Implementation of Space Vector PWM In FOC of a Servo Motor Drive

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Abstract

ASELSAN Inc. has been instructed by Turkish Army forces to develop Radar Systems which include various electronic and mechanical subsystems. Among these subsystems, rotating part of the system, including its motor drive and mechanical assemblies, is designed by Radar, Electronic Warfare and Intelligence Systems Division Mechatronics & Mechanism Technology department. The power rating of the designed motor drives is currently between 150W and 2.2kW. New products are also developed according to the system requirements of the projects. In the implemented systems, the motor drives are used with permanent magnet synchronous motors (PMSM). Speed and position control is performed with field oriented control (FOC) which is a widely used method in drive applications.

In this paper, simulation and implementation of space vector pulse width modulation (SVPWM) technique in FOC is discussed. The system is modelled in MATLAB/SIMULINK and the implementation is performed by a product of ASELSAN INC. named "AVAR Servo Drive" and a direct drive brushless dc motor. After validating the SVPWM simulation model, the experimental results are given to show the advantage of the SVPWM technique in terms of motor speed.

Keywords— Permanent Magnet Synchronous Motor (PMSM), Field Oriented Control (FOC), Space Vector Pulse Width Modulation (SVPWM)

1. Introduction

Development in switching power devices and microprocessors results in wide usage of PWM inverters in motor drive applications. Among these motor drives, permanent magnet synchronous motor (PMSM) drives are widely used in industrial and military applications due to their fast response and accurate control [1].

In addition to the hardware implementation, the control method preferred in the system design plays a critical role. In order to control the AC machines there exist several methods such as scalar control (V/f), direct torque control (DTC), and field oriented control (FOC). Among these techniques, FOC is most widely used one due to its accurate steady state and transient control structure. FOC is simply based on controlling the stator current vectors in orthogonal reference frame (d-q) of the rotor. Transformation of 3 phase stator currents into d-q reference frame is the initial step of the control. Once the projection of current vectors is completed, the control method becomes easier, similar to that of a DC machine. In permanent magnet type motors, there is no need to create a flux reference in d-axis component. The useful torque can be generated by applying a q-axis reference which also results in rotation. PI control is applied to maintain the d-axis current component at zero and q-axis component at the given reference command. Three reference voltage vectors (Va^{ref}, Vb^{ref}, Vc^{ref}) are generated by applying inverse transformations to the output of PI controllers.

Moreover, obtained three phase voltage references are used to generate PWM signals by using a scalar or space vector PWM method. In the scalar method which is called sinusoidal pulse width modulation (SPWM), voltage references are compared with a carrier signal to produce switching pulses [2]. SPWM method is commonly used in power electronics inverter applications due to its simplicity of implementation with the improved signal processors. However, relatively new technique called space vector pulse width modulation (SVPWM) technique has become popular for inverter applications due to its high DC link utilization, less harmonic content and less copper loss [3].

In this paper, simulation and experimental results of PMSM motor drive which is utilized with FOC and SVPWM technique is represented. Firstly, the field oriented control and space vector modulation is discussed. The control algorithm is modelled and simulated by MATLAB/SIMULINK. After validating the simulation model, the implementation details and experimental results are given. Finally, advantages of the SVPWM technique are summarized.

2. FOC and SVPWM Principles

2.1. Field Oriented Control (FOC)

Field oriented control method can be summarized as controlling capability of both flux and speed similar to control of a DC machine. It is performed directly in the d-q rotating rotor reference frame. Three phase stator current vectors (i_a, i_b, i_c) can be represented in complex form as given in Fig. 1.

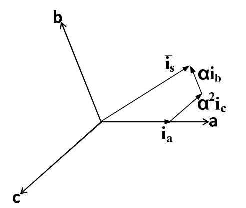

Fig. 1 Stator Current vectors in a,b,c coordinates

$$\overline{i_s} = \frac{2}{3} \times (i_a + \alpha i_b + \alpha^2 i_c) \text{ where } \alpha = e^{j2\pi/3} \quad (1)$$

By applying Clarke and Park transformations respectively, i_a, i_b, i_c current vectors are transformed from three phase stationary reference frame into two axis rotating d-q reference frame (2) - (4).

$$i_{s\alpha} = i_a \quad (2)$$

$$i_{s\beta} = \frac{1}{\sqrt{3}} i_a + \frac{2}{\sqrt{3}} i_b \quad (3)$$

$$i_{sd} = i_{sa\ \cos\theta} + i_{s\beta\ \sin\theta} \quad (4)$$

$$i_{sq} = -i_{sa\ \sin\theta} + i_{s\beta\ \cos\theta} \quad (5)$$

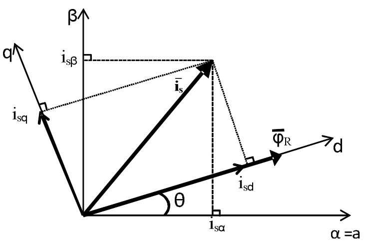

Fig. 2 Current Vectors in α-β and d-q rotating reference frame (θ: rotor flux position)

If the rotor position is obtained accurately and current vectors are transformed into d-q reference frame, two independent PI control can be applied for direct and quadrature component of current. Direct component (i_{sd}) is responsible for flux component and its reference (i_{sdref}) should be set to zero for PMSM. Because, in permanent magnet motors the rotor flux is created by the magnets and there is no need to create it. However, the quadrature part of the current (i_{sq}) is responsible for the required torque. Therefore, the reference for the quadrature part of PI controller (i_{sqref}) should meet the torque demand and can be set to the output of the speed regulator [3]. Speed controller including field oriented control diagram is given below.

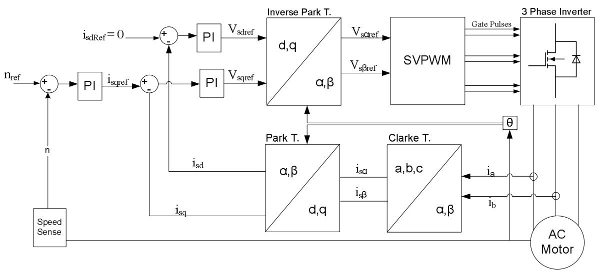

Fig. 3 Field Oriented Control

Outputs of the current regulators produce the voltage references (V_{sdref} , V_{sqref}) in d-q rotating reference frame. The stator voltage reference vectors in stationary α-β reference frame are obtained by applying inverse park transformation. Then, these references are subjected to SVPWM block to produce the appropriate gate signals of the inverter side.

2.2. Space Vector PWM

Development in solid state power switches and microprocessor technology has increased the popularity and usage of PWM inverters. The motor is driven by the inverter and the magnitude/frequency of the voltage/current vector applied to the motor is controlled by the applied PWM signals of the power switches.

PWM methods can be divided into two groups as scalar and space vector PWM methods [3, 4]. In scalar PWM, the reference signal is compared with a carrier signal and the switching pulses are generated at the intersections of these signals [2, 8]. It is also named as sinusoidal PWM (SPWM) which has a large application area. On the other hand, space vector PWM is an improved technique which is preferred to increase the output voltage of the inverter with less total harmonic distortion.

SVPWM technique is based on producing the reference voltage signal from the eight voltage vector of a three phase inverter. These voltage vectors are defined according to the switching state of each phase.

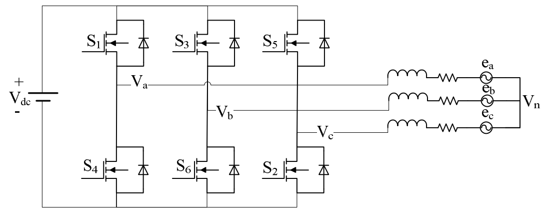

Fig. 4 Three Phase Voltage Source Inverter

Output voltage of the inverter can be represented as

$$V = (^2/_3)Vdc \times (S_A + \alpha S_B + \alpha^2 S_C) \quad (6)$$

Where $\alpha = e^{j2\pi/3}$

If the switching state of the upper leg is denoted with "1", one can obtain the possible vectors and voltages as given in Table 1. V_0 and V_7 are named as zero voltage vectors since they produce zero line to line voltages. The remaining six vectors are called as non-zero voltage vectors forming the axes of a hexagonal.

Table 1 On/Off States and Voltage Vectors

Voltage Vector	Switch $S_1S_3S_5$	Line-neutral			Line-Line		
		V_a	V_b	V_c	V_{ab}	V_{bc}	V_{ca}
V_0	000	0	0	0	0	0	0
V_1	100	2/3	-1/3	-1/3	1	0	-1
V_2	110	1/3	1/3	-2/3	0	1	-1
V_3	010	-1/3	2/3	-1/3	-1	1	0
V_4	011	-2/3	1/3	1/3	-1	0	1
V_5	001	-1/3	-1/3	2/3	0	-1	1
V_6	101	1/3	-2/3	1/3	1	-1	0
V_7	111	0	0	0	0	0	0

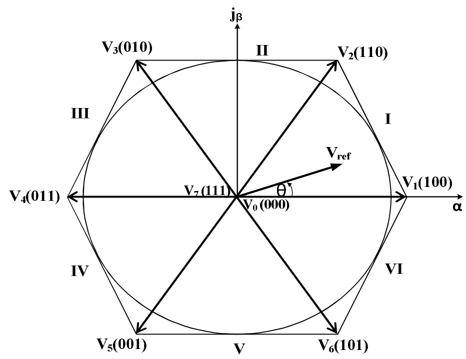

Fig. 5 Voltage Space Vectors Diagram

If the sector of the reference voltage vector is calculated, three stationary vectors can be selected to generate it. For instance, when the reference voltage is in sector 1, it can be formed by composed of V_1, V_2 and V_0. According to the volt-second balancing rule [4] during the sampling period T_s

$$V_{ref} \times T_s = V_1\, T_1 + V_2\, T_2 + V_0\, T_0 \qquad (7)$$

$$T_s = T_1 + T_2 + T_0 \qquad (8)$$

T_1, T_2 and T_0 are operating times of the vectors. By using (6), space vectors can be represented as:

$$V_1 = (2/3)V_{dc}\,, V_2 = (2/3)V_{dc}\, e^{j\pi/3}\ and\ V_0 = 0 \qquad (9)$$

Substituting (9) in (7) and decompose them in α-β plane we have:

$$V_{ref} \times (\cos\theta)\, T_s = (2/3)V_{dc}\, T_1 + (1/3)V_{dc}\, T_2 \qquad (10)$$

$$V_{ref} \times (\sin\theta)\, T_s = \left(1/\sqrt{3}\right) V_{dc}\, T_2 \qquad (11)$$

Solve (10) and (11) with Ts = T1 + T2 + T0 produces:

$$T_1 = \frac{\sqrt{3} T_s\, V_{ref}}{V_{dc}} \sin(\frac{\pi}{3} - \theta)$$

$$T_2 = \frac{\sqrt{3} T_s\, V_{ref}}{V_{dc}} \sin(\theta) \qquad 0 \le \theta \le \pi/3$$

$$T_0 = T_s - T_1 - T_2 \qquad (12)$$

If the reference vector lies on other sectors with an angle of θ', (12) can also be used if multiple of π/3 is subtracted.

$$\theta' = \theta - \frac{(k-1)\pi}{3}\ where\ k = 1,2 \ldots 6 \qquad (13)$$

The largest circle radius that can be fit in the vector hexagon given in Fig. 5 defines the maximum possible reference voltage vector. Since we have six active non-zero vectors with a magnitude of $2V_{dc}/3$, $V_{ref,max}$ is ;

$$V_{ref,max} = \frac{2V_{dc}}{3}\frac{\sqrt{3}}{2} = \frac{V_{dc}}{\sqrt{3}} \qquad (14)$$

Moreover maximum fundamental rms line to line voltage generated by SVPWM is;

$$V_{max,SVPWM} = \sqrt{3}\left(\frac{V_{ref,max}}{\sqrt{2}}\right) = 0{,}707\, V_{dc} \qquad (15)$$

If the inverter is controlled by sinusoidal PWM, maximum fundamental rms line to line voltage is $0{,}612V_{dc}$. Therefore, by utilizing SVPWM 15.5% higher line voltage can be achieved for a defined DC link bus when compared to SPWM technique [5, 6].

3. Simulation Model and Results

Space vector pulse width modulation technique is modeled in MATLAB/SIMULINK. The focus is based on generating the appropriate gate pulses of the inverter. In Fig. 6, block diagram of the overall system model is represented. Sector determination and switch time calculation algorithm is based on [7].

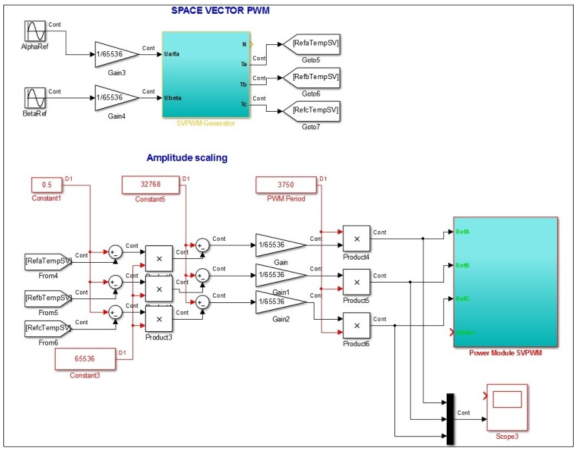

Fig. 6 Simulation Model in Simulink

3.1. Sector Determination

As discussed previously, there exist six sectors for voltage vectors. Let constants A, B, C and N as follows [7];

$$if\ V_\beta > 0 \rightarrow A = 1$$

$$if\ (\sqrt{3}V_\alpha - V_\beta) > 0 \rightarrow B = 1$$

$$if\ (\sqrt{3}V_\alpha + V_\beta) > 0 \rightarrow C = 1$$

$$N = A + 2B + 4C \qquad (16)$$

Corresponding sector number with respect to N is given in Table 2.

Table 2 Sector Number and N

Sector	I	II	III	IV	V	VI
N	3	1	5	4	6	2

3.2. Operation Time of Vectors and Switches

As discussed previously, the operation time of the vectors can be defined in terms of sampling period, angle of the reference voltage, magnitude of the DC link and the reference voltage (12). In the simulation, model given in [7] is utilized. According to this, three fundamental vectors named X, Y, Z are generated (Fig. 7) where;

$$X = T_s\,(-\sqrt{3}V_\alpha + V_\beta)/\sqrt{2}V_{dc} \qquad (17)$$

$$Y = T_s\,(\sqrt{3}V_\alpha + V_\beta)/\sqrt{2}V_{dc} \qquad (18)$$

$$Z = 2T_s\,(V_\beta)/\sqrt{2}V_{dc} \qquad (19)$$

Moreover, operation time of these fundamental vectors is given with respect to N and operation times of active adjacent vectors T_1 and T_2 (Table 3, Fig. 8).

Table 3 Operation Time of Fundamental Vector

N	1	2	3	4	5	6
T_1	Z	Y	-Z	-X	X	-Y
T_2	Y	-X	X	Z	-Y	-Z

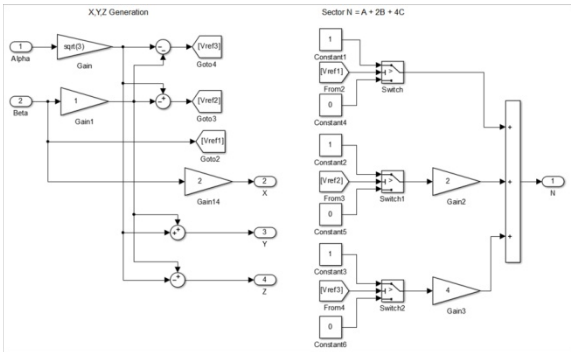

Fig. 7 Fundamental Vectors and Sector (N) Model

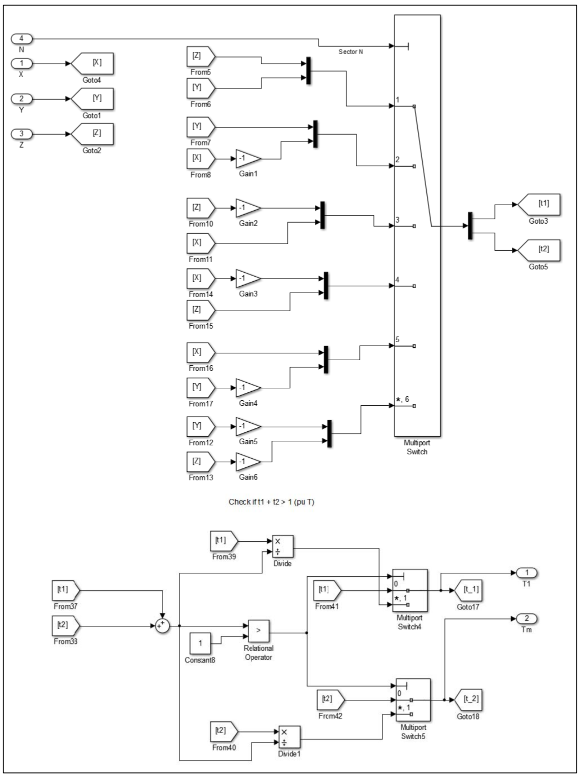

Fig. 8 Operation Time Model

Transition to the switch operation time of three phases (T_{cm1}, T_{cm2}, T_{cm3}) is performed using where $T_a = (T_s - T_1 - T_2) / 4$, $T_b = (T_a + T_1)/2$ and $T_c = (T_b + T_2)/2$

Table 4 Operation Time of Switches

N	1	2	3	4	5	6
$\mathbf{T_{cm1}}$	T_b	T_a	T_a	T_c	T_c	T_b
$\mathbf{T_{cm2}}$	T_a	T_c	T_b	T_b	T_a	T_c
$\mathbf{T_{cm3}}$	T_c	T_b	T_c	T_a	T_b	T_a

Finally, symmetrical PWM pattern is obtained by comparing the T_{cm1}, T_{cm2} and T_{cm3} references with a triangular carrier wave [7].

3.3. Simulation Results

When 90° phase shifted reference voltage is applied in α-β frame, the final references T_{cm1}, T_{cm2} and T_{cm3} are obtained as below (Fig. 9). The switching frequency is selected as 20 kHz.

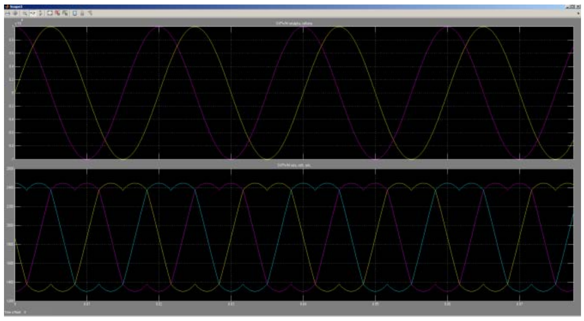

Fig. 9 Reference Generation in SVPWM

If the switching scheme is investigated, transition from one switching state to the next is performed by changing the state of only two switches in one leg of the inverter (Fig. 10, Fig. 11). For instance, transition from (000) to (100) is performed by turning on S1 and turning off S4 in Fig. 11.

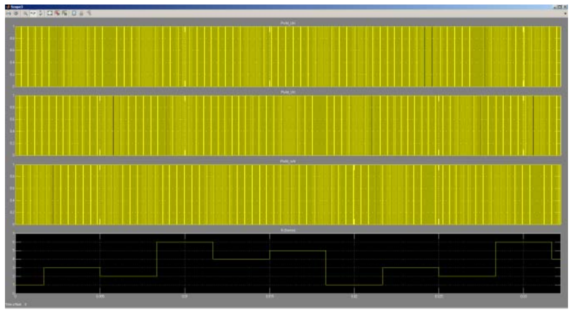

Fig. 10 PWM Pulses and Sector (N)

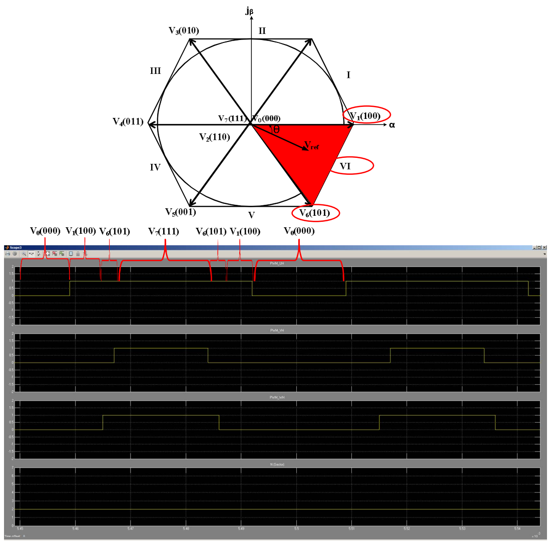

Fig. 11 PWM Pulses for a Defined Sector 6 (N = 2)

Moreover, the simulation is run to generate a 50Hz sinusoidal voltage output both with SPWM and SVPWM techniques. The frequency spectrum of the line voltage shows that the fundamental component obtained with SVPWM is nearly 15% higher than that of SPWM which is an expected advantage due to higher DC link utilization.

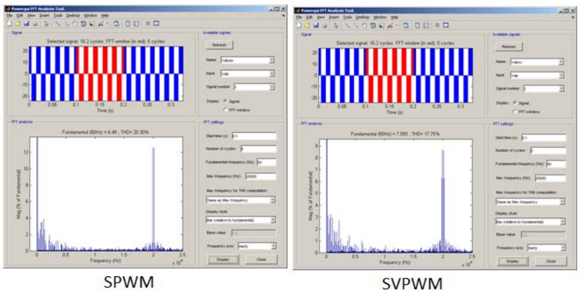

Fig. 12 Line Voltage Analysis

4. Experimental Results

After verifying the switching scheme in simulation model, the algorithm is implemented in the motor drive. Below are the properties of the experimental set up.

Table 5 Operation Time of Fundamental Vector

Parameter	Description
Motor Drive Power Output	~150W
$f_{switching}$	20kHz
Microcontroller	TI DSP F28335
Motor	Kollmorgen D061A-22-1290-029, Direct Drive Brushless DC, 230VAC-500rpm

Firstly, the brushless dc motor is driven for a given speed reference to validate the FOC with SPWM and SVPWM techniques (Fig. 13, Fig. 14).

In order to observe the effect of the SVPWM, the motor is driven with a high speed reference (228 rpm). By utilizing SPWM, the maximum speed that can be reached is measured as nearly 160 rpm (Fig. 15). The speed reference cannot be reached and the speed settles its maximum value at steady state.

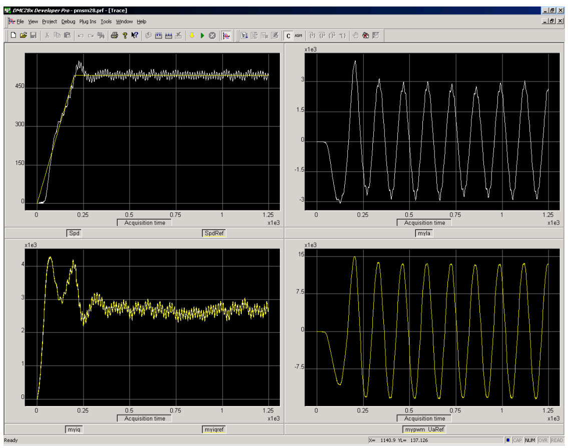

Fig. 13 Speed, Current and Voltage Reference with SPWM

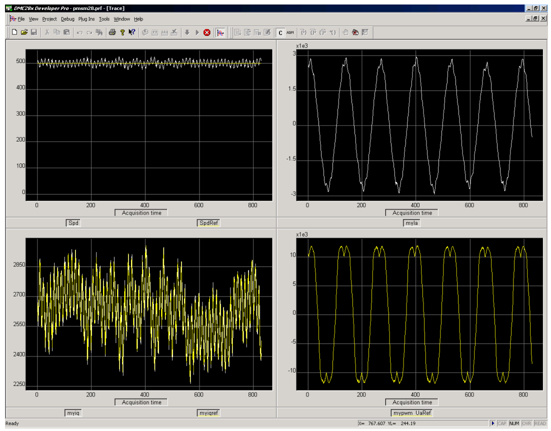

Fig. 14 Speed, Current and Voltage Reference with SVPWM

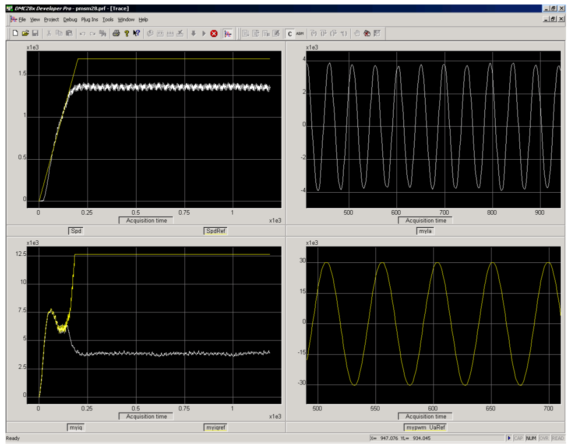

Fig. 15 Max Speed with SPWM

Moreover, same test is performed also with SVPWM technique with the same 24V dc link voltage. Similarly the speed does not reach to the reference value but it settles to a higher value nearly 184 rpm (Fig. 16, Fig. 17). Space vector pulse width modulation results in an increase of nearly 14% at motor speed. In brushless dc motors, speed is proportional to the applied terminal voltage. Therefore, higher DC link utilization advantage of SVPWM technique provides a better speed performance at the motor side.

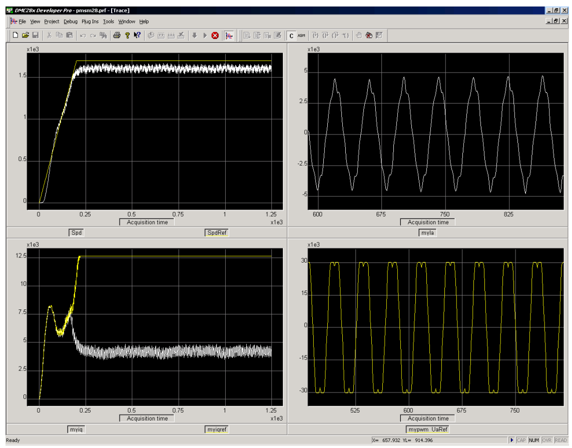

Fig. 16 Max Speed with SVPWM

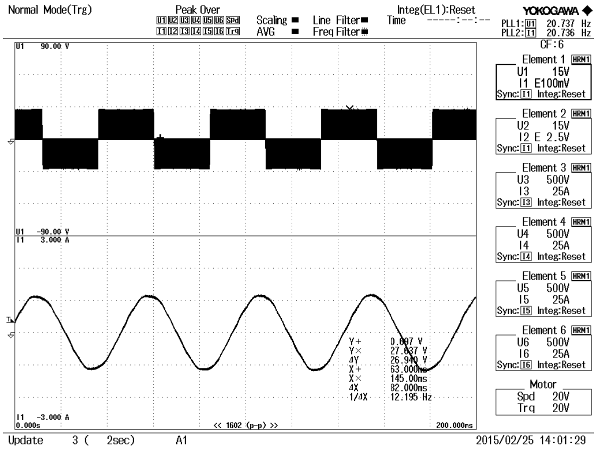

Fig. 17 Phase Current & Line Voltage of SVPWM

5. Conclusions

In this paper, SVPWM technique in field oriented control algorithm is discussed. Firstly their principles available in the literature are presented. Then, the simulation model is formed to validate the PWM pattern before the implementation procedure. The simulation model is also verified with the experimental results by utilizing an ASELSAN INC. product named “AVAR Servo Drive”. As expected, SVPWM method results in higher DC link utilization nearly 15%. Its effect is observed in terms of maximum speed that can be obtained by keeping all the parameters constant except for PWM technique. Therefore, it is concluded that for a given DC link voltage, SVPWM can be a better way to reach higher speeds when compared to SPWM. However, both PWM methods should be compared by considering all aspects such as harmonic distortion, losses etc. which is not included in this study.

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