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A Novel Approach for Space Vector Based PWM Algorithm for Diode Clamped Three level VSI Fed Induction Motor Drive

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ABSTRACT

Performance of voltage source inverter depends on pulse width modulation algorithms. Various algorithms exist for conventional space vector as well as space vector based bus clamped pulse width modulation for multilevel inverter in the literature. In this paper appropriate region selection algorithm for conventional space vector pulse width modulation (CSVPWM) and bus clamped pulse width modulation (BCPWM) techniques are proposed for diode clamped three level voltage source inverter. The proposed techniques are implemented on a three level voltage source inverter feeding power to induction motor drive for open loop operation. The schemes are simulated in MATLAB/SIMULINK environments. The merit of proposed region selection algorithm is tested and verified through simulation result. Further performance comparisons between SVPWM and BCPWM for different modulation index are discussed.

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1. INTRODUCTION

Nowadays, multilevel inverter becomes very popular in high-power medium voltage applications. The most important topologies for multilevel inverters are given in [1]-[2]. There exist different types of conventional and advanced PWM techniques for multilevel inverters [3]-[4]. (SHEPWM) and Conventional Space Vector PWM (CSVPWM) are most popular conventional PWM strategies for three level inverters [5]-[6]. Bus Clamping PWM (BCPWM) technique is one of the most popular advanced PWM technique for multilevel inverters [7]-[9].

In this paper, a MOSFET based three-level diode clamped inverter is considered. An advanced PWM technique i.e. space vector based bus clamping PWM is introduced in [9]. BCPWM is better compared to conventional SVPWM in respect of current ripple; switching loss is given in [9]-[12]. A novel approach has been proposed for implementing these both PWM techniques is introduced in [11]. In this paper the modified approach is discussed and verified in MATLAB/SIMULINK on an open loop three-phase induction motor.

There are different techniques to implement conventional as well advanced PWM techniques for three-level inverter. Those techniques are based on mapping concept [5]-[10]. In this paper a new technique is introduced to implement CSVPWM and BCPWM techniques for three-level inverter. The proposed technique is based on algebraic equations. It is easy to understand as well as simple to implement.

The effectiveness of the proposed technique is achieved by proper simulation of three-level inverter in MATLAB. It is observed that the BCPWM technique, based on proposed technique has all the advantages compared to CSVPWM technique. Further, for higher (above three) level inverter, this technique is also applicable.

2. CSVPWM TECHNIQUE FOR THREE-LEVEL INVERTER

The hexagon formed by space vectors for three-level inverter is shown in Figure 1. It consists of 27 number of space vectors. There are four kinds of space vectors namely large, medium, small and zero. There are six number of large, six number of medium, three number of zero and 12 number of small space vectors in the hexagon. Out of twelve numbers of small space vectors, six are known as redundancy space-vectors. The hexagon is divided into six sectors of equal duration of 60° which is shown in Figure 1. There has been different approaches reported in the literature i.e. carrier based approach and program based approach. In program based approach concept of mapping is introduced in [13]. Each sector has four regions. So for generating reference vector the sector, region and vector sequence selection are very important. After sector selection, in which region the reference vector is located is needed to be find out. After region selection, the reference vector is generated by applying nearby space vectors.

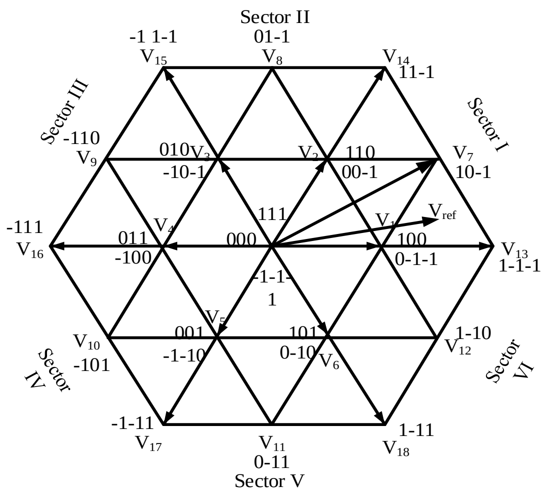


Figure 1. Division of sectors and regions for three-level inverter

3. BCPWM TECHNIQUE FOR THREE-LEVEL INVERTER

Bus clamped PWM technique is one of the most popular advanced type of PWM technique. In this technique, each phase of inverter is clamped to one of the DC bus terminals for certain duration over the fundamental cycle. During the, clamping duration, the clamped phase is not switching but the other two phases keep switching.

Based on the region of clamping four types of bus clamped PWM namely TYPE1, TYPEII, TYPEIII and TYPE IV can be defined [9]. The clamping region and the clamping phase for TYPE II BCPWM are shown in Figure 2. In each sector, there has a clamped phase. So clamping duration is 60°. This BCPWM is popularly known as 60° BCPWM technique.

In sector 1, R-phase gets clamped to positive DC bus whereas in sector 4, R-phase is clamped to negative DC bus. So over a fundamental cycle, the total clamping duration is120°. It has been observed that at high modulation index the inverter performs better in BCPWM compared to conventional PWM techniques [9].

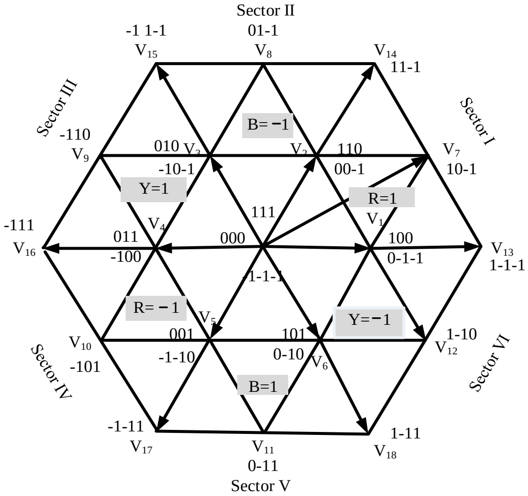


Figure 2. Space vector diagram for TYPE II clamping

At same carrier frequency, the switching loss of inverter is less for BCPWM as compared to CSVPWM whereas at same switching frequency and high modulation index, the output current ripple is significantly less in BCPWM compared to conventional PWM techniques [9]. In this paper, TYPE II BCPWM is selected for analysis.

4. PROPOSED REGION SELECTION TECHNIQUE

For generating the reference vector, the region in which the reference vector is located needs to find out. In the proposed method, the actual sector containing the tip of the reference space vector need not be identified. A general method is proposed in [13] for the multilevel inverters. The SVPWM is implemented using mapping concept. The proposed method is to identify the center of a sub-hexagon containing the reference space vector. Using the center of the subhexagon, the reference space vector is mapped to the inner most sub hexagon, and the switching sequence corresponding to a two-level inverter is esteblished. A new technique based on algebraic equations is proposed in this paper to find out the region in any sector. There are four regions in a sector for three level inverter as shown in the Figure 2. Figure 3 shows two consecutive sectors (sector 1 and sector 2). As the hexagon is symmetric, the procedure for region selection in one sector is applicable to other sectors.

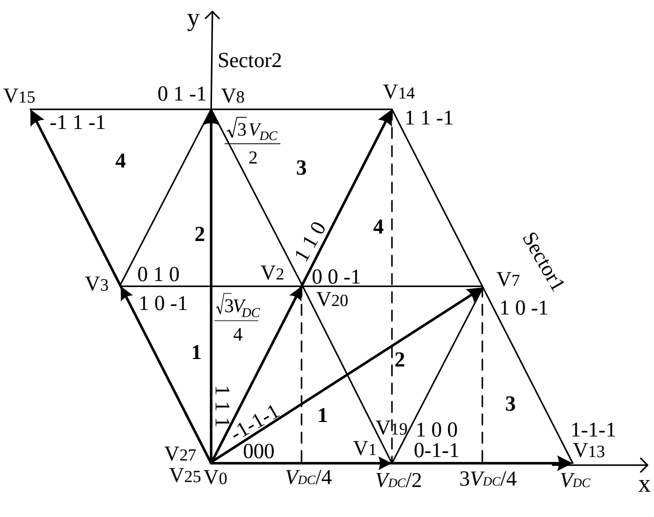


Figure 3. Region selection technique for sector 1 and 2.

Consider zero vectors (V_0, V_{25}, V_{27}) as origin, the co- ordinates for other vectors in a sector can be found in x-y plane as shown Figure 4. The x coordinate is in phase with the starting vector of any sector and y coordinate is perpendicular to the x coordinate. Theta (θ) is the angle between the reference vector and the starting vector of any sector. The co-ordinates for different vectors in sector 1 are as follows.

Table 1. The Performance of The Co-ordinates For Different Vectors in Sector 1

Vector	Name	C-ordinate(X,Y)
V_0, V_{27}, V_{25}	Zero	(0,0)
V_1, V_{19}	Small	$\left(V_{DC}/2, 0\right)$
V_{13}	Large	$\left(V_{DC}, 0\right)$
V_7	Medium	$\left(3V_{DC}/4, 0\right)$
V_{14}	Large	$\left(V_{DC}/2, \sqrt{3}V_{DC}/2\right)$
V_2, V_{20}	Small	$\left(V_{DC}/4, \sqrt{3}V_{DC}/4\right)$

For region selection, two algebraic equations are needed to form. One equation is for straight line between vectors V_1 and V_2. Other equation is for straight line between vectors V_1 and V_7. The equations are as follows.

$$y = -\sqrt{3}\ (x - \frac{V_{DC}}{2}) \tag{1}$$

$$y = \sqrt{3}\ (x - \frac{V_{DC}}{2}) \tag{2}$$

The reference vector V_{ref} has two components

$$x_1 = \left|V_{ref}\right| Cos\theta \tag{3}$$

$$y_1 = \left|V_{ref}\right| Sin\theta \tag{4}$$

Now by using (1), (2) and (3), the y components corresponding x_1 can be found out for region selection. By putting (3) in (1) and (2), the following y component values are achieved.

$$y_{11} = -\sqrt{3}\ (x_1 - \frac{V_{DC}}{2}) \tag{5}$$

$$y_{22} = \sqrt{3}\ (x_1 - \frac{V_{DC}}{2}) \tag{6}$$

Now by comparing the above coordinates, it can be found out in which region the reference vector is located. The conditions for region selection are tabulated in Table 2. For other sector, the region selection is same as that for sector 1 expect the x-y coordinate shifted by 60°.

Table 2. Conditions for region selection in sector 1

Region	Condition
1	$0 < x_1 \le V_{DC}/4$ and $0 \le \theta \le 60^{\circ}$ Or $V_{DC}/4 < x_1 < V_{DC}/2$ and $y_1 \le y_{11}$
2	$V_{DC}/4 < x_1 \le V_{DC}/2$ and $y_{11} < y_1 \le \sqrt{3}V_{DC}/4$ Or $V_{DC}/2 < x_1 \le 3V_{DC}/4$ and $y_{22} < y_1 \le \sqrt{3}V_{DC}/4$
3	$V_{DC}/2 < x_1 \le 3V_{DC}/4$ and $y_1 \le y_{22}$ Or $3V_{DC}/4 < x_1 \le V_{DC}$ and $0 \le \theta \le 30^{\circ}$
4	Conditions for regions 1 , 2 and 3 are not satisfied then region 4 will be selected

5. VECTOR SEQUENCE AND DWELL TIME CALCULATION FOR CSVPWM

For generating the reference vector in any region of any sector the following two conditions should be satisfied:

a. Only one switch is switched during state transition. That is transition from state 1 to state -1 and vice-versa is not allowed.
b. Final state of the present sample is the first state of the next sample.

The vector sequence in each region is selected in such way that the above two condition satisfy. The vector sequences for different regions in sector 1 are tabulated in Table 3.

Table 3. Vector sequence for different region in sector 1

Region	Vector Sequence
1	$V_{27} \Leftrightarrow V_{19} \Leftrightarrow V_{20} \Leftrightarrow V_0 \Leftrightarrow V_1 \Leftrightarrow V_2 \Leftrightarrow V_{25}$ (-1-1-1) (0-1-1) (00-1) (000) (100) (110) (111)
2	V_{19} $V_{20} \Leftrightarrow V_7 \Leftrightarrow V_1 \Leftrightarrow V_2 \Leftrightarrow$ (0-1-1) (00-1) (10-1) (100) (110)
3	$V_{19} \Leftrightarrow V_{13} \Leftrightarrow V_7 \Leftrightarrow V_1$ (0-1-1) (1-1-1) (10-1) (100)
4	Conditions for regions 1 , 2 and 3 are not satisfied then region 4 will be selected

By volt-sec balance the dwell times are calculated and tabulated in Table 4 for sector 1.

Where $T_S =$ Sample Time $= T_a + T_b + T_c$

$m =$ Modulation Index $= \frac{2}{\sqrt{3}}(V_{ref}/V_{DC})$

Figure 4 shows the timing diagram for region 1 in sector 1. It is observed that at a time only one switch is switched for each transition. The timing diagrams for other regions in sector 1 are as per Table 3.

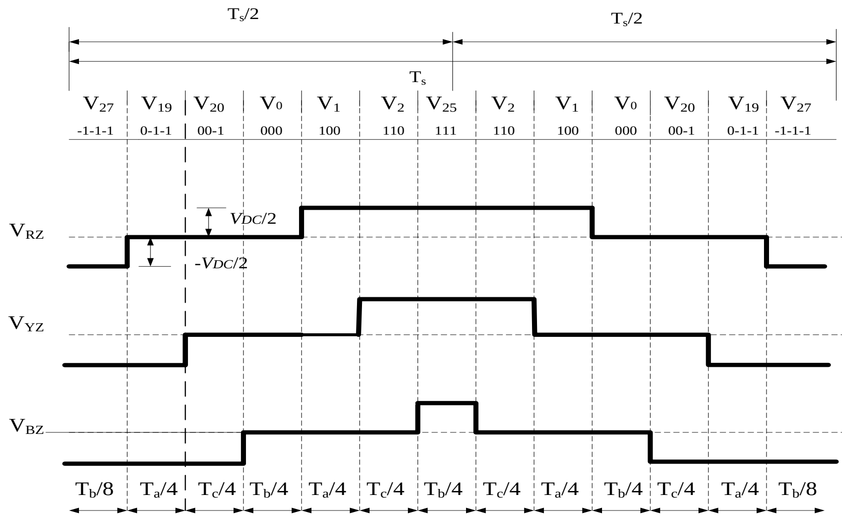


Figure 4. Timing diagram of vector sequence for region 1 in sector 1 for CSVPWM

Table 4. Dwell times for sector 1

Region	Vectors	Dwell Time
1	V_1	$T_a = T_S\{2mSin(\pi/3-\theta)\}$
	$V_0\,V_{27}\,V_{25}$	$T_b = T_S\{1-2mSin(\pi/3+\theta)\}$
	V_2	$T_c = T_S\{2mSin\theta\}$
2	$V_1\,V_{19}$	$T_a = T_S\{1-2mSin\theta\}$
	V_7	$T_b = T_S\{2mSin(\pi/3+\theta)-1\}$
	$V_2\,V_{20}$	$T_c = T_S\{1-2mSin(\pi/3-\theta)\}$
3	$V_1\,V_{19}$	$T_a = T_S\{2-2mSin(\pi/3+\theta)\}$
	V_7	$T_b = 2T_S mSin\theta$
	V_{13}	$T_c = T_S\{2mSin(\pi/3-\theta)-1\}$
4	V_{14}	$T_a = T_S\{2mSin\theta-1\}$
	V_7	$T_b = T_S\{2mSin(\pi/3-\theta)\}$
	$V_2\,V_{20}$	$T_c = T_S\{2-2mSin(\pi/3+\theta)\}$

6. VECTOR SEQUENCE AND DWELL TIME CALCULATION FOR BCPWM

For generating the reference vector in any region of any sector the following two conditions should be satisfied:

a. Only one switch is switched during state transition. That is transition from state 1 to state -1 and vice-versa is not allowed.
b. Final state of the present sample is the first state of the next sample.

The vector sequence in each region is selected in such way that the above two conditions satisfy. The vector sequences for different regions in sector 1 are tabulated in Table 5**a**. Dwell times for sector 1as shown in Table 5b

Table 5a. Vector sequence for different region in sector 1

Region	Vector Sequence	Clamped Phase
1	V_1 V_2 $\Leftrightarrow V_{25}$ $\Leftrightarrow$ (100) (110) (111)	+R
2	V_2 V_1 $\Leftrightarrow V_7$ $\Leftrightarrow$ (110) (100) (10-1)	+R
3	V_1 V_7 $\Leftrightarrow V_{13}$ $\Leftrightarrow$ (100)(10-1) (1-1-1)	+R
4	V_2 V_{14} $\Leftrightarrow V_7$ $\Leftrightarrow$ (110) (11-1) (10-1)	+R

Table 5b. Dwell times for sector 1

R	Vectors	Dwell Time
1	V_1	$T_a = T_S\{2mSin(\pi/3-\theta)\}$
	V_0	$T_b = T_S\{1-2mSin(\pi/3+\theta)\}$
	V_2	$T_c = 2mT_S Sin\theta$
2	V_1	$T_a = T_S\{1-2mSin\theta\}$
	V_7	$T_b = T_S\{2mSin(\pi/3+\theta)-1\}$
	V_2	$T_c = T_S\{1-2mSin(\pi/3-\theta)\}$
3	V_1	$T_a = T_S\{2-2mSin(\pi/3+\theta)\}$
	V_7	$T_b = 2mT_S Sin\theta$
	V_{13}	$T_c = T_S\{2mSin(\pi/3-\theta)-1\}$
4	V_{14}	$T_a = T_S\{2mSin\theta-1\}$
	V_7	$T_b = T_S\{2mSin(\pi/3-\theta)\}$
	V_2	$T_c = T_S\{2-2mSin(\pi/3+\theta)\}$

Figure 6(a) and 6(b) show the timing diagrams of vector sequence for region 1 and region 4 of sector 1. It is observed that R phase gets clamped to positive DC bus terminal. In similar fashion the other sectors can be analyzed.

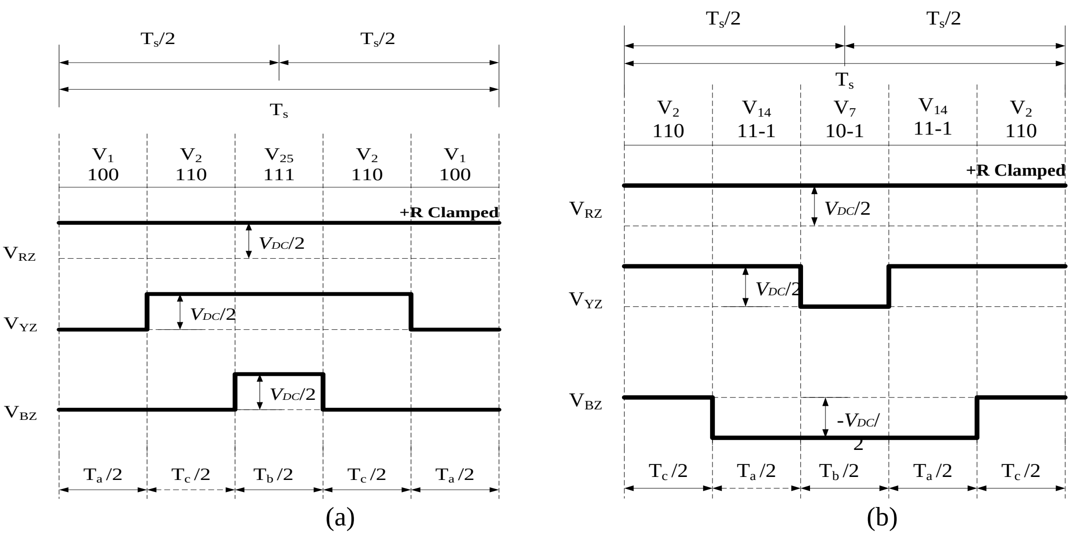
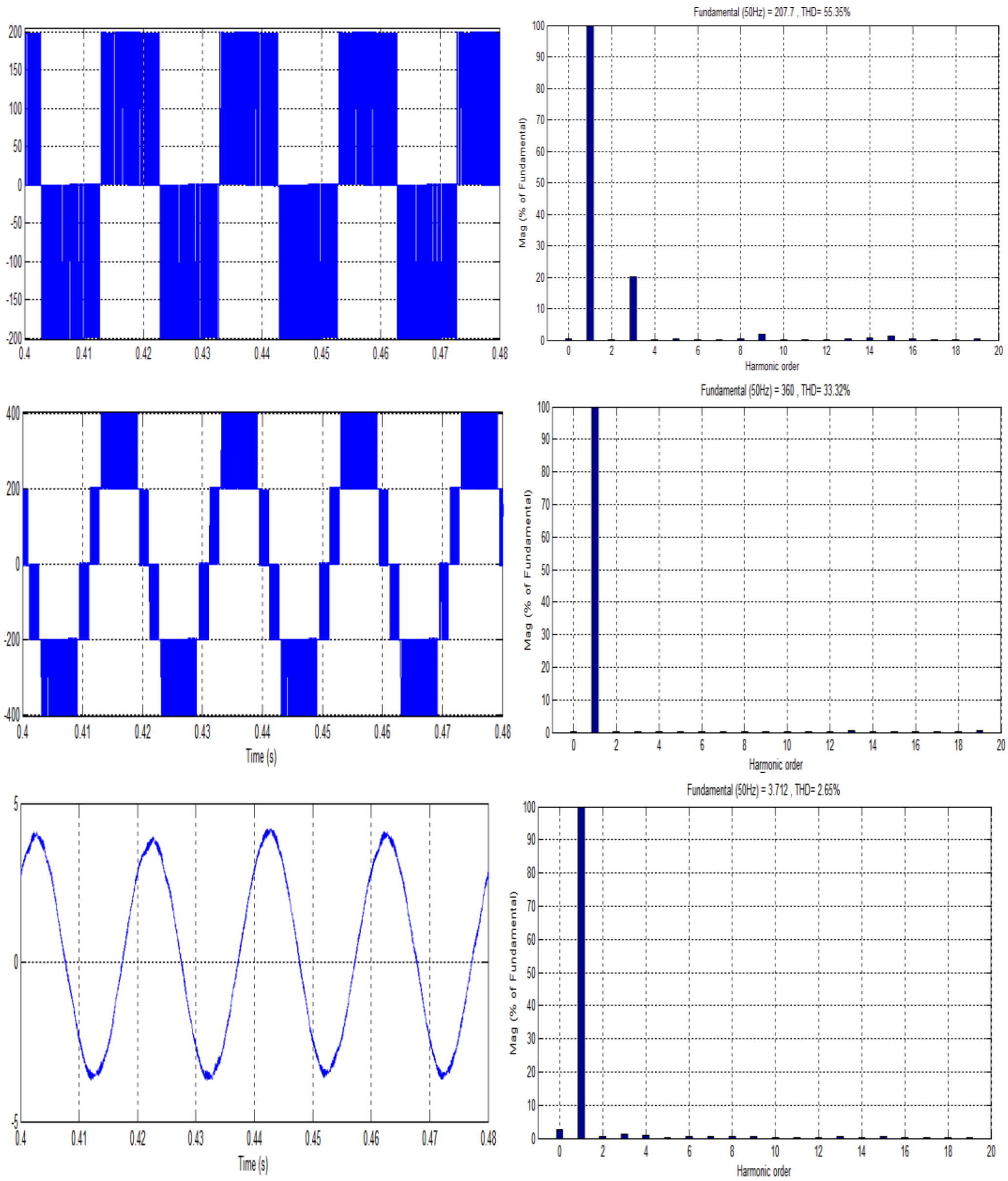


Figure 6 (a). Timing diagram of vector sequence for region 1 in sector 1 for BCPWM (b). Timing diagram of vector sequence for region 4 in sector 1 for BCPWM

7. SIMULATION RESULTS AND COMPARISON STUDY

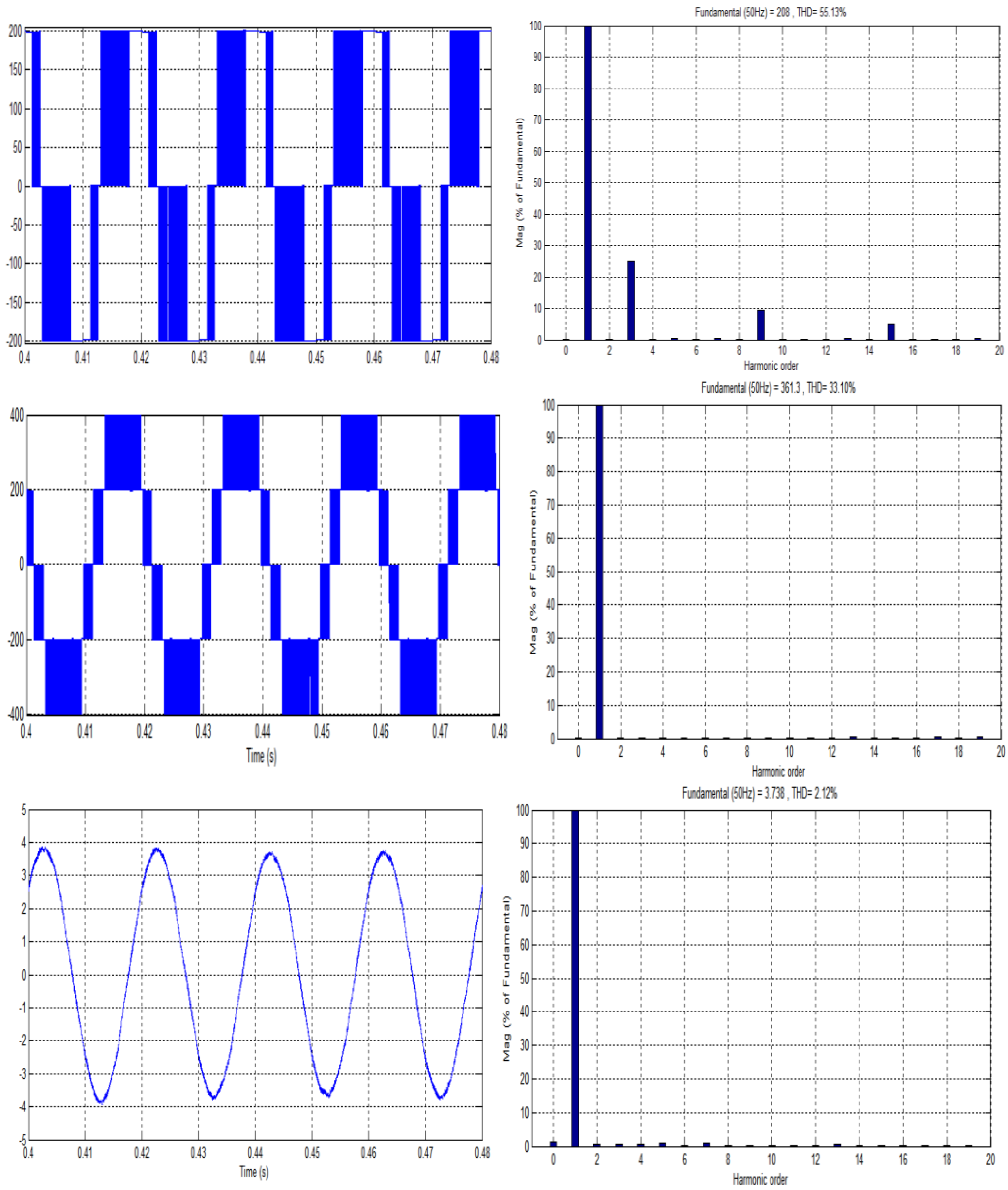
The algorithms using proposed region selection technique for conventional SVPWM and BCPWM for three-level inverter are verified through simulation on a 4KW 400V 50Hz 1430 rpm induction motor drive supplied from a three phase three level diode clamped inverter. A comparison has been studied for different PWM technique using three phase induction motor. The inverter is modelled using MATLAB/SIMULINK. The comparison is considered for same sampling frequency. But f_{sw} of CSVPWM is 1.86667 times that of bus clamping PWM. The simulation is done by considering the following conditions:

1. DC bus voltage, *VDC*= 400 V
2. 5 HP, 3 phase, 3 wire, 230 V, 4 pole squirrel cage induction motor with parameters $r_s = 0.531\Omega$, $r_r = 0.408\Omega$, $J = 0.1kg - m^2$ $L_{ls} = L_{lr} = 2.52mH$, $L_{ls} = 84.7mH$.
3. Modulation index=0.9; Switching frequency, $f_{sw} = 10kHz$.



(a)

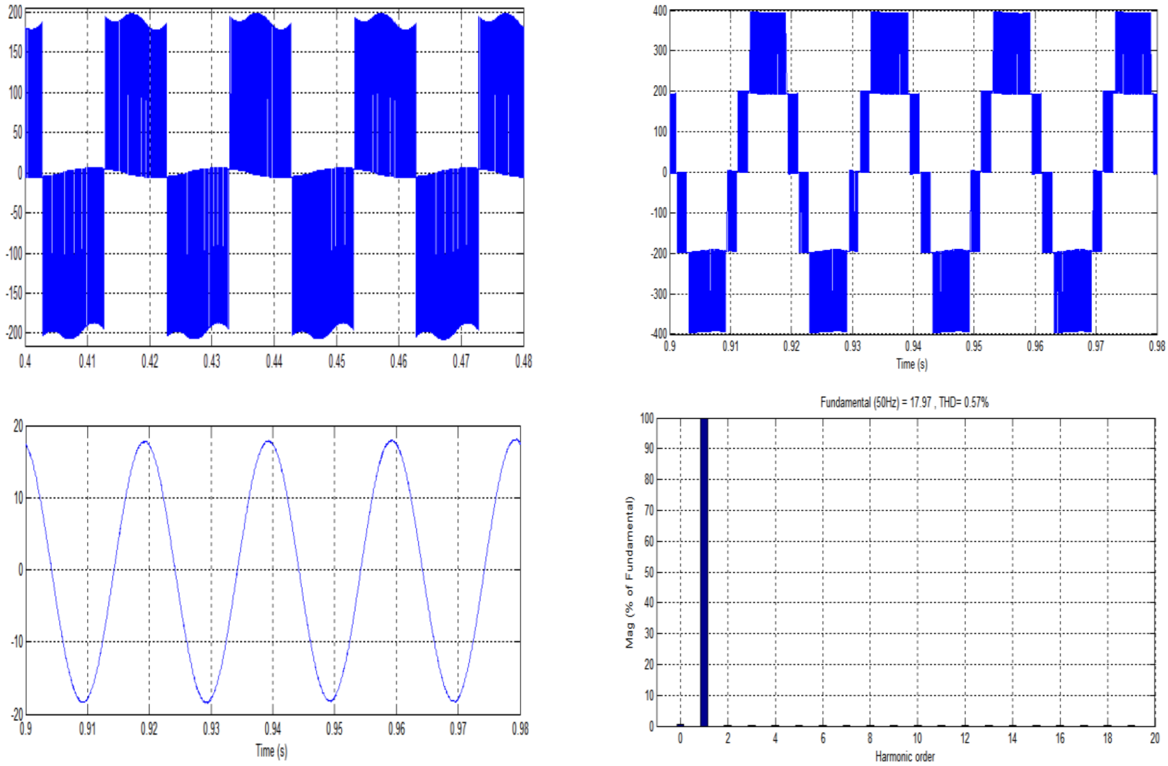
Figure 7. Simulation results: Vp,V_L, I_{NL} and their harmonic analysis at no load for m=0.9.
(a) CSVPWM (b) BCPWM



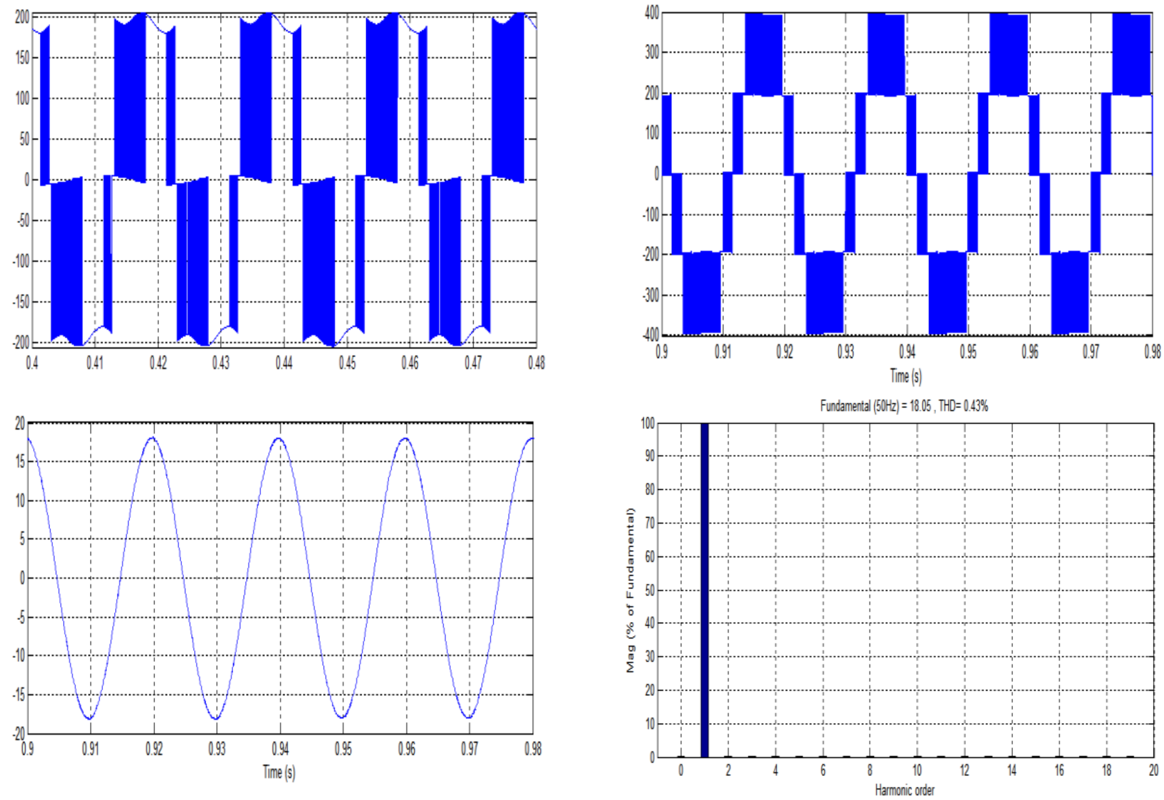
(b)

Figure 7. Simulation results: V_p,V_L, I_{NL} and their harmonic analysis at no load for m=0.9. (a) CSVPWM (b) BCPWM

The plot of pole voltages (V_P), line voltage (V_L), line current and harmonic analysis of line current for both the PWM techniques has been shown in Figure 7 and Figure 8 under no-load and full load respectively at 0.9 modulation index. The rms value of fundamental component is 360 V for CSVPWM and 361.3 V for V for BCPWM. The rms value of fundamental component of the motor no-load current I_{NL1} is 3.712 A for CSVPWM and 3.738 A for CSVPWM and BCPWM respectively. The total harmonic distortion line current is 2.65% for CSVPWM and 2.12% for BCPWM at no load.



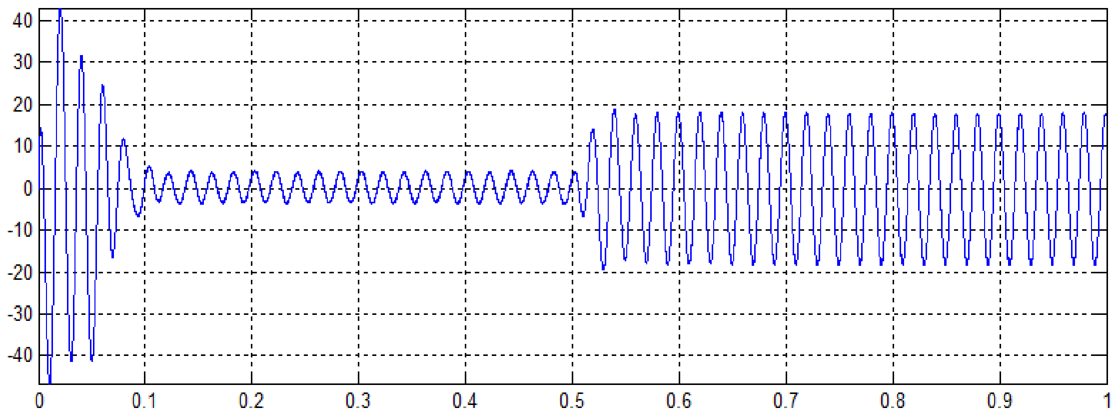
(a)



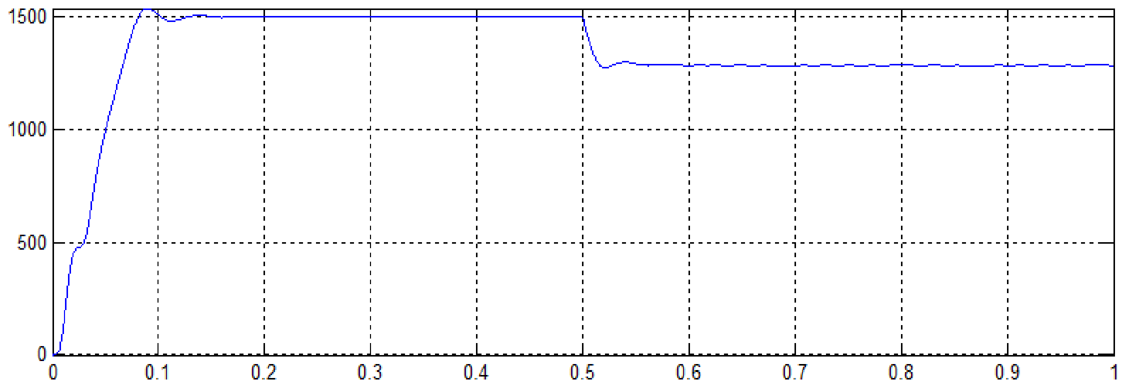
(b)

Figure 8. Simulation results: V_L, I_{FL} and their harmonic analysis at full load for m=0.9.
(a)CSVPWM (b)BCPWM

At full load under same modulation index the rms fundamental component of line voltage is 353.9 V for CSVPWM and 355 V for BCPWM. The fundamental component of line currents are 17.97 A and 18.05 A respectively. The (%) THD of line currents are 0.57% for CSVPWM and 0.43% for BCPWM technique.



(a)



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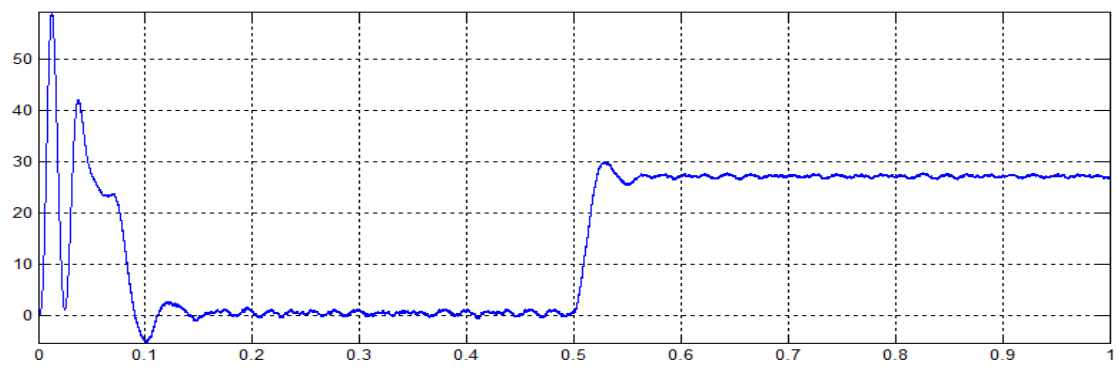


(c)

Figure 9. Simulation results for CSVPWM at m=0.9 (a) phase A stator current (b) dynamic speed characteristic (c) torque characteristic of induction motor

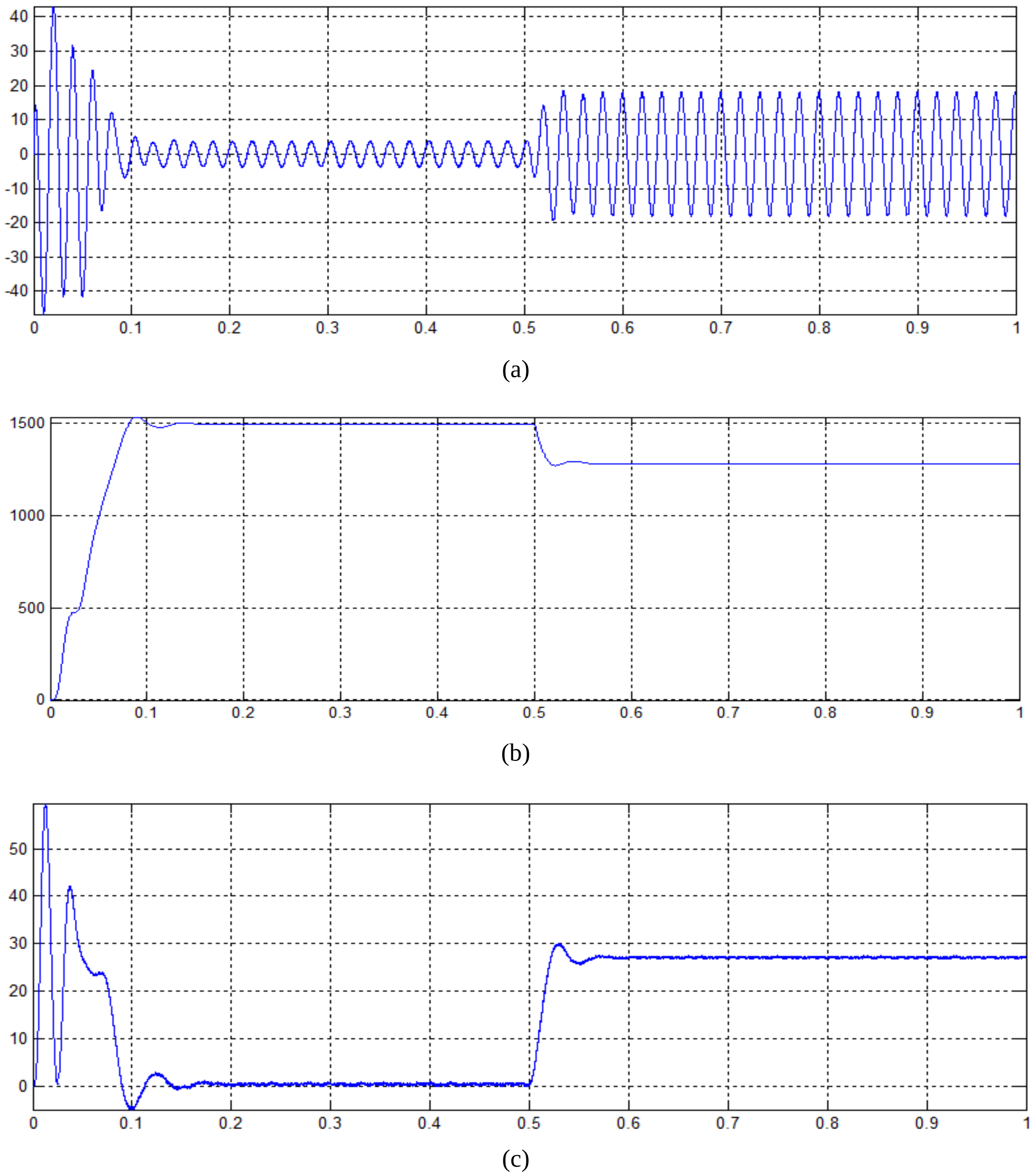
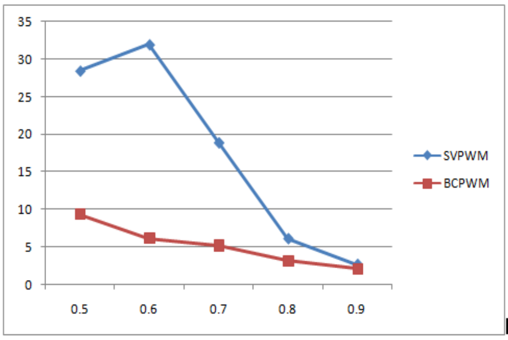


Figure 10. Simulation results for BCPWM at m=0.9 (a) phase A stator current (b) dynamic speed characteristic (c) torque characteristic of induction motor

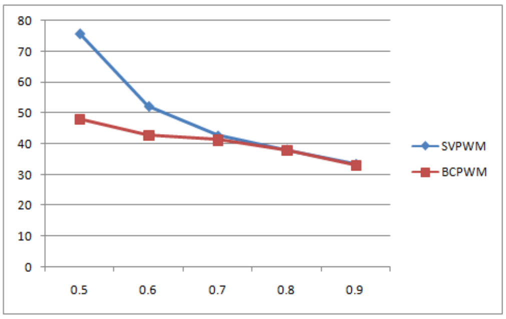
From the simulation results as shown in the Figure 7, it can be noticed that the triplen harmonics are present in the pole voltages in both the cases, but due to the three phase symmetry, these are absent from the line voltages as well as line currents. The even harmonics are also be negligible due to half wave symmetry. The stator current, speed characteristic and torque characteristics of an induction motor is shown in Figure 9 and Figure 10 for CSVPWM and BCPWM respectively. After 0.5 seconds dynamically motor is run under full load and the corresponding effects is shown in the figures above.

8. PERFORMANCE ANALYSIS

The performance of voltage source inverter is dependent on the PWM technique and its algorithm. The PWM algorithms are evaluated in terms of THD, fundamental component of line voltage and pole voltage. The %THD of line voltage is evaluated at different modulation index (m) for CSVPWM and BCPWM respectively and it is seen from the Figure 11(a) that for higher modulation index the THD is getting lower. The figure also depicts the superiority of BCPWM over CSVPWM. The Figure 11(b) explains the (%)THD of line current over the range 0.5 to .9 of modulation index. The variation of V_{L1} for the simulation data are given in Figure 11(c) for the mentioned region of modulation. The V_{L1} is linear in the linear modulation region as shown in the Figure 11(c) for both the modulation techniques.



(a)



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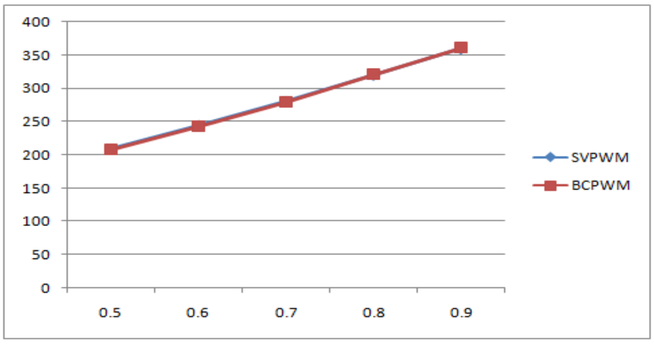

(c)

Figure 11. Simulation results. (a)V_{LTHD} versus m. (b) I_{LTHD} versus m. (c) V_{L1} versus m.

9. CONCLUSION

The new technique for region selection for CSVPWM as well as BCPWM is proposed in this paper. The performance comparison in terms of are made between CSVPWM and BCPWM for three-level inverter and it is validated through simulated results and it shows that BCPWM technique is better than the CSVPWM technique in respect of THD and current ripple. The simulated results also show the effectiveness of the proposed technique. The proposed techniques are tested on open loop induction motor drive system. The real implementation of proposed technique for closed loop drive system will be a challenging work for the future.

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