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Harmonic Analysis of Universal Motor Supplied by Single Phase PWM Inverter-Fed Drive

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Abstract: Universal motor is a series DC motor that can be operated by both AC and DC supply. These are commonly used in small household appliances and control circuits for industrial processes. Speed of universal motor is controlled using power electronic interface such as TRIAC and variable frequency drives. Single phase PWM inverter is common technique for supply when universal motor operates on AC. Harmonics are generated due to use of power electronic circuits. These harmonics may affect performance of other components connected to supply system and should be kept below 5% as suggested by IEEE standard 519.

In this paper, harmonic analysis of single phase PWM based inverter fed universal motor is presented. SIMULINK® and SIMSCAPE® environments of MATLAB® are used as simulation platform. Experimental results are obtained for validation of simulation results. Harmonic analysis show that THD for both voltage and current are in excess of the limit set by IEE standard 519. Further it is observed that THD decreases when carrier frequency is increased for PWM of inverter.

Keywords: Universal motor; PWM inverter; Harmonic analysis; Total harmonic distortion.

1. INTRODUCTION

A series motor that can be operated with both AC and DC supplies is termed as Universal motor (Sen, 2007). It is widely used in household appliances, such as food processors, drilling machines, sewing machines, vacuum cleaners, washing machines, mixers and industrial process. Large universal motors are used for traction applications when they are operated at the range of 500 hp. Its attractive features include precise speed control, easy start, better power factor and efficiency under varying load conditions (Mirafzal, *et. al.* 2007). Universal motor is desirable where a high power to weight ratio is needed.

Speed control techniques of universal motor have remained interest area for researchers. Several PWM techniques are used to produce variable frequency and voltage source (Bodur, *et. al.* 2000). Universal motor when supplied with Variable Frequency Drives (VFD), produces harmonic distortions in the system. Harmonic distortions in motors also cause temperature rise and affects their normal operation. Significant improvements can be achieved by using PWM controlled Insulated Gate Bipolar Transistor (IGBT) convertor, which decreases RMS and peak to peak values of motor currents (Lai, 2003). Thus power losses and brush temperature are also reduced. Noise created by universal motor primarily depends on variations in electromagnetic torque developed by motor due to current feeding the machine.

Power Quality has become most serious issues in recent years, causing most industrial consumers suffer the financial losses imposed by utility regulations. It has become mandatory to observe Total Harmonic Distortions (THD) created by consumer appliances to ensure quality power to other consumers (Halepoto *et. al.* 2016). Common problems resulting from harmonics include interference with communication lines, insulation degradation, heating of winding, excessive currents, increased power losses and reduction of equipment life. VFDs use switching power electronic converters and therefore will contribute to increased harmonics in system (Sahito *et. al.* 2015). Low cost energy efficient VFDs are the interest area for semiconductor suppliers and design engineers.

According to IEEE Std 519, THD for both voltage and current must be below 5% (Sahito *et. al.* 2015). PWM controllers reduce THD as compared to TRIAC control scheme. PWM controlled AC chopper provides most stable speed control system in universal motor, with wide speed range and better respond to sudden load changes (Wang and Walter, 2000).

In this research work harmonic analysis of universal motor supplied through single phase PWM inverter drive is presented. A simulation model is developed for harmonic analysis of universal motor when it's fed by PWM controlled single phase inverter-drive. Same work is done experimentally, by using a reference variable generator, PWM controller, single phase IGBT driver set. Harmonic analysis is done with different carrier frequencies. It is observed that simulation and experimental results are nearly similar and satisfactory. Harmonic contents are lower at higher carrier frequencies while keeping the modulation index constant.

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Section 2 contains equations related to voltage and current for universal motor. Different speed control techniques are also discussed in this section. Simulation model for Universal motor supplied by single phase inverter is described in section 3. Details of experimental setup for harmonic analysis of the system is also given in this section. Section 4 contains simulation and experimental results for harmonic analysis, Results are compared and discussed. Finally paper is concluded in section 5.

2. SPEED CONTROL OF UNIVERSAL MOTOR

Single phase AC current is most common to use as supply to universal motors (Mirafzal *et. al.* 2007). (Fig. 1) shows circuit diagram of universal motor. Voltages for field and armature are given in Eq. (1)

$$\begin{bmatrix} V_f \\ V_a \end{bmatrix} = \begin{bmatrix} R_f + L_f P & 0 \\ -M_\omega & R_a + L_a P \end{bmatrix} \begin{bmatrix} i_f \\ i_a \end{bmatrix} \quad \textbf{(1)}$$

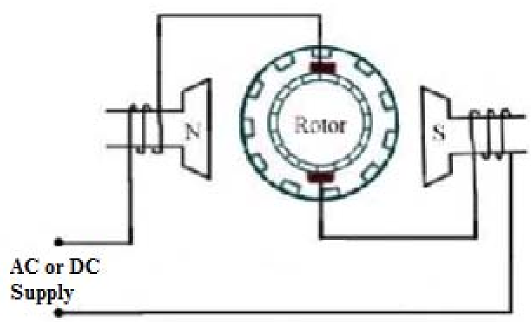

Fig. 1. Universal motor

Where the field and armature currents are related by Eq. (2)

$$\begin{bmatrix} i_f \\ i_a \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \end{bmatrix} [i(t)] \quad \textbf{(2)}$$

The voltage across the winding are related by

$$V(t) = [1 \quad 1] \begin{bmatrix} V_f \\ V_a \end{bmatrix} \quad \textbf{(3)}$$

By using eqs. (2) and (3) voltage equation can be rewritten as

$$V(t) = [R \quad L\,P \quad -M\omega]\; i(t) \quad \textbf{(4)}$$

Where

$$R = R_a + R_f \quad \textbf{(5)}$$

$$L = L_a + L_f \quad \textbf{(6)}$$

Phase angle control drive and AC chopper are widely used for the speed control of universal motor.Value of the voltage applied to the motor can changed by varying the phase angle of that applied voltage by using Phase angle control technique (Lai, 2003). TRIAC is used in phase angle control drive as shownin (Fig. 2)

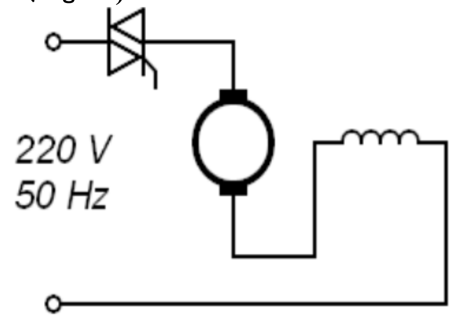

Fig. 2. Speed control of motor using TRIAC

In the chopper control application, voltage applied to the motor is adjusted by using PWM technique. Variable voltage for motor is effectively achieved by changing duty cycle of PWM signal (Barge and Jagtap, 2013). Compared to a phase-angle drive, the AC chopper drive requires a more complicated power stage with an input rectifier, a power switch and a fast power diode. Simplified chopper control technique using IGBT is shown in (**Fig. 3)**

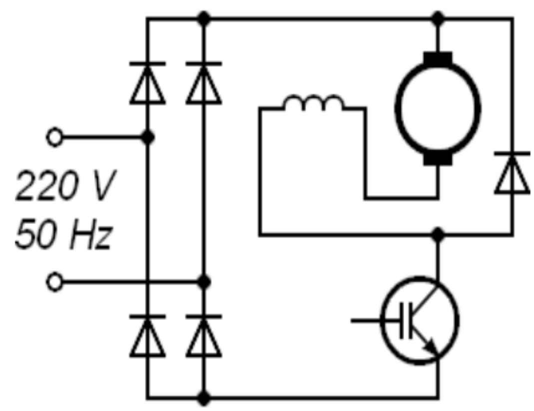

Fig. 3. Speed control of motor using chopper

Industrial applications requiring superior performance are using PWMbased VFDs. Improvement in power electronics control circuits is caused by recent developments in power semiconductor industry. Hence, different circuit configurations, namely PWM inverters have become popular. A number of PWM schemes are used to obtain variable voltage and frequency supply. The most widely used PWM scheme for voltage source inverters is sinusoidal PWM (Aboadla*et. al.* 2016).In this scheme the width of each pulse is varied in proportion to the amplitude of a sine wave evaluated at the center of same pulse. The gating signals are generated by comparing a sinusoidal reference signal with a triangular carrier wave of frequency f_c. The frequency of reference signal $f_r$determines the inverter output frequency f_o; and its peak amplitude $A_r$controls the modulation index *M*, and then in turn the RMS.

If δm is the width of the pulse, output RMS voltage V_o can be determined by:

$$V_o = \left(\sum_{m=1}^{2p} \frac{\delta m}{\pi}\right) \quad (7)$$

3. SYSTEM DESCRIPTION

Simulation model of universal motor fed by single phase PWM inverter-fed drive is shown, in (**Fig. 4**).The model consist of Simscape which creates physical systems within the simulink environment. Universal motor and its related control block diagrams are created using Simscape, whereas the single phase PWM inverter is created in Simulink. Carrier or switching frequency and Modulation index can be changed from PWM Generator. The model is analyzed using FFT tools available in MATLAB, with different switching frequencies and modulation indices.

Ideal mechanical rotational sensor is represented by ideal Rotational Motion Sensor block, which is a device to convert an across variable measured between two mechanical rotational nodes into a control signal proportional to angular velocity orangle. The ideal source of mechanical energy is represented by ideal Torque source block. Parameters to develop the simulation model of universal motor are given in the table below.

Table.1 Universal Motor Parameters

Resistance of Stator and Rotor (Ra+Rs)	90 **Ω**
Inductance of Stator and Rotor (La+Ls)	181 mh
Coefficient of Inertia (J)	2 e-4
Coefficient of Friction (B)	1 e-6

Experimental setup of harmonic analysis of universal motor when it's fed by PWM controlled single phase inverter-fed drive is shown in (**Fig. 5).**Starting from the left DC Power supply module that is required to provide DC power supply to reference variable generator for single phase PWM controller. The output voltage of reference variable generator is used as command input voltage of the single phase PWM controller. Single phase PWM controller module is used to generate gating signals of IGBT drive set module.

IGBT driver set produces AC at its output terminals from DC voltage at its input. Frequency of output voltage depends upon the frequency of command voltage and the peak value of reference signal controls the average output voltage. Power quality analyzer is used to measure THD for current and voltages, it also display harmonic orders with respect to fundamental frequency.

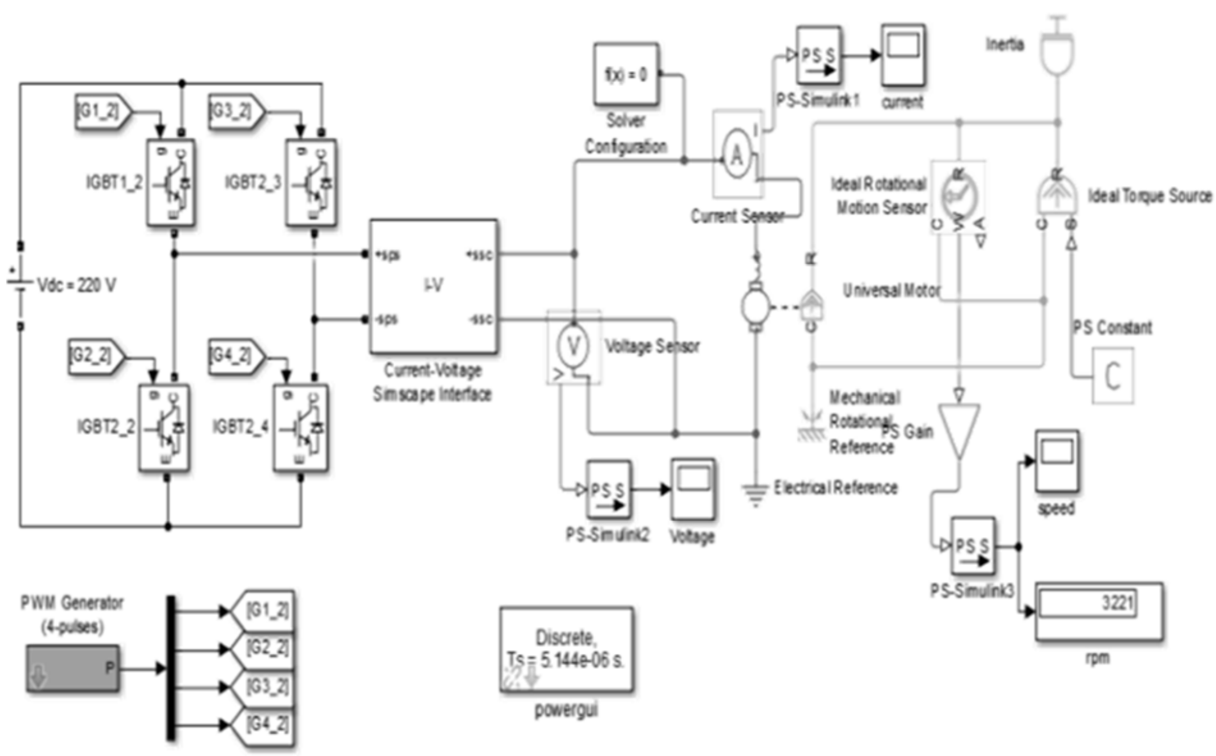

Fig. 4. Simulation model for universal motor fed by single phase PWM inverter

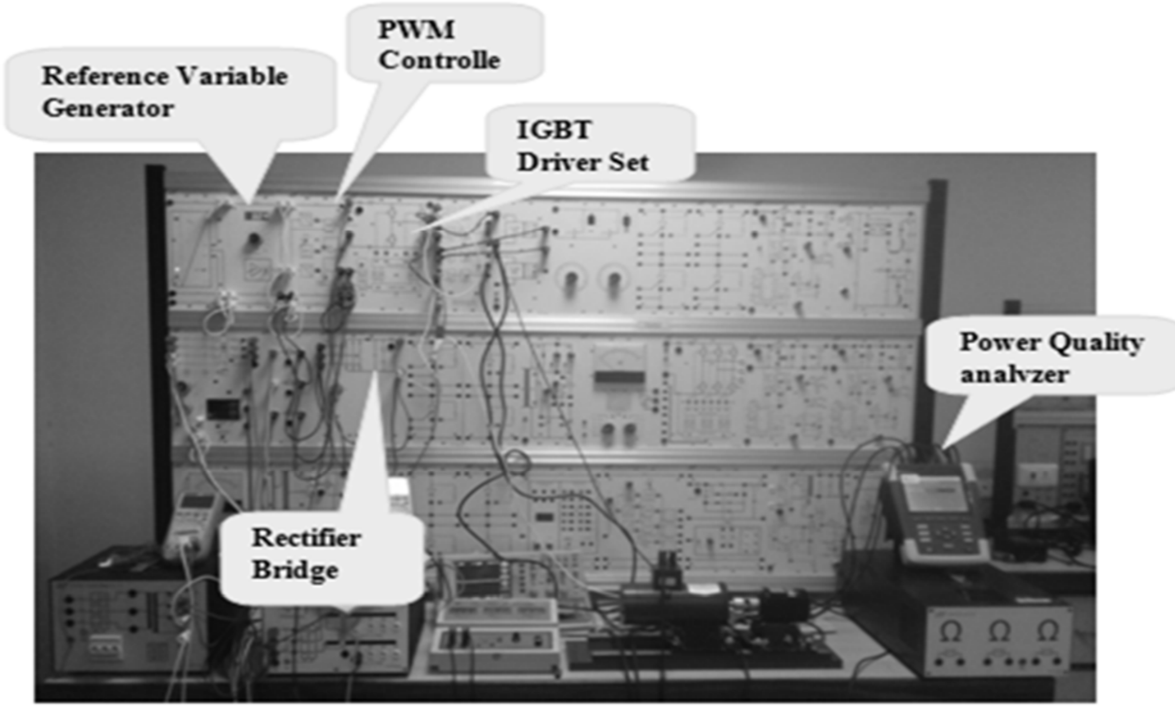

Fig. 5. Experimental setup for universal motor fed by single phase PWM inverter

4. RESULT DISCUSSIONS

Harmonic analysis of single phase PWM inverter fed universal motor is performed for different carrier frequencies. **(Fig. 6)**shows FFT analysis for current of system under discussion for carrier frequencies of 1 kHz. It shows a THD_i of 50.10%. Both even and odd harmonics are present in harmonic spectrum.

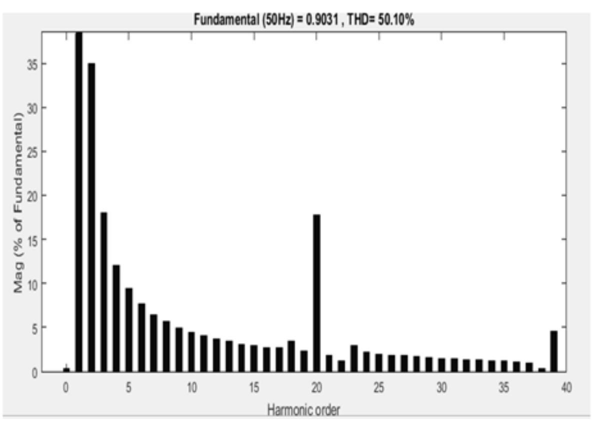

Fig. 6. Simulation harmonic spectrum of PWM based inverter fed universal motor with 1 kHz carrier frequency

(Fig. 7)shows experimental results for harmonic spectrum of system with 1 kHz carrier frequency. It shows THD_i of 50.10% which is quite acceptable considering system parameter variations with temperature, parasitic effects in motor as well as single phase PWM inverter circuit, wiring and supply voltage.

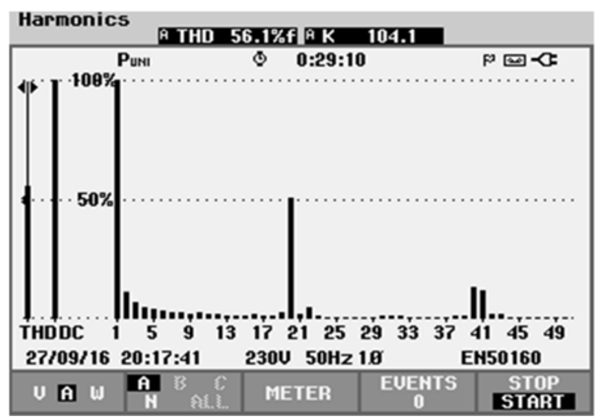

Fig. 7. Experimental harmonic spectrum of PWM based inverter fed universal motor with 1 kHz carrier frequency

(**Fig. 8)**and(**Fig. 9)**respectively show simulation and experimental harmonic analysis for current of system under discussion with carrier frequencies of 5kHz. (**Fig. 10)**and(**Fig. 11)**respectively show simulation and experimental harmonic analysis for current of system under discussion with carrier frequencies of 15 kHz. Results of THD_i for different carrier frequencies are tabulated in **(Table 2)**. Modulation index is fixed at 0.6. It is clear that increasing carrier frequency reduces THD_i. It is because of the fact that increased frequency reduces pulse duration. But this in turn will increase switching losses. (**Fig. 12)** graphically shows comparison of THD_i for three different carrier frequencies.

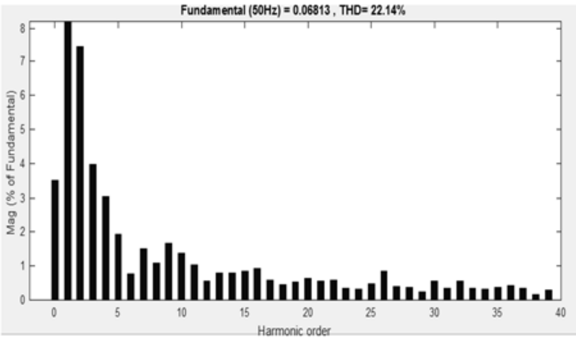

Fig. 8. Simulation harmonic spectrum of PWM based inverter fed universal motor with 5 kHz carrier frequency

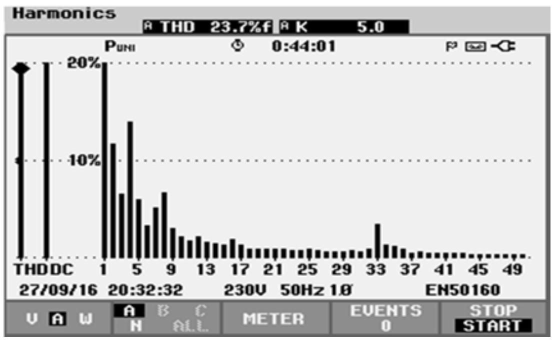

Fig. 9. Experimental harmonic spectrum of PWM based inverter fed universal motor with 5 kHz carrier frequency

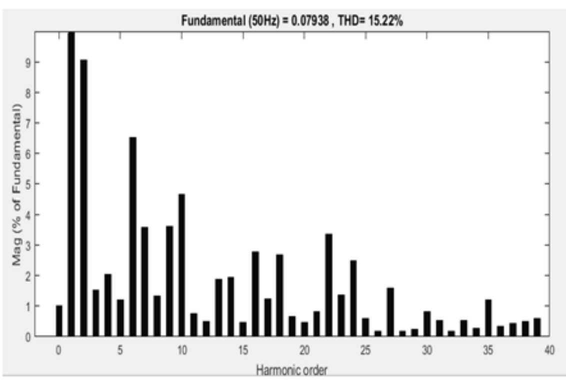

Fig. 10. Simulation harmonic spectrum of PWM based inverter fed universal motor with 15 kHz carrier frequency

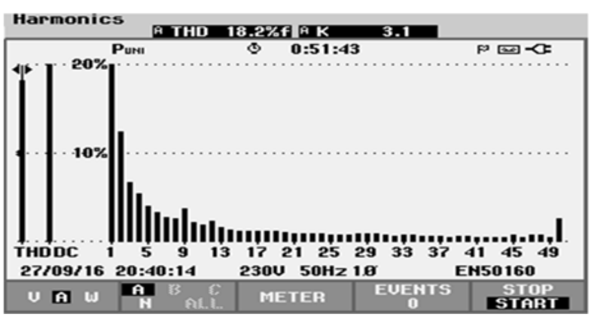

Fig. 11. Experimental harmonic spectrum of PWM based inverter fed universal motor with 15 kHz carrier frequency

Table 2. Comparison of THDi for single phase PWM inverter fed universal motor with different carrier frequencies

Carrier Frequency (kHz)	%THD$_i$	
	Simulation	Experimental
1	50.10	56.1
5	22.14	23.7
15	15.22	18.2

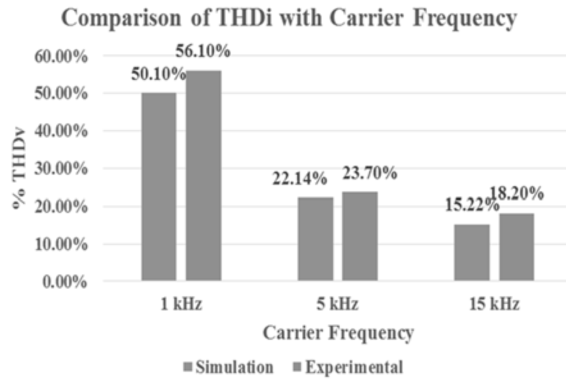

Fig. 12. Comparison of THD$_i$ with carrier frequency

Current harmonics will cause harmonics in voltage. These voltage harmonics will affect operation of other appliances connected to the supply network. THD$_v$ for three frequencies were also observed using simulation and experimental work. Comparison of THD$_v$ for different frequencies is given in **(Table 3)** and graphically shown in (**Fig. 13**).

Table 3. Comparison of THDvfor single phase PWM inverter fed universal motor with different carrier frequencies

Carrier Frequency (kHz)	%THD$_i$	
	Simulation	Experimental
1	73.42	84.5
5	38.43	45.1
15	36.86	37.8

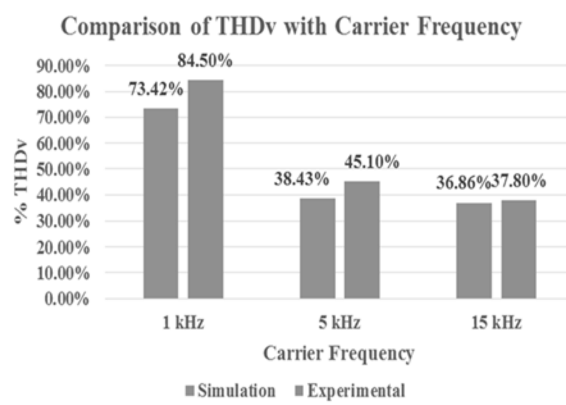

Fig. 14. Comparison of THD$_V$ with carrier frequency

5. CONCLUSION

Universal motor is commonly used home appliances and some large scale industrial applications. Its output torque is controlled through variations in supply voltage. Harmonics are generated due to power electronic control of motor. These harmonics can affect performance and life of the other consumer appliances connected to the system.

In this research work, harmonic analysis of single phase PWM based inverter fed universal motor is performed with different carrier frequencies. Simulation model is developed in MATLAB using SIMULINK and SIMSCAPE environments. Experimental setup is developed in laboratory to validate simulation results. Harmonic analysis shows that THD in both voltage and current are greater than acceptable limit of 5% as set by IEEE Standard 519. It is also concluded that THD decreases with increasing carrier frequency.

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