SENSOR-LESS CONTROL OF A PERMANENT MAGNET SYNCHRONOUS MOTOR USING A NOVEL FOUR SWITCH THREE PHASE INVERTER AND EXTENDED KALMAN FILTER

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ABSTRACT: *This paper presents the sensor-less control of a PMSM using extended Kalman Filter and a four switch three phase inverter implemented using FPGA Spartan 3-e. The system was modeled in Matlab/Simulink® and verified using experimental setup. System-Generator along with Xilinx® was used to develop control on Spartan 3-e plat form. The dynamic model of permanent magnet synchronous motor simulated in Matlab/Simulink® environment was validated and used to extract parameters for the design of extended Kalman filter. The EKF was tuned to estimate the speed and rotor position and results have been presented to ensure the performance of estimation of EKF. The estimation using EKF has reduced the parametric variation effect on speed and rotor position. The estimated parameters were used to implement the speed and current loops for vector control of PMSM using space vector pulse width modulation based four switch three phase inverter. The authentic working of this four switch three phase inverter was also checked against the usual six switch inverter. The reduction of power switches by two reduced the initial cost, switching losses and made inverter configuration compact. The complete System Generator model has been presented along with the result to demonstrate the performance of the PMSM drive using EKF based estimation on FPGA plate form.*

KEYWORDS: Permanent Magnet Synchronous Motor(PMSM), Space Vector Pulse Width Modulation(SVPWM), Extended Kalman Filter(EKF), Field Programmable Gate Array, Xilinx System Generator®, Estimation of Parameters, Four switch three phase inverter(FSTPI)

1. INTRODUCTION

In industry, variable speed applications require the need of Permanent magnet synchronous motor drives. Features such as high power density, dynamic performance and high torque to weight ratio has allowed these drives to surpass induction machines [2].

Power processing by use of high computational devices has shifted the interest to sensor-less control of PMSM [9]. Different commonly used algorithms for sensor-less control for the operation of PMSM has been are described in reference [8]. In early days V/F scalar control was used quite extensively. In order to control the speed of the motor, Frequency and terminal voltage are maintained in a proportionality relation over a wide range. Field weakening mode in [10] has also used the same scalar control in order to control the speed of the PMSM. The sensor-less operation however is not complete without introducing an estimator to estimate required parameters even in the noisy environment to ensure complete control of the machine.

In early decade of 1990, introduction of vector controlled scheme changed the whole dynamics for the control of PMSM. Field oriented vector control, direct vector control and indirect vector control has been presented in reference [5] and [6] for the high performance operation of PMSM drives. The main disadvantage of using the sensors were slow response, enhancement in size and reduction in reliability. The high end cutting edge computational power availability at reduced cost has encouraged industry to adopt sensor-less operation in all vector control technique. Reference [3] has presented the sensor-less vector control for the speed control of PMSM.

Reference [4] describes the modern control techniques that are being adopted in order to investigate the performance of PMSM eliminating the effects of position and speed sensors. Sliding mode observer (SMO), model adaptive reference system (MRAS), extended Kalman filter (EKF) and reduced order EKF are some of the strategies that has been adopted for sensor-less control of PMSM recently [2].

Slide Mode Observer technique provides briskness to certain disturbances and crucial parameter variation. In the high speed region of the motor, the gain of slide mode observer should be large enough for a stable operation. But in low speed region and flux weakening region, the estimated values of the currents and back EMF cannot help as they have large ripples. These ripples produce large number of chattering components. Large ripple back EMF is the base of sensor-less control of PMSM as information about the position of rotor and rotor speed are contained in this EMF. Slide mode observer has to be operated for short periods in order to get signal of the back EMF (estimated) and also the current (estimated) which are ripple free. For this it has to be operated with a digital signal processor (DSP) or FPGA which provides very fast computational power. In MRAS, an adaptive model is compared with dynamic model of the machine and adopts the variation in the estimated parameter to minimize error in the estimated value. Usually the stator model acts as the reference model and rotor model is used for adoption. The detailed mechanism of MRAS has been explained in reference [10]. An MRAS has been observed to be quite accurate in the estimation of speed in over the wide range of variation including the very low speed profile [11].

The Kalman filter is an *NxN* stochastic observer which provides real time state estimation by using the measured states and covariance of the noisy signals [12, 14].Comparing with SMO, EKF provides the best solution to estimate the speed and position using the filtering action along with estimation. It also owns a very high convergence rate which can give a more rapid speed response [3]. Extended Kalman filter can estimate the initial opposition of the rotor for accurate estimation of the speed. However EKF requires heavy *NxN* matrix computing, where N defines the number of state variables.

For this reason, this paper proposes Field Programmable Gate Arrays (FPGAs) based estimation of the speed and position of the machine.

Inverters are of extreme importance in daily life being used in motor drives, uninterruptable power supplies, induction heating, DC transmission lines, variable frequency drives and electroshock weapons [23]. Conventionally six-switch inverters have been used that comprise of two switches in each of the three legs. AC drives with six switch three phase inverters were popular few decades ago but now-a-days, they are losing attention because of their complex algorithms, more switching losses and generation of six switching signals as compared to four in modern three phase inverters [24],[25]. Unipolar as well as bipolar switching can be done on these inverters depending upon the type of control. Different switching techniques can be implemented to generate control signals. Few of them include 180° conduction, 120° conduction, sinusoidal pulse width modulation (PWM), harmonic injected PWM, trapezoidal PWM, multiple PWM, space vector PWM [22]. Each of these techniques possesses benefits as well as drawbacks over others [26],[22].

Space vector PWM technique of six switch configuration can be modified and analogy may be developed for four switch configuration. Space vector has been implemented for FSTPI because of its advantages over other switching techniques [27]. Several papers have been reported on four switch inverters. [25],[27] have presented four switch three phase inverter with space vector pulse width modulation but have resulted in severe unbalancing of currents. Total Harmonic Distortion found in [22] is also very poor. Currents obtained on hardware discussed in [27] are not reasonable.

In this paper, a sensor-less control has been modeled by a Xilinx System Generator (XSG) in Matlab/Simulink® environment with speed and position estimation and using space vector pulse width modulation technique for the operation of a novel four leg three phase inverter. The results of speed and position estimation have been presented to establish the achievement of the proposed FPGA based estimation of the parameters.

2. DYNAMIC MODEL OF A PMSM

For the implementation of the sensor-less control the observers require the dynamic model of the machine under experiment. The equation (2.1) presents the state space equation defining the d-q axis model of the machine.

$$\frac{di_d}{dt} = -\frac{R_s}{L_d} i_d + \omega \frac{L_q}{L_d} i_q + \frac{V_d}{L_d}$$
$$\frac{di_q}{dt} = -\omega \frac{L_d}{L_q} i_d - \frac{R_s}{L_q} i_q - \omega \frac{\phi_f}{L_q} + \frac{V_q}{L_q} \quad (2.1)$$

Where V_q, V_d, i_d and i_q are the respective q and d axis voltages and currents in synchronously rotating frame of reference. The q and d axis inductances are represented by L_q and L_d, ω represents the rotating speed and ϕ_f represents the permanent magnet flux linkage. The mechanical system model was developed using the following set of equation in synchronously rotating frame of reference.

$$I_m \frac{d\omega_r}{dt} + B\omega_r = T_e - T_L \quad (2.2)$$

$$T_e = \frac{3}{2} \cdot \frac{P}{2} \cdot \phi_f . i_q = K_a . i_q \quad (2.3)$$

Where T_e is the electromagnetic torque of the motor, P represents the no. of poles, K_a is torque constant, I_m is the inertia value, B is the damping ratio and T_L is the load torque and ω_r is the speed of rotor.

3. FOUR SWITCH THREE PHASE INVERTER

Figure 1 shows the configuration of the four switch three phase inverter. DC voltage source can be obtained after doing single phase half wave, full wave or three phase rectification. This DC voltage is fed to FSTPI which converts it back to three phase AC power. Output of FSTPI is provided to SM from which we can do different analysis. Control signals required by FSTPI will be provided by Texas instruments TMS320F2812 development kit.

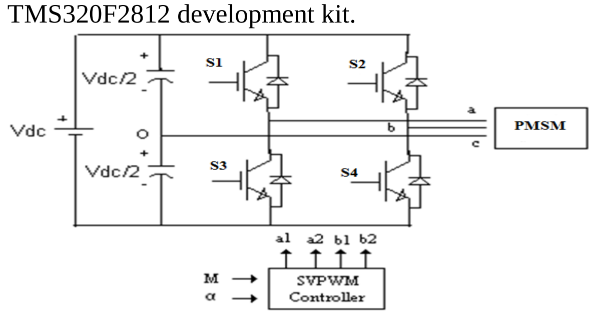

Figure 1: Four Switched Three Phase Inverter Configuration

If V_{DC} is the maximum voltage available, $V_{C1}=V_{C2}=V_{av}$ will be equal to $V_{DC}/2$. Two of the phases namely 'a' and 'b' are connected to the inverter legs while third phase 'c' is connected to center point of split DC capacitors. Power switches are represented by symbols S_1-S_4, considered ideal and are operated in complementary mode to prevent short circuiting of DC supply such that following equations hold

$$S_1 + S_2 = 1 \quad (3.1)$$

$$S_3 + S_4 = 1 \quad (3.2)$$

Table: 1 Switching combinations and output voltages

Switching Combinations		Output Phase Voltages			Voltages in Space
S_1	S_3	V_A	V_B	V_C	$\vec{V} = V\alpha + V\beta$
0	0	$-V_C/3$	$-V_C/3$	$2V_C/3$	$\overrightarrow{V1} = \frac{V_{DC}}{3} e^{-i\frac{2\pi}{3}}$
0	1	$-V_C$	$+V_C$	0	$\overrightarrow{V2} = \frac{2V_{DC}}{3} e^{-i\frac{\pi}{6}}$
1	1	$V_C/3$	$V_C/3$	$-2V_C/3$	$\overrightarrow{V3} = \frac{V_{DC}}{3} e^{i\frac{\pi}{3}}$
1	0	$+V_C$	$-V_C$	0	$\overrightarrow{V4} = \frac{2V_{DC}}{3} e^{i\frac{5\pi}{6}}$

Where 1 corresponds to turning ON of switch and 0 will represent its OFF state. Terminal voltages are expressed by equations (3.3),(3.4) and (3.5).

$$V_A = V_{av} * \left(4S_1 - 2S_3 - 1\right)/3 \qquad (3.3)$$

$$V_B = V_{av} * \left(4S_3 - 2S_1 - 1\right)/3 \qquad (3.4)$$

$$V_C = V_{av} * \left(-2S_1 - 2S_3 + 2\right)/3 \qquad (3.5)$$

where V_A, V_B and V_C are phase voltages; V_{av} is the voltage across the DC link capacitors.

4. SPACE VECTOR REPRESENTATION

SVPWM for four-switch three-phase inverter has been modeled on the basis of similarity with six-switch three-phase inverter. Four switching states can be possible with FSTPI and are listed in table. Table 1 discusses different modes and output voltage vectors. The combinations of switching S1-S4 result in four general space vectors as shown in figure2.

In order to form the required voltage vector V_{ref}.

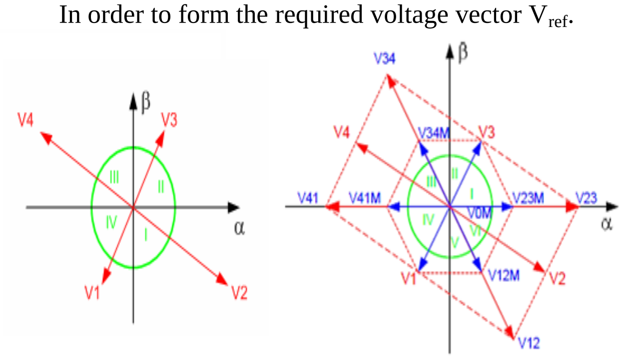

Figure 2: Space vectors using (a) conventional method (b) similarity with Six Switch Three Phase Inverter

The switching algorithm of SVPWM for four-switch three phase inverter can be based on the one for six switch inverter where orthogonal plane is divided into six sectors and the formation of required reference vector is done in the same way as for six switch inverter. This facilitates the calculation for FSTPI and same studies for six switch three phase inverter(SSTPI) can also be implied on FSTPI. Representing voltage in α and β coordinates and solving for duty cycles will result in following equations as discussed in [26].

$$T_1 = \frac{2\sqrt{3}}{\pi} T_a \sin\left(\frac{n\pi}{3} - \theta_{ref}\right)$$
$$T_2 = \frac{2\sqrt{3}}{\pi} T_a \sin\left(\theta_{ref} - \frac{n-1}{3}\pi\right) \qquad (4.1)$$
$$T_o = \frac{T_a}{2} - (T_1 + T_2)$$

The active vectors are switched for time T_1 and T_2. The null vectors are switched for time T_o in switching interval T_a. The equation (4.1) ensures that the average vector produced over this time period is equal to V_{ref} both in respect of magnitude and angle.

5. DESIGN OF EKF BASED ESTIMATOR

For high performance sensor-less drives, it is necessary to devise an algorithm for accurate and robust estimation of the motor variables. For this many observers have been proposed, but very few of them are able to handle wide speed range sensor-less operation accurately and persistently. Due to the high sensitivity of the observers to the nonlinearities and disturbances, small magnitude of the back EMF signal and the offsets in integral, their performances are poor at lower speeds [20].

The Kalman filter takes the effects of noises of both system and surroundings into account using the covariance matrices which are updated in each iteration, thus providing estimation and filtering. The errors in parameters are also rendered as noises [14, 15]. For a motor, the dynamic state model for non-linear stochastic system is defined in equation (5.1) where all symbols are representing vectors or matrices [18, 19].

$$\dot{x}(t) = g[x(t)] + Bu(t) + w(t)$$
$$y(t) = h[x(t)] + v(t) \qquad (5.1)$$

TABLE: 2 SWITCHING COMBINATIONS FOR FSTPI USING THE SYMMETRY BETWEEN THE PLANES OF FSTPI AND SSTPI.

Switching vectors with SSTPI	Switching vectors with FSTPI	Switching vector Timings	ON-time of a switch	Optimized switching pattern
Vb, V3, Vnull=(V0+V7)/2	Vb:(V2+V3)/2, V3, Vnull=(V1+V3)/2	V1: T0/2=Ta V2: T1/2=Tb V3: T0/2+T1/2+T2=Tc	S1=Tb+Tc S2=Tc	V1,V2,V3, V3,V2,V1
V3, Vc, Vnull=(V0+V7)/2	V3, Vc:(V3+V4)/2, Vnull=(V1+V3)/2	V1: T0/2=Ta V3: T0/2+T1+T2/2=Tc V4: T2/2=Td	S1=Tc S2=Tc+Td	V1,V4,V3, V3,V4,V1
Vc, Vd, Vnull=(V0+V7)/2	Vc:(V3+V4)/2, Vd:(V1+V4)/2, Vnull=(V1+V3)/2	V1: T0/2+T2/2=Ta V3: T0/2+T1/2=Tc V4:T1/2+T2/2=Td	S1=Tc S2=Tc+Td	V1,V4,V3, V3,V4,V1
Vd, V1, Vnull=(V0+V7)/2	Vd:(V1+V4)/2, V1, Vnull=(V1+V3)/2	V1: T0/2+T1/2+T2=Ta V3: T0/2=Tc V4: T1/2=Td	S1=Tc S2=Tc+Td	V1,V4,V3, V3,V4,V1
V1, Va, Vnull=(V0+V7)/2	V1, Va=(V1+V2)/2, Vnull=(V1+V3)/2	V1: T0/2+T1+T2/2=Ta V2: T2/2=Tb V3: T0/2=Tc	S1=Tb+Tc S2=Tc	V1,V2,V3, V3,V2,V1
Va, Vb, Vnull=(V0+V7)/2	Va=(V1+V2)/2, Vb:(V2+V3)/2, Vnull=(V1+V3)/2	V1: T0/2+T1/2=Ta V2: T1/2+T2/2=Tb V3: T0/2+T2/2=Tc	S1=Tb+Tc S2=Tc	V1,V2,V3, V3,V2,V1

Where $w(t)$ and $v(t)$ represents system noise and measurement noise matrices. Both these matrices are zero-mean white Gaussian distribution matrices with covariance Q and R. The linearized model of the above system of equations is written in equation (5.2).

$$\delta\dot{x}(t) = G[x(t)]\delta x(t) + Bu(t) + w(t)$$
$$\delta y(t) = H[x(t)]\delta x(t) + v(t) \qquad (5.2)$$

Where G and H are the Jacobean matrices.

$$G[x(t)] = \lim_{x \to x(t)} \frac{\delta g}{\delta x}$$
$$H[x(t)] = \lim_{x \to x(t)} \frac{\delta h}{\delta x} \qquad (5.3)$$

The discrete model for above system with sampling time T_s is presented in equation (5.4) as:

$$x(k) = (1 + GT_s)[x(k-1)] + BT_s[u(k-1)] + w(k-1)$$
$$y(k) = H[x(k-1)] + v(k-1)$$

(5.4)

The EKF algorithm is basically described by the following two steps.

Step 1-- Prediction Step: It performs the prediction of state and determines the covariance matrices based on the previous estimates. Covariance matrix is updated in every iteration using equation (5.5) as:

$$\hat{x}_{k|k-1} = \hat{x}_{k-1} + (g[\hat{x}_{k-1}] + Bu_{k-1})T_s$$
$$P_{k|k-1} = \pi_{k-1} P_{k-1} \pi^T_{k-1} + Q \qquad (5.5)$$

Step 2 -- Innovation Step: Through a feedback correction scheme the state vector and covariance matrix are modified by introducing the effects of Kalman gain.

$$\hat{x}_{k|k-1} = \hat{x}_{k-1} + A_k(y_k - H\,\hat{x}_{k|k-1})$$
$$P_k = P_{k|k-1} + A_k H P_{k|k-1} \qquad (5.6)$$
$$A_k = P_{k|k-1} H^T [H P_{k|k-1} H^T + R]^{-1}$$

The state vector along with input and output vectors are chosen as given in equation (5.7) as:

$$x(t) = \left[i_\alpha i_\beta \omega \theta_e\right]^T$$
$$y(t) = \left[i_\alpha i_\beta\right]^T \qquad (5.7)$$
$$y(t) = \left[V_\alpha V_\beta\right]^T$$

Following are nine steps those are adopted for the estimation of position and speed of PMSM based on EKF

Step 1: Starting values of R, P, Q, and n are set.
Step 2: The values of $i_{\alpha(k)}$, $i_{\beta(k)}$, $V_{\alpha(k)}$, and $V_{\beta(k)}$ from system are measured.
Step 3: The temporary state variables are estimated.
Step 4: Calculate the g_{k-1}
Step 5: Obtain the temporary covariance matrix $P_{k|k-1}$
Step 6: Kalman gain is calculated by equation (5.6).
Step 7: State variables are then modified.
Step 8: Present covariance matrix P_k is then updated.
Step 9: The rotor speed is calculated.

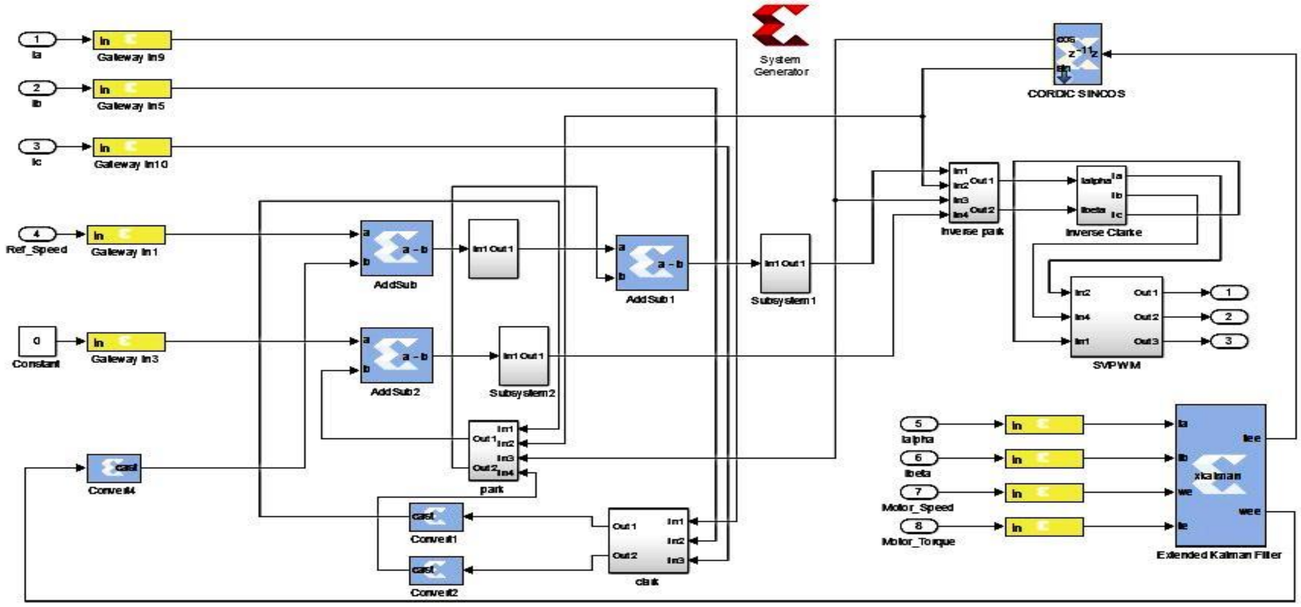

Figure 3: Complete Simulink Modeling of Sensor-less control of PMSM via System Generator

6. REAL TIME SYSTEM MODELING USING SIMULINK

Xilinx system generator® tool is being developed for Matlab/Simulink® package. It allows the user to perform algorithm development and verification in both DSP and FPGAs. It allows automatic translation of traditional Simulink block sets into hardware implementations that are efficient and synthesizable [21].

Authors have modeled a sensor-less control of PMSM via SVPWM and extended Kalman filtering using Matlab/Simulink® and Xilinx system generator®. All the control signals in the model were generated by the Xilinx system generator® tool which provides an interface between FPGA and Simulink block-sets. These block-sets were then translated to the VHDL codes that are necessary for the controller to be embedded into the FPGA. These Xilinx block-sets can be added to the Matlab/Simulink® library to be used by the Simulink software. The complete system model is shown in Figure 3.

All the control blocks and related sub-blocks of the system developed using Xilinx block-sets in Matlab/Simulink® Environment are shown in the Figures 4, 5 and 6.

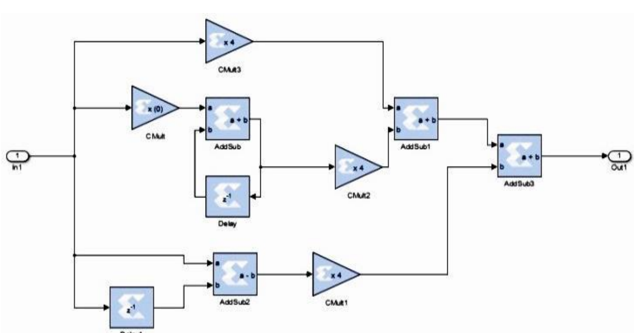

Figure 4: Design of PI controller via System Generator

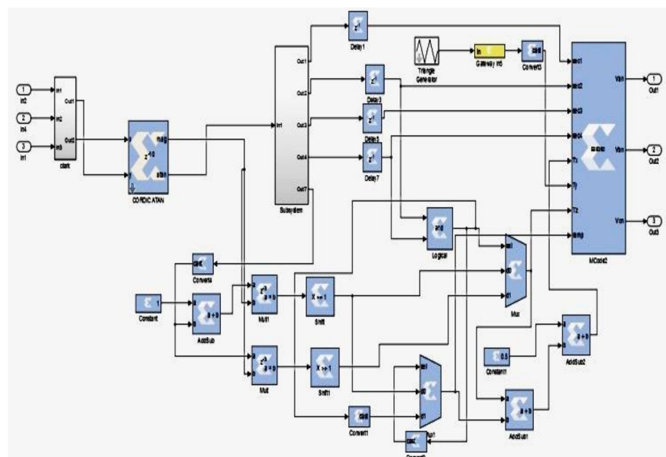

Figure 5: SVPWM block-set via System Generator

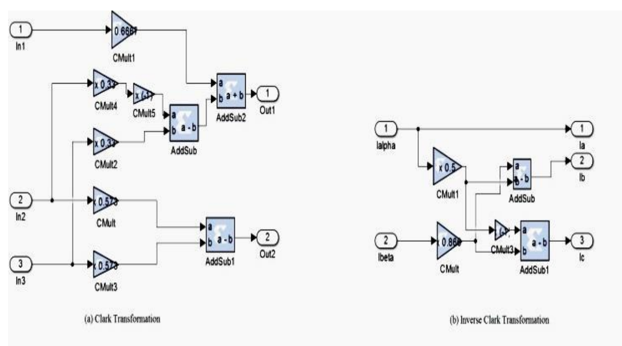

Figure 6: Transformation from abc to abo and vice versa

8. RESULTS AND DISCUSSION

The proposed algorithm was simulated in Matlab/Simulink® and was implemented using the FPGA kit Spartan 3e. The observed results are shown in Figure 7, 8 and 9. Figure 7 presents the actual and estimated speed using EKF. The proportional and integral gains were adjusted in order to obtain satisfactory performance of the.

Table 3: Motor Parameters

Parameters	Symbol	Values	Units
Stator Resistance	R_S	0.2	ohms
Stator Inductance	$L_d = L_q$	0.0085	Henry
Inertia	I	0.089	kg*m^2
No of Poles	P	4	
Rotor Magnetic Flux	φ_f	0.175	Wb
Friction Factor	F	0.005	N*m*s
Proportionality Gain	K_P	5	
Integral Gain	K_I	10	

speed control loop at low speed ranges. Figure 7 shows the estimated speed closely follow the actual speed and verifies the performance of the system. The rotor position and electromagnetic torque has been shown in Figure 8 and Figure 9 respectively

The graphs of speed and position shows that extended Kalman filter is a direct estimate to the exact speed and position of the rotor.

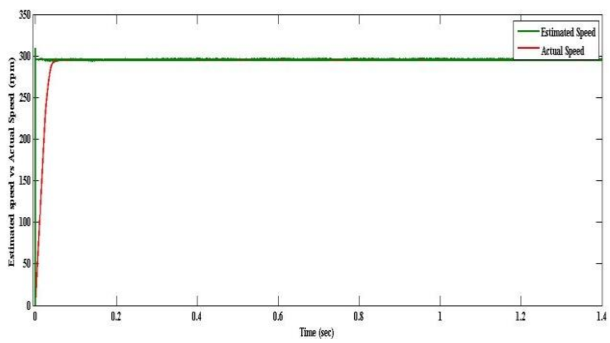

Figure 7: Actual and Estimated Rotor Speeds

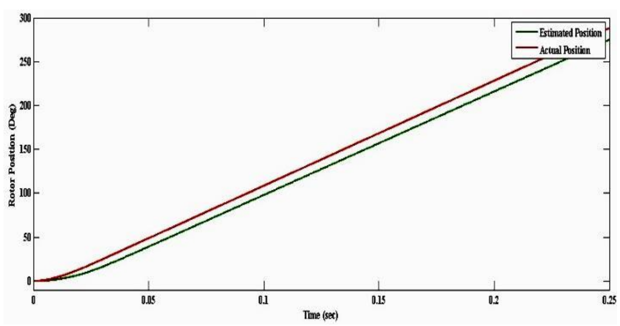

Figure 8: Real Position of the Rotor

However the estimated position is slightly lagging the actual speed because of computational time in the hardware structure. Kalman filter is a deterministic type state observer that provides an estimation of state variables of the system, by minimizing the square error, when both system inputs and outputs are subjected to random disturbances. It is utilized to estimate speed and stator resistance and compensate the effects of parameter variation, which makes flux and torque estimation more accurate and insensitive to parameter variation. As can be seen from the graphs, EKF estimates speed, position, rotor-fixed current and load torque. It is capable of tracking actual rotor speed, position and load torque provided that elements of covariance matrices are properly selected. The torque and speed results have shown that the performance of EKF works perfectly.

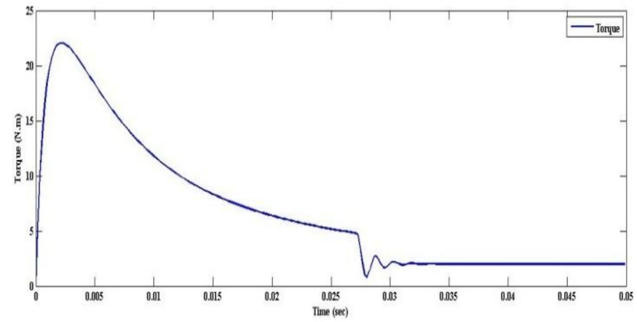

Figure 9: Electromagnetic Torque

EKF based estimation and control in this work has shown that EKF provides better solution for speed and position estimation than model adaptive reference system (MRAS) in reference [10, 11] and sliding mode observer (SMO) in reference [2]. The supply currents of PMSM are shown in Figure 10.

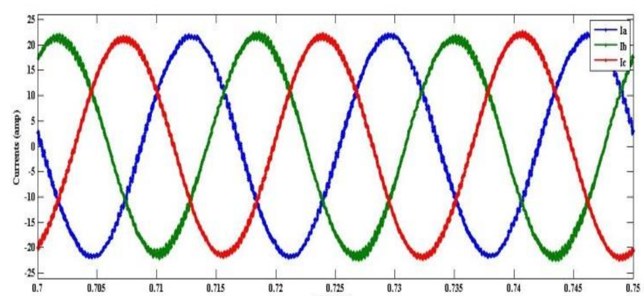

Figure 10: Phase currents (abc)

The phase current 'a' is shown in Figure 11. This current is due to the Clark's transformation. Figure 12 shows different segments of state vector pulse width modulation (SVPWM) being implemented by Xilinx system generator® in Matlab/Simulink®. Figure 10, 11 and 12 are showing a remarkable achievement of the results obtained by using FSTPI instead of SSTPI. With lesser number of switches , we are able to obtain the exact same results thus reducing the cost of extra switches and minimizing the effects of switching losses.

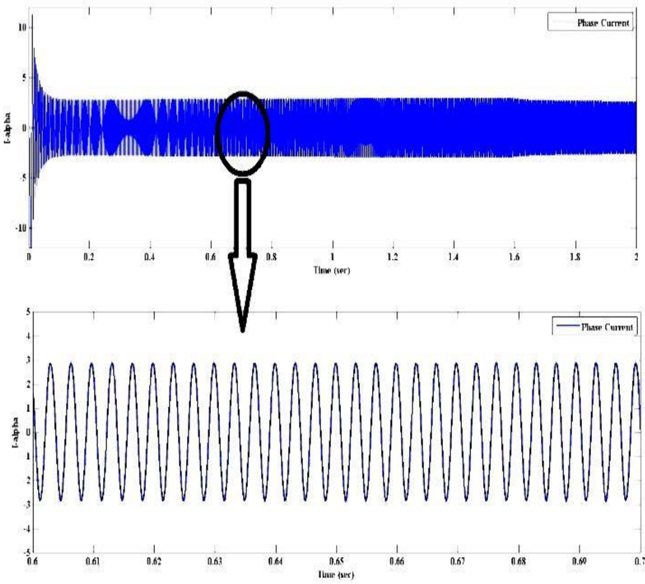

Figure 11: Clark Transformation 'a' phase current

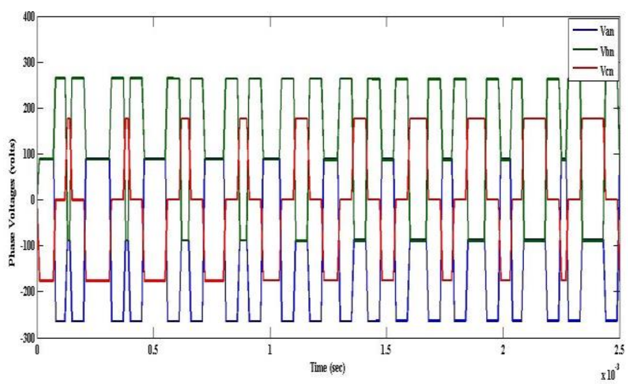

Figure 12: Phase Voltage of SVPWM

7. CONCLUSION

This paper has presented a FPGA based implementation of sensor-less control of a PMSM using the extended Kalman filter algorithm and four switch three phase inverter. The whole system was modeled in Matlab/Simulink® with the use of Xilinx system generator® block-sets. The VHDL code generated by Xilinx system generator® was then downloaded on Spartan 3E FPGA using Xilinx ISE®, on basis of which, the behavior of EKF algorithm was described. FPGA provided single cycle implementation of space vector and implemented the observer and estimator with reduced cost. Thus, a reliable and time saving design realization option is now available to the designer. It was observed that EKF based implementation of sensor-less control is much more efficient as compared to SMO and MRAS. The presented results verified EKF performance for sensor-less control of PMSM. Moreover, it was also seen that EKF based estimation is efficient even though initial position of rotor is not known. The authenticity of four switch three phase inverter is also checked and it is shown by the graphs of phase voltages and currents that these results are quite close to that of using a six switch three phase inverter. Thus, reducing our cost to a significant extent. In simulated results, it was evident that the use of EKF in sensor-less PMSM drive can accurately estimate the rotor position and rotor speed.

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