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[1] Mitul Patel
[2] Gaurang Buch
[3] Tejas Patel

V/f control of Induction Motor by sine PWM control using Inverted Sine Carrier

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Abstract: - Sine PWM (SPWM) is a carrier-based modulation technique. It is widely used with power electronics converters, especially for the control of voltage source inverter (VSI). It is dominant because of its easy implementation, capability to efficiently regulate voltage and current, and reduce the harmonics from the output of the inverter. Still this method suffers from the limitation of reduced power output in the over-modulation region. In 2007 R.Nandhakumar et al. proposed a novel approach for sine PWM using Inverted sine carrier PWM (ISCPWM) method. They have shown the advantages of their proposed method in terms of increased duty cycle and reduced harmonics for varying values of Modulation Index (*m*) and carrier frequency.

In this research, ISCPWM method has been used instead of conventional SPWM method for the V/f control of Induction Motor. In the paper it shown that, using ISCPWM method the response time of motor to speed change command is reduced and the torque ripples are reduced. The proposed V/f control using ISCPWM method has been simulated in matlab and the results are compared with conventional triangular wave based SPWM method. The results of motor speed, torque, and total harmonic distortion (THD) for different values of load torques for both the techniques are compared.

Keywords: Pulse Width Modulation, SPWM, ISCPWM, Modulation Index, V/f control, Total Harmonic Distortion, VSI

I. INTRODUCTION

Carrier-based PWM (Pulse Width Modulation) techniques have evolved through the work of many researchers and engineers in the field of power electronics over a period. The great research in the field of PWM techniques was made by famous people such as Ned Mohan, Irving L. Kosow and others who marked the path of modern power electronics. The development of the carrier based PWM methods has been affected by the progress in the fields of control theory, digital signal processing and semiconductor technology, by many researchers and engineers who have perfected and applied it in various industrial applications.

Holtz in his paper [2] presented various PWM approaches for the control of the power electronics converters. The properties of various methods are evaluated by mathematical analyses and results from the drive systems that are controlled. He has shown the significance of performance criteria in the selection of a PWM scheme for a given application. The sentence underlines the importance of switching frequency in the identification of system losses and presents the trade-off between high frequency switching and modulation methods at low power levels and the complex techniques at high power levels [3].

Ned Mohan, Bimal K Bose and other stalwarts in power electronics have presented various methods for scalar control and vector control of ac motors [4-6] and [12-14]. El-Saady et al have compared the performance of an induction motor with SPWM, Third Harmonic PWM and Space vector PWM [7].

Scalar or V/f control of Induction motor is widely used for the speed control of induction motor in industry because of its simplicity in control algorithm. Conventional sine PWM uses triangular carrier wave for generation of switching pulses. When the value of Modulation Index (*m*) is increased beyond 1, by increasing the amplitude of the modulating wave, the technique enters the overmodulation region. In this region output no longer follows the modulation index and tends to increase slowly with increase in m. Nandkumar et al introduced a novel approach of sine PWM control using inverted sine shaped carrier wave (ISCPWM), instead of triangular carrier waves. They have shown the advantage of their proposed method with increased output voltage and low THD for different values of *m* and switching frequency [1][11].

In this paper ISCPWM method is used for scalar V/f control of induction motor. The proposed V/f control is simulated along with the conventional SPWM method in MATLAB®. The results of speed, torque and THD of

[1] *Corresponding author: Author 1 Assistant professor, Electrical Engineering, L. D. college of Engineering, Ahmedabad, GJ (India)
[2] Author 2 Assistant professor, Electrical Engineering, L. D. college of Engineering, Ahmedabad, GJ (India)
[3] Author 3 Assistant professor, Electrical Engineering, L. D. college of Engineering, Ahmedabad, GJ (India)

both the methods are compared for different values of load torque. It has been shown that for different values of load torque the reference speed is reached quicker with ISPWM. Also, the torque ripple and THD in voltage and current are less than the conventional SPWM.

II. Generation of Switching Pulses in Conventional SPWM and ISCPWM

In carrier based PWM technique, switching pulses are generated by comparing carrier pulse with modulating wave. In the case of SPWM, the modulating wave is a sine wave of fundamental frequency. Generation of switching pulse for triangular carrier wave based SPWM and for ISCPWM technique is shown in Fig.1. Frequency of carrier signals (f_c) is 500 Hz and that for modulation signal (f) is 50 Hz. The modulation index (m) as defined in Equation below, is 0.8 for the waveform shown in Fig.1.

$$Modulation\ Index, m\ = \frac{V_{Pm}}{V_{Pc}}$$

Where, V_{Pm} and V_{Pc} are peak values of modulating wave and carrier wave respectively.

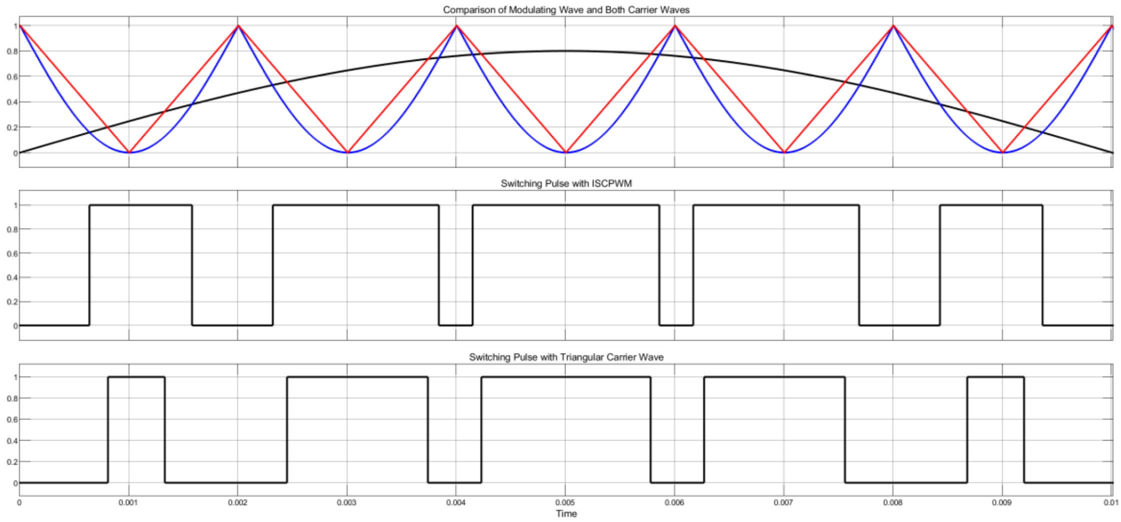


Fig.1 Generation of switching pulse of sine PWM and ISCPWM

From Fig.1 it is observed that more pulse width is obtained at each point with ISCPWM compared to conventional SPWM which results in more output power with the same switching frequency of devices.

$$\textit{Carrier to modulating frequency ratio, } m_f = \frac{f_c}{f} = 10$$

III. Variation of Output in Conventional SPWM and ISCPWM

In Fig.2 the comparison of both the methods is given for output voltage, which is mentioned in terms of the percentage of square wave output of the inverter that is $4V_d/2\pi$. Where, V_d is dc link voltage.

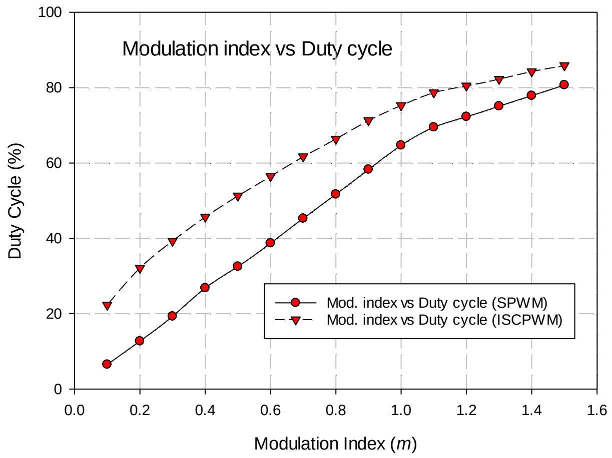


Fig.2 Variation of output voltage with Modulation index in sine PWM and ISCPWM

In conventional SPWM method, output voltage varies linearly with modulation index (*m*) upto *m*=1, at which it is 78.55% of maximum possible output. This region below *m*=1 is referred to as under modulation region. For *m*>1 the technique enters in the over modulation region and the output voltage no longer follows *m*. In this region the pulses near the center of a half cycle vanishes with increase in *m*. Further increase in the value of *m* results in slight increase in the output voltage in this region.

Whereas in case of ISCPWM, linear relation between the value of *m* and output voltage is not observed for lower values of *m*, even though the output voltage is notably higher than that of conventional SPWM in under modulation region and over modulation region both [1]. The reason for this difference lies in cross over points of modulating wave with triangular carrier wave and ISCPWM as explained in Fig.3 and shown in Fig.1

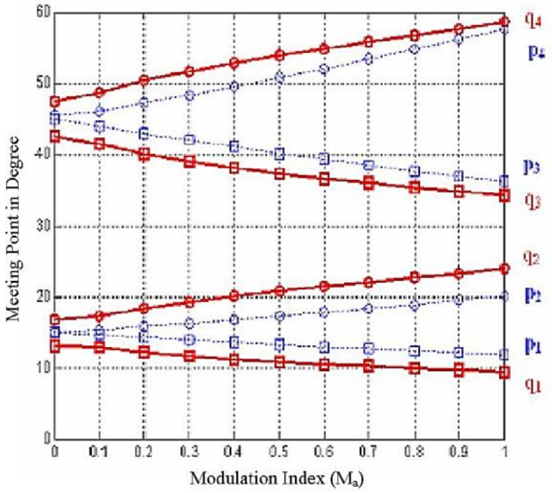


Fig.3 Variation of output voltage with Modulation index in sine PWM and ISCPWM [1]

In Fig. 3 crossover points of modulating wave and carrier signal for $m_f=5$ in degree for first two pulses in a half cycle are shown. Larger difference between p_1-p_2 and p_3-p_4 (also between q_1-q_2 and q_3-q_4) correspondence to larger pulse width and larger output voltage.

IV. Generation of Switching Pulses for V/f Control of Induction Motor Using ISCPWM

Inverted sine carrier signals are generated using the equations (1) to (3) for upper half switches and equations (4) to (6) for lower half switches of three phase inverter.

$$y_1= 1\text{-}abs(sin(2\pi f_c t)); \quad \dots(1)$$
$$y_2= 1\text{-}abs(sin((2\pi f_c t)+(2\pi/3))); \quad \dots(2)$$
$$y_3= 1\text{-}abs(sin((2\pi f_c t)-(2\pi/3))); \quad \dots(3)$$

$$y_4= -1+abs(sin(2\pi f_c t)); \quad \dots(4)$$
$$y_5= -1+abs(sin((2\pi f_c t)+(2\pi/3))); \quad \dots(5)$$
$$y_6= -1+abs(sin((2\pi f_c t)-(2\pi/3))); \quad \dots(6)$$

To remove dc component, triplen harmonics, even harmonics and inter harmonics from the output, the switching pulse should maintain full wave symmetry, half wave symmetry and quarter wave symmetry. Higher value of m_f is desired to reduce harmonics, but it is limited by the max switching frequency of switching devices.

In synchronous modulation the carrier and modulation are to be synchronized and there is a fixed number of carrier cycles in each modulation cycle. m_f must be a fixed integer ratio at moderate and high speed to avoid the subharmonics from happening, the asynchronous operation of the carrier frequency is acceptable at low speeds where the number of carrier cycles per modulation cycle is small. Nevertheless, a switch to synchronous operation is needed at some speed, and some kind of "phase locking" technique should be introduced to acquire the synchronization. To achieve synchronous switching for all phase, carrier signals for phase-B and C set by equations (2), (3), (5) and (6) are delayed by $\pm\ m_f*(2\pi/3)$ angle instead of $\pm(2\pi/3)$, so that starting of carrier wave and modulating wave coincide with each other.

V. Simulation of V/f Control of Induction Motor Using ISCPWM

The simulation was performed on 4 kW, 1430 rpm, 400 V, 50 Hz, 3-phase induction motor, with full load torque of 26.72 Nm. For V/f control of this motor by ISCPWM, individual carrier signals of 900 Hz frequency are generated at m_f =18 using the equations (1) to (6) for upper switches and lower switches. Carrier pulses for all the three phases are synchronized with respective modulating signals. The load torque connected with the motor is 22 Nm.

The Simulation of ISCPWM fed V/f control of induction motor is shown in Fig.4.

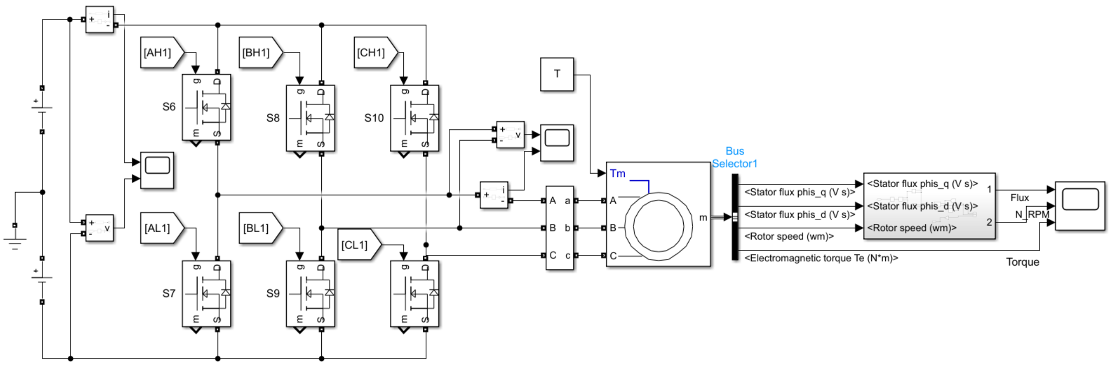


Fig.4 ISCPWM fed V/f control of induction motor

The control block for generating ISCPWM pulses for inverter is shown in Fig.5(a). Fig.5(b) shows generation of ISCPWM pulse for phase-A. Similar pulses generated for phase-B and phase-C are shown in Fig.5(c). The present simulation is in an open loop.

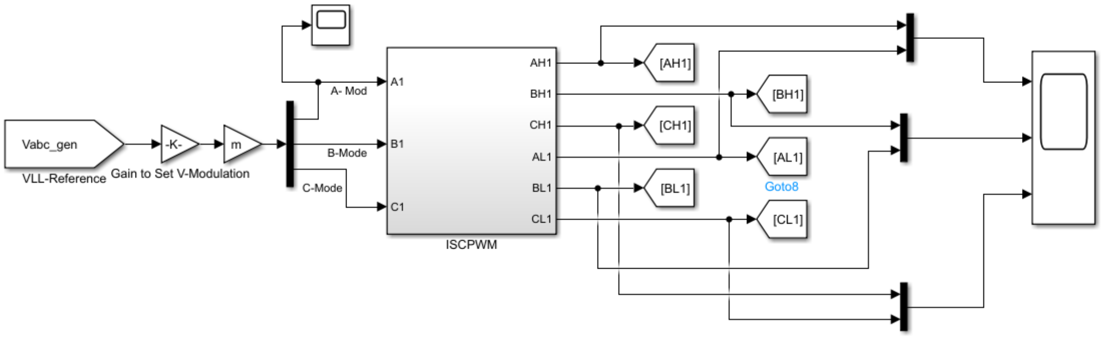


Fig.5(a) Generation of 6-switch pulses for V/f control by ISCPWM

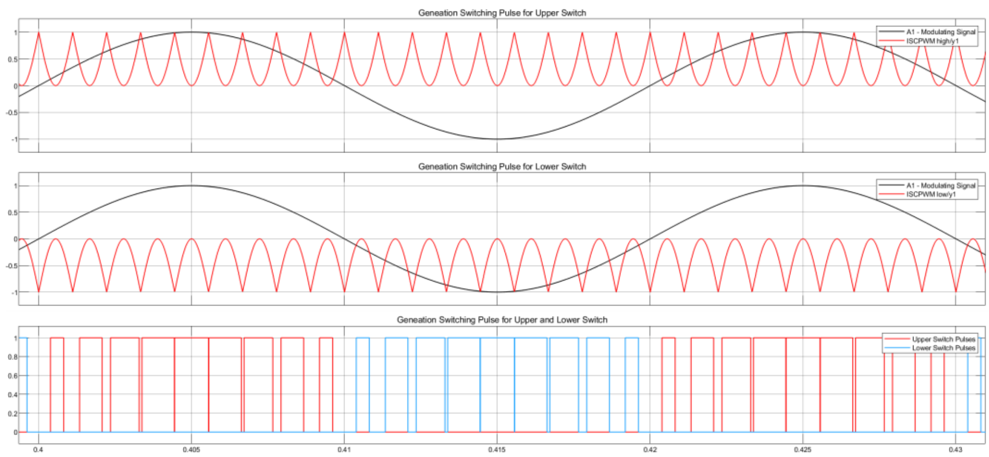


Fig.5(b) Generation of switch pulses for upper and lower switches by ISCPWM

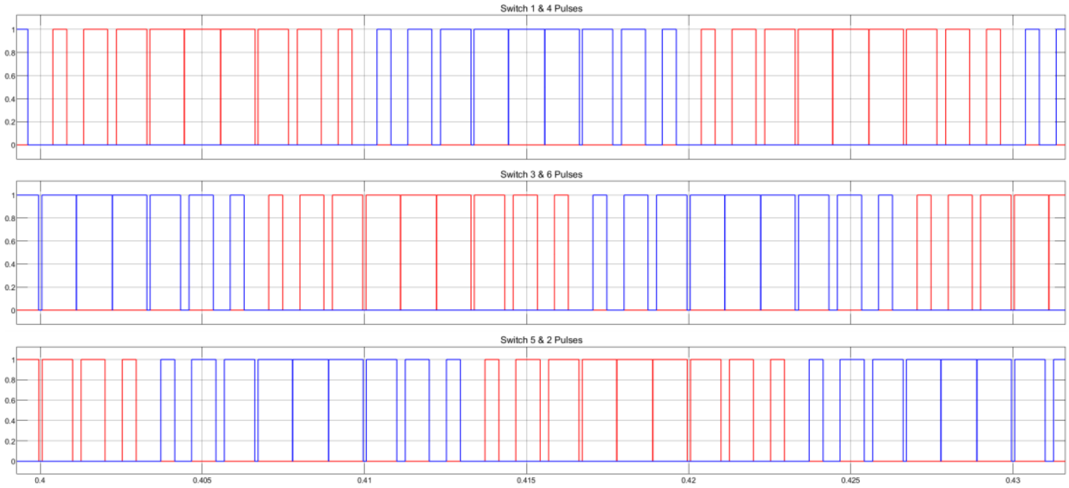


Fig.5(c) Generation of 6-switch pulses for V/f control by ISCPWM

VI. Results and Comparison

A. Flux, Speed and Torque response of the Motor with ISCPWM control.

The Flux, torque and speed response is shown in Fig. 6(a).
Flux Ripple: 0.09 Wb, Average Flux: 0.7 Wb, Torque ripples are around 9.9 Nm.
The motor speed stabilizes at 1385 rpm, in around 0.65 seconds.

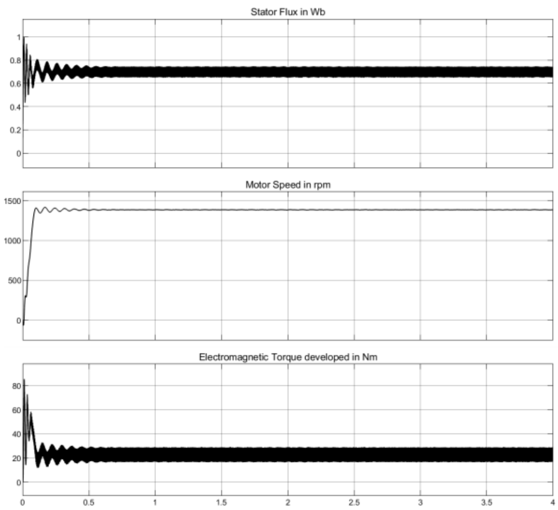


Fig.6(a) Motor Parameters

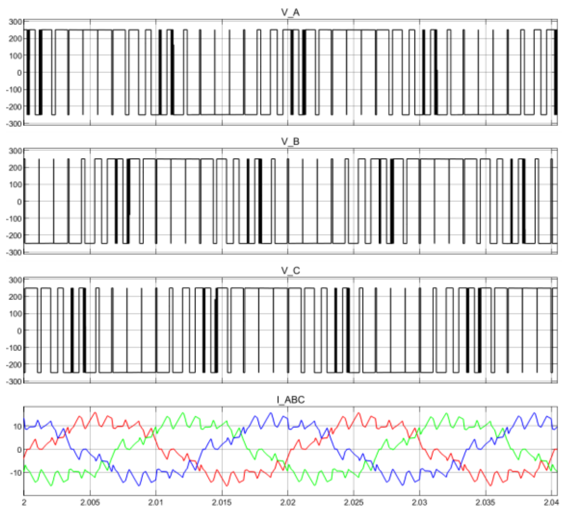


Fig.6(b) Inverter output voltage & Motor Current

B. Inverter output voltages and motor currents

The inverter output voltage and motor current are shown in Fig.6(b).

C. THD

Frequency of harmonics generated by carrier based PWM technique in 3-phase inverters are given by,

$$(M*fc + N*f) \qquad \ldots(7)$$

Here, M and N are integers and (M + N) is an odd integer.
Fig. 6(c) shows current harmonics of induction motor fed ISCPWM. Overall current THD (total harmonic distortion is 22.57% of fundamental current of 12.28 A. 5th, 17th, 19th are dominant harmonics in decreasing order of their magnitude. THD of inverter output voltage is 112.11 % in which 15th, 21st, 17th and 19th are major harmonics in decreasing order as they are side bands of 18th (m_f=18) as per equation 7.

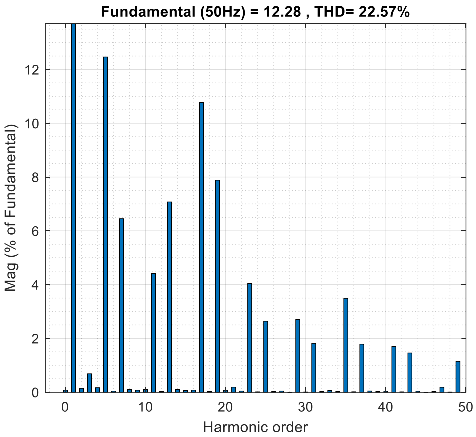


Fig.6(c) Harmonic for motor current

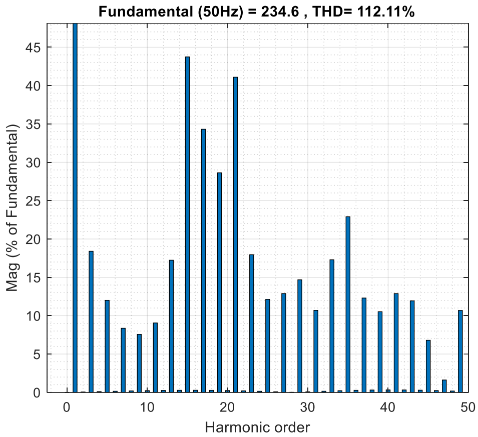


Fig.6(d) Harmonic for Inverter Voltage

D. Comparison with conventional sine PWM technique

Fig. 7 shows the comparison of the motor response with conventional SPWM and ISCPWM. For comparison modulation index, carrier to modulation frequency ratio and other parameters are kept same as in Section-V. It is observed that torque and torque ripples developed by both the method is same. As the amount of voltage developed by ISCPWM is more, more flux is developed in ISCPWM control hence the speed response of the motor with ISCPWM is faster than conventional SPWM and motor operates at higher speed.

In the case of ISCPWM the motor reaches a final speed in 0.1 sec whereas with conventional SPWM motor takes 0.2 seconds to reach to final speed. The stable speed with SPWM is 1303 rpm and it is 1386 rpm with ISCPWM.

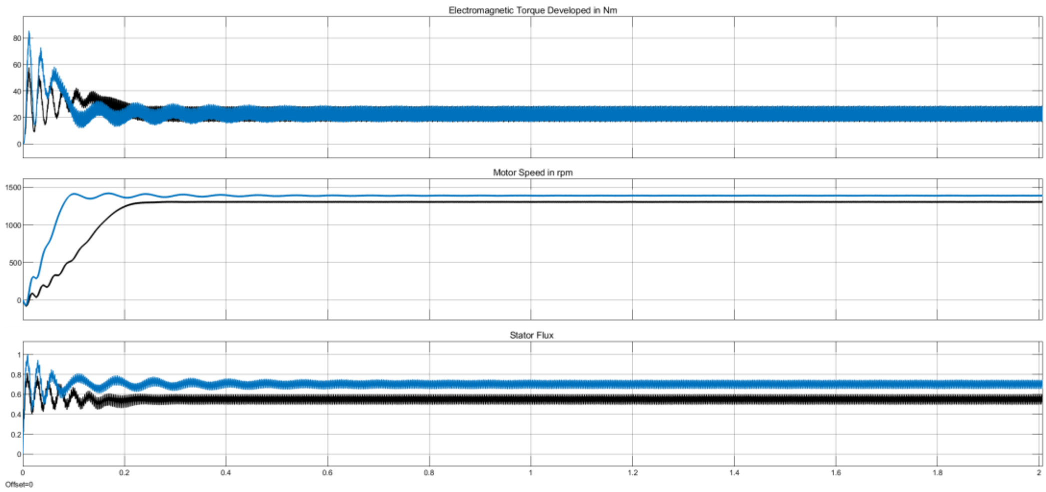
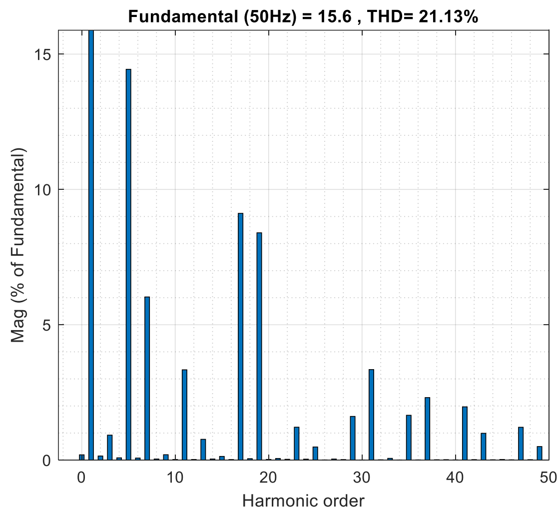


Fig.7 Comparison of Motor Response with Convention SPWM and ISCPWM control

Fig.8 (a) and (b) shows the Current and voltage harmonics with conventional SPWM. The comparison of harmonics for both the methods is given in Table.1.

Harmonic Order	Harmonic with Conventional SPWM	Harmonic with ISCPWM
Fundamental	15.6 A (THD = 21.13%)	12.28 A (THD = 22.57%)
5^{th}	14.44	12.16
7^{th}	6.03	6.42
11^{th}	3.34	4.47
13^{th}	0.37	7.10
17^{th}	9.12	10.74
19^{th}	8.40	7.77

Table-1 Comparison of Harmonics for both the methods



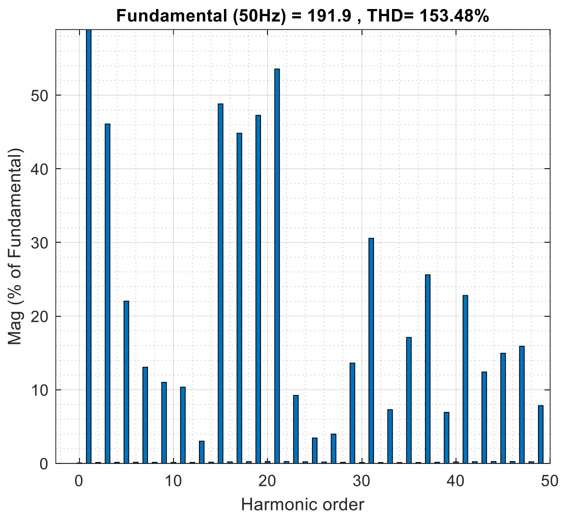


Fig.8(a) Harmonic for motor current with SPWM *Fig.8(b) Harmonic for Inverter Voltage with SPWM*

E. Power flow and Efficiency Comparison

Power	Power in Conventional SPWM (watt)	Power in ISCPWM (watt)	Efficiency in Conventional SPWM (%)	Efficiency in ISCPWM (%)
DC Input	4090	3875	78.81	84.13
Inverter Output	4050	3845		
Motor Mechanical Output	3060	3260		

Efficiency in inverter with conventional SPWM is 99.02 % and that is with ISCPWM is 99.22 %.

VII. Conclusion

The promising results of ISCPWM technique were shown in earlier literature. In this paper, this technique is used for applying *V/f* control for induction motor. By comparing the results with conventional SPWM, it is observed that ISCPWM develops more inverter output voltage for the given modulation index. This causes higher flux to develop as increase in *V* causes *V/f* ratio to increase resulting in increase in flux at given modulation index. Hence to produce given load torque, which is proportional to stator flux and current, less current is drawn by the motor. So, the losses associated with current i.e. I^2R losses in motor and slightly conduction losses in inverter, reduce to deliver same amount of mechanical output by induction motor.

Alternatively, in under modulation region the given flux, torque and speed can be developed by motor with lesser *V/f* ratio with ISCPWM technique compared to convention SPWM. Whereas in overmodulation region this technique can maintain linear relation between constant *V/f* ratio and load for modulation index greater than one, which becomes nonlinear with conventional SPWM.

The results of this method for *V/f* control in overmodulation region can be compared with triplen harmonic injection method. Also, the injection of dc bias in carrier wave during overmodulation should be studied to increase the output voltage.

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