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Investigation on Five Phase Inverter

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Abstract
In this paper, Sinusoidal Pulse width modulation (SINE-PWM) and Space Vector Pulse width modulation (SVPWM) techniques are implemented in the five phase inverter. Space vector modulation is realized using min-max method. Both SINE-PWM and SVPWM techniques are tested in simulation and hardware set-up. Results are obtained satisfactorily and it confirms the features of both PWM techniques.

Keywords: *Five phase inverter, SINE-PWM, SVPWM*

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INTRODUCTION

Induction machines are the work horse of the industry. In the present scenario, five-phase machines are popular in comparison with the conventional three-phase one. Multiphase drives are possessing low torque ripple, reduces harmonic content and reduction in current rating of the inverter leg.

Preliminary investigation of an inverter fed five phase induction motor was initiated by Ward. E. E and Harer H. in 1969[1]. Levi. E *et al.* reviewed the various aspects of multiphase induction motor drives. Despite the mass production of three phase motors with low cost, there has been an upsurge of interest in multiphase machines due to the following principal reasons[2].

1. Improvement in efficiency due to the lower harmonic content in the field produced by multiphase machines.
2. Greater fault tolerance in the absence of one, two or three phases of supply.
3. Less susceptible than their three phase counterparts to time harmonic components in the excitation waveform.
4. Elaborate flux and torque control with reduced torque ripple due to the availability of 32 space voltage vectors instead of eight vectors in three phase inverter fed induction motor drives[3].

Hamid A. Toliyat implemented an indirect field oriented control including hysteresis type pulse width modulated current regulator. Also the author described the fault tolerant analysis of five phase drive with the loss of one, two or even three legs of inverter[4]. C´esar Cataldo Scharlau *et al.* implemented a modified open loop V/f control method with the improvement in iron utilization and higher output torque through the imposition of an appropriate combination of the third harmonic and fundamental stator voltages[5]. Libo Zheng *et al.* proposed a dual plane vector control of a five phase induction machine for the achievement of better iron utilization and higher torque density without the increase in size of the inverter[6]. Martin Jones *et al.* developed modified current control scheme for multiphase drives experimentally, which provides the operating ability with a perfect sinusoidal and balanced system of five phase currents[7]. Libo Zheng *et al.* proposed a novel Direct Torque Control scheme for a Sensor less five-phase Induction Motor Drive which eliminates low harmonic currents with the full utilization of DC voltage[8].

K. N. Pavithran *et al.* studied the five phase inverter fed five phase induction motor and fabricated five phase induction motor for conducting research experiments. The authors established the satisfactory operation of five phase drive when fed from pulse width- modulated inverter[9].

G.K. Singh investigated the technical economic viability of using a number of phases higher than three in induction motor. The author highlighted the advantages of five phase induction motor and its applications such as in nuclear power plants[10].

Atif Iqbal accomplished flexible modeling and independent control of multi-phase multi machines fed from a single VSI. The model developed by the author is very flexible so that any control strategies can be implemented[11]. Optimum performance achievement of five phase induction motor for weak and remote grid system was presented by Shaikh Moinoddin *et al.*[12].

M. Rizwan Khan and Atif Iqbal designed an improved estimator for rotor position/speed of a vector controlled five phase induction motor drive[13]. M. Rizwan Khan *et al.* implemented Model Reference Adaptive System (MRAS)-based sensor less control of vector controlled five phase induction machine with current control in the stationary reference frame. The experimental results obtained by the authors are identical with that of three phase induction machines[14].

Ned Mohan *et al.* proposed a simple Space Vector Pulse width modulation (SVPWM) Algorithm for VSI-fed AC Motor Drives[15]. The authors explained Space Vector PWM control of voltage source inverter and implemented using classical carrier-based approach. The space vector PWM is explained without use of any additional definitions such as sector calculation, hexagon of states and vector decomposition. In continuation of this SVPWM is implemented by using the above mentioned algorithm in five-phase inverter.

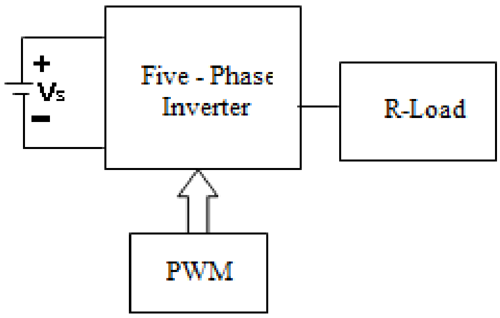

Fig. 1: *Block Diagram for Five-Phase Inverter with R-Load.*

Five-Phase Inverter

The block diagram of five-phase inverter is shown in Figure 1. Here, five phase inverter is controlled by PWM techniques. Circuit diagram for five phase inverter with resistive load is shown in Figure 2. The five-phase inverter legs a, b, c, d, e are having one upper and one bottom switch. The switch status is S_a, S_b, S_c, S_d, S_e. If S_a is ‘1’ means it represents upper switch, if it is ‘0’ means it represents bottom switch. Output phase voltage waveform for five phase inverter under 180° mode of operation is shown in Figure 3. It clearly indicates the phase shift between each phase is 72°.

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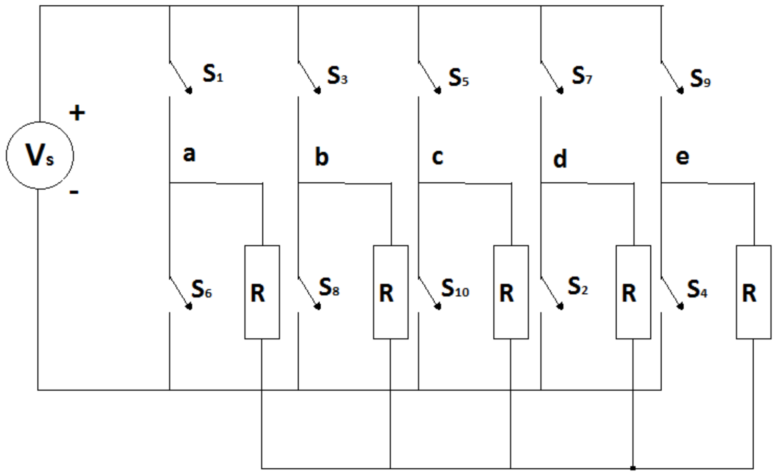


Fig. 2: *Circuit Diagram of Five-Phase Voltage Source Inverter.*

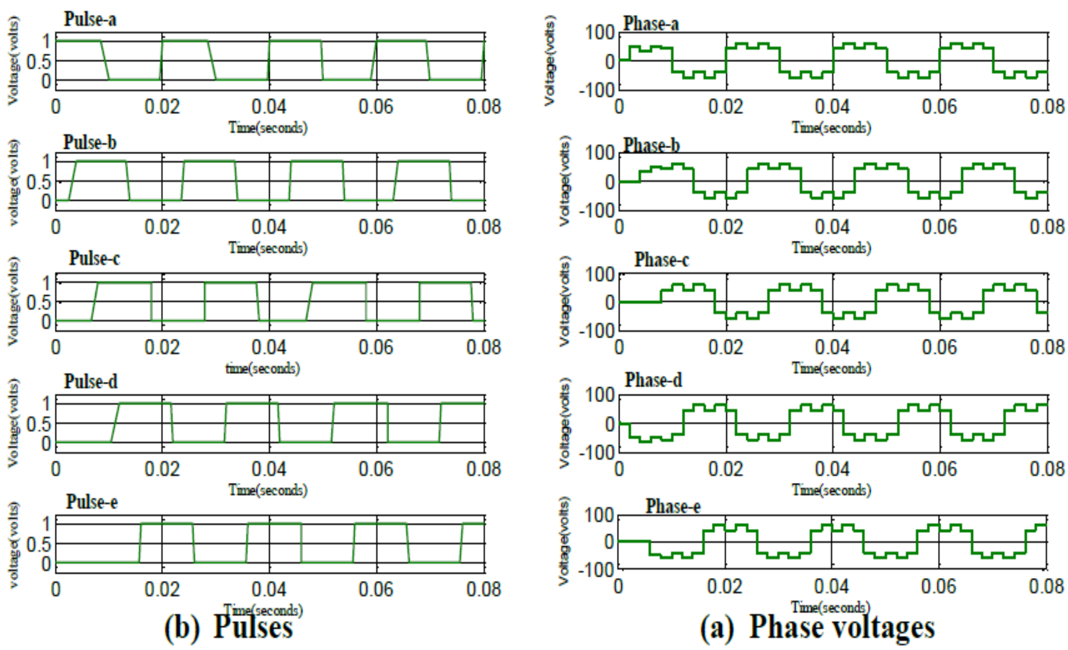


Fig. 3: *180° Mode Operation.*

From the Figure 3, it is confirmed that peak value of the phase voltage is 60 V and the phase voltages are balanced.

Space Vector Pulse Width Modulation (SVPWM)

Space Vector Pulse Width Modulation (SVPWM) is one of the preferred real time modulation techniques and is widely used for digital control of Voltage Source Inverters. The SVPWM operates on the principle of 'Volt-second balance' which states that, product of voltage and second for the positive half cycle should be equal to the product of voltage and second for the negative half cycle. By simple digital calculation of the switching time one can easily implement the SVPWM scheme. Space vector diagram for five phase inverter is shown in Figure 4. It consists of 2^5 states.

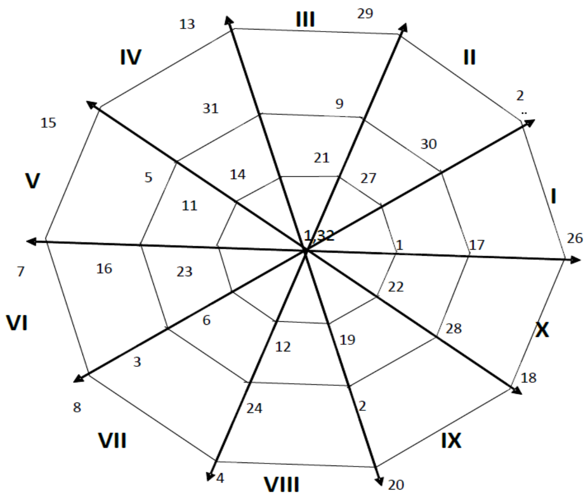


Fig. 4: *Space Vector diagram for Five-Phase Inverter.*

In order to avoid the sector identification, the SVPWM is implemented by using Min-Max method. The main advantages of Min-Max method are Implementation of SVPWM without using Space vectors.

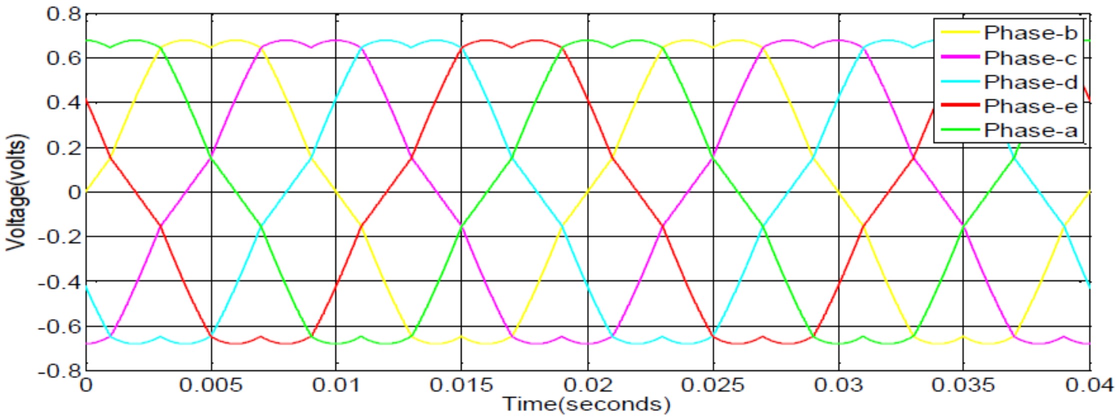


Fig. 5: *Waveform of Five-Phase Supply for Min-Max Method of SVPWM.*

In SVPWM each reference voltages are obtained from comparison of SINE wave and a triangular carrier. Common mode voltage is added in order to achieve maximum conceivable peak amplitude of the fundamental phase voltage[15] with the reference phase voltage,

$V_{offset} = -(V_{max} + V_{min})/2$ Eq. (1)

Where,

V_{offset} = Common mode voltage

V_{max} = maximum magnitude of the three sampled reference phase voltages

V_{min} = minimum magnitude of the three sampled reference phase voltages

The equation is based on the reference phase which has lowest magnitude (min-phase) crosses the triangular carrier first and cause the first transition in the inverter switching state. Once the first-cross and fifth crossed are determined, the offset voltage is calculated from the equation mentioned above. The time instants at which the three reference phases cross the triangular are determined.

Sinusoidal Pulse Width Modulation (SINE-PWM)

SINE-PWM is one of the conventional control techniques for inverter. In this SINE-PWM, SINE wave is compared with a carrier triangular wave which will generate the PWM pulses for the inverter devices. SINE-PWM pulses can be varied by changing the modulation index value. In SINE-PWM there is no need for sector calculation, hexagon states and vector decomposition. This is a simplest PWM technique.

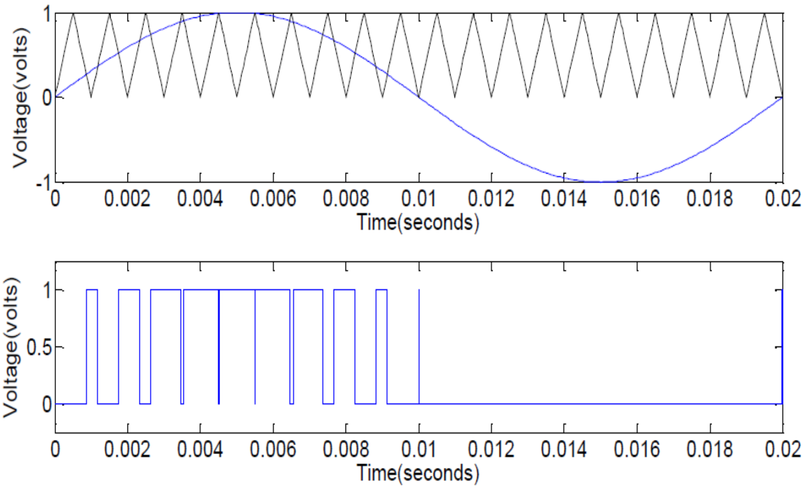


Fig.5: *SINE-PWM.*

RESULTS

In order to compare SINE-PWM and SVPWM in five-phase inverter with resistive load, simulation and experimental study are completed with the specification mentioned in Table 1. Simulation is done using MATLAB (Matrix Laboratory) [13].

Table 1: *Specification of Five-Phase Inverter.*

S.No	Parameters	Values
1	Switching Frequency (fs)	1 kHz
2	Device	MOSFET
3	PWM Technique	SINE-PWM
		SVPWM
4	Resistance	150 Ω
5	Input dc voltage(v)	100 V

Simulation

Simulation results of SVPWM and SINE-PWM are shown in Figure 5 and Figure 6. Total harmonic distortion (THD) for the modulation techniques are presented in Figure 7.

From the Figure 5, it is seen that the peak value of the phase voltage is 80 V and the phase voltages are balanced. The pulse pattern and the corresponding phase voltages for SINE-PWM, for the switching frequency, f_s = 1 kHz are shown in Figure 6.

From this Figure it is inferred that, the peak value of the phase voltage is 66 V and the phase voltages are balanced.

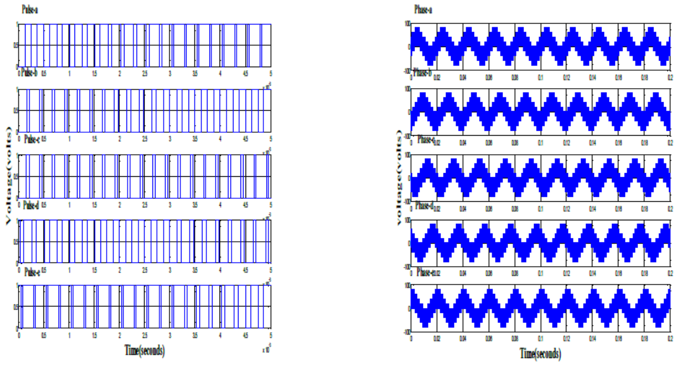
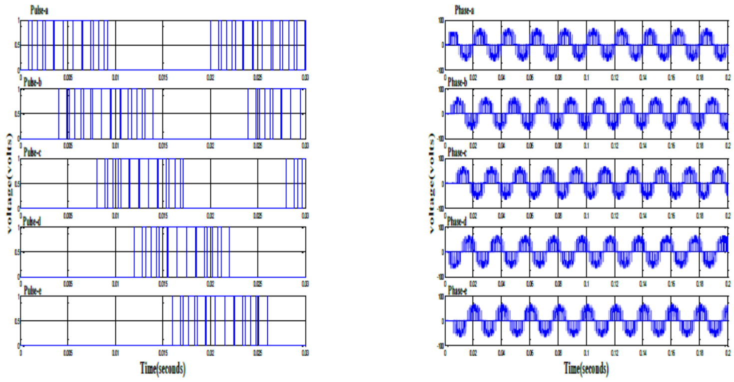


Fig. 5: *Simulation Results for Phase Voltages of SVPWM Inverter.*



(a) Pulses **(b) Phase voltages**

Fig. 6: *Simulation Results for Phase Voltages of SINE-PWM Inverter.*

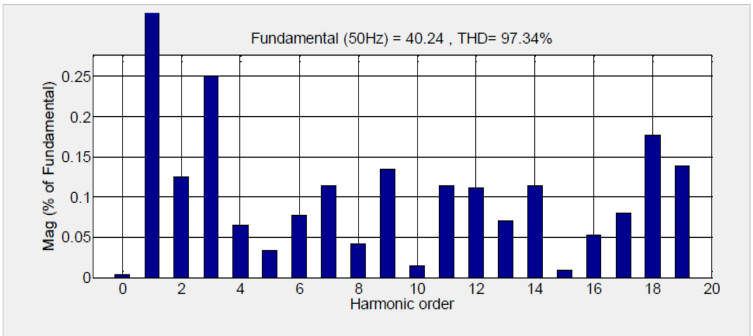


Fig. 7(a): *THD for SVPWM.*

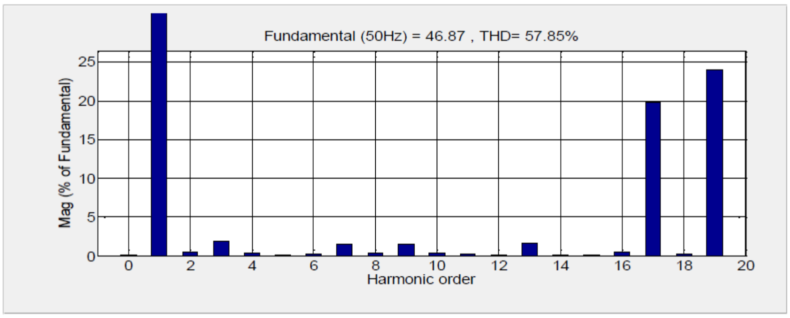


Fig. 7(b): *THD for SINE-PWM.*

Comparison of SINE-PWM and SVPWM for five-phase inverter with R-load is completed based on the THD values in the output voltage of inverter with R-load. From the THD graph 7, it can be concluded that SINE-PWM will produces less amount of harmonics in comparison with SVPWM. This is due to the maintenance of half wave symmetry in SINE-PWM in comparison with SVPWM.

Hardware Implementation

The experimental setup for Five-phase inverter with R-load is shown in Figure 8. 100 V DC supply is given to the Five-phase inverter with R-Load of 100 Ω. Here for different modulation index the phase and were varied with SINE-PWM & SVPWM and THD value obtained using YOKOGAWA-WT 180. For increase in modulation index the output voltage value will increase.

The hardware results of SVPWM phase and line voltages for different modulation index and the PWM pulses for each device are completed and Figure 9–26 represents the results for modulation index 0.7.

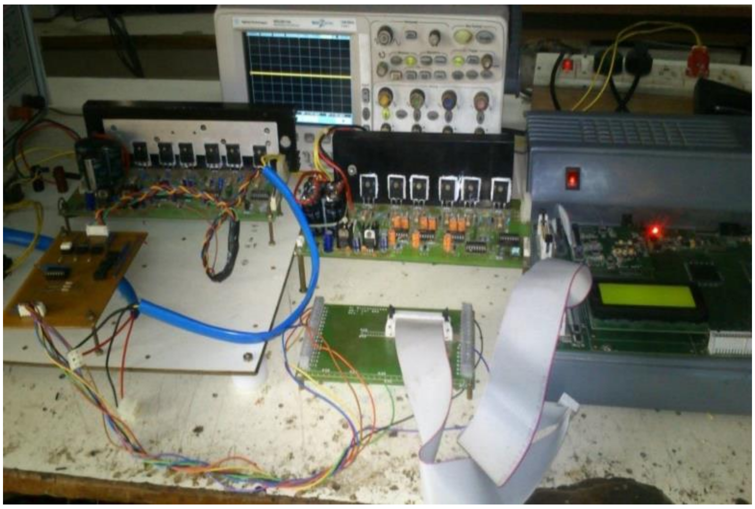


Fig. 8: *Five-Phase Inverter with Resistive Load Hardware Setup.*

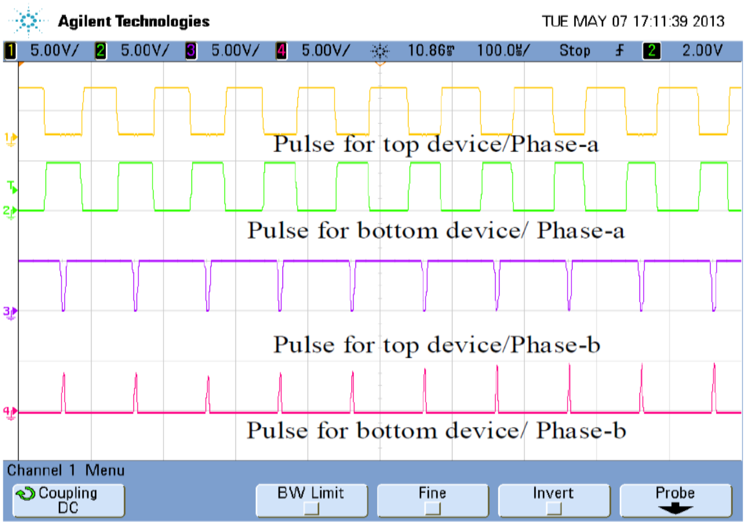


Fig. 9: *Hardware Results of Pulses for a-Phase and b-Phase.*

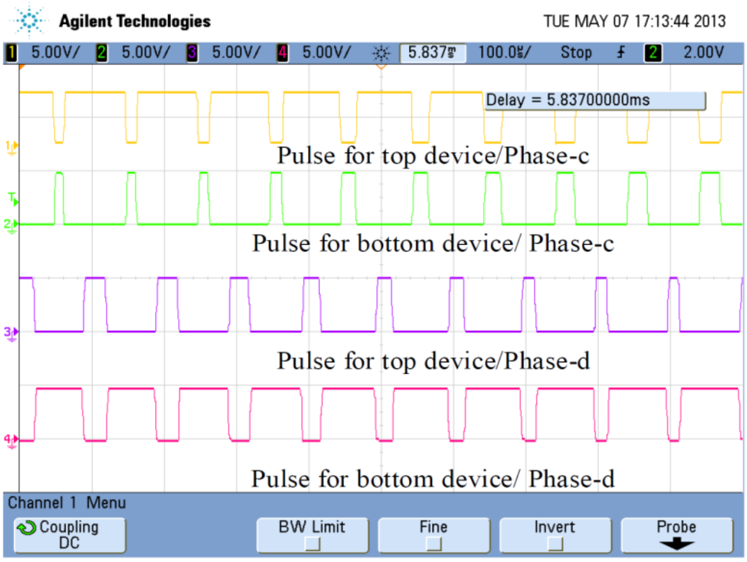


Fig. 10: *Hardware Results of Pulses for c-Phase and d-Phase.*

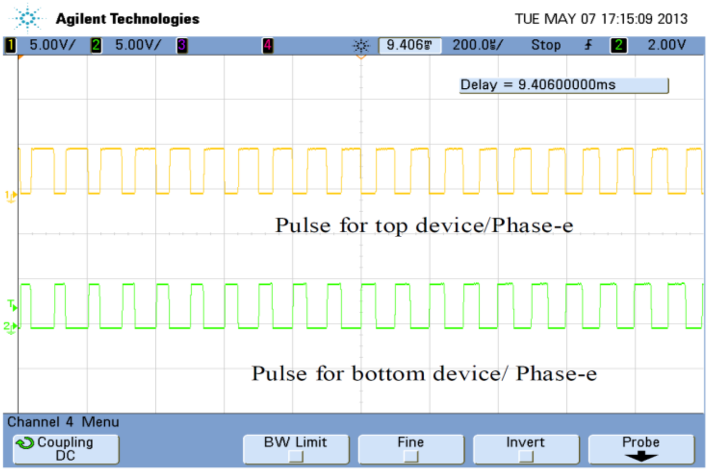


Fig. 11: *Hardware Results of Pulses for e-Phase.*

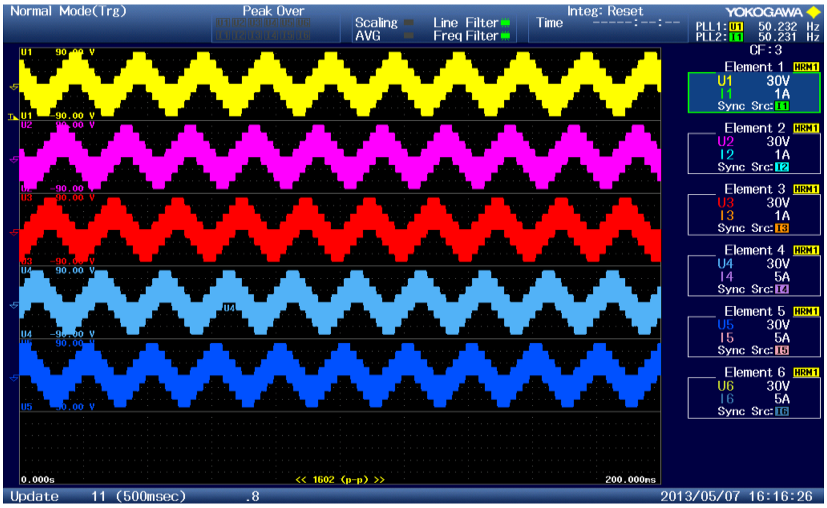


Fig. 12: *Hardware Result of Phase Voltages Waveform of SVPWM.*

From the Figure 12, it is seen that all the phase voltages are balanced and having peak voltage of 53V.

Fig. 13: *Voltage and Current Values for Each Phases of SVPWM.*

From the figure 13, it is confirmed that, Root mean Square (RMS) value of the phase voltages are same for all the phases. The Peak voltage for all the phases is unbalanced in hardware results, because the device drop for each device is different i.e., device mismatch.

Fig. 14: *THD Values for a-Phase of SVPWM.*

From the Figure14 THD value of Phase voltage is obtained as 38.914%.

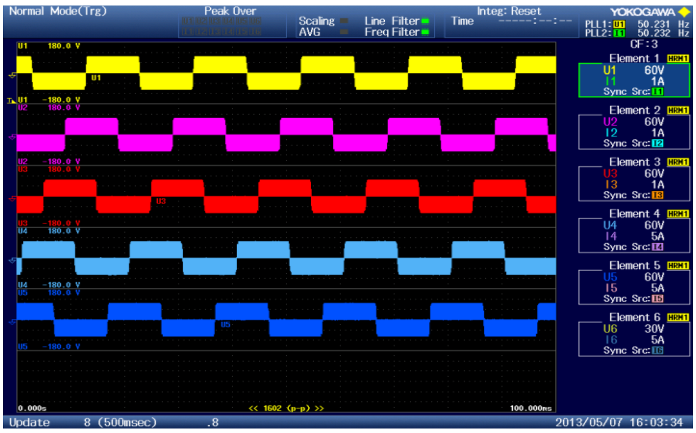


Fig. 15: *Line Voltages Waveform of SVPWM.*

Figure 15 shows that, the line voltages are balanced and its peak voltage is 71 V.

Fig. 16: *Voltage and Current Values for SVPWM for M=0.*

From the Figure 16, it is found that the RMS value of the line voltage, 50.270 V. The Peak voltage for all the line voltages is unbalanced in hardware results which is due to the difference in the device drop for each device.

Fig. 10: *THD Values for Line Voltage of SVPWM for M=0.7.*

Figure 17 shows the THD value of Phase voltage with SVPWM is 50.103%. Hardware results of SINE-PWM phase and line voltages for different modulation index and the PWM pulses for each device are shown in Figure18–26.

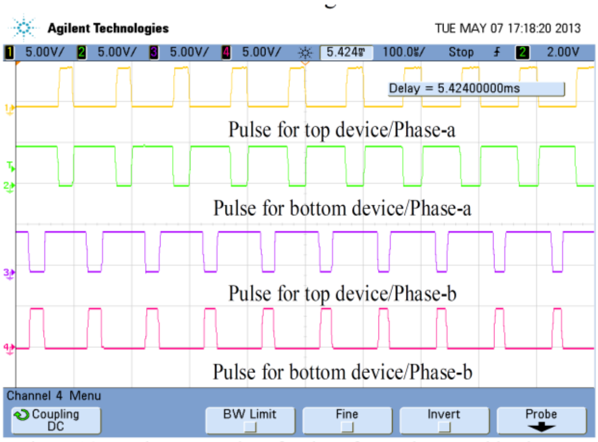


Fig. 18: *Hardware Results of Pulses for a-Phase and b-Phase.*

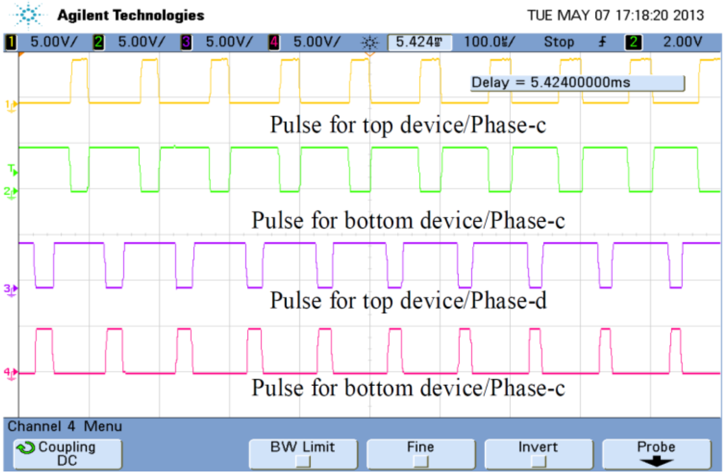


Fig. 19: *Hardware Results of Pulses for c-Phase and d-Phase.*

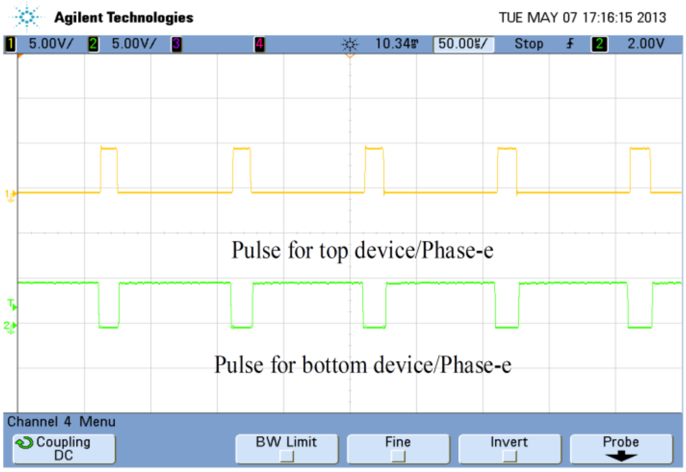


Fig. 20: *Hardware Results of Pulses for e-Phase.*

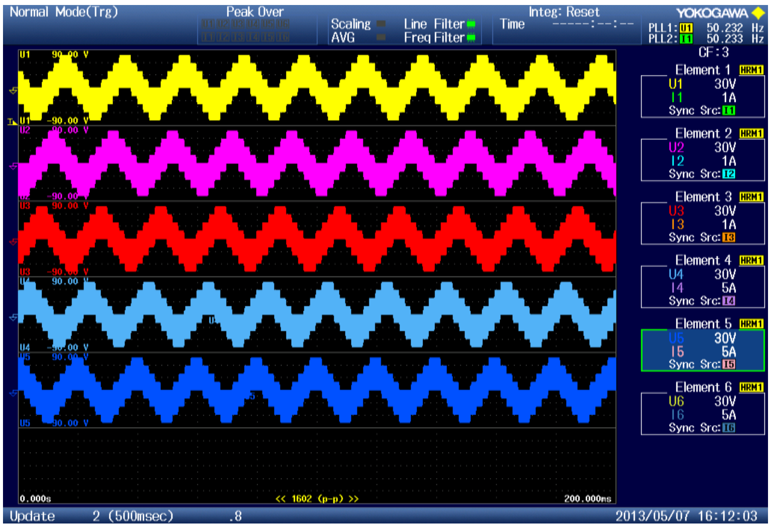


Fig. 21: *Phase Voltages Waveform with SINE-PWM.*

Fig. 22: *Voltage and Current Values for SINE-PWM.*

Fig. 23: *THD Values for Phase-a of SINE-PWM for M=0.7.*

Figure 24 reveals that the RMS value of the phase voltages are same for all the phases. The Peak voltage for all the phases is unbalanced in hardware results and it is due to the mismatch in the device drop. THD value of Phase voltage is 37.595% in Figure 25.

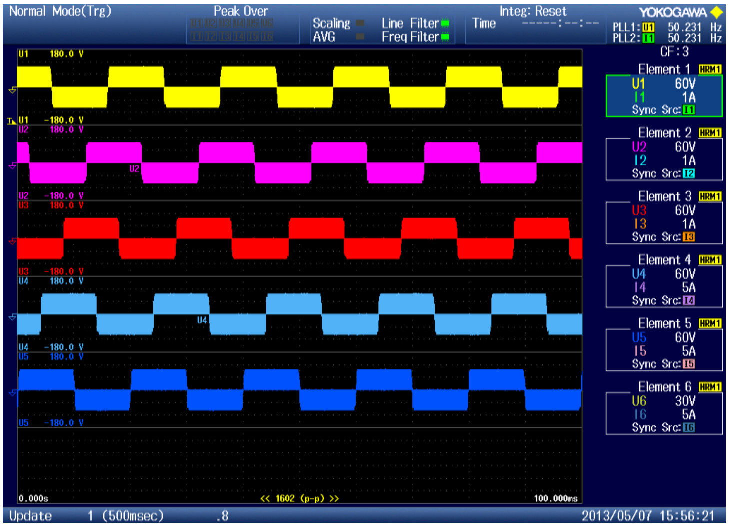


Fig. 24: *Line Voltages Waveform of Sine-PWM.*

Fig. 25: *Voltage and Current Values for Sine-PWM.*

Fig. 26: *THD Values for Line Voltage of Sine-PWM.*

From the Figure 26, THD value of Phase voltage is found to be 47.082%. Table 2 shows the comparison between SINE-PWM and SVPWM. From the table, it can be confirmed that, SINE-PWM performs better than SVPWM due to the maintenance in symmetry.

Table 2: *THD Comparison of SINE-PWM and SVPWM.*

Modulation Index, M	0.5	0.7	0.8
SVPWM	49.382	38.914	39.773
SINE-PWM	29.126	37.595	39.19

CONCLUSION

This paper has explained the five-phase inverter operation for both r-load with 180° mode of operation, SINE-PWM, and SVPWM. Basic operation of five-phase inverter is theoretically studied and simulated. Further, performance of SINE-PWM and SVPWM are compared in simulation and hardware for five-phase inverter with r-load. From the results, it can be concluded that THD for SINE-PWM is lesser in comparison with SVPWM. Investigation of five phase inverter fed induction machine is in progress.

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