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# A New Five Leg Vsi to Control Special Machine Using Dual Level Hysteresis Current Control

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***Abstract*—A five leg inverter (FLI) control is incorporated to drive two independent rated permanent magnet synchronous motors (PMSMs) for automotive applications. Also in these cases one leg of inverter is common to both the motors. The expanded two arm modulation (ETAM) has been engaged in FLI. This makes the FLI drives to use the dc link in efficient way, which is due to the fact that conventional ETAM works with voltage reference. This paper modifies the ETAM in an ingenious way to improve voltage utilization factor(VUF) further through current reference (HCC). In addition, the developed current reference expanded two arm modulation minimizes the current harmonics and torque ripple as well. The simulations are conducted in MATLAB-Simulink software. Based on the simulation results, a practical system is designed and implemented that is explained in the paper.**

***Keywords- PMSM, hysteresis current control, five-leg VSI, SVPWM, HCC, DHCC,VUF,ETAM, CRETAM***

## I. INTRODUCTION

The goal of this paper is to design and implement a novel drive system of a permanent magnet synchronous machine (PMSM). A dual-level hysteresis current control is proposed for the five-leg drive system. Two same three-phase permanent-magnet synchronous machines are controlled by one five-leg voltage source- inverter. To overcome the coupling of the two PMSMs, the master-slave selection principle is introduced. Phase-switch-states of four individual phases are directly assigned to the four individual legs. Dual-level hysteresis current control is evaluated.On the other hand, many reduced-switch-count VSI topologies have been proposed and the fault-tolerant operation of normal VSI topologies. The reduced-switch-count VSI topologies, the five-leg VSI especially attracts more attentions since it can replace two three-leg VSIs in many industrial applications. The typical application is that five-leg VSI is used to control two three-phase machines. This topology is called as the five-leg drive system in this paper. A new PWM method was proposed for the five-leg drive system. It enables an arbitrary distribution of the available dc bus voltage between two machines. It is also found that the five-leg drive system with the new PWM method is especially suitable for two motor constant power applications. The process of DHCC does not requires any machine parameters and hence it increases the system robustness.

In this paper, a dual-level HCC (DHCC) is proposed for the five-leg VSI to control two permanent-magnet synchronous machines (PMSMs). This paper is organized as follows. The five-leg drive system is defined in Section II. The standard HCC (SHCC) for the three-leg drive system is presented in Section III. Current reference expanded two arm modulation(CRETAM) for the five-leg drive system is proposed in Section IV. The effectiveness of DHCC is verified by experiments in Section V. Finally, some conclusions are drawn in Section VI using hardware results.

## II. FIVE LEG DRIVE SYSTEM POWER CIRCUIT

The power circuit of FLI which consists of five legs, each leg consists of pair of power switching device (MOSFET) with anti-parallel diode. The third (C) phases of both the motor switch connected to one common leg where other two phases of them are attached with separate set of arms[1].

The switching function and the restriction condition can be described by the following equation.

Switch on: Sma = 1

Switch off: Sma = 0 Restricted Function= Sm1+Sm2 = 1

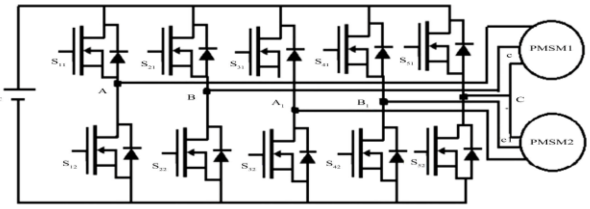

Figure 1. Five leg drive system

Where m ε {1, 2, 3, 4, and 5} is the number of legs and a ε {1,2} is the number of arms.

It is worth noting that even though the FLI is an integrated drive for double PMSM arrangement, it is always possible to control the motors independently with different set points, speed control schemes, dynamic performance requirements, frames of control schemer etc.

Usually when two motors are driven with two individual three-leg inverters, there are twelve power switching devices are needed. A two motor drive supplied using the FLI topology offers a saving of two switches. The size, gate drive requirement and control complexity of the inverter are therefore reduced. All of these features lead to a potential reduction in capital cost when compared with standard dual three phase inverter approach. Driving two motors independently, the amplitude of the peak current flow in common leg can be up to twice of others, hence its design must be taken care of appropriate rating. This makes the drive to lose its modularity in terms leg interchange ability.

## III. EXISTING STANDARD HYSTERESIS CURRENT CONTROL TECHNIQUE

The proposed DHCC is developed on the basis of SHCC. To implement SHCC, two phase currents iA1 and iB1 are necessary while the mechanical rotor position θm1 is also required. As shown in Fig.2, the SHCC-based controller outputs the three-phase switching vector kABC1 to control the three-leg VSI. The mechanical rotor position θm1 is obtained by the position sensor and the electrical rotor position θe1 can be calculated by

$$\theta_{e1} = P_n \theta_{m1} \qquad (1)$$

where Pn is the pole pairs of the PMSM.

The mechanical rotational speed ωm1 can be calculated by θm1. Then, ωm1 is compared with the reference mechanical rotational speed ωm_ref and one PI regulator is utilized to acquire the q-axis reference current iq1_ref. In this paper, the d axis reference current id1_ref is set as 0, which is usually called as id=0 control. According to Park transformation and θe1, id1_ref and iq1_ref are transformed to the reference phase current vector iABC1_ref, iABC1_ref=[iA1_ref, iB1_ref, iC1_ref]. iA1_ref, iB1_ref and iC1_ref are reference currents of Phase-A1, Phase-B1 and Phase C1 respectively.

$$\begin{bmatrix} i_{\mathrm{A1\_ref}} \\ i_{\mathrm{B1\_ref}} \\ i_{\mathrm{C1\_ref}} \end{bmatrix} = \begin{bmatrix} \cos\theta_{\mathrm{e1}} & \sin(-\theta_{\mathrm{e1}}) \\ \cos(\theta_{\mathrm{e1}} - 120^\circ) & \sin(120^\circ - \theta_{\mathrm{e1}}) \\ \cos(\theta_{\mathrm{e1}} - 240^\circ) & \sin(240^\circ - \theta_{\mathrm{e1}}) \end{bmatrix} \begin{bmatrix} i_{\mathrm{d1\_ref}} \\ i_{\mathrm{q1\_ref}} \end{bmatrix} \qquad (2)$$

Based on iA1 and iB1, the third phase current iC1 can be calculated by

$$i_{\mathrm{C1}} = -(i_{\mathrm{A1}} + i_{\mathrm{B1}}) \qquad (3)$$

The three measured phase currents iA1, iB1 and iC1 are briefly named as the measured phase current vector iABC1. iABC1_ref and iABC1 are compared by a hysteresis comparator to obtain kABC1, kABC1=[kA1, kB1, kC1]. kA1, kB1 and kC1 are switch states of Phase-A1, Phase-B1 and Phase-C1 respectively, which are denoted as phase-switch-states. The comparison principle is given as

$$k_p = \begin{cases} 1, \Delta i_p > H \\ 0, \Delta i_p < -H \end{cases} \qquad (4)$$

where Δip is the phase current error between the reference phase current and the corresponding measured phase current, Δip=ip_ref-ip, p=A1, B1, C1; H is the hysteresis-band width, H≥0. The nature of SHCC is to limit the phase current error Δip between –H and +H. If Δip is not out of the value range (-H, H), the corresponding phase-switch-state kp will keep unchanged.

Because the phase number and the leg number are the same, kA1, kB1 and kC1 can be directly assigned to leg-1, leg-2 and leg-3 respectively, that is, s1=kA1, s2=kB1 and s3=kC1. s1, s2 and s3 are leg-switch-states of leg-1, leg-2 and leg-3 respectively

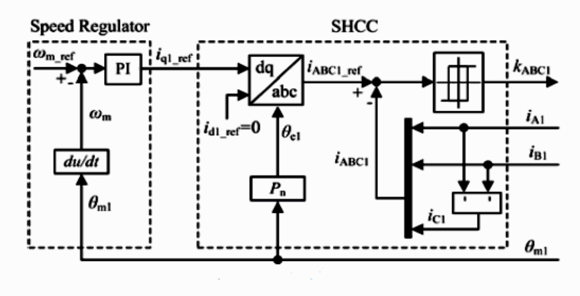

Figure 2. Structure of SHCC Based Controller

## IV. CONFIGURATION OF INDEPENDENT VECTOR CONTROL OF AN INTEGRATED DRIVE

The configuration of independent vector control scheme of an integrated dual PMSM under CRETAM technique is shown in Figure 3. It is very common to assume in this kind of system that ids = 0, which keeps linearity between motor torque and current. The main traction motor and auxiliary compressor motor share the common fifth leg.

Two speed controllers are employed both of which are PI types. The speed controller generates torque producing current component iqs, which in turn is transformed into a, b, c frame, for the purpose of reference current generation.

It is seen from the above figure that both main and auxiliary PMSMs generate independent reference current signal. For CRETAM, current control current error is necessary, which is the difference of reference and sensed current. The current error which is generated by the difference of reference and sensed current is compared with triangular waveform and necessary switch in the leg is made to be turned on or off. By properly selecting hysteresis band, the hysteresis control can also be employed in the above scheme. At the driving two motors independently, the amplitude of the peak current flow in common leg is up to twice as others, so it is necessary to equip the power switching devices of common leg to double the capacity compared to others.

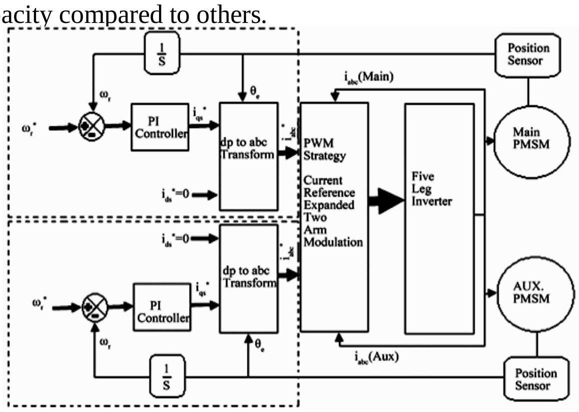

Figure 3. Independent vector control of main and auxiliary PMSMs under CRETAM technique

### A. *Dual-level hysteresis current control*

DHCC includes two levels: machine-level and system-level. In machine level, the control method just focuses on each machine. Generally, the machine level control is just SHCC for the three-leg drive system[3]. In system-level, the five-leg topology is taken into account. Besides, the torque calculator is used to respectively generate the reference q-axis current iq1_ref for PMSM-1and iq2_ref for PMSM-2[2]. The structure of the torque calculator depends on the specific operation mode. There are two main operation modes: independent mode and coupling mode. In the independent mode, two electrical machines are controlled independently, and they have different speed regulators and torque commands. In the coupling mode, two electrical machines are coupled together, and they share one speed regulator and same torque command. The structures of the torque calculator used for the independent mode and the coupling mode are illustrated.

In Fig .4 iA1, iB1, iA2 and iB2 are measured currents of Phase-A1, Phase-B1, Phase-A2 and Phase-B2 respectively; θm1 and θm2 are mechanical rotor positions of PMSM-1 and PMSM-2 respectively; kABC1 and kABC2 are three-phase switching vectors of PMSM-1 and PMSM-2respectively, kABC1=[kA1, kB1, kC1], kABC2=[kA2, kB2, kC2]; kA1, kB1, kC1, kA2, kB2 and kC2 are phase-switch-states of Phase-A1, Phase-B1, Phase- C1, Phase-A2, Phase-B2 and Phase-C2 respectively; VSI is the five-leg switching vector, sVSI=[s1, s2, s3, s4, s5]; s1, s2, s3, s4 and s5 are leg-switch-states of leg-1, leg-2, leg-3, leg-4 and leg-5 respectively.

### B. Existing problem

Because Phase-A1, Phase-B1, Phase-A2 and Phase-B2 are directly connected to leg-1, leg-2, leg-5 and leg-4 respectively, kA1, kB1, kA2 and kB2 can be directly assigned to leg-1, leg-2, leg-5 and leg-4 respectively, that is

$$\begin{cases} s_1 = k_{A1} \\ s_2 = k_{B1} \\ s_5 = k_{A2} \\ s_4 = k_{B2} \end{cases}$$

However, leg-3 is shared by both Phase-C1 and Phase-C2, which means both kC1 and kC2 only can be implemented by leg-3. If kC1 is equal to kC2, both kC1 and kC2 can be easily implemented by setting s3 as kC1 or kC2. However, kC1 may be different from kC2, which brings an implementation trouble since s3 only can have one value during one switching period. The task of the system-level control is to determine the final value of s3 if kC1 is different from kC2.

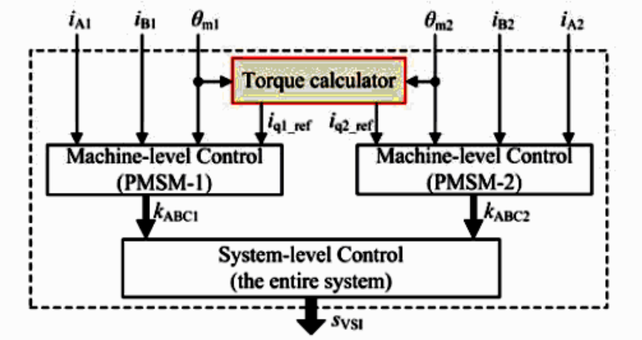

Figure 4. Main Structure of DHCC

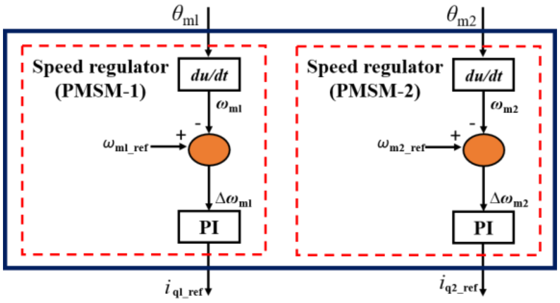

Figure 5. Structure of torque calculator for independent mode in DHCC

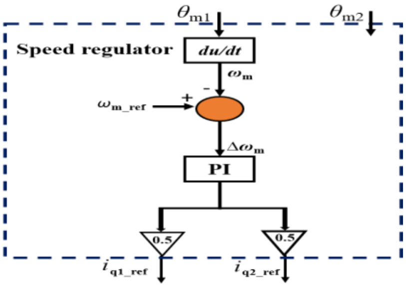

Figure 6. Structure of torque calculator for coupling mode in DHCC

### C. Master-slave selection principle

To determine the value of s3, the master-slave selection principle is proposed. According to the master-slave selection principle, two coupling phases (Phase-C1 and Phase-C2) can be divided into one master coupling phase and one slave coupling phase, and the value of s3 is determined by the master coupling phase. Correspondingly, the phase-switch state of the master coupling phase is directly assigned to leg-3. In FC1 and FC2, one coupling phase is free while another one is un free. Since the un free coupling phase has the priority to determine the value of s3 and there is only one un free coupling phase in these two freedom combinations, the un free coupling phase is selected as the master coupling phase. In FC3, both Phase-C1 and Phase-C2 are un free. In other words, each coupling phase expects their phase-switch-state to be implemented by leg-3, which makes the determination of the master phase difficult. To find the master phase, the importance of the phase-switch-state for each coupling phase is evaluated. If |ΔiC1| is greater than |ΔiC2|, kC1 should be implemented firstly since the phase current error of Phase-C1 is larger, and vice versa. This strategy will be helpful to reduce the maximum phase current error of the total system. In FC4, both Phase-C1 and Phase-C2 are free. Because there is no un free coupling phase, the master coupling phase also cannot be easily determined. Although both |ΔiC1| and |ΔiC2| are not greater than H, the phase current error is still used to determine the master coupling phase, that is, the coupling phase with larger absolute value of the phase current error is selected as the master coupling phase. The purpose of this solution is to determine the master coupling phase instead of reducing the system maximum phase current error. Obviously, the unfree coupling phase has greater phase current error than the free coupling phase. That is to say, the determination process of the master coupling phase in FC1 and FC2 is similar to that in FC3 and FC4. Therefore, determination process of the master coupling phase can be simply summarized as: the coupling phase with larger absolute value of the phase current error is the master coupling phase, no matter in which freedom combination.

## V. SIMULATION PROCESS

In this paper the configuration of independent vector control of main PMSM and auxiliary PMSM are simulated using the Matlab/Simulink/Sim Power system environment. The simulation is carried out such that parameter of main PMSM (PMSM_01) and auxiliary PMSM (PMSM_02) is same as shown in Table I.

The PMSM_01 and PMSM_02 are set to run at 50% of rated speed (1500 rpm) and 25% of rated speed (750 rpm) respectively, with load torque of half the rated load 0.4 Nm and full load (0.8 Nm) respectively.

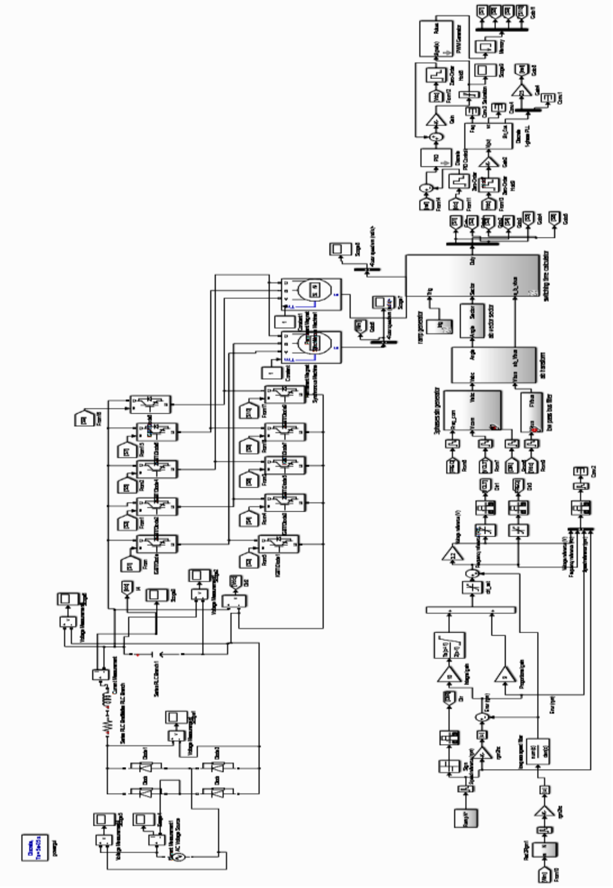

Figure 7. Simulation diagram of FLI in Two PMSMs

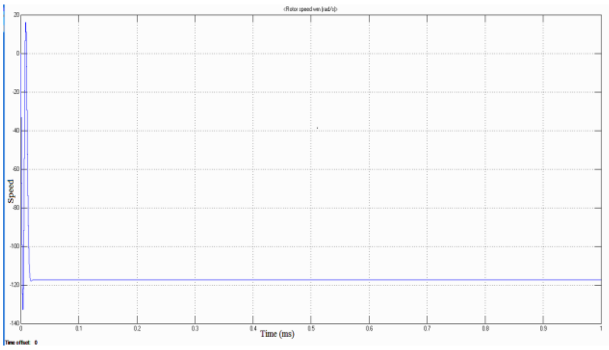

Figure 8. Output speed response of PMSM_01 SVPWM

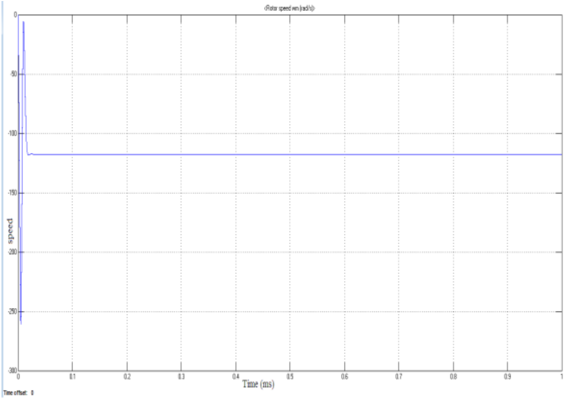

Figure 9. Output speed response of PMSM_02 SVPWM

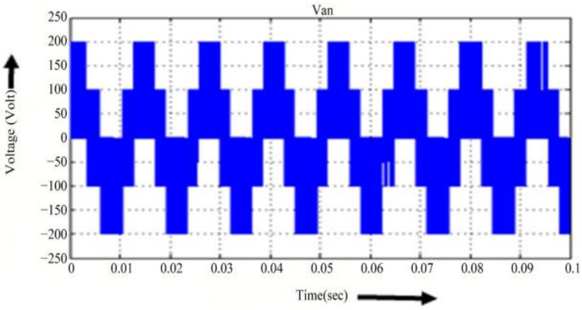

Figure 10. Simulation result of phase voltage of Main PMSM FLI SVPWM

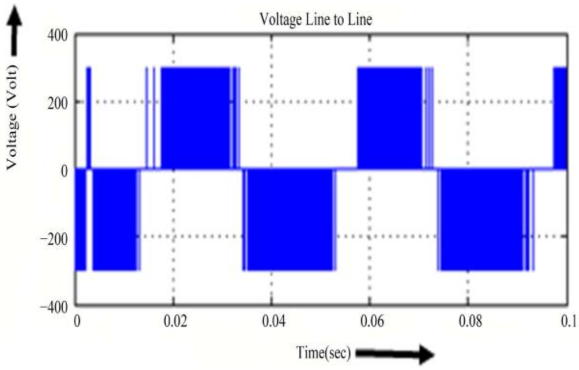

Figure 11. Simulation result of phase voltage of PMSM Auxiliary PMSM FLI SVPWM

Figure 12. Input voltage of the line

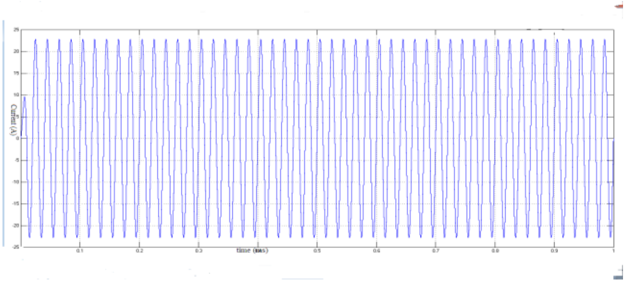

Figure 13. Input current of the line

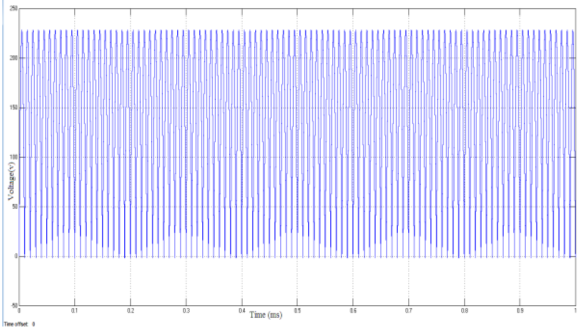

Figure 14. Rectified voltage

TABLE I. SIMULATION RESULT

| SL.NO | RATINGS | VALUES | UNITS |
|---|---|---|---|
| *1.* | INPUT VOLTAGE | 230 | Volts |
| *2.* | INPUT CURRENT | 23.96 | Ampere |
| *3.* | RECTIFIED VOLTAGE | 230.12 | Volts |
| *4.* | CAPACITOR VOLTAGE | 156.231 | Volts |
| *5.* | SPEED OF LOAD 1(PMSM) | 117.836 | Rpm |
| *6.* | SSIMULATIONRESULTSPEED OF LOAD 2(PMSM) | 117.837 | Rpm |

## VI. HARDWARE PROCESS

### *A. Functional block diagram*

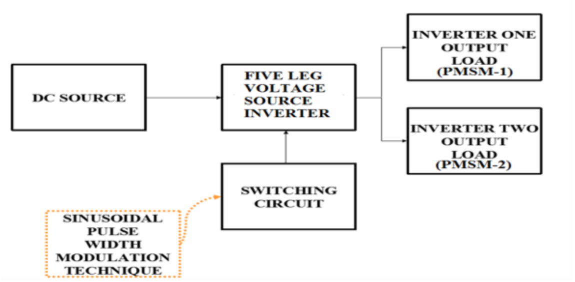

Figure 15. Block diagram of Five Leg Inverter in Two PMSMs

The above block diagram explains about the function of a dual level five leg inverter to control two PMSMs. A dual level five leg inverter illustrates that two PMSM is connected through five leg i.e, ten switches. But in current scenario the working of two motor uses six leg i.e, twelve switches. The two PMSM is connected to five leg inverter by taking one phase in common to two motor. The input supply is given through 12-0-12 volts 1amps transformer. The input voltage given is 230 V and input current of 26.8 amps. The input voltage is rectified through bridge rectifier where the voltage is rectified to 230 V. Bridge rectifier supplies the switching circuit. The pulses to the switching circuit is given through driver circuit. Driver circuit controls the switching pulse through PIC microcontroller. The switching sequence is already programmed to the PIC microcontroller. Here PIC microcontroller is programmed with three switching sequences as S1, S2, S3. The load PMSM is connected to the switching circuit. With the selection of corresponding switching sequence the motor runs. It is observed experimentally that both the motor runs at same speed of 117 rpm using five leg inverter.

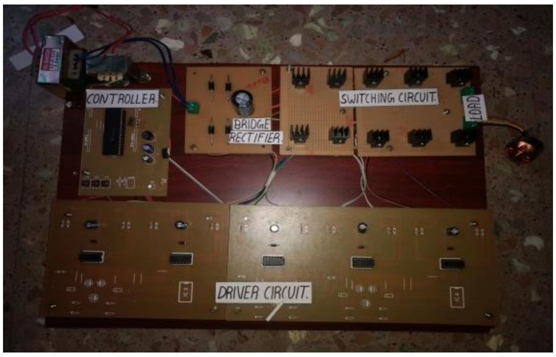

Figure 16. Working model of DHCC five leg inverter

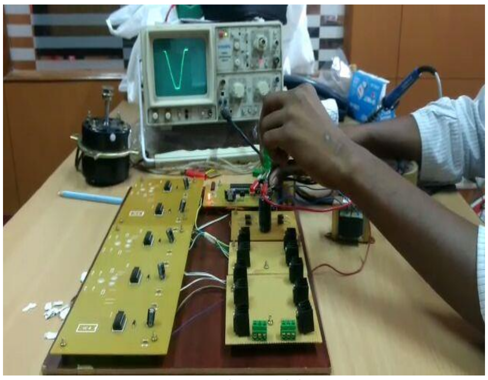

Figure 17. Output waveform of five leg inverter

TABLE II. HARDWARE RESULT

| SL.NO | RATINGS | VALUES | UNITS |
|---|---|---|---|
| 1. | INPUT VOLTAGE | 230 | Volts |
| 2. | INPUT CURRENT | 24 | Ampere |
| 3. | TRANSFORMER-1 OUTPUT VOLTAGE | 24 | Volts |
| 4. | TRANSFORMER-1 OUTPUT VOLTAGE | 12 | Volts |
| 5. | RECTIFIED VOLTAGE | 24 | Volts |
| 6. | SPEED OF LOAD 1(PMSM) | 117.836 | Rpm |
| 7. | SPEED OF LOAD 2(PMSM) | 117.837 | Rpm |

## VII. CONCLUSION

A novel independent vector control of an integrated PMSM drive is proposed which can be extended to automotive application to control main traction PMSM and auxiliary HVAC compressor PMSM. The control algorithm for driving two Three phase PMSMs is achieved. A modified PWM method for FLI i.e. CRETAM technique has been adopted and tested in MATLAB/simulink. The simulation result reveals that, main and auxiliary PMSM motors can be independently controlled with different speed and torque commands even though the parameters for main and traction motor are different and it also clarifies the adopting of ETAM technique for independent control of traction and HVAC drive suffers from poor voltage utilization, increased THD and objectionable torque ripple.

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