

Space Vector Based High Performance Discontinuous Pulse Width Modulation Algorithms for VSI Fed AC Drive

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Abstract: This paper presents Space Vector based Simplified Discontinuous Pulse width modulation (DPWM) algorithms for VSI fed Induction motor drive. To avoid the complexity due to angle calculation and sector identification involved in Conventional space vector pulse width modulation (CSVPWM), the proposed algorithms use the concept of Imaginary Switching times to generate modulating waveforms. It is observed that the proposed algorithm results in reduced current ripple and switching losses over CSVPWM. To validate the proposed methods, simulation and experimental studies have been carried out on V/f controlled Induction Motor drive using MATLAB/SIMULINK and dSPACE kit and the results have been presented.

Keywords: CSVPWM, DPWM, Imaginary Switching times, V/f control

1. Introduction

Improvements in fast switching power devices have led to an increased interest in voltage source inverters (VSI) with pulse width modulation (PWM) control. Out of several approaches, triangular comparison (TC) approach and space vector (SV) approach are main implementation techniques. The space vector approach offers additional degrees of freedom in designing PWM techniques over the triangle-comparison methods. The conventional SVPWM algorithm employs equal division of zero voltage vector times within a sampling period or sub cycle [1, 2]. In this method the reference voltage vector is synthesized by time averaging two active states and two zero states in every sampling period [3]. However, the CSVPWM is known as continuous PWM (CPWM) method in this switching loss is high. Hence to reduce the switching losses and to improve the performance several discontinuous PWM (DPWM) methods have been reported [3-9]. If the zero sequence signals are continuous it produces CPWM scheme and if it is discontinuous it results in DPWM schemes. A carrier based generalized PWM method comprising of all DPWM methods is considered as generalized discontinuous PWM scheme (GDPWM)[3][4][5].

The conventional space vector pulse width modulation sector identification and switching sequences are discussed in [10]. CSVPWM suffers from the drawbacks like computational burden and it takes more time to execute. Hence the complexity involved in CSVPWM is more. To reduce the complexity involved in CSVPWM algorithm, a simplified approach is developed in [6-9] by using the concept of imaginary switching times. This paper presents Space Vector based high performance Discontinuous Pulse width modulation (HDPWM) algorithms for VSI fed Induction motor drive using the concept of imaginary switching times.

2. Proposed Space Vector Based High performance DPWM algorithms

SVPWM is a continuous PWM (CPWM) method where Discontinuous SVPWM results when one of the two zero vector is not used in the implementation of the SVPWM. One leg of the inverter does not switch during the whole switching period and remains tied to either the positive or negative DC bus. This is known as Discontinuous SVPWM, since the switching is not continuous. Due to the manipulation of the Zero Space vector application in a Switching period one branch of the inverter remains unmodulated during one Switching interval. Switching takes place in two branches: one branch either to the positive DC bus or the negative DC bus, [when zero voltage [000] is eliminated the leg voltage is tied to the positive DC bus $0.5V_{dc}$ or when zero voltage [111] is eliminated the leg voltage is tied to the negative bus voltage $0.5V_{dc}$]. The number of switching's thus reduced to two-thirds compared to the continuous SVPWM and hence switching losses are reduced significantly. Moreover, complexity involved in conventional SVPWM is more. To avoid the complexity due to angle calculation and sector identification involved in CSVPWM.

Different switching sequences can be obtained by using conventional space vector approaches, which uses the reference voltage vector and angle information and increases the complexity of the control algorithm. In order to reduce the complexity, the proposed DPWM algorithms use the concept of imaginary switching times. The imaginary switching times are proportional to the instantaneous three phase reference voltages V_{an} , V_{bn} and V_{cn} and are defined as

$$V_{an} = V_p * \sin(\omega_e t)$$

$$V_{bn} = V_p * \sin(\omega_e t - 2\pi/3)$$

$$V_{cn} = V_p * \sin(\omega_e t - 4\pi/3)$$

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The imaginary switching times are expressed as

$$\begin{aligned} T_{as} &\equiv \left(\frac{T_s}{V_{dc}} \right) V_{an} ; \\ T_{bs} &\equiv \left(\frac{T_s}{V_{dc}} \right) V_{bn} ; \\ T_{cs} &\equiv \left(\frac{T_s}{V_{dc}} \right) V_{cn} ; \end{aligned}$$

Where T_s is the sampling time period and V_{dc} is dc link voltage.

If the instantaneous reference voltages are negative, the corresponding switching times will also be negative. Hence these times are called as imaginary switching times. In every sampling time, the maximum, minimum and medium values of imaginary switching times are calculated as [7-8].

$$T_{max} = \text{Max} (T_{as}, T_{bs}, T_{cs})$$

$$T_{min} = \text{Min} (T_{as}, T_{bs}, T_{cs})$$

$$T_{mid} = \text{Mid} (T_{as}, T_{bs}, T_{cs})$$

Where max, min and mid are three nominal values used during the sampling interval.

The function $\text{Max}(T_{as}, T_{bs}, T_{cs})$, $\text{Min}(T_{as}, T_{bs}, T_{cs})$ and $\text{mid}(T_{as}, T_{bs}, T_{cs})$ select the maximum, minimum and middle values among T_{as} , T_{bs} and T_{cs} , respectively.

Actual gating signals for inverter can be generated by the time shifting operation as follows:

$$T_{ga} = T_{an} + T_{offset}$$

$$T_{gb} = T_{bn} + T_{offset}$$

$$T_{gc} = T_{cn} + T_{offset}$$

Where

$$T_{offset} = T_s(1 - \mu) + (\mu - 1)T_{max} - \mu T_{min}$$

In the proposed method μ can be defined as

$$- 0.5[\text{sgn}(\cos 3(\omega t - \delta))]$$

Where ω is angular frequency of reference voltage.

$\text{sgn}(y)'$ is the sign function,

Where

$$\text{sgn}(y) = \begin{cases} 1 & \text{if } y > 0 \\ 0 & \text{if } y = 0 \\ -1 & \text{if } y < 0 \end{cases}$$

' δ ' is modulation phase angle

When $\mu=0.5$, $\mu=0$ and $\mu=1$ the CSVPWM, DPWMMAX and DPWMMIN algorithms can be obtained. Similarly, the variation of modulation phase angle δ yields to infinite number of DPWM methods. If $\delta = -\pi/3, \pi/6, 0, -\pi/6$ then

DPWM1, DPWM2, DPWM3 and DPWM4 can be obtained respectively. Thus by varying μ and δ the switching time periods of zero voltage vectors can be changed and so that different DPWM sequences can be obtained.

The modulating waveforms of different DPWM sequences, SPWM and CSVPWM are as shown in Fig 1. DPWM sequences are obtained based on their clamping sequences.

In DPWMMIN method, the clamping of 120 takes place at the middle of 180°– 360° for every 360° of fundamental voltage. In DPWMMAX method, the clamping of 120° takes place at the middle of 0°-180° for every 360° of fundamental voltage.

In DPWM1, the clamping of 60 takes place at the middle 0-180 for every 180 of fundamental voltage. In DPWM2 method, the clamping of 60 takes place at the start of 90-180 for every 180 of fundamental voltage. DPWM3 clamps every phase during the middle 30 for every 90 of its fundamental voltage. In DPWM4 method, the clamping of 60 takes place at the end of 0 for every 180 of fundamental voltage.

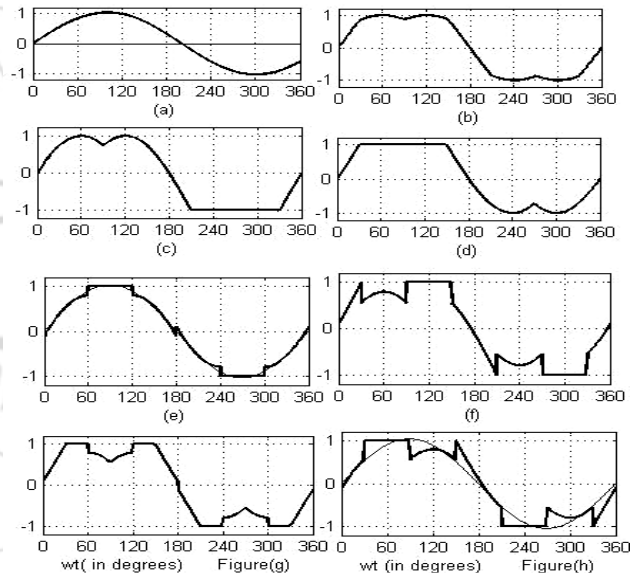


Figure 1: Modulating waveforms of different sequences (a) SPWM (b) SVPWM (c) DPWMMIN (d) DPWMMAX (e) DPWM1 (f) DPWM2 (g) DPWM3 (h) DPWM4

3. Results

To validate proposed Space Vector Based High Performance DPWM Algorithms, Simulation & Experimental tests on a constant v/f voltage source inverter fed induction motor drive have been conducted using Matlab/Simulink & d-Space Kit in the laboratory. DC link voltage 540 volts & 4.5 KHz switching frequency have been applied. Simulation and experimental results are shown in Figure 2 to Figure 23. The induction motor used in this case study is a 4 KW, 1430 rpm, 4-pole, 3-phase induction motor having the following parameters:

Table 1: Parameters of Induction motor

Parameter	Value
Stator Resistance (R_s)	1.4 Ω
Rotor Resistance (R_r)	1.39 Ω
Magnetizing Inductance (L_m)	0.1722 H
Stator Self Inductance (L_s)	0.005839 H
Rotor Self Inductance (L_r)	0.005839 H
Moment of inertia (J)	0.0131 Kg-m ²

3.1 Simulation Results

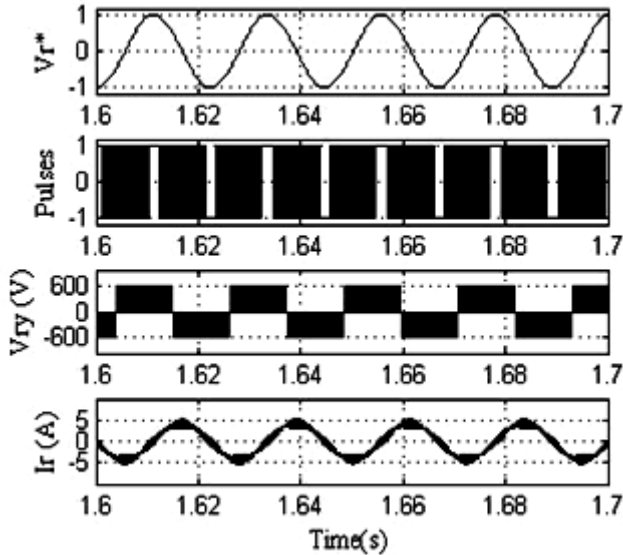


Figure 2: SPWM algorithm at $M_i=0.81$

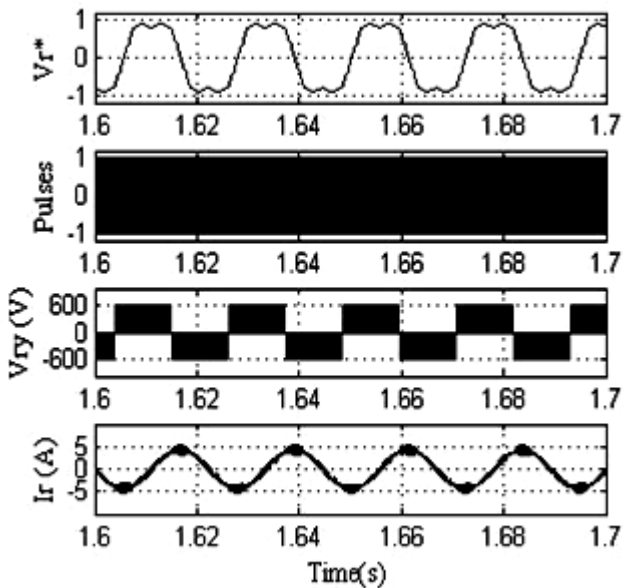


Figure 3: SVPWM algorithm at $M_i=0.81$

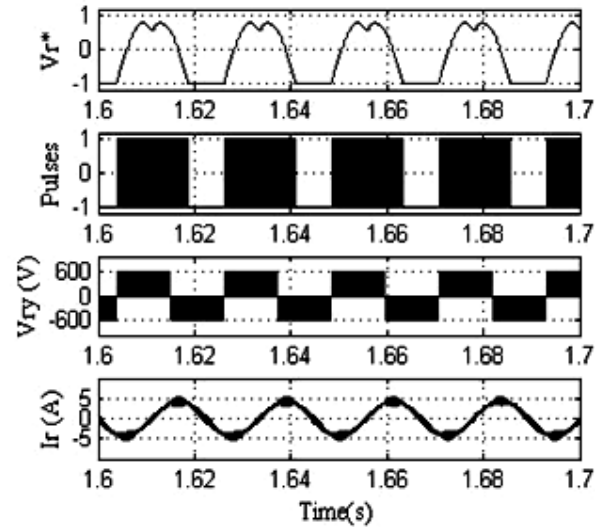


Figure 4: DPWMMIN algorithm at $M_i=0.81$

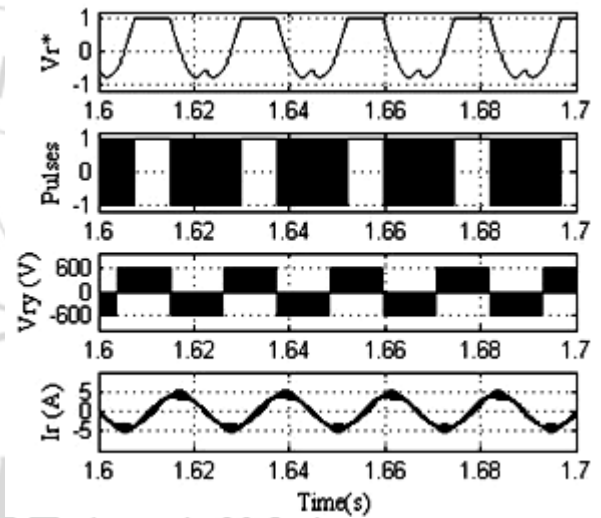


Figure 5: DPWMMAX algorithm at $M_i=0.81$

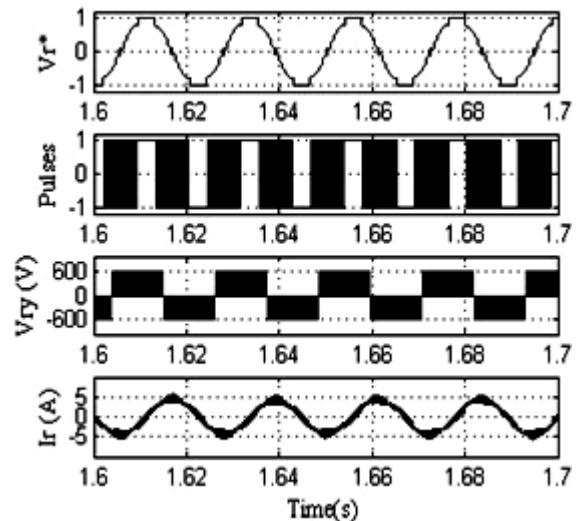


Figure 6: DPWM1 algorithm at $M_i=0.81$

3.2 Experimental Results

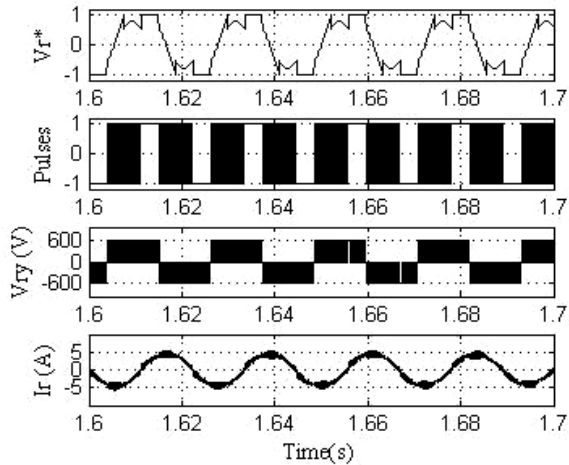


Figure 7: DPWM2 algorithm at $M_i=0.81$

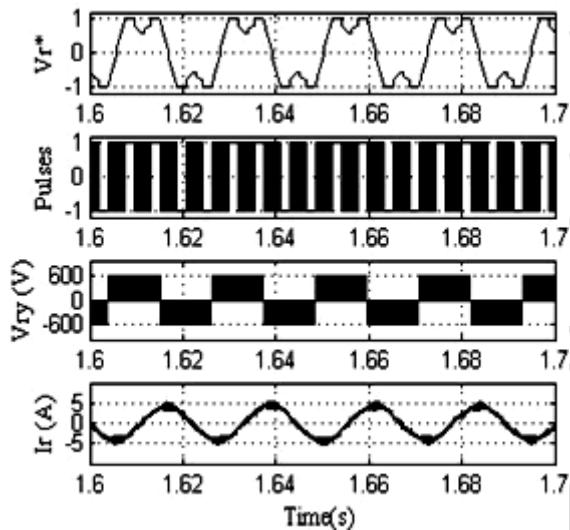


Figure 8: DPWM3 algorithm at $M_i=0.81$

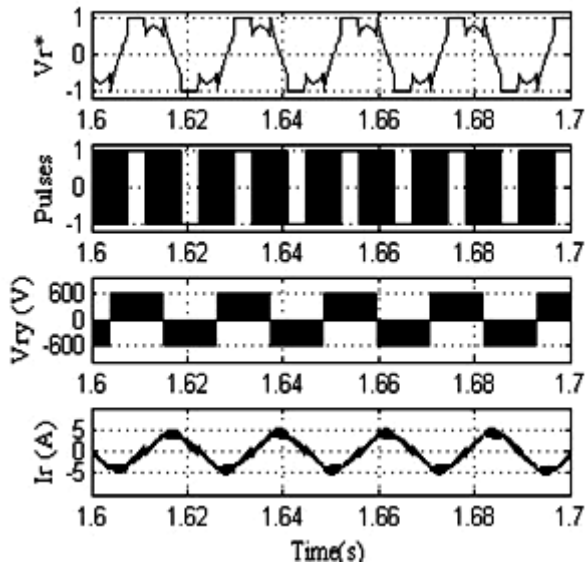


Figure 9: DPWM4 algorithm at $M_i=0.81$

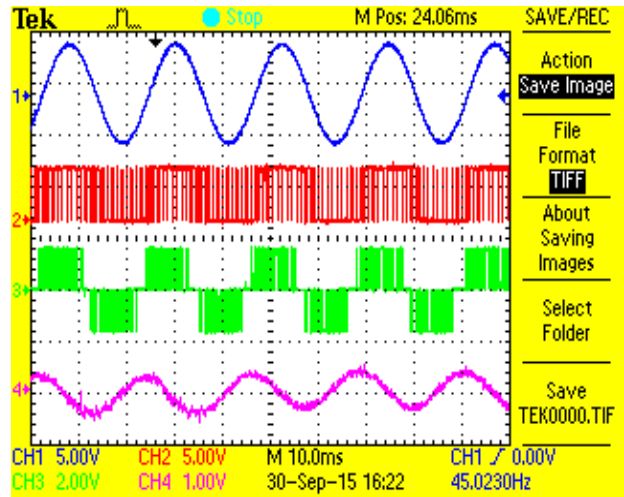


Figure 10: SPWM algorithm at $M_i=0.81$: Modulating Signal, Pulses, Line Voltage and Stator Current

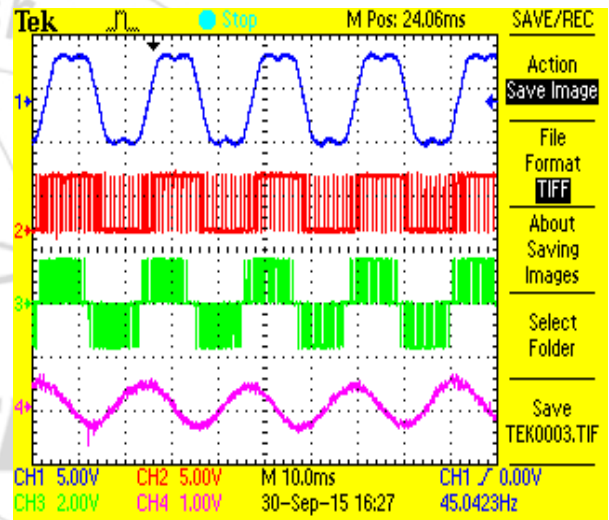


Figure 11: SVPWM algorithm at $M_i=0.81$: Modulating Signal, Pulses, Line Voltage and Stator Current

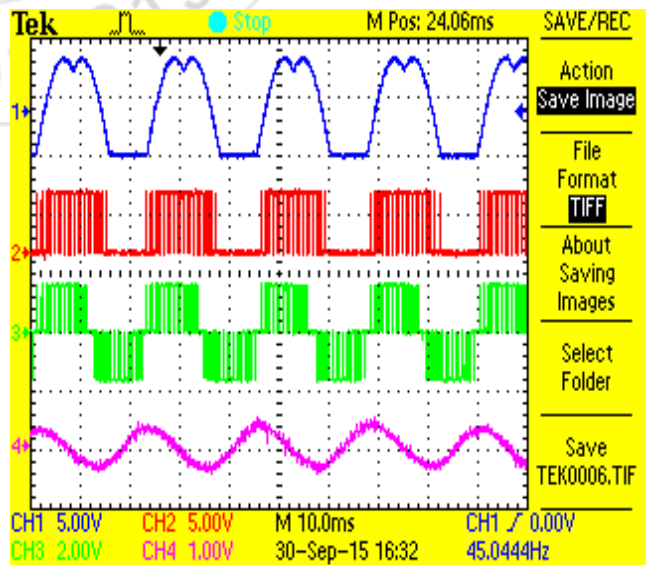


Figure 12: DMPWMMIN algorithm at $M_i=0.81$: Modulating Signal, Pulses, Line Voltage and Stator Current

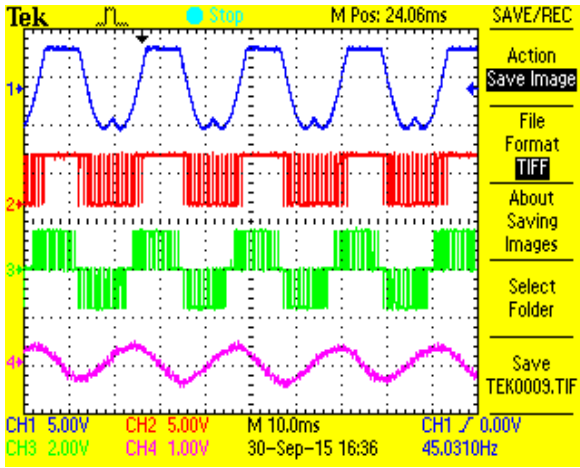


Figure 13: DMPWMAX algorithm at $M_i=0.81$: Modulating Signal, Pulses, Line Voltage and Stator Current

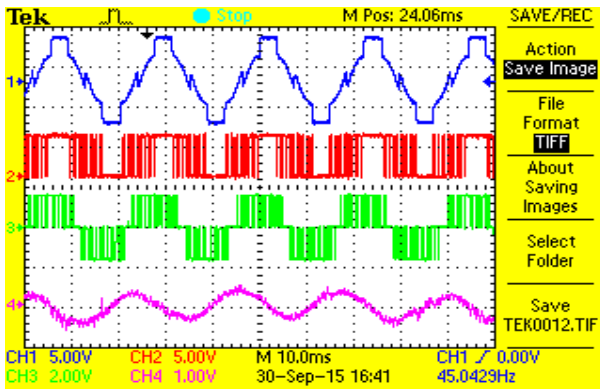


Figure 14: DMPWM1 algorithm at $M_i=0.81$: Modulating Signal, Pulses, Line Voltage and Stator Current

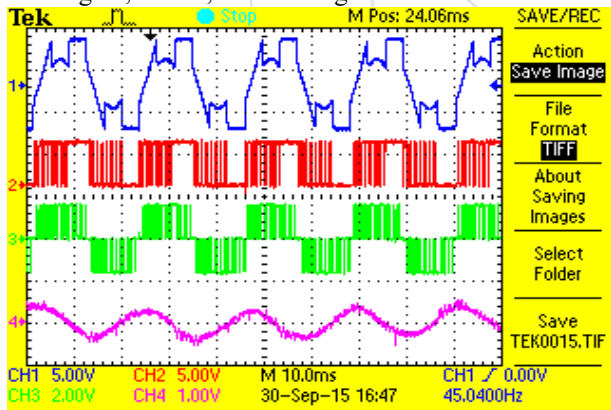


Figure 15: DMPWM2 algorithm at $M_i=0.81$: Modulating Signal, Pulses, Line Voltage and Stator Current

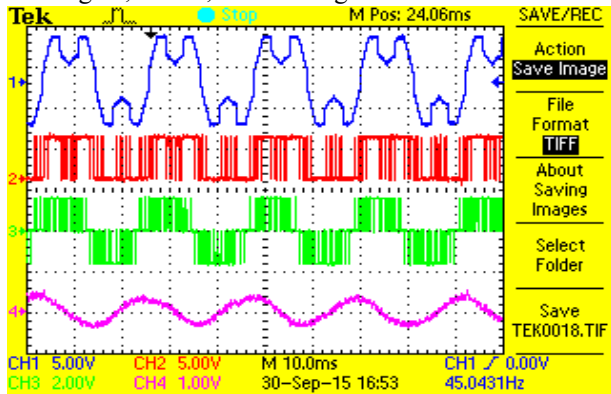


Figure 16: DMPWM3 algorithm at $M_i=0.81$: Modulating Signal, Pulses, Line Voltage and Stator Current

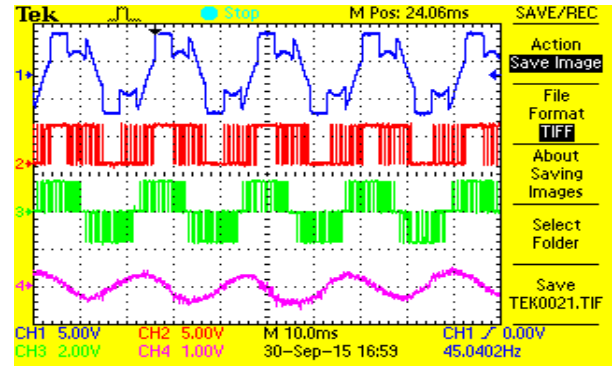


Figure 17: DMPWM4 algorithm at $M_i=0.81$: Modulating Signal, Pulses, Line Voltage and Stator Current

3.3. Stator Current Harmonic Comparison

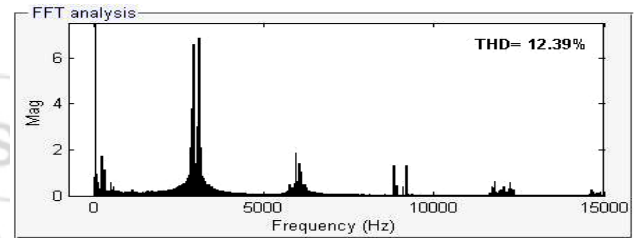


Figure 18: SPWM: Harmonic distortion of line current along with THD at $M_i=0.81$

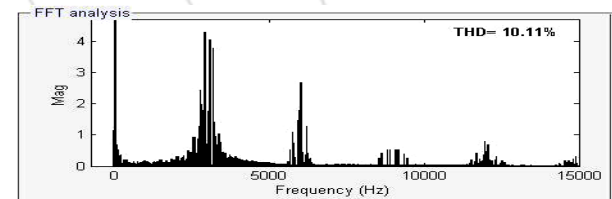


Figure 19: SVPWM: Harmonic distortion of line current along with THD at $M_i=0.81$

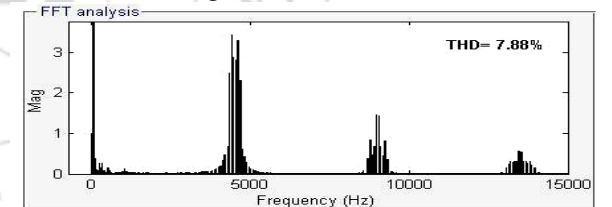


Figure 20: DPWMMIN: Harmonic distortion of line current along with THD at $M_i=0.81$

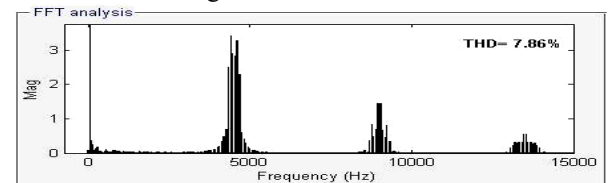


Figure 21: DPWMMAX: Harmonic distortion of line current along with THD at $M_i=0.81$

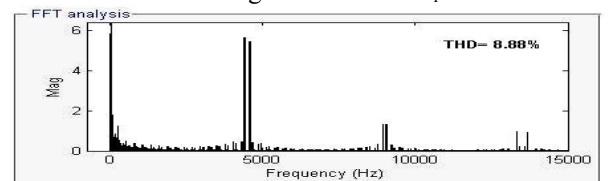


Figure 22: DPWM1: Harmonic distortion of line current along with THD at $M_i=0.81$

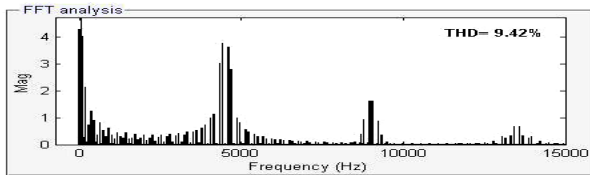


Figure 23: DPWM2: Harmonic distortion of line current along with THD at $M_i=0.81$

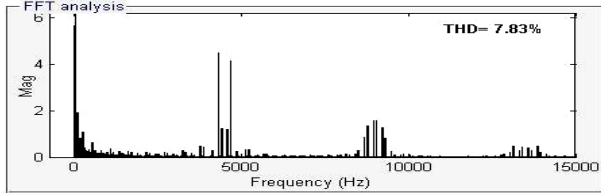


Figure 24: DPWM3: Harmonic distortion of line current along with THD at $M_i=0.81$

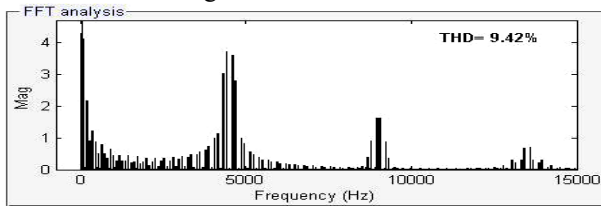


Figure 25: DPWM4: Harmonic distortion of line current along with THD at $M_i=0.81$

4. Conclusion

The proposed space vector based High performance discontinuous PWM algorithms uses the concept of imaginary switching times. To avoid the complexity due to angle calculation and sector identification involved in Conventional SVPWM also the execution time and memory required is reduced by eliminating the angle and sector estimation.

From the simulation results of V/f control of induction motor drive the total harmonic distortions of the motor phase current in Continuous SVPWM are more compared to the various DPWM sequences. The Total THD values for the proposed HDPWM algorithms are listed. It is observed that there is a gradual decrement of the %THD in motor phase currents and also it is observed that in every fundamental cycle, DPWM modulating signal clamp to either negative dc bus or positive dc bus for a period of 120 degrees which results reduction in the switching losses of the inverter by 33.33%. Hence DPWM sequences give better performance. The simulation & Experimental results show the validity of the proposed algorithm.

Table 2: Comparison of Line Current THD

S. No	PWM Algorithm	THD in Line Current (%) At $M_i=0.81$
1	SPWM	12.39
2	SVPWM	10.11
3	DPWMMIN	7.88
4	DPWMMAX	7.86
5	DPWM1	8.88
6	DPWM2	9.42
7	DPWM3	7.83
8	DPWM4	9.42

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