducing shoot through of minimal one pair of the inverter arm for a short period of time which called shoot-through time.

$$B = \frac{1}{1-2\frac{T_o}{T}} = \frac{1}{1-2D_o} \tag{5}$$

Where in equation (5) above, To is Shoot Through Time, T is Switching Period and Do is Shoot through Duty Ratio. Thus, in the 3-phase Z-source inverter e 9 permissible switching states are acquired, unlike the traditional 3-phase V-source inverter that has eight. They comprise 6 active states, 2 zero states, and 1 additional zero state called shoot through zero states that is forbidden in traditional voltage source inverter.

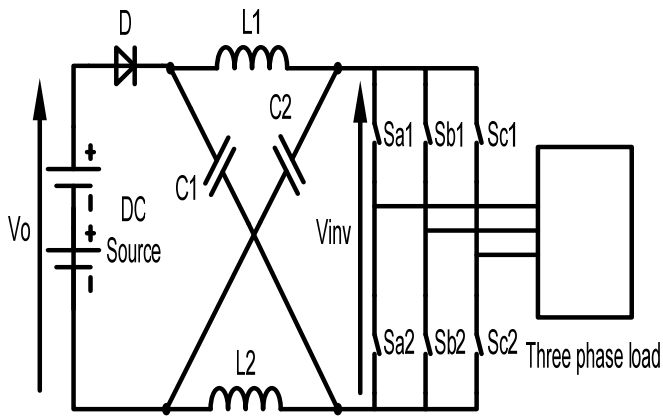

FIG. 1 THREE-PHASE Z-SOURCE INVERTER

Simple Boost Method

Actually, this control strategy inserts shoot through in all the PWM traditional zero states during one switching period, which maintains the six active states unchanged as in the traditional carrier based PWM. The simple boost control method is illustrated in Fig. 2. Two straight lines are employed to realize the shoot through duty ratio (Do). The first one is equal to the peak value of the three-phase sinusoidal reference voltages while the other one is the negative of the first one. Whenever the triangular carrier signals is higher than the positive straight line or lower than the negative straight line, the inverter will be operated in shoot-through, otherwise, it works as a traditional PWM inverter. Fig. 2 shows the modulation, the driver signals for the six switches, and the ST signals of simple boost control method. Since the value of the positive straight line is equal to the maximum of the sinusoidal reference signals and the value of the negative straight line is equal to the minimum of the sinusoidal reference signal, then the modulation index (M) and the shoot-through duty ratio (Do) are interdependent of each other. The relation between these two parameters is expressed in equation (6). It can be seen from the equation that shoot-through duty ratio (Do) decreases with increasing modulation index (M).

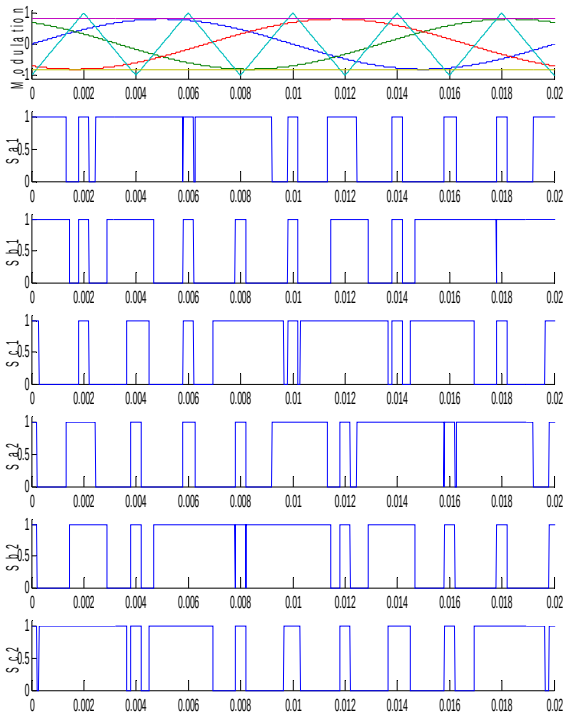

FIG. 2 PWM SIGNAL OF SIMPLE BOOST CONTROL

$$D_o = 1 - M \tag{6}$$

Recall that from (3) and (5) we get

$$G = BM = \frac{M}{1-2D_o} \tag{7}$$

Since $D_o = 1 - M$, thus

$$G = \frac{M}{1-2D_o} = \frac{M}{1-2(1-M)} = \frac{M}{2M-1} \tag{8}$$

Equation (8) infers that the inverter gain (G) can be controlled by adjustment of modulation index (M). If we rearrange (1) in the original PWM output voltage equation form, we get

$$\hat{v}_{out} = M\frac{BV_o}{2} \tag{9}$$

In (9), BV_o should be the dc input voltage of the traditional voltage source inverter, which in the case of Z-source inverter is the dc voltage applied to inverter's bridge. Let say,

$$BV_o = V_{inv} \tag{10}$$

From Fig. 1, V_{inv} is the voltage stress of the inverter's devices. From equations (3) and (8), equation (11) can be derived as

$$B = 2G - 1 \tag{11}$$

If (11) is substituted to (10), then the voltage stress across the devices is

$$V_{inv} = (2G-1)V_o = \frac{1}{2M-1}V_o \tag{12}$$

Maximum Boost Method

Maximum boost control method converts all traditional zero states to shoot-through while maintaining the six active states remain unchanged, which is obtained by comparing the maximum and the minimum curve of the sinusoidal reference with the triangular carrier. Whenever the maximum is lower than the triangular or the minimum is higher than the triangular, the inverter shoots through. Otherwise, it is operated in the traditional PWM mode. By using this switching strategy, the shoot-through duty cycle varies each cycle. The inverter gains maximum shoot-through time, which in turn gives the inverter a higher boost factor, as pointed in equation (5). Thus, with the same modulation index as in simple boost control method, a higher voltage gain is obtained. Fig. 3 shows the maximum boost control strategy.

As the shoot-through duty cycle varies each cycle, what we are interested in is the average value of the duty cycle. In the interval ($\pi/6$, $\pi/2$), the average shoot through duty ratio can be expressed as following (Peng, F. Z., Shen, M., and Qiang, Z., 2004).

$$\begin{aligned}\frac{\overline{T}_o}{T} &= \int_{\pi/6}^{\pi/2}\frac{(2 - M\sin\theta - M\sin(\theta - 2\pi/3))}{2}d\theta \\ &= \frac{2\pi - 3\sqrt{3}\pi}{2\pi}\end{aligned} \tag{13}$$

From (5) and (13),

$$B = \frac{1}{1-2\frac{\overline{T}_o}{T}} = \frac{\pi}{3\sqrt{3}M - \pi} \tag{14}$$

The inverter voltage gain (G) is obtained as

$$G = BM = \frac{\pi}{3\sqrt{3}M-\pi}M = \frac{\pi M}{3\sqrt{3}M-\pi} \tag{15}$$

Similarly, as with the simple boost control method, the voltage gain can be controlled by adjustment of the modulation index.

Fig. 4 shows voltage gain as the function of modulation index for both simple boost and maximum boost control methods. It is clear from the figure that

maximum boost control method gives higher voltage gain for the same modulation index.

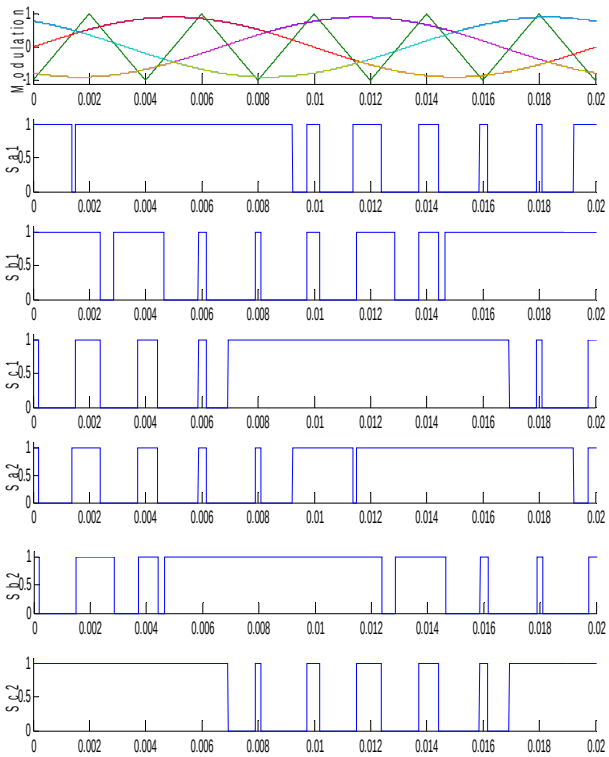

FIG. 3 PWM SIGNAL OF MAXIMUM BOOST CONTROL

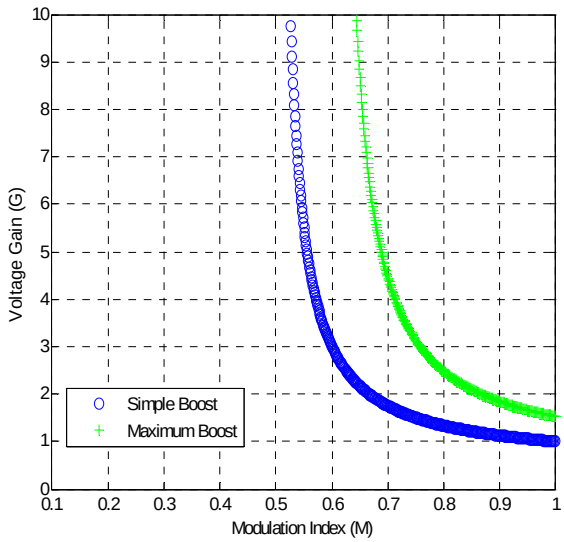

FIG. 4 VOLTAGE GAIN VERSUS MODULATION INDEX

Obviously, the voltage stress across the inverter's devices is

$$V_{inv} = BV_o = \frac{\pi}{3\sqrt{3}M - \pi} V_o \tag{16}$$

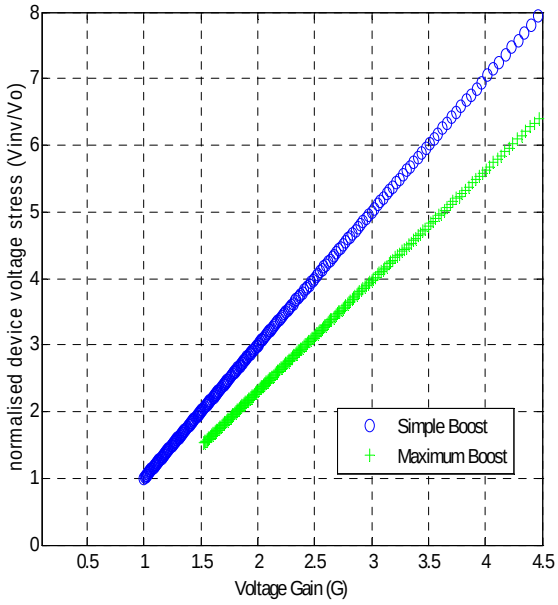

FIG. 5 DEVICES VOLTAGE STRESS

The voltage stress across the devices in obtaining a specified voltage gain for both the simple boost and the maximum boost control method is depicted in Fig. 5. From the figure, it is shown that the maximum boost control method can reduce the voltage stress across the inverter's devices for the same voltage gain compared with the simple boost control, which means that for given devices, the inverter can obtain higher voltage gain.

Operation of Z-Source Inverter under Simple Boost Control Method with Independent Relationship between the Modulation Index and the Shoot-through Duty Ratio (Modified Simple Boost Method)

As previously discussed, usually the simple boost control method is achieved by using a pair of straight line which is equal to the maximum peak and minimum peak of the reference sinusoidal, implying that the modulation index (M) and the shoot through duty ratio are related to each other. The relationship is expressed by (6) as $D_o = 1 - M$. In the rest of this paper, simulation of simple boost operation of z-source inverter whose modulation index and shoot-through duty ratio are independent of each other is carried out. This control strategy is done by setting the straight lines unequal to the peak maximum and minimum of the sinusoidal reference signals. The parameters of z-source inverter used in this simulation are presented in Table 1 below.

TABLE 1. SIMULATION PARAMETERS

Parameters	Value	Unit
V_o	150	V
L	150	mH
C	250	μF

Simulation is conducted using various values of shoot-through duty ratio (D_o) and modulation index (M). The straight line value is normalized by the peak value of the triangular carrier wave. Initially, simulation is carried out with fixed duty ratio and variable modulation index. Then on the contrary, simulation is conducted with variable duty ratio and fixed modulation index at various values.

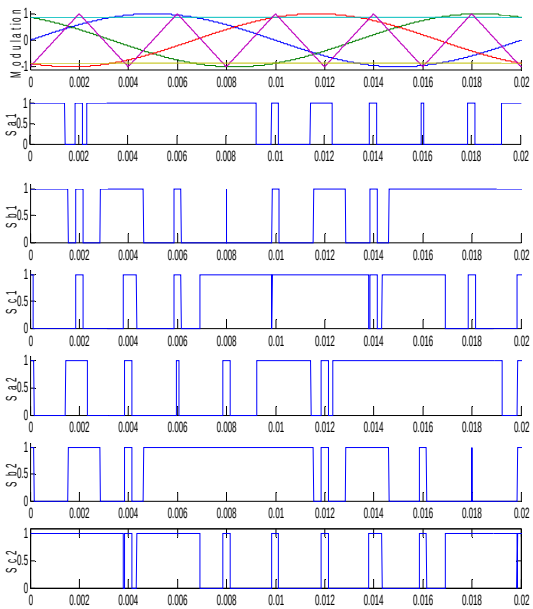

FIG. 6 PWM SIGNAL OF MODIFIED SIMPLE BOOST CONTROL

Simulation Results and Discussion

Simulation results for fixed duty ratio and variable modulation index are presented in Table 2 which shows the phase output voltage and phase output current at various modulation index for D_o = 0.45 and D_o = 0.1. It can be seen from the table that at fixed shoot-through duty ratio, the output voltage remains constant at a specific value irrespective of the variation of the modulation index while the output current rises with the increase of the modulation index. Since the output voltages are equal, higher output current of the inverter means higher output power, which confirms the advantage of using high modulation index. The output voltage and output current at D_0= 0.45 for M = 1, M = 0.7, M = 0.55, and M = 0.40 are presented in Fig. 7. The waveforms are similar to that produced with original simple boost control.

According to Table 2, the output voltage that is produced at D_0 = 0.45 and M = 0.55 is 1000 V. This condition actually reflects ordinary simple boost operation where $D_0 + M = 1$. The same output voltage is obtained at D_0 = 0.45 and M = 1, which infers that higher modulation index may be utilised.

Meanwhile, Table 3 presents the output voltage and output current at fixed modulation index and variable shoot-through duty ratio. It is shown from the table that the output voltage and output current rise with the increase of shoot-through duty ratio. The waveform of the output voltage and output current at M = 0.9 for D_0 = 0.49, D_0 = 0.45, D_0 = 0.25, and D_0 = 0.1 can be seen in Fig. 8. In addition, the waveforms are similar to that produced with original simple boost control. The plot of output voltage for different values of shoot-through duty ratio at M = 0.9 is depicted in Fig. 9. The plot has asymptote at D_0 = 0.5, which implies that the inverter should not be operated with D_0 very close to 0.5 since it could be burnt resulting from a very high voltage built at the output of the inverter.

At Fig. 10, the voltage gain for variable shoot through duty ratio at constant modulation index is presented for various values of modulation index. The plots consistently show the growth of voltage gain with increasing shoot-through duty ratio.

TABLE 2. SIMULATION RESULTS WITH FIXED DUTY RATIO AND VARIABLE MODULATION INDEX

D_o	M	V_{out} [V]	I_{out} [A]
0.45	1	1000	3.1
	0.9	1000	3
	0.8	1000	2.93
	0.7	1000	2.85
	0.6	1000	2.75
	0.55	1000	2.7
	0.4	1000	2
0.1	0.9	125	0.5
	0.55	125	0.2
	0.4	125	0.18

TABLE 3. SIMULATION RESULTS WITH VARIABLE DUTY RATIO AND FIXED MODULATION INDEX

M	D_o	V_{out} [V]	I_{out} [A]
0.9	0.49	5000	13
0.9	0.48	2600	6
0.9	0.47	1650	5
0.9	0.45	1000	3
0.9	0.4	500	1.5
0.9	0.35	330	1
0.9	0.25	200	0.6
0.9	0.2	170	0.5
0.9	0.1	125	0.45

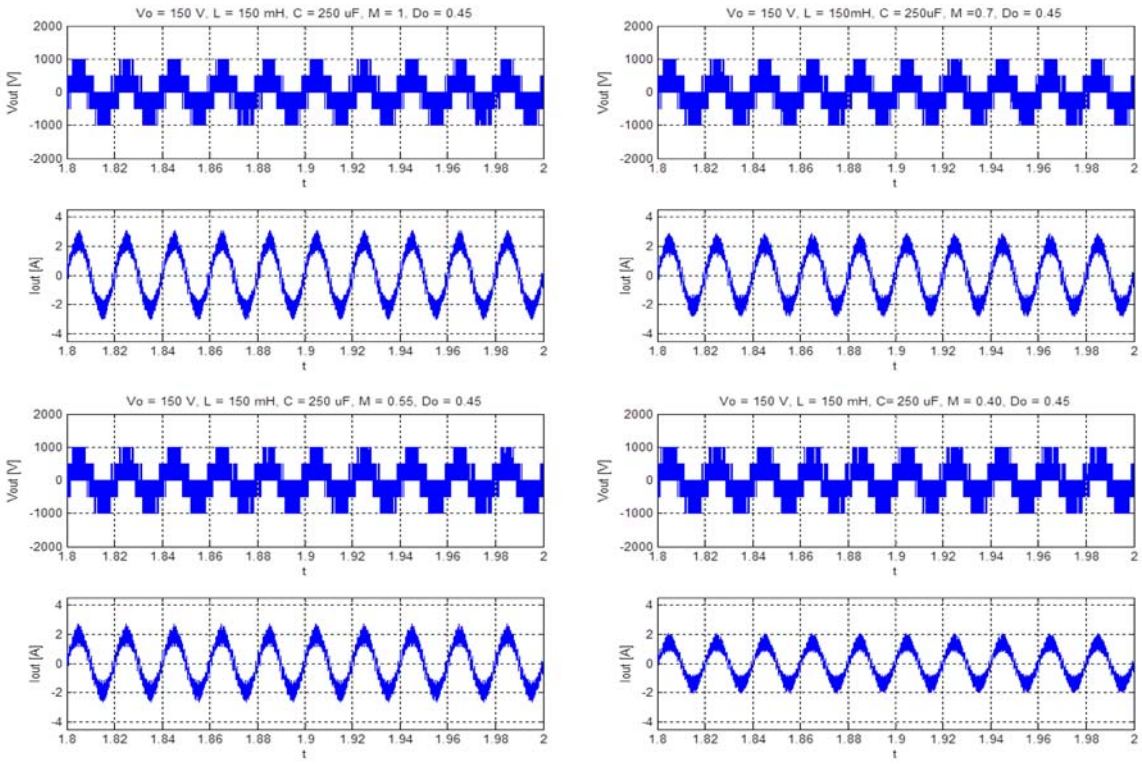

FIG. 7 OUTPUT VOLTAGE AND OUTPUT CURRENT WAVEFORMS AT FIXED SHOOT-THROUGH DUTY RATIO AND VARIABLE MODULATION INDEX

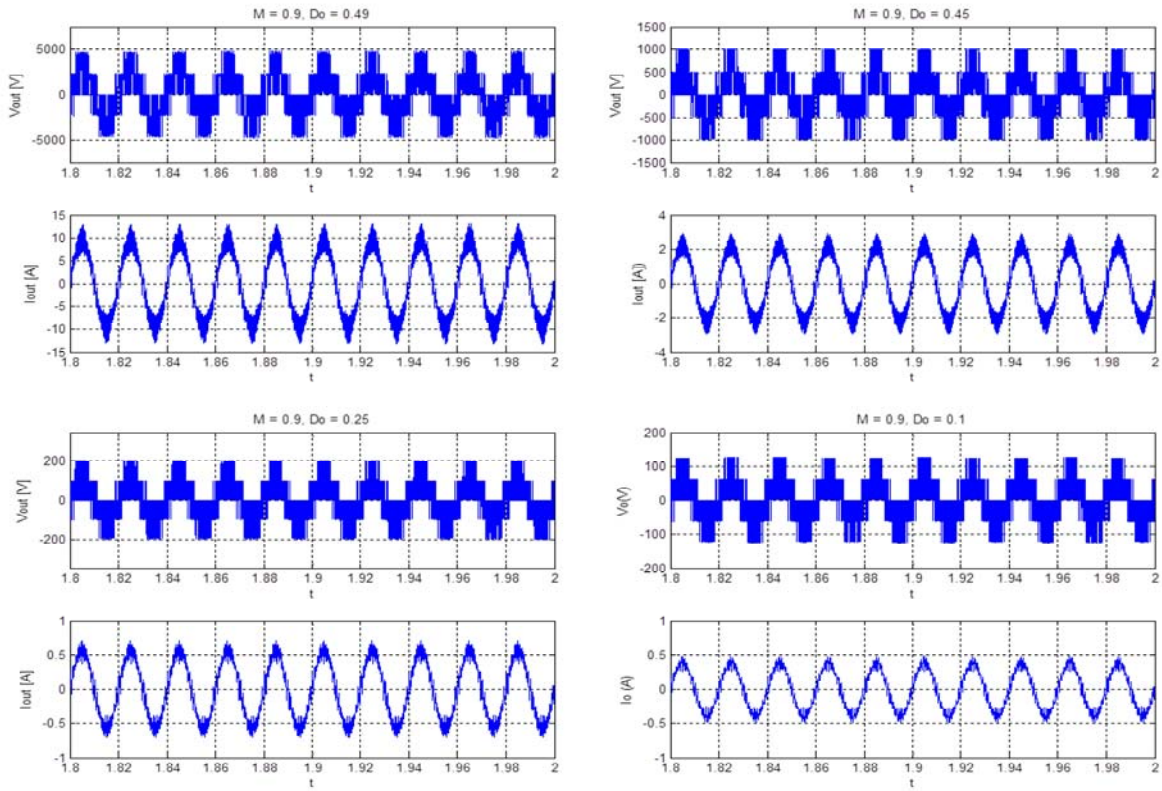

FIG. 8 OUTPUT VOLTAGE AND OUTPUT CURRENT WAVEFORMS AT VARIABLE SHOOT-THROUGH DUTY RATIO AND FIXED MODULATION INDEX

TABLE 4. VOLTAGE GAIN FOR VARIABLE SHOOT-THROUGH DUTY RATIO AND FIXED MODULATION INDEX AT VARIOUS VALUES OF MODULATION INDEX

D_o	B	G					
		$M = 0.9$	$M = 0.8$	$M = 0.7$	$M = 0.6$	$M = 0.5$	$M = 0.4$
0.49	50	45	40	35	30	25	20
0.48	25	22.5	20	17.5	15	12.5	10
0.47	16.666667	15	13.333333	11.666667	10	8.3333333	6.6666667
0.45	10	9	8	7	6	5	4
0.4	5	4.5	4	3.5	3	2.5	2
0.35	3.3333333	3	2.6666667	2.3333333	2	1.6666667	1.3333333
0.25	2	1.8	1.6	1.4	1.2	1	0.8
0.2	1.6666667	1.5	1.3333333	1.1666667	1	0.8333333	0.6666667
0.1	1.25	1.125	1	0.875	0.75	0.625	0.5

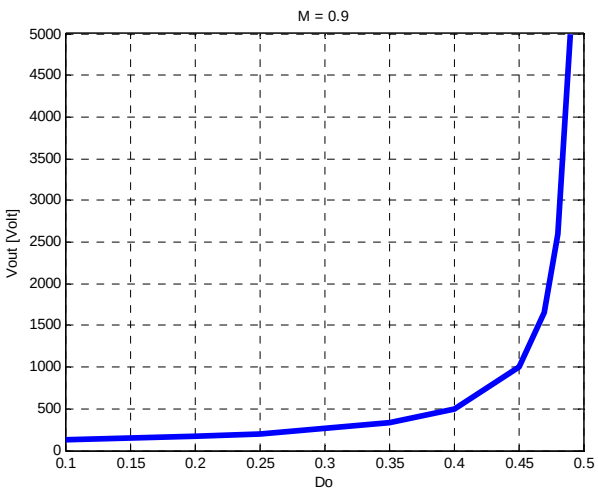

FIG. 9 OUTPUT VOLTAGE AT FIXED MODULATION INDEX AND VARIABLE SHOOT-THROUGH DUTY RATIO

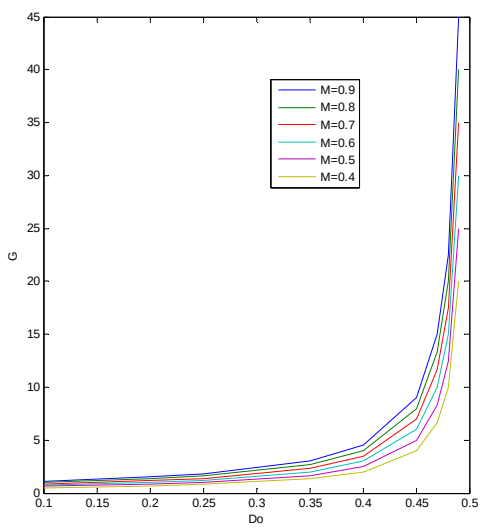

FIG. 10 VOLTAGE GAIN AT FIXED MODULATION INDEX AND VARIABLE SHOOT-THROUGH DUTY RATIO

Conclusions

After simulating and analysing the simple boost control, the maximum boost control, and the modified simple boost control, it can be concluded that:

1. The modified simple boost control generates output waveforms similar to those of ordinary simple boost control.
2. The modified simple boost control can utilize high modulation index to produce output voltage that requires high voltage gain, which may minimize voltage stress on inverter's devices.
3. Higher output voltages and output currents are obtained with higher modulation indices and or shoot-through duty ratio.
4. The shoot-through duty ratio range for the modified simple boost control is lower than 0.5.

These conclusions are derived from simulation results. Further analyses and investigation should be conducted to elaborate the results, which will be done in the next paper.

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Shahrin Md. Ayob (member IEEE) was born in Kuala Lumpur, Malaysia in 1979. He obtained his Bachelor degree, Master degree, and PhD, all in electrical engineering, from Universiti Teknologi Malaysia in 2000, 2003, and 2009 respectively. Presently, he is a senior lecturer at the same university. Dr. Ayob current research interests are in the application of artificial intelligence to power converters, distributed generation, and electric vehicles.

Makbul Anwari was born in Pontianak, Indonesia. He received B.Eng degree in electrical engineering from University of Tanjungpura, Indonesia, in 1995, M.Eng degree in electrical engineering from Bandung Institute of Technology, Indonesia, in 2000, and Dr.Eng. degree from Nagaoka University of Technology, Japan, in 2005. From 1995 to 2006, he joined the Electrical Engineering Department at University of Tanjungpura, Indonesia. He then joined the Department of Energy Conversion, Faculty of Electrical Engineering, Universiti Teknologi Malaysia until 2010. Currently, he is an Associate Professor at the Electrical Engineering Department, Umm Al-Qura University in Mecca, Saudi Arabia. Dr. Anwari is a member of the IEEE Power and Energy Society and Industry Application Society.

Taufik (senior member IEEE) was born in Jakarta, Indonesia. He received his BSEE degree with minor in computer science from Northern Arizona University in 1993. He then continued his study and received his MS degree in electrical engineering and computer science from the University of Illinois at Chicago in 1995. Following this, he spent one year working as a research assistant at the Microelectronic Fabrication Lab at the University of Illinois at Chicago before pursuing his Doctoral degree in electrical engineering at Cleveland State University in 1999. Since then, Dr. Taufik joined the Electrical Engineering Department at California Polytechnic State University in San Luis Obispo where he is currently a Professor. Dr. Taufik has had industrial experience working with engineering companies such as Capstone Microturbine, Picker International (currently Philips Medical System), Allen-Bradley (Rockwell Automation), Rantec Power Systems, San Diego Gas & Electric, and APD Semiconductor (currently Diodes Inc.). Dr. Taufik main areas of interests are in power electronics and engineering educations.