SPEED PERFORMANCE OF SPACE VECTOR PULSE WIDTH MODULATION DIRECT TORQUE CONTROL FOR FIVE LEG INVERTER SERVED DUAL THREE-PHASE INDUCTION MOTOR

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Speed Performance of Space Vector Pulse Width Modulation Direct Torque Control for Five Leg Inverter Served Dual Three-phase Induction Motor.

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Abstract—**Independent control of multi-machine with single-converter systems is the motivation of this research study. As in the previous literature review, there is no report regarding speed control applying space vector pulse width modulation direct torque control (SVPWM-DTC) method for dual three-phase induction motor (IM) fed by a five leg inverter (FLI). Therefore, in this paper, a new and simple control method based on SVPWM-DTC for dual three-phase induction motors with only one drive of five-leg voltage source inverter is investigated. The method effectively allows independent control of two three-phase IMs. Simulations of different speed commands and variation of load condition tests have been performed. Future work is to do comparative study between vector controls (VC) versus DTC methods to the FLI performance.**

Keywords-component; dual motor, two three-phase motors, five-leg inverter, space vector pulse width modulation direct torque control.

I. INTRODUCTION

Presently, to drive two three-phase IMs with single drive independently has attracted major interest among the researchers and industries because of cost reduction, saving space and reduction of inverter losses. It is believed to be a potentially interesting solution for two-motor constant power applications, for example, centre-driven winders [1]. Although a large number of studies have been made on VC method applying to the FLI [1-3], none is known about employing DTC to FLI.

It is now recognized that the two high-performance control strategies for IM are FOC and DTC [4-6]. These methods have been invented in the 70's and 80's. They have different operational strategies but with the same target that is to control effectively the motor torque and flux. Both control methods have successfully implemented in industrial products [7]. DTC [8-9] has been gaining more popularity since it is invented due to its exceptional dynamic response and less dependence on machine parameters. It also has been applied to the multi-phase motor [10-11] applications.

FLI had been introduced with decrease of switch count compare to standard two three-phase two-level inverter which has six legs. There are researches on FLI applying SVPWM techniques in its application [12-13] and also there are researches on applying SVPWM in DTC using normal three-phase motor [14-15]. Hence, by combining both methods to a system, this paper investigated the new SVPWM-DTC to control FLI. SV-based PWM introduced by [1, 12] is implemented herein.

II. CHARACTERISTIC OF FIVE-LEG INVERTER

A. Main Circuit Topology of Five-leg inverter

Five-leg two-motor drive structure offers a saving of two switches when compared with the standard dual three-phase voltage source inverter (VSI) [16-18]. Fig. 1 shows the main structure of the FLI. The FLI serves two three-phase IMs. Both motors need three inputs, as the results the C leg works as a common leg. Leg A_1 and B_1 are connected to phase U and V of motor one (M1), while leg A_2 and B_2 are connected to phase U and phase V of motor 2 (M2) respectively. Switching functions S_i (i=1,2, 3,4,5) are defined as $S_i = 1$ when the upper switch is on and $S_i = 0$ when it is off. There are a total of 32 switching states (2^5) in a five-leg VSI, available for control of the two motors [1].

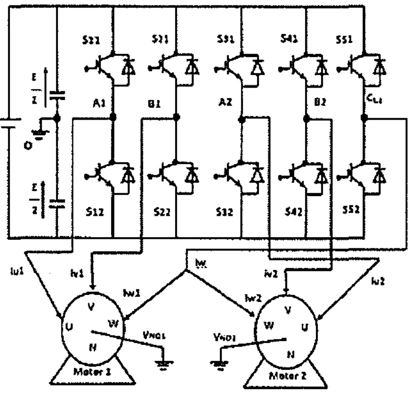


Figure 1. Main circuit topology of two three-phase IM fed by five-leg inverter.

As reported by [20] for FLI, the maximum voltage value at terminals of an open switch is always equal to the DC voltage V_{DC} (i.e. at rated value such that full operating range of one motor can be achieved). This voltage must be greater than the greatest phase-to-phase voltage. Thus, for the same DC voltage, the capability of five-leg structure leads to a reduction of the supply voltages for the IMs. As the results, the speed range and load variations that the motors can handle also reduced.

B. SVPWM-based DTC

DTC has simple structure and fast torque response advantages. DTC with space vector modulation (SVM) scheme is proposed in order to improve the classical hysteresis DTC. Reference [8] reported that compare with the steady-state performance of lookup table DTC and SVPWM-DTC, the latter produces much lower torque ripple. This is results from the injection of zero-vector instead of backward active vectors to reduce torque. Another advantage of SVPWM-DTC is it operates at a constant switching frequency.

The three-phase IM SVPWM-DTC will be discuss because in the schemes that being developed in this paper the standard three-phase modulators are used to produce the 5 gates signals to trigger the FLI (as in fig. 3). In the control structures, SVM algorithm is used. The type of SVPWM-DTC strategy depends on the applied flux and torque control algorithm. In this paper SVPWM-DTC scheme with PI controllers will be implemented as in fig.2 below [21]. Fig 2 shows the block diagram of SVPWM-DTC with PI controllers IM drive.

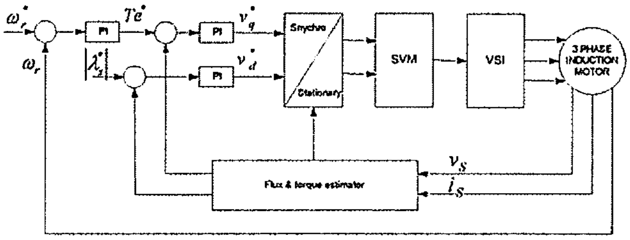


Figure 2. Block diagram of SVPWM-DTC three-phase IM drive.

Equations (1) and (2) show the principle of DTC on calculating the flux and electromagnetic torque. Here $\widehat{V_s^s}$ and $\hat{I}_s^s$ are voltage and current vector respectively in stationary reference frames. The stator flux linkage ($\widehat{\varphi_s^s}$) calculated as (1).

$$\varphi_s^s = \sqrt{}(\hat{V}_s^s - \hat{I}_s^s e R_s)dt \qquad (1)$$

The electromagnetic torque $\hat{T}_e$ can be calculated as (2).

$$\hat{T}_e = \frac{3P}{4}(\hat{\varphi}_{ds}^s \hat{I}_{qs}^s - \hat{\varphi}_{qs}^s \hat{I}_{ds}^s) \qquad (2)$$

Where P is the number of poles, Rs is the stator resistance, [ohm] Ω.

The basic principle of SVPWM algorithm is it has eight voltage vectors. There are six base vectors has same amplitude and two zero vectors (000) and (111). As shown in fig. 3, in the first sector adjacent to the two voltage vector U_1 and U_2 as well as the zero vector can synthesis reference vector U_{ref} in accordance with the method of voltage-second balance.

$$U_1T_1 + U_2T_2 + U_0T_0 = U_{ref}T_S \qquad (3)$$

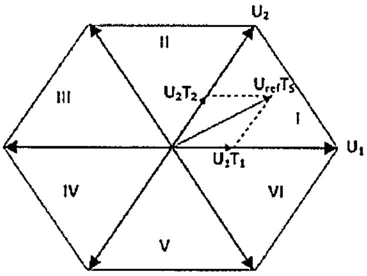


Figure 3. Voltage vectors and sectors.

Where T_1 and T_2 are the duration time of active vectors, T_0 is the duration time of zero vectors and T_s is the PWM cycle. From these times switching signals S_1, S_2 *and* S_3 are obtained.

C. SVPWM in FLI

There are lots of different PWM methods have been applied as the switching techniques to the FLI [2, 21-25]. Unfortunately by using this conventional PWM the DC bus utilization is restricted to 50% to each of the motor. As a consequence, many attempts to improve the DC bus utilization with the five-leg topology have been reported [1, 12, 26-27].

Two PWM techniques are introduced by [7, 12] for FLI, that is carrier base and SV-based PWM. SV-based technique is chosen to be implemented in DTC. The technique utilizes standard three-phase modulators to generate modulation signals for all legs of a FLI. The end result enables any portion of the DC bus voltage to be allocated to any of the two motors. It produces a symmetrical switching pattern, with identical switching frequency in all the inverter legs. The more interesting factor is that all of the 32 available inverter switching states are utilized.

Consider a SV approach to the inverter modeling. Similar principles to those explained in the case of carrier-based PWM [1] of the FLI apply when one considers the SVPWM method for two-motor drive. The existence of zero-sequence signal injection makes it possible for the FLI being able to independently control two three-phase IMs. It is well known that the zero-sequence signal represents a degree of freedom that is normally used to improve the DC bus utilization and reduce harmonic current losses of the carrier-based method [1]. The zero-sequence signal does not appear in either line-to-line or phase voltages of the three-phase motor. This offer a possibility to utilize the principle of zero-sequence signal injection in a very different manner for a five-leg two-motor drive.

Two-independent three-phase SV modulators are used to control each motor. Voltage references for each motor are vectors situated in any of the six sectors in their d-q plane of stationary reference frame (as in DTC schemes). Assuming that

SV. The three-phase SVPWM modulators will generated the duty cycle values δ over the switching period t_s (time 'ON' over the total switching period) for each of the three legs. A simple summing of the duty cycles generated can be used to determine the resulting five duty cycles for the FLI. That is,

$$\begin{aligned} &\delta_{A_1} = \delta_{a_1} + \delta_{c_2} \qquad \delta_{B_1} = \delta_{b_1} + \delta_{c_2} \\ &\delta_C = \delta_{c_1} + \delta_{c_2} \\ &\delta_{A_2} = \delta_{a_2} + \delta_{c_1} \qquad \delta_{B_2} = \delta_{b_2} + \delta_{c_1} \end{aligned} \tag{4}$$

The values of duty cycles calculated by each three-phase SV modulator are in the range (0:1), where the switching period t_s is equal to 1 p.u. Then as in normal SV zero space vector 111 should be injected in the middle of the switching pattern, generated duty cycles will have values equal to 0.5 when the input reference is zero. After summation defined with (4), the FLI duty cycles get shifted into the range (0.5:1.5), which is not applicable with the value of the witching period. Due to this the value from the resulting duty cycles calculated using (4) must continuously subtracted by 0.5. This is shown in Fig. 3 where the principle of SVPWM for a FLI supplying a two-motor drive is illustrated [1, 12].

The net effect of the duty cycle summation is the redistribution of the application times of the zero SVs. From the first three equations of (4), it is visible that the addition of the value of the duty cycle δ_{c_2} increases all three duty cycles, originally generated by the M1 modulator, in the same manner. Thus, the application time of the zero SV 111 is effectively increased, and as a consequence the application time of the zero SV 000 is decreased (before shifting by – 0.5), without affecting the application times of the two active SVs. The same explanations apply to M2 on the basis of the last three equations of (4).

After the application of the SVPWM principle, these sequences and application time durations of active SVs for M1 and M2 stay preserved in the final five duty cycles of the five-leg VSI. It can be further seen that the distribution of the application times for zero vectors 000 and 111 for each of the two machines is different in FLI compared with in M1 and M2, whereas the total zero vector application time (sum of 000 and 111 application times) is kept the same. It is also noticeable that there are instants within the switching period when both machines simultaneously receive their active SVs (overlapped parts, for example, vector 11001 of the five-leg VSI, which corresponds to the active vectors 110 and 010 of the two machines, respectively, since inverter legs A_2 and B_2 supply phases a and b of the second machine while phases c are paralleled to the inverter leg $C_{1,2}$). Thus the individual SV references of each machine are complementary and the modulator is able to simultaneously satisfy the needs of both motors. It is also visible that in the remaining instants the individual SV references of each machine are conflicting and so the needs of one machine are met, whereas the second machine receives zero SV (111 or 000). What this means is that all 2^5=32 switching states of a five-leg VSI are utilised and there are no restrictions regarding the use of any of them. The resulting PWM pattern is symmetrical with two commutations per inverter leg and is thus easy to implement using standard DSP PWM units.

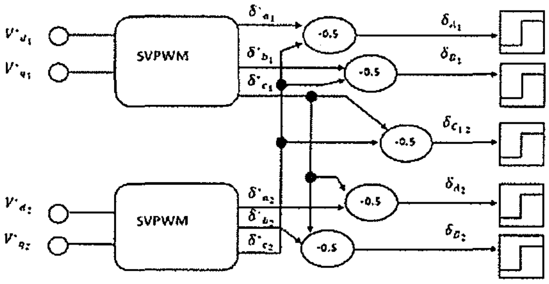


Figure 4. Principle of SVPWM for the FLI

III. PROPOSE SVPWM-DTC IN THE FIVE-LEG INVERTER FED TWO THREE-PHASE INDUCTION MOTOR DRIVE

Fig. 5 below shows the block diagram of the proposed SVPWM-DTC in five-leg inverter fed two three-phase motors. In the torque producing d^s and q^s axis in a stationary reference frame, the torque and flux estimator equations are the same as the conventional three-phase DTC drive for each motor.

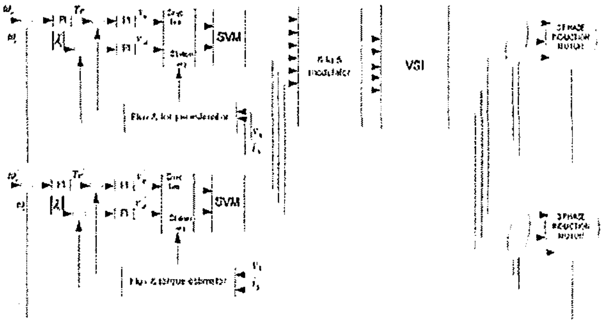


Figure 5. Proposed SVPWM-DTC in FLI control block diagram.

IV. SIMULATION RESULTS

The simulation investigation is performed using SVPWM-DTC to control FLI. Two identical 4 poles, 415V, 50Hz IMs are used. The rated load applicable for each motor is 4Nm (half of the full single three-phase motor drives). Both the transient and steady-state performance of the drive is investigated with a series of tests. No load, with load variations, and different speed references operation are considered. SVPWM-based DTC of section III is implemented. Reference speeds are selected in such a way it follows the limit explained in the last paragraph section II.A, which correspond to the available DC bus voltage for one motor operation.

Fig. 6 shows the first test where different speed references (100%=600, 50%=300 and 25%=150 rpm) are applied for motor two (M2) while motor one (M1) is maintain constant at 600 rpm, both are under no load condition. The figure also shows that the controller can well control independently both motor at different speed references. Table 1 shows the observation of this test. Transient speeds performance of the lowest speed reference gives faster respond, followed by the next speeds reference accordingly. While the steady-state performance is excellent for all difference speed command.

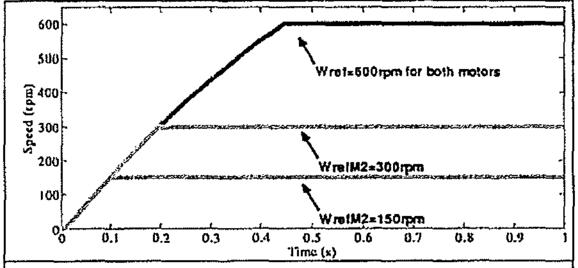


Figure 6. Variation of speeds reference for M2= 600, 300 and 150 rpm while M1=600rpm, both motors under no load

TABLE 1. OBSERVATIONS OF INDEPENDENT SPEEDS CONTROL UNDER NO LOAD TESTS.

No.	Description	Speed (rpm)		Observation
		M1	*M2*	*Transient response time*
1.	100% rated	600	600	Longest
2.	50% rated	600	300	Shorter
3.	25% rated	600	150	Fastest

Fig. 7-11 shows the simulations of with load conditions. The analysis can be seen in table 2. The first one is applying same speed and same load at the same time for both motors. Both motors archived a very stable steady-state operation after a slight speed reduction after load disturbance. As in fig.8-9 applying same load to both motors that having different speeds, it also resulting in a very stable after load disturbance reaching the steady state operation. For fig. 10, with same speed reference to both motors (M1=M2=600rpm) and load is applied to only M1 (4Nm), while M2 is at no load condition, the result is the speed for M1 is stable, equal to fig. 7 and no influences to the performance of M2. The torque rated applicable for each motor in this five-leg drive performance is 4Nm, so the total is 8Nm. The last load test done is to apply to only one motor, M1 the total torque (8Nm) that FLI able to handle while M2 is at no load as in fig. 11. Comparing the results with fig. 7, it is obvious that the FLI can handle 8Nm but must be dividing equally to both motors, if only one having full loaded the control system could not be well performed.

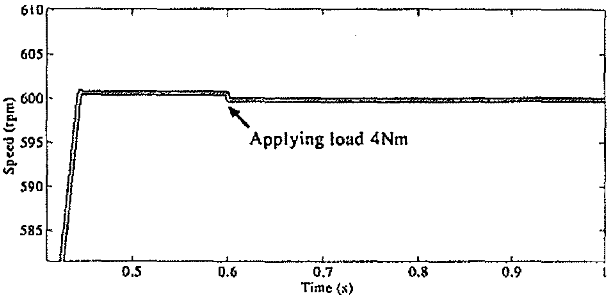
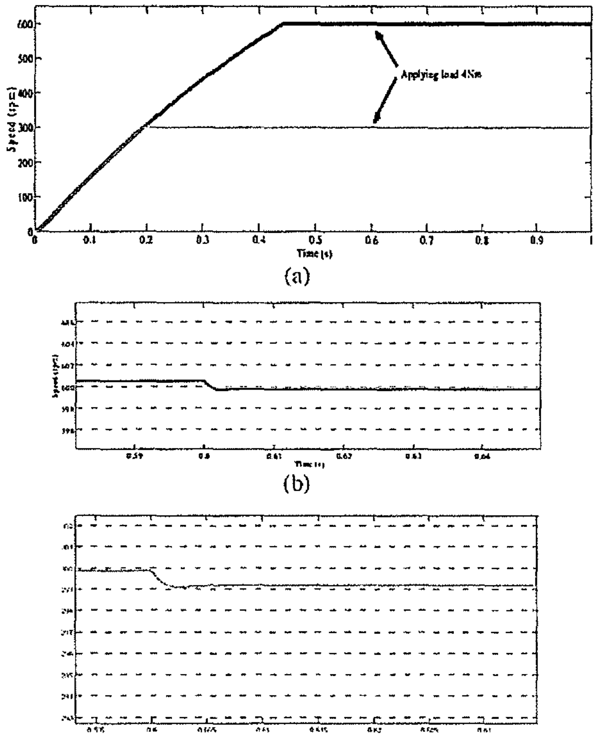


Figure 7. M1 and M2 having same speed reference with same load, 600 rpm, 4Nm at t=0.6s.

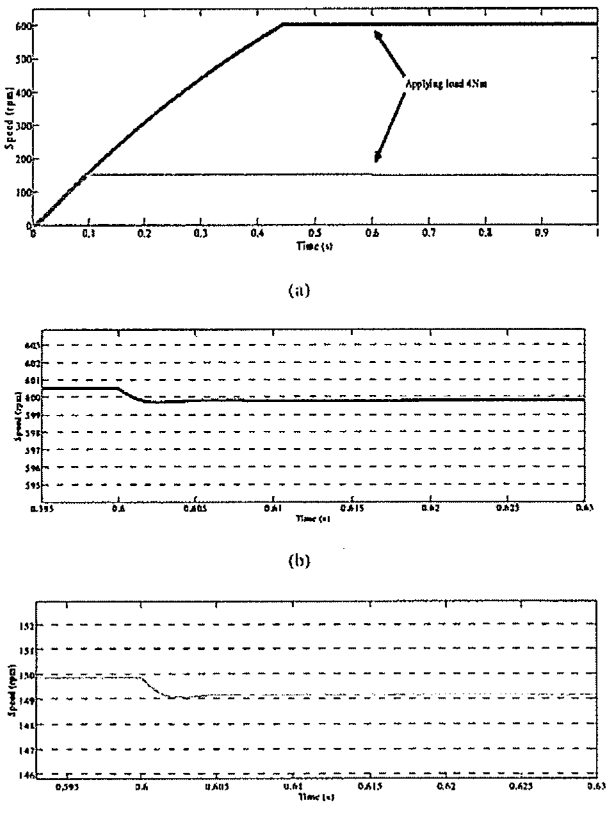


(a)

(b)

(c)

Figure 8. Speed M1=600 rpm, M2=300 rpm with same load 4Nm at t=0.6s. (a) Whole process; (b) and (c) enlarge picture of M1 and M2 at t=0.6s.



(a)

(b)

(c)

Figure 9. Speed M1=600 rpm, M2=150 rpm with same load 4Nm at t=0.6s. (a) Whole process; (b) and (c) enlarge picture of M1 and M2 at t=0.6s.

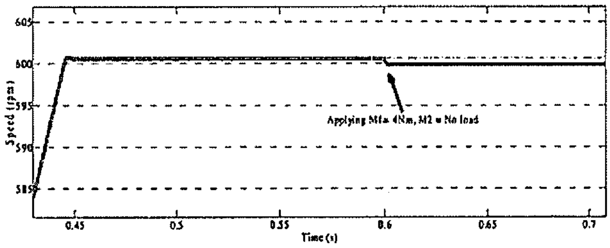


Figure 10. Same speed reference M1 and M2=600 rpm, Applying load 4Nm at t=0.6s to only M1, M2 no load.

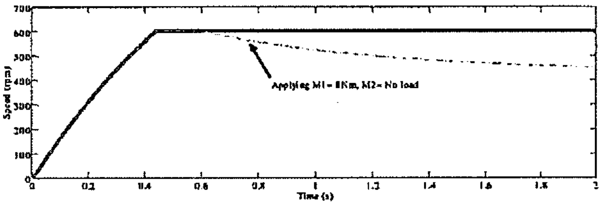


Figure 11. Same speed ref. M1 and M2=600 rpm, Applying total of two rated load possible for both motor to only one motor M1=8Nm at t=1s, M2 no load.

TABLE II. OBSERVATIONS OF INDEPENDENT SPEEDS CONTROL UNDER LOAD TESTS

No.	Description	Speed (rpm)		Load (N.m)		Observation
		M1	*M2*	*M1*	*M2*	
1.	Same load and speed	600	600	4	4	Stable
2.	Same load, different speed	600	300	4	4	Small speed reduction after load disturbance
3.		600	150	4	4	Small speed reduction after load disturbance
4.	Same speed, one loaded, another no load	600	600	4	0	Stable
5.	Same speed, One full FLI rated load, another no load	600	600	8	0	Out of steady-state

Fig. 12 shows the forward reversed operation of the two motors supplies by the FLI. Smooth operation appeared at both motors during transient and steady-state. In fig. 13 shows the reversed operation of both motors at no load but with different speed references M1 at -600 rpm and M2 at -300 rpm. The result shows that both achieved a very stable steady-state condition.

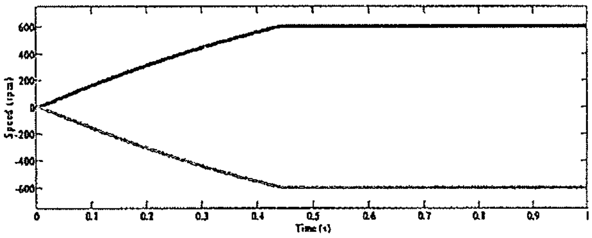


Figure 12. M1 forward +600 rpm, M2 reversed -600 rpm.

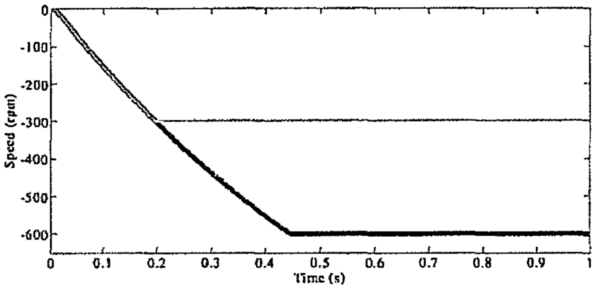


Figure 13. Reversed operation M1 = -600 rpm and M2 = -300 rpm

V. CONCLUSION

Simulation of a SVPWM-DTC fed FLI has been developed to control independently the speed of two three-phase IMs. Simulation results investigate and proven this structure. The FLI really enables different speeds reference command and load torque on both motors.

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