# Development of New Modulation Technique to Combined Drive for Dual PMSMs applicable in automotive application

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## Abstract

A new modulation technique is incorporated to the five leg inverter to drive dual permanent magnet synchronous motors (PMSMs) applicable to automotive applications which are rated independently. The conventional modulation technique for five leg inverter (FLI) results reduced voltage utilization factor (VUF), current harmonics and torque ripple etc. From the literature, many modulation techniques has been trained for FLI employed for controlling five phase motors/dual motor. One leg of inverter is reduced and it is connected common to both the motors. The Expanded two arm modulation (ETAM) and space vector modulation (SVPWM) has been generally engrossed in FLI. However still the performance enhancement is required in FLI. This paper revises the ETAM in an imaginative way to improve the performance such as current harmonics, VUF, torque ripple through current reference. The current reference expanded two arm modulation (CRETAM) has been proposed as a new modulation technique to FLI. A complete results of CRETAM is presented. The MATLAB based simulation has been performed. The designed architecture has been configured to the SPARTAN-6 FPGA (XC6SLX45) device. The functionality of each block in the architecture has been simulated thoroughly using the Modelsim software.

## Keyword

EV/HEV traction drive, Five leg inverter, dual PMSM, current reference expanded two arm modulation (CRETAM), expanded two arm modulation (ETAM).

## 1.INTRODUCTION

In applications, the necessity of more than one distinct motion controls are always there. This demand is accomplished through motor than one dissimilar motors and drives. For instance, in a paper mills, separate motion controls are required for grinding the raw materials and collecting the rolled paper. For such an applications, it requires two different driver circuits to operate the motors. The cost and design of the driver circuit is complex, hence the multi-leg inverter has been proposed to drive the two motors independently. Traditionally two independent drives has been controlled by a separate three phase VSI, thus it gains independent control. Even though for an automotive applications, cost and reliability are major concerns, small size and volume, light weight and high efficiency are also equally important. A six-phase motor, integrated with two motors, has been often established to operate on the principle of indirect vector control that ensures the current control in stationary reference frame [1] – [3]. In Hybrid Electric Vehicle/Electric Vehicle (HEV/EV) applications, it often requires more than one motor control [4]. With the arrival of high-energy permanent-magnet (PM) materials such as neodymium-iron-born (Nd-Fe-B), Samarium-cobalt (Sm-Co) etc., the development of PM motor drives has created an accelerated pace in automotive industries [5]-[6]. The permanent magnet synchronous motor (PMSM) becoming more popular because of its uniqueness in improved performance. Higher efficiency, less weight, reduced acoustic noise and lower vibration are merits in PMSM motor. The majority of electric drives require more than one motor for its operation in industries such as paper mills, electric vehicles etc. The main motor to deliver the mechanical driving force to grind the raw materials and sub motor to deliver the driving force for collecting the paper. Normally the main motor is rated at a relatively high power level and mandatory to provide fast dynamic response and high efficiency. The sub motor drive is rated at a lower power level and high dynamic performance are not required.

The figure 1. Shows the modified integrated inverter called five leg inverter (FLI). The FLI has been achieved from two separate three phase Voltage source inverter with proper modification.
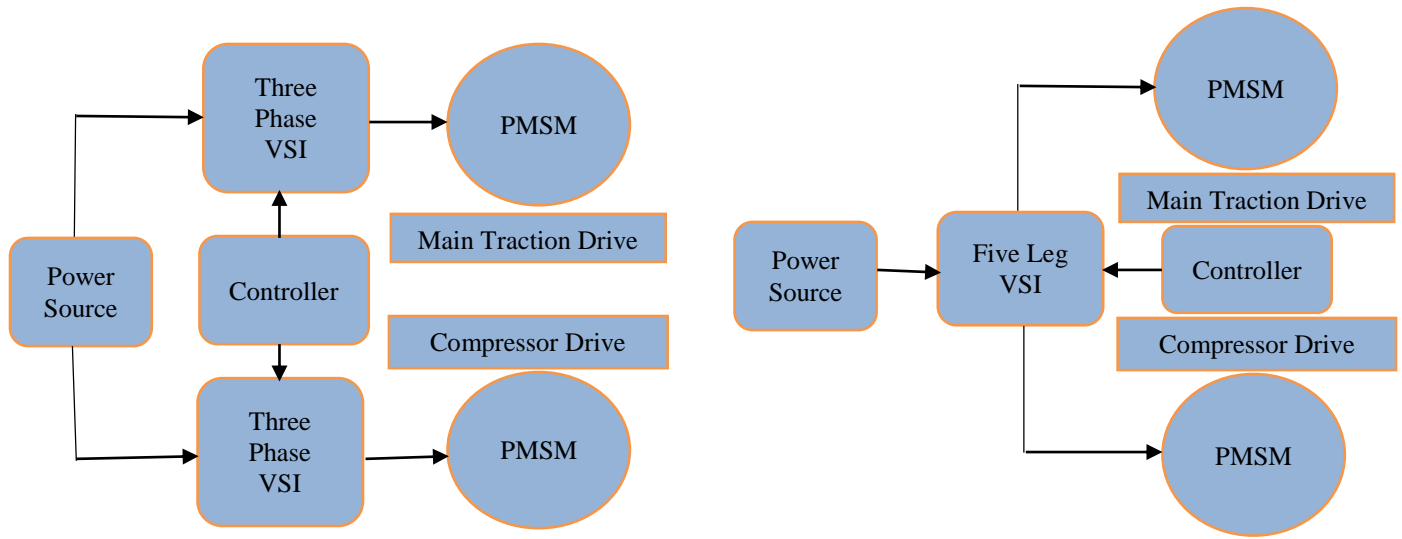
Figure 1.Two motor drives options (a) Three Leg VSI (b) FLI

A six phase inverter drive has been proposed to drive two motors which often work on the principle of indirect vector control, the current control strategy through a stationary reference frame [7]. The mathematical model of system uses set of d-q equation to ensure current control. However the proposed method increases the stator winding losses. In EV/HEV drive, it often requires more than one motor for it application. The first intention to reduce the installation cost of converter topology, minimization of semiconductor switches and the second intention to develop a suitable PWM technique for dual motor drive [8]-[9]. A (B4 topology) along with multiple current-regulated pulse width modulated(PWM)-VSI based dual motor drive has been proposed which employs eight switches to produce two sets of 3 phase and 2 phase output currents [10]. The proposed topology results reduced power semiconductor switch count, lowers switching losses, weight and cost of the drive. A revised control algorithm has been developed for multi leg converter which is utilized for balanced and unbalanced load [11]. The proposed method satisfies the load performance but fails to satisfy the inverter performance such as line current harmonics, torque ripple etc. Variety of PWM technique have been testified in the literature for FLI, they are inversion table method (IVM), Dual voltage modulation (DVM), Modulation block method(MBM) and double zero-sequence method(DZM) [12] . Among these method the DZM method provides the best modulation, and also improves the utilization factor, results satisfactory current ripple.

Further in the review, the above modulation techniques has utilized the DC bus voltage fully, but it uses many switching states. The computation of torque ripple and voltage utilization factor (VUF) has not been described in the above modulation method. Further the expanded two arm modulation control (ETAM) has been proposed. The ETAM technique utilizes the reference voltage for generation of pulses for FLI. The conventional ETAM results 50% voltage utilization when the third harmonic wave is added in the reference it improves the voltage utilization to 86.6% [13]-[14]. But addition of harmonic causes poor current harmonic outline.

The output voltages performance has been increased with increasing number of phases in VSI which results staircase waveforms with reduced THD. However more number of switches required to increase the number of phases which resulting in difficulty of implementing the algorithm. The digital signal processor (DSP) has been implemented for five leg drive is addressed in [15]. However the DSP implementation, requires larger time for execution of instruction. Hence the field programmable gate array (FPGA) is an array of programmable logic blocks uses parallel process of instruction makes the configurable architecture in efficient manner. A modulation method, which treats the VUF of two motors separately and results effective utilization of dc link voltage, has been devised when the motor is operated in constant power region [16]-[18].

The extra modified modulation technique has been reported by C.B. Jacobina et al. The developed modulation methods reduces the dc link voltage [19]. Later the PWM strategy has been addressed for two motors which are connected in wye (Y) and delta (D) arrangements. The proposed PWM strategy for motor model of YD-parallel, DD- parallel and YD-series has been reported. More recently, the FPGA processor based space vector Modulation (SVPWM) technique has been addressed for FLI to drive the five phase induction motor [20]. The closed loop integrated dual ac drive has been proposed to control two PM motors, which ensures the merit of neglecting the copper loss in the main motor drive influenced by the auxiliary motor current [21]. The references of dual motor become vectors in separate d-q planes with completely random reference, located in any of the six sectors of the planes. The zero vectors are correspondingly shared to operate in continuous modulation. Recent implementations have used the sampled amplitude of reference phase voltages to realize the simple SVPWM method [22], where the computation time has been reduced as it does not involve in any sector identification. The common mode voltage in five phase inverter drive has been reduced by realization of simple carrier based PWM (CBPWM). The proposed coupled inductor inverter (CII) which helps in reducing the common mode voltage [23].

Though the earlier schemes of FLI driven two motors control targeted the performance enhancements such as VUF, switch count, overall losses and magnitude of dc link current, these schemes need to be further improved in terms of THD, torque ripple minimization, VUF etc. This paper presents a current reference expanded two arm modulation (CRETAM) technique to control the two differently rated PMSMs. The main involvement of this paper is to detail the analysis of a completely new and optimised FPGA implementation of the CRETAM technique.

## 2.FIVE LEG INVERTERDRIVE FOR DOUBLE PMSM

The power circuit of FLI which consists of five legs, each leg consists of pair of power switching device (MOSFET) with anti-parallel diode, is shown in Figure 2. 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.
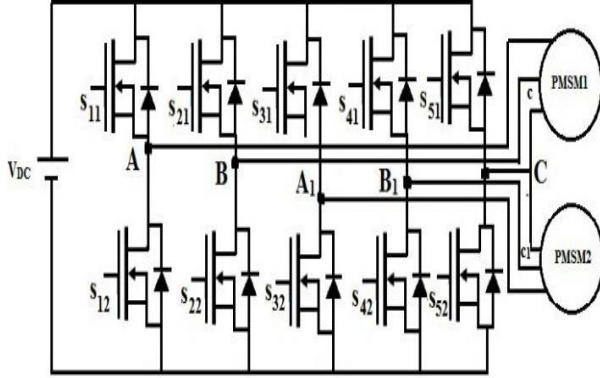


Figure 2. Structure of five leg VSI

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

Switch on: $S_{ma} = 1$

Switch off: $S_{ma} = 0$

Restricted Function = $S_{m1} + S_{m2} = 1$

Where, $m \in \{1, 2, 3, 4, \text{and } 5\}$ is the number of legs and $a \in \{1, 2\}$ 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. The drive can be operated in various conditions such as,

- Reference speed commands of main and auxiliary PMSM drives are different.
- Loads torque commands of main and auxiliary PMSM drive are different.
- Rated specification and parameters of two motors are different 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 interchangeability. The switching table and various modes of operation is shown in Figure. 3.

Table 1 Five Leg Inverter switching table

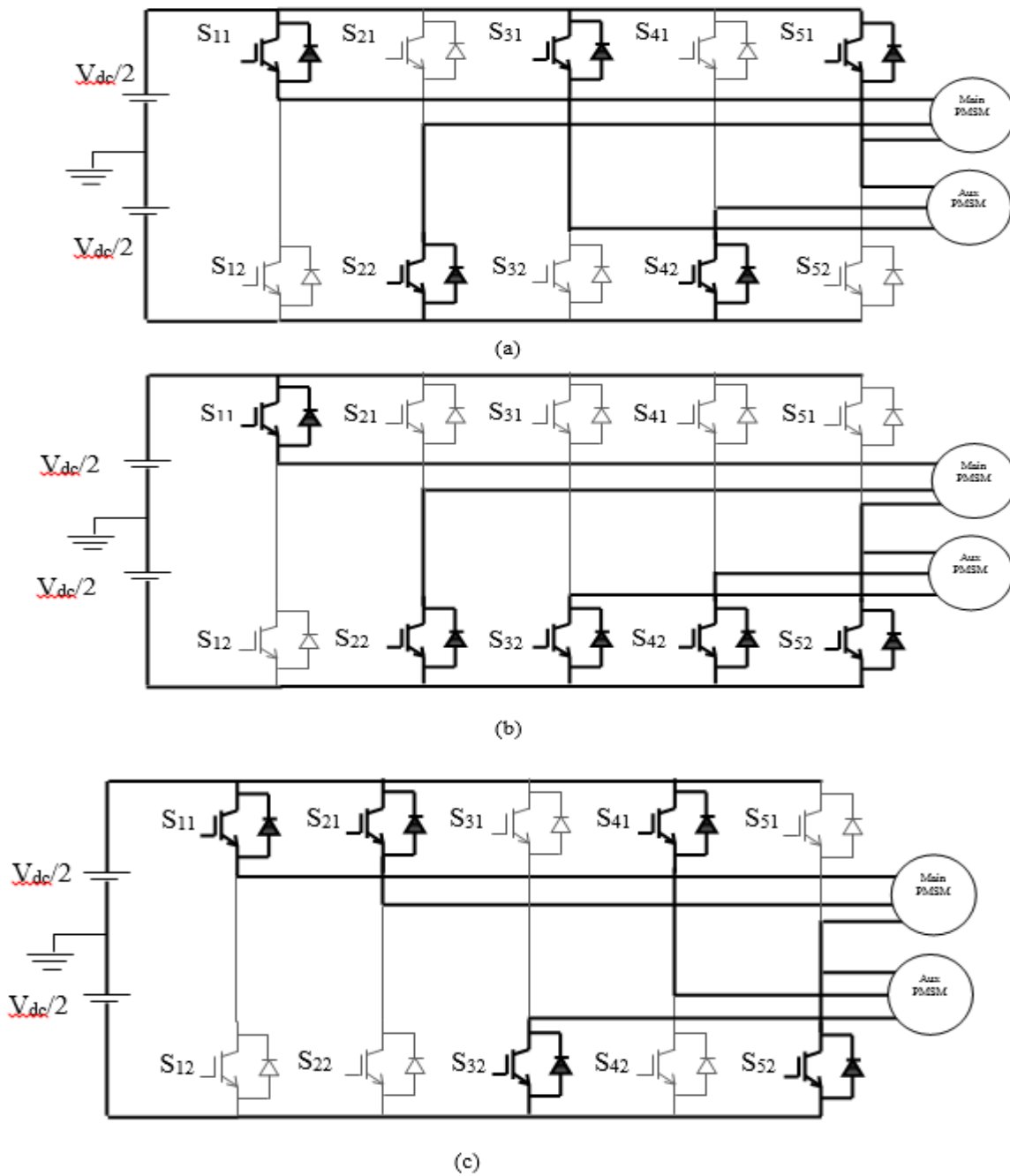| Interval | $S_{11}$ | | $S_{12}$ | $S_{21}$ | $S_{22}$ | $S_{31}$ | $S_{32}$ | $S_{41}$ | $S_{42}$ | $S_{51}$ | $S_{52}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 to 60º | ON | | OFF | OFF | ON | ON | OFF | OFF | ON | ON | OFF |
| 60º to 120º | ON | | OFF | OFF | ON | OFF | ON | OFF | ON | OFF | ON |
| 120º to 180º | ON | | OFF | ON | OFF | OFF | ON | ON | OFF | OFF | ON |
| 180º to 240º | OFF | | ON | ON | OFF | OFF | ON | ON | OFF | OFF | ON |
| 240º to 300º | OFF | | ON | ON | OFF | ON | OFF | ON | OFF | ON | OFF |
| 300º to 360º | OFF | | ON | OFF | ON | ON | OFF | OFF | ON | ON | OFF |

(a)



(b)



(c)

Figure 3. Various operating modes of five leg inverter

(a) (0 to 60°); $S_{11}$, $S_{22}$, $S_{31}$, $S_{42}$, $S_{51}$ closed

(b) (60° to 120°); $S_{11}$, $S_{22}$, $S_{32}$, $S_{42}$, $S_{52}$ closed

(c) (120° to 180°); $S_{11}$, $S_{21}$, $S_{32}$, $S_{41}$, $S_{52}$ closed

## 3. PWM MODULATION METHODS FOR FLI

The conventional PWM techniques applicable to the three phase VSI cannot be used for the FLI in the independent drive mode. The state-of-the-art PWM techniques of the FLI, applicable when two motors are controlled, are as follows.

    3.1 ETAM

    3.2 Voltage reference based Space Vector Approach.

## 3.1 Expanded Two Arm Modulation Method

The ETAM is type of modulation technique usually adopted for generation of pulse for FLI. The ETAM is basically voltage reference PWM technique logically extended to FLI. The voltage reference functions are taken from the inverter output. Actually it generates six phase voltage references which are decoupled among two sets of reference functions shown in Figure 4. This decoupling makes the dual motor to work independently. Here in dual motor drive one phase is common to both the motor hence it requires four reference functions which are manipulated by synthesizing procedure normally carried out in conventional

three phase system. The equations of voltage reference of individual leg has been given in (1)-(5). The fifth reference function (common phase to both the motors) is theoretically zero, but the practically the fifth phase voltage is not zero hence the $V_{cmin}$ is added.
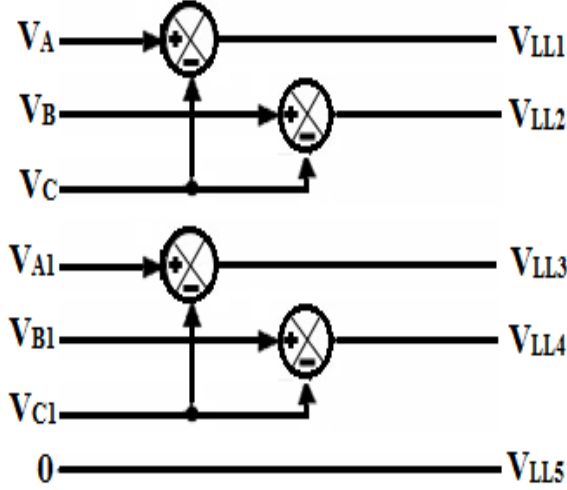


Figure 4.Generation of reference functions of ETAM

The voltage commands (reference functions) of individual leg are calculated as follows.

$$V_{LL1} = V_A - V_C \qquad (1)$$
$$V_{LL2} = V_B - V_C \qquad (2)$$
$$V_{LL3} = V_{A1} - V_{C1} \qquad (3)$$
$$V_{LL4} = V_{B1} - V_{C1} \qquad (4)$$
$$V_{LL5} = V_C - V_C = V_{C1} - V_{C1} = 0 \qquad (5)$$

Where, $V_{LLm}$ is the voltage command of $m^{th}$ leg. m = {1,2,3,4,5}; $V_A$, $V_B$, $V_C$, $V_{A1}$, $V_{B1}$, and $V_{C1}$ are the phase voltage commands(references involved in two VSI based drive system). The common rule in the natural sampled PWM scheme is the expected (terminal) voltage must be the reference function or at least it must be the function expected voltage. The reference functions described in (1) to (5) are just functions derived from fictions dual three-phase supply system. Those reference functions can always be related with the output voltage command as follows.

$$V_{AB}^* = V_{LL1} - V_{LL2} = V_A - V_B \qquad (6)$$
$$V_{BC}^* = V_{LL2} - V_{LL5} = V_B - V_C \qquad (7)$$
$$V_{CA}^* = V_{LL5} - V_{LL1} = V_C - V_A \qquad (8)$$
$$V_{A1B1}^* = V_{LL3} - V_{LL4} = V_{A1} - V_{B1} \qquad (9)$$
$$V_{B1C1}^* = V_{LL4} - V_{LL5} = V_{B1} - V_{C1} \qquad (10)$$
$$V_{C1A1}^* = V_{LL5} - V_{LL3} = V_{C1} - V_{A1} \qquad (11)$$

Equations (6) to (11) are for just validation purpose while the functional references are obtained by adding $V_{cmin}$ with them.
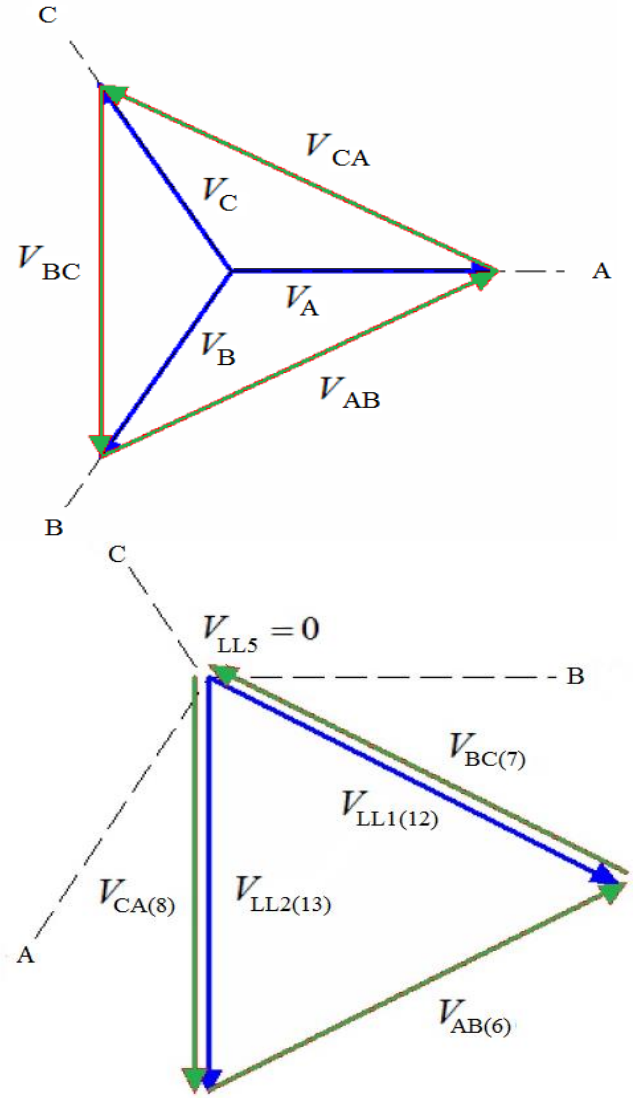
$$V_{LL1} = V_A - V_C + V_{cmin} \qquad (12)$$
$$V_{LL2} = V_B - V_C + V_{cmin} \qquad (13)$$
$$V_{LL3} = V_{A1} - V_{C1} + V_{cmin} \qquad (14)$$
$$V_{LL4} = V_{B1} - V_{C1} + V_{cmin} \qquad (15)$$
$$V_{LL5} = 0 + V_{cmin} \qquad (16)$$

The references from (12) to (16) can be used with regular carrier for generating the gating pulses.



5a. Conventional three-phase system
5b. One phase suppression scheme

Figure 5.Formulation of line voltages from phase voltages

## 3.2 Space Vector Approach

The digital counterpart PWM technique has been extended to FLI. For generating the pulses it requires two three phase SVPWM voltage references to control the two PMSMs independently. Using space vector principle, the separate reference functions can be obtained for each PMSM in synchronously rotating frame, the d-q axis. For any arbitrary position of the reference vector, apposite two active vectors are chosen from the six vector group. The generated output from SV modulators are restructured to obtain the duty cycle δ over the total switching period. Adopting both modulators in the standard manner to operate for application under equally shared total timing between zero vectors 000 and 111, and each reference vector will be realized on average over the switching period by means of two adjacent

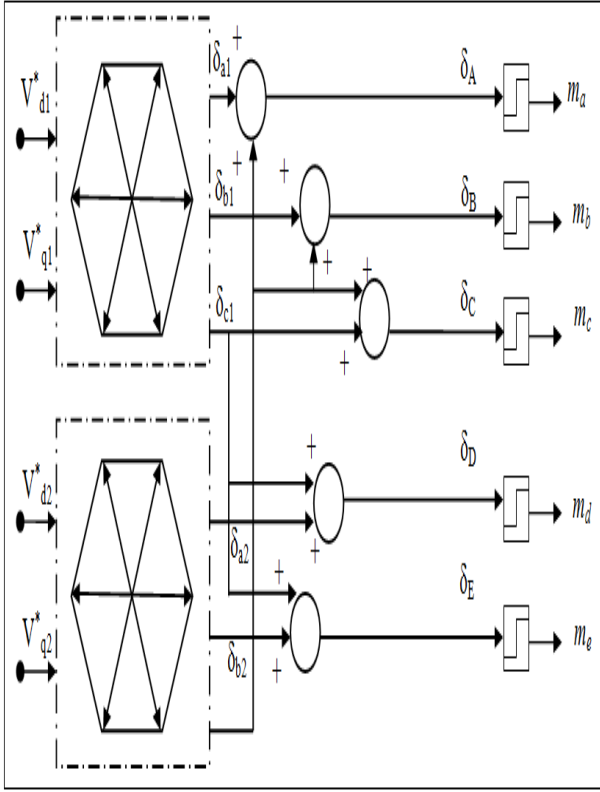active vectors. Figure 6 represents the outline of SVPWM strategy applicable to FLI.



Figure 6.Extension of SVPWM to FLI

In a similar way as in case of ETAM, a simple summing of the duty cycles ($\delta$) generated from each modulator can be used to determine the culminating (five) duty cycles for the FLI.

$$\delta_A = \delta_{a1} + \delta_{c2};$$
$$\delta_B = \delta_{b1} + \delta_{c2};$$
$$\delta_C = \delta_{c1} + \delta_{c2}; \qquad (17)$$
$$\delta_D = \delta_{a2} + \delta_{c1};$$
$$\delta_E = \delta_{b2} + \delta_{c1};$$

The first three relations of equation of (17), duty cycle, $\delta_{c2}$ is added to all the three duty cycles of modulator 1, while $\delta_{c1}$ is added to outcomes of modulator 2.

Thus the individual SVPWM signals are generated for each PMSM drive and the modulator is able to satisfy the needs of both main and auxiliary PMSMs simultaneously.

## 4.PROPOSED PWM STRATEGY

An ingenious PWM technique for FLI to command each motor is suggested in this section. The proposed current reference expanded two arm modulation (CRETAM), is similar to hysteresis control, and requires actual current and reference current signals to generate the pulse pattern. The crux of the CRETAM is schemed in Figure 7.
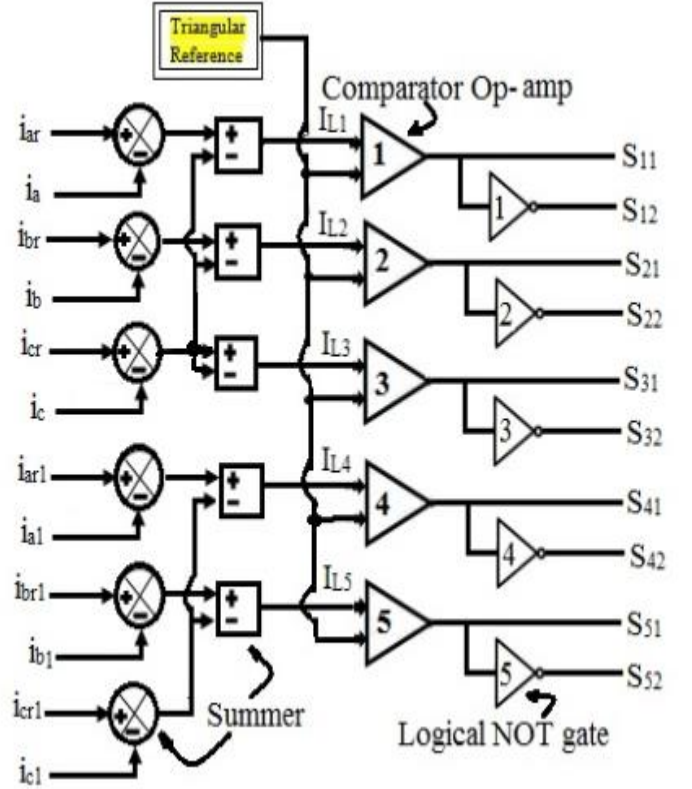


Figure 7. Proposed CRETAM

In the CRETAM, current references are given by the equations.

$$I_{ea} = i_{ar} - i_a \qquad (18)$$
$$I_{eb} = i_{br} - i_b \qquad (19)$$
$$I_{ec} = i_{cr} - i_c \qquad (20)$$
$$I_{ea1} = i_{ar1} - i_{a1} \qquad (21)$$
$$I_{eb1} = i_{br1} - i_{b1} \qquad (22)$$
$$I_{ec1} = i_{cr1} - i_{c1} \qquad (23)$$

Where, $i_a, i_b$ and $i_c$ are the actual currents of motor1.$i_{ar}, i_{br}$, and $i_{cr}$ are the reference currents of motor1. Similarly, $i_{a1}, i_{b1}$ and $i_{c1}$ are the actual currents of motor 2 and $i_{ar1}, i_{br1}$ and $i_{cr1}$ are the reference currents of motor2.

$$I_{L1} = I_{ea} - I_{ec} = i_a - i_c \qquad (24)$$
$$I_{L2} = I_{eb} - I_{ec} = i_b - i_c \qquad (25)$$
$$I_{L3} = I_{ec} - I_{ec} = 0 \qquad (26)$$
$$I_{L4} = I_{ea1} - I_{ec1} = -i_{a1} - i_{c1} \qquad (27)$$
$$I_{L5} = I_{eb1} - I_{ec1} = -i_{b1} - i_{c1} \qquad (28)$$

$I_{ea}, I_{eb}$ and $I_{ec}$are the current errors of motor1 and $I_{ea1}, I_{eb1}$ and $I_{ec1}$ are the current errors of motor2.$I_{L1}, I_{L2}, I_{L3}, I_{L4}$ and $I_{L5}$are the current references which are compared with triangular carrier signals to generate the pulses of FLI. The CRETAM paves to reduction in both torque ripple and THD, and enhancement in VUF.

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

### 5.1 CRETAM Technique

The arrangement of independent vector control scheme of unified dual PMSM under CRETAM technique is shown in Figure 8. To ensure the linearity between motor torque and current it is essential to keep the direct axis current ids=0. The two motors share the common fifth leg as a third phase. Two independent tuned speed controllers are employed both of which are PI types. Actually the speed controller generates torque producing current component iqs which in turn is shifted into abc frame for the purpose of reference current generation.
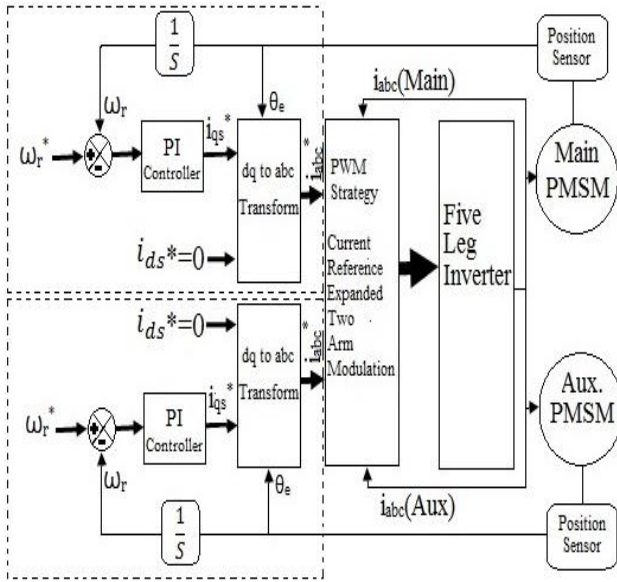


Figure 8. Independent vector control of main and auxiliary PMSMs under CRETAM technique

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.

### 6. SIMULATION RESULTS

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 1.The dynamic response of PMSM_01 and

PMSM_02under CRETAM technique running independently with different speed commands and load torques is shown from Figure 10 to Figure 13.The PMSM_01 and PMSM_02are 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. Also the step load torque commands to the PMSM_01 (0.2Nm to 0.4Nm) and PMSM_02 from (0.3Nm to 0.6Nm) are given at 0.24s and 0.26s.Figures 14.(a)–(f) show the line to line voltages, phase voltages and stator current f integrated PMSM drive with FLI in adopting CRETAM technique. It is evident that from the Figure 14, as the reference speed of PMSM_01 and PMSM_02 are different, the operating frequency of line to line and phase voltages are also different. Hence through a single solid state converter (FLI), it is possible to generate line and phase voltages at two different frequencies simultaneously.
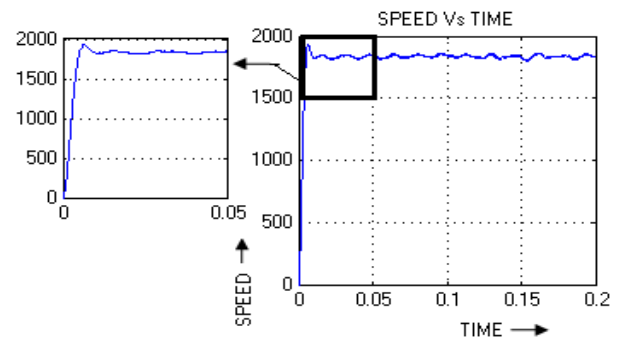


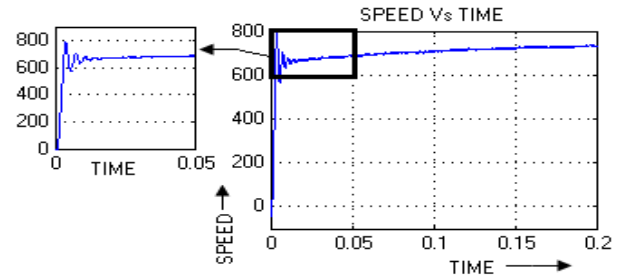Figure 9. Speed response of PMSM_01–CRETAM
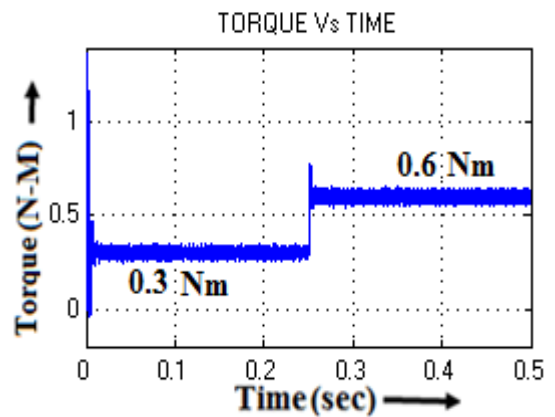


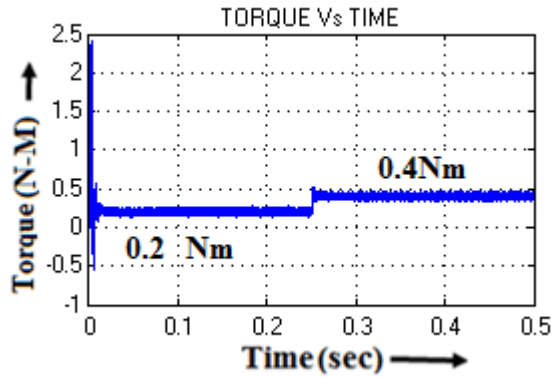Figure 10. Speed response of PMSM_02 –CRETAM



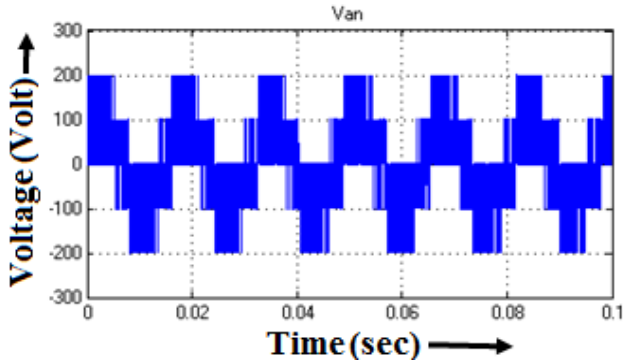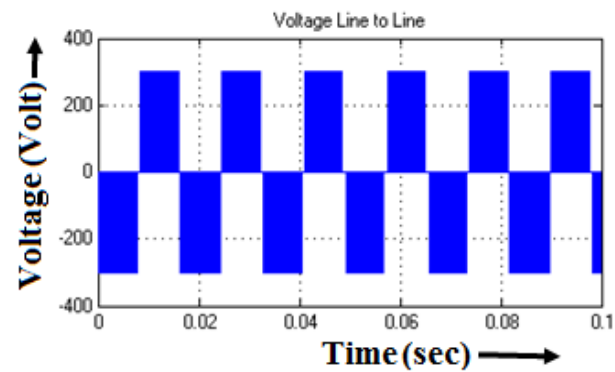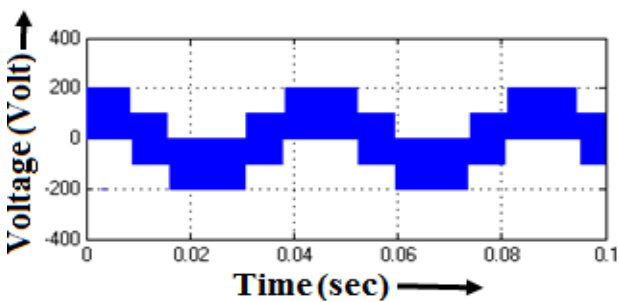Figure 11. Torque response of PMSM_01-CRETAM

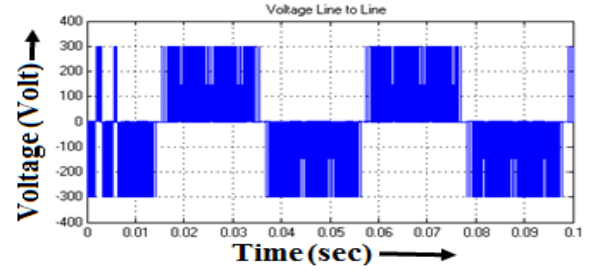Figure12.Torque response of PMSM_02 –CRETAM



A. Simulation result of phase voltage of Main PMSM-FLI-CRETAM
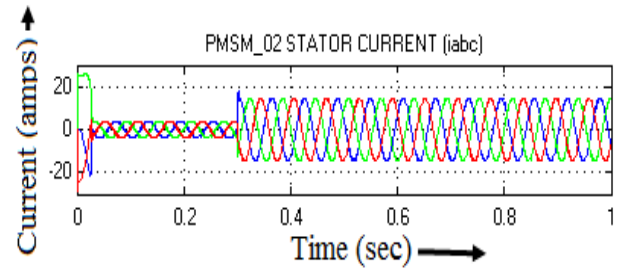


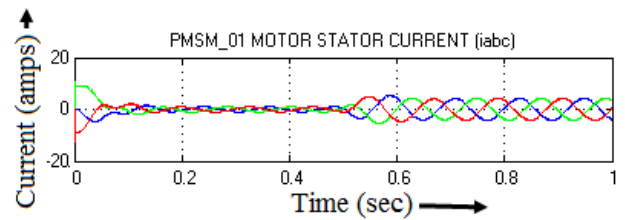B. Simulation result of line to line voltage of Main PMSM-FLI-CRETAM



C. Simulation result of phase voltage of PMSM Auxiliary PMSM-FLI-CRETAM



D. Simulation result of line to line voltage of PMSM Auxiliary PMSM-FLI-CRETAM



E. Simulation result of Stator Current of Main PMSM-FLI-CRETAM



E. Simulation result of Stator Current of Auxiliary PMSM-FLI-CRETAM

Figure14.Simulation results of line to line voltage, phase voltage& stator current of integrated Main & Auxiliary PMSM drive in Five Leg VSI in adopting CRETAM technique.
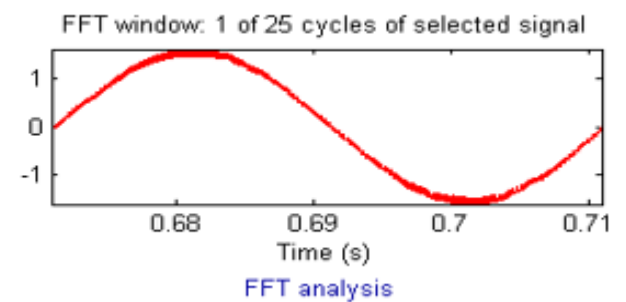


Aux PMSM current under CRETAM technique respectively

Fundamental (25Hz) = 1.554 , THD= 3.11%

Fundamental (50Hz) = 124.4 , THD= 82.25%
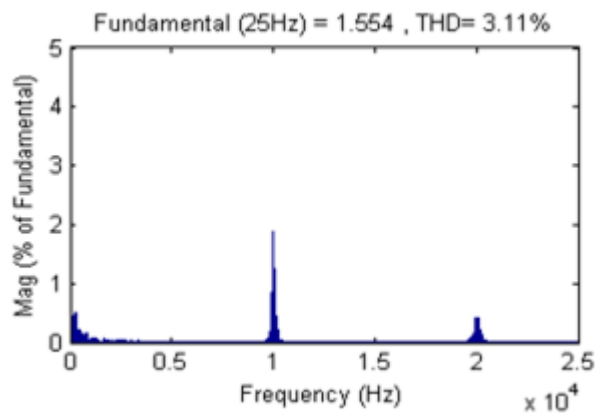
Harmonic Spectrum of current of CRETAM technique respectively.
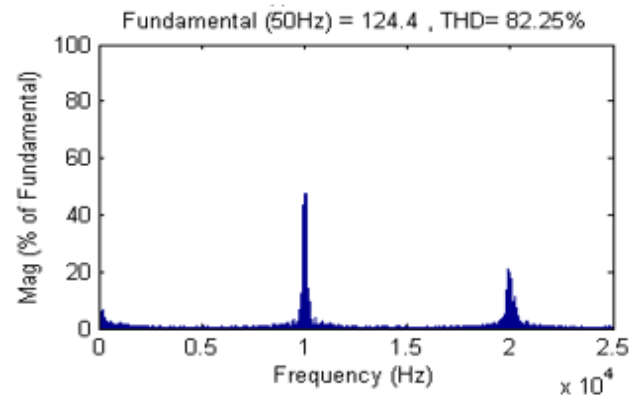
Harmonic Spectrum of line voltage of Main PMSM with CRETAM technique respectively.

Figure 15.Various Performance Measures of Main & Auxiliary PMSM drive in Five Leg VSI in the CRETAM technique.

There is a considerable increase in DC bus voltage utilization in CRETAM Table 2.shows relative performance of voltage utilization at different values of modulation index in CRETAM techniques. On observing the Table 2.the voltage utilization in CRETAM technique is satisfactory in comparison with SVPWM technique. Table 3.shows the value of stator current THD for PMSM1 and PMSM2.

Table 2. PMSM drive parameters for simulation

| Parameters | PMSM_01 | PMSM_02 |
|---|---|---|
| Rated output power (kW) | 0.25 | 1.65 |
| Rated speed (rpm) | 3000 | 2000 |
| Back EMF constant ($V_{L\text{-}L\ peak}$/krpm) | 62.2859 | 62.28 |
| No of Poles | 4 | 8 |
| Rated Torque (Nm) | 0.8 | 8 |
| Stator Resistance ($\Omega$) | 18.7 | 0.9585 |
| Stator d and q axis inductance (H) | 0.02682 | 0.00525 |
| Inertia ($Kg.m^2$) | 2.26e-5 | 0.0006329 |
| Friction Factor (N.m.s) | 1.349e-5 | 0.0003035 |
| Flux Linkage | 0.171 | 0.1827 |

Table 3. Relative performance of CRETAM technique

| PWM Techniques | CRETAM | |
|---|---|---|
| Modulation Index | $V_{line}$_RMS (V) | $V_{phase}$_RMS (V) |
| 1 | 168.3 | 97.39 |
| 0.8 | 152.3 | 87.86 |
| 0.6 | 133.3 | 76.96 |
| 0.4 | 111.5 | 64.47 |
| 0.2 | 84.56 | 48.54 |

TABLE 4. CURRENT THD VALUE PMSM1 AND PMSM2 FOR VARYING INPUT VOLTAGE

| Input Voltage | PMSM1 | PMSM2 |
|---|---|---|
| | Current THD (%) | Current THD (%) |
| 150 | 24.77 | 19.16 |
| 200 | 31.19 | 9.23 |
| 250 | 41.23 | 10.34 |
| 300 | 43.03 | 12.78 |
| 350 | 48.28 | 12.41 |

The Figure 16. shows the experinmetal system suggested to implement the proposed CRETAM. It consists of a diode rectifier, adc link capacitor, a three-phase VSI, a personal computer, SPARTAN-6 FPGA (XC6SLX45) device and a motor load. The proposed CRETAM architecture is designed using the VHDL language. The functional simulation of the architecture has been carried out using the tool Modelsim 6.3. The Register Transfer Level (RTL) level verification and implementation are done using the synthesize tool Xilinx ISE 13.2. Then the designed architecture has been configured to the SPARTAN-6 FPGA (XC6SLX45) device. The functionality of each block in the architecture has been simulated thoroughly using the Modelsim software.
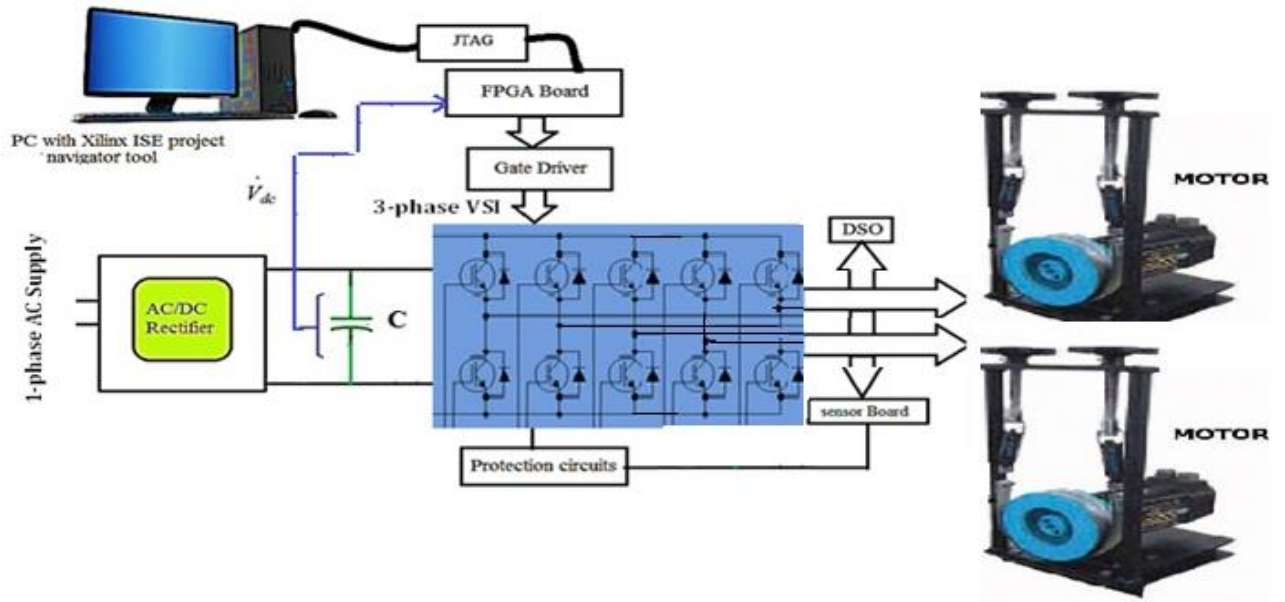


Figure 16. Hardware implementation of FPGA based FLI for Two PMSM motor.

Figure 17. shows the pulse pattern generated from CRETAM with the help FPGA processor. Figure 18. Shows the line to line voltage of FLI implemented in FPGA processor.
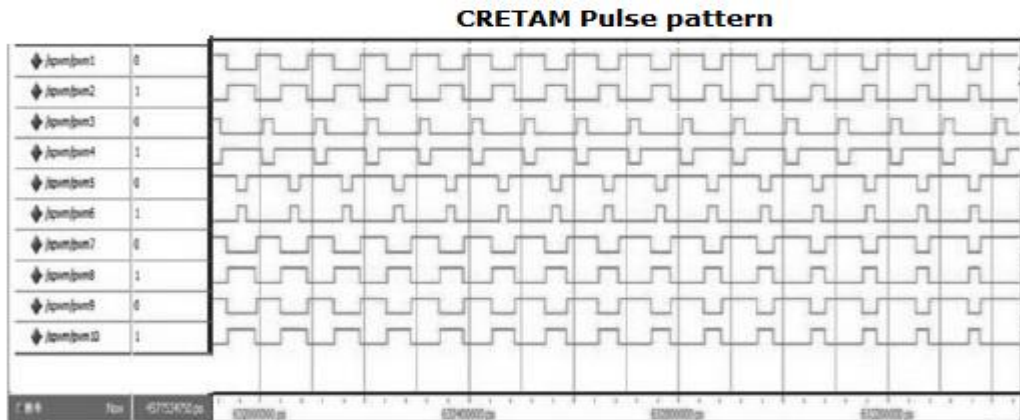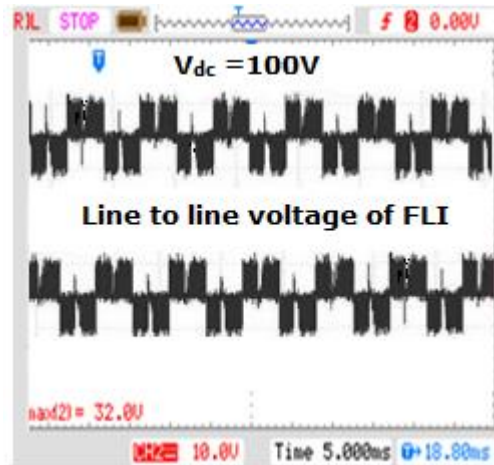


Figure 17. CRETAM pulse pattern

Figure 18. Line to line voltage of FLI

### 7.CONCLUSION

A new modulation technique is proposed to combined drive for dual PMSMs applicable to automotive application. The control algorithm for driving dual three phase PMSM is achieved. A new reformed PWM method for FLI i.e. CRETAM technique has been carried out and tested in MATLAB/Simulink and practically implemented and tested in FPGA processor. The experimental results reveals that the independent control i.e for different torque and speed commands the main and auxiliary PMSM motors works efficiently. The increased THD and minimized torque ripple has been achieved when adopting the CRETAM modulation technique to FLI.

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