SIMULATION AND EXPERIMENTAL EVALUATION ON PMSM WITH FPGA

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Abstract: *This work presents FPGA implementation of Direct Torque Control (DTC) for Surface Mounted Permanent Magnet Synchronous Motor (SPM) using fuzzy logic controller. Using VHDL, the Direct Torque Control algorithm with fuzzy controller is designed and implemented on a Xilinx Spartan-3 FPGA board. The important characteristic of a DTC is its precise control and quick response. Three sets of DTC space vectors are considered for analysis purpose and the performance of the three control schemes are evaluated in terms of torque ripple, flux ripple and transient response to step variations in torque and speed control commands. By choosing proper membership functions and rule base in FLC an accurate voltage space vector with a smaller hysteresis band is possible, which reduces torque and flux ripples to a great extent. Experimental results with FPGA for transient response of the drive using fuzzy logic controller are implemented for step changes in speed and load torques.*

Keywords: *DTC, Surface Mounted Permanent Magnet Synchronous Motor (SPM), FPGA, Fuzzy Logic Controller*

1. Introduction

Surface mounted permanent-magnet synchronous motor (SPM) also known as the axial flux permanent magnet motor, in which the permanent magnets are placed on the surface of a cylindrical iron-laminated rotor body, where as stator possesses three phase winding [1]. The absence of rotor winding and its related losses, leads to high efficiency, high torque/weight ratio, and reduced cooling requirements [2]. Also due to high equivalent magnetic air gap results in a very low synchronous inductance by which the armature reaction effect on pole flux of SPM is low when compared with other machines of similar size [3] [4].
Due to its high efficiency, high power density and linear torque characteristics made suitable for a wide range of applications like in high performance elevator drive systems, actuators for industrial robots and wheel in motor for hybrid vehicles. The flux-weakening operation with sufficient torque capability of SPM finds applications in wind generators in attaining a wide range of speed control [1].

PMSMs have been introduced with DTC in 1990's. DTC with its decoupling feature controls torque and flux independently. Since DTC does not have explicit mathematical model [5], selecting exact voltage space vector is difficult which results in torque and flux ripples considerably. But keeping torque and flux within limits is important with the help of proper voltage space vector. The amount of the tolerance limit of the torque ripple is subject to its application. The torque ripple is negligible if the PMSM drive is used in pump applications. In surface finish of metal working machines the magnitude of the torque ripple directly proportional to the smoothness of the produced torque. For heavy load operating conditions, PMSM produces non linear electromagnetic torque which introduces transient torque oscillations.

The control methods of AC drives depend on advanced microprocessor and DSP techniques to implement the complex, real-time control algorithms necessary for high dynamic performance of the AC drive. These conventional techniques have the disadvantages like complexity in design, more power consumption and limited computational capability. Many control functions tend to migrate from microcontrollers (or DSP) platforms to SoPCs.

In 1984 Xilinx developed the fist FFGA which broke the barrier of developing register-intensive programmable devices [6]. Those devices evolved to the high performance CPLDs and FFGAs that are now being commercialized in the market [7].

The use of FPGAs, instead of other architectures in the field of drives, was mainly based on three factors: the acceleration of the design or parts of it, the flexibility of the reconfigurable hardware (RH), the reduction of costs [8]. Hence the dynamic and fast change in VLSI technology has radically changed the design process. The life cycle of modem electronic products may be even shorter than its design cycle. Therefore, the need for rapid prototyping becomes a design challenge for modem electronic products. The advent of field-programmable gate array (FPGA) technology has enable rapid prototyping of digital systems [9]. The FPGA realization of the PWM strategies provides advantages such as fast prototyping, simple hardware and software design, higher switching frequency, reuse, restructure and release the computation load of the microprocessor.

In the proposed digital DTC controller with FPGA implementation has the following special features: very fast dynamic response, less failure chances, since this controller works under 1,2v input voltage it has very less power consumption (56 mW), re programmability, low cost, high accuracy (about 99%), high speed. Verilog HDL is a rich and versatile language that can be used for synthesis, modelling and simulation. Verilog HDL is supported by all major Computer Aided Engineering (CAE) platforms and synthesis tools can compile Verilog HDL designs into a large variety of target technologies [10].

The conventional PID controller fairly works with linear control system, In PID controller; the pre defined sets are unable to adapt automatically the non linear systems such as DTC. Whereas Fuzzy Logic Controller adopts adapts non linear systems automatically [11]. FLC converts a set of natural linguistic variables into a automatic control method with expert knowledge [12]. In conventional DTC, torque hysteresis controller is normally divided in to two or three levels. But in FLC, torque error can be sub divided very easily in to more than three sub divisions to obtain precise torque control. In this paper, FPGA implementation of SPM drive is realized using fuzzy logic controller.

2. Proposed Digital DTC Controller

The goal of the proposed control system is to control the torque which in turn controls the speed of a SPM. The function of the digital DTC controller realizes the optimal switching logic to select the appropriate stator voltage vector that will satisfy both the torque status output and the flux status output. The SPM is modelled using sensor less DTC contains a speed control loop with Fuzzy logic controller to obtain a reference electromagnetic torque.
Three sets of DTC space vectors (CDTC, DTCI and DTCII) are considered for analysis purpose and the performance of the three control schemes are evaluated in terms of torque ripple, flux ripple and transient response to step variations in torque and speed control commands. Simulation results using MATLAB/SIMULINK show the effectiveness of the proposed method. The three sets of DTC are given table1.The SPM is modelled using sensor less DTC contains a speed control loop with Fuzzy logic controller to obtain a reference electromagnetic torque.

Table 1: Space Vector Division

Sector No.	CDTC (Conventional DTC)	DTCI	DTCII
1	$-30^0 \rightarrow +30^0$	$0^0 \rightarrow 60^0$	$-45^0 \rightarrow 15^0$
2	$+30^0 \rightarrow 90^0$	$60^0 \rightarrow 120^0$	$15^0 \rightarrow 75^0$
3	$90^0 \rightarrow 150^0$	$120^0 \rightarrow 180^0$	$75^0 \rightarrow 135^0$
4	$150^0 \rightarrow 2\ 100^0$	$180^0 \rightarrow 240^0$	$135^0 \rightarrow 195^0$
5	$210^0 \rightarrow 270^0$	$240^0 \rightarrow 300^0$	$195^0 \rightarrow 255^0$
6	$270^0 \rightarrow 330^0$	$300^0 \rightarrow 360^0$	$255^0 \rightarrow 315^0$

An accurate dynamic model of the motor is necessary which can explain the dynamic behaviour of the machine under both transient and steady state conditions. In the rotor reference frame, the voltage equation and the torque equation of SPM are expressed as follows. In the rotor reference frame, the voltage equations, flux and the torque equations of SPM are given in equations (1) to (7).

$$V_d = R_s i_d + L_d \frac{di_d}{dt} - (\omega_r) L_q i_q \qquad (1)$$

$$V_q = R_s i_q + L_q \frac{di_q}{dt} + (\omega_r) L_d i_d + (\omega_r)\lambda_f \qquad (2)$$

$$\lambda_d = L_d i_d + \lambda_f \qquad (3)$$

$$\lambda_q = L_q i_q \qquad (4)$$

$$T_e = \frac{3}{2}\frac{P}{2}[L_d i_q i_d + \lambda_f i_q - L_q i_q i_d] \qquad (5)$$

As indicated in [1], stable torque control can be achieved if

$$\lambda_s \le \frac{1}{2}\lambda_f \qquad (6)$$

Equation (5) consists of two terms, the excitation torque which is produced by permanent magnet flux and the reluctance torque. In SPM the d-axis and q-axis inductances namely L_d and L_q are equal to synchronous inductance (Ls) without saliency, therefore the reluctance torque becomes zero and torque is simplified as

$$T_e = \frac{3}{2}\frac{P}{2}[\lambda_f i_q] \qquad (7)$$

Also motor model is designed to generate three internal feedback signals namely stator flux (λ), rotor speed (ω_r), phasor angle between stator flux linkage (θ) and the reference stator flux. The equations are given equations (8) to (11).

$$\lambda_s = \sqrt{\lambda_d^{\,2} + \lambda_q^{\,2}} \qquad (8)$$

$$T_e - T_L = \frac{2}{p} J \frac{d\omega_r}{dt} \qquad (9)$$

$$\theta = Tan^{-1}\left[\frac{\lambda_{qs}}{\lambda_{ds}}\right] \qquad (10)$$

$$\lambda_{ref} = \sqrt{\left[\lambda_f^{\,2} + L_q^{\,2}\left[\frac{2T_{e\,ref}}{(3p\lambda_f)}\right]^2\right]} \qquad (11)$$

Nomenclature for (1) to (11) is given below:

R_s	stator armature resistance, Ω
$L_d = L_q$	direct and quadrature inductances, H
ω_r	rotor speed in electrical, rad/s
T_e	electromagnetic torque, Nm
P	no. of poles
λ_f	magnetic flux linkage, wb
T_L	Load torque in Nm
J	Moment of inertia in $Kg.m^2$
λ_s	stator flux linkage, wb

3. Design of a Fuzzy Logic Controller

It is obvious that the selection of a controller is important for any drive to achieve desired performance. The basic problem associated with DTC is lack of exact mathematical analysis and low continuous torque hence when DTC along with conventional PID controller is used, it results in more torque and flux ripples. In such cases when there is ambiguity in representing exact mathematical model for DTC, FLC is a better option instead of PID controller.

In conventional DTC the torque comparator consists of three levels ($+\Delta T_e$, 0, $-\Delta T_e$). Further increase of torque levels wil reduces torque ripples but leads to complexity in modelling torque comparator. The advantage of FLC is that the hysteresis comparator can be sub divided in to several sub sections with different membership functions. In this paper, change in torque is divided in to six membership functions and each membership function has a wide range of limits.

The input to the torque comparator is the speed error and change in speed error. Each are divided in to five and three membership functions respectively. This is not possible in conventional controller. Each membership is taken in a triangular shape with three main limits. The possible levels of change in torque are 36, results in less torque ripples. The general block diagram of FLC is shown in Fig 2.

The mathematical tool for the FLC is the Fuzzy set theory introduced by Zadeh [13]. As compared to the (maximum torque per ampere) MTPA, and their adaptive versions, the FLC has some advantages such as:

i). It does not need any exact system mathematical model
ii). It can handled nonlinearity of arbitrary complexity
iii). It is based on the linguistic rules with an IF-THEN general structure, which is the basis of human logic.

Fuzzy logic control consists of fuzzification process, linguistic rule base, and defuzzification process. The input variables for fuzzy logic controller are speed error and change of speed error. The speed is fed to the fuzzy speed estimator. The speed error and change in speed error are defined as given in equations (12) and (13).

$$e(k) = \omega(k)^{*} - \omega(k) \quad (12)$$
$$\Delta e(k) = e(k) - e(k-1) \quad (13)$$

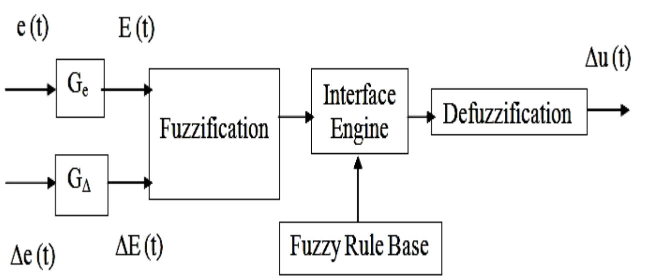

Fig.1 Block Diagram of Fuzzy Logic Controller

The two input variables are e(k), Δe(k) and output variable T_e are divided into different fuzzy segments shown in fig. 2, 3 and 4 respectively.The rules used for the proposed FLC algorithms are as follows:

(i) if $\Delta\omega e$ is PH (Positive High), T_e is PH (Positive High).

(ii) if $\Delta\omega e$ is PL (Positive Low), T_e is PM (Positive Medium).

(iii) if $\Delta\omega e$ is ZE (Zero) and ωe is PS (Positive Small) T_e is PL (Positive Low).

(iv) if $\Delta\omega e$ is ZE (Zero) and ωe is not PS (Positive Small) T_e is NC (No change).

(v) if $\Delta\omega e$ is NL (Negative Low), T_e is NL (Negative Low).

(vi) if $\Delta\omega e$ is NH (Negative high), T_e is NH (Negative high).

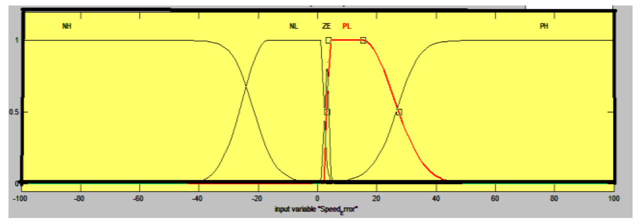
Fig. 2.Membership function for speed error

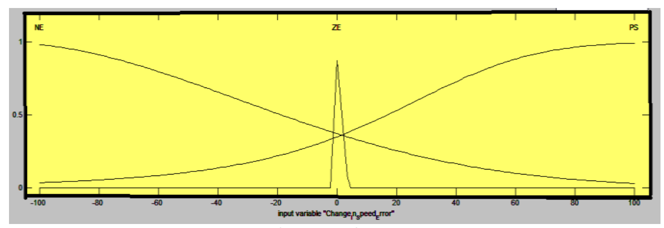
Fig. 3. Membership function for change in speed error

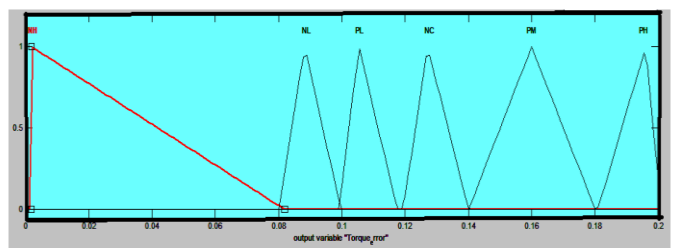
Fig..4 Membership function for Electromagnetic Torque

Based on the above rules the fuzzy rule base matrix is show in table.2. In this present work, Man dent type fuzzy inference is used. The values of the constants, membership functions, fuzzy sets for the input output variables and the rules used in this paper are selected by trial and error to obtain the optimum drive performance.

Table.2: Rule Base Table

ω_e \ $\Delta\omega_e$	NH	NL	ZE	PL	PH
NE	NH	NL	NC	PM	PH
ZE	NH	NL	NC	PM	PH
PS	NH	NL	PL	PM	PH

4. Simulation Results

Simulation is carried out using MATLAB/SIMULINK for three sets of DTC space vectors (CDTC, DTCI and DTCII).
The SPM drive with specification details mentioned in Table 7 is considered for the study.

Analysis is carried out with different sets of load torques and reference speeds. The electromagnetic torque response, speed response, stator flux response, torque ripple, flux ripple and phase current THD comparison are shown in figures.5 to 16.
At no load condition, when the drive system started with the speed reference set at 1500 rpm (half of the rated speed), it is noticed that the proposed drive with FLC followed the command speed within 0.08 sec without any over shoot, steady state error and with little under shoot (Ref. Fig. 5).
When a load torque of 2.3 N-m is applied to the motor shaft in a step wise manner (At t= 0.3 sec) it is observed that the speed momentarily follows load disturbances and immediately reaches to the reference value at 0.4 sec with Fuzzy controller. Whereas the torque response reaches to the steady state value at 0.31 sec with Fuzzy controller. This is very well depicted in Fig. 6.

The dynamic analysis of SPM drive (Ref. Fig. 7) is carried out for various load torques applied at different instants with constant set speed (1500 rpm).It is observed with no time and less over shoot the torque response is reaching steady state using Fuzzy controller. When speed is varied from 500 rpm to 1000 rpm at t=1.59 sec, the torque response is slower and the speed response is faster in reaching the steady state with fuzzy controller shown in Fig. 8.
From Fig 9 and 10, the torque ripple is 10.2% and flux ripple is 6.81 % for SPM drive with the proposed CDTC using Fuzzy controller for rated speed 3000rpm and load torque 2.0 Nm. The torque ripple, flux ripple comparison and phase current THD for the three space vector DTCs with fuzzy controller for various loads is given in tables 3, 4 and 5. For the same load and speed, the phase current THD is 1.49 %with fuzzy controller. The phase THD comparison with fuzzy controllers for different loads at rated speed 3000rpm torque ripple and THD are less with CDTC whereas flux ripple is less with DTCII (little difference compared to CDTC).

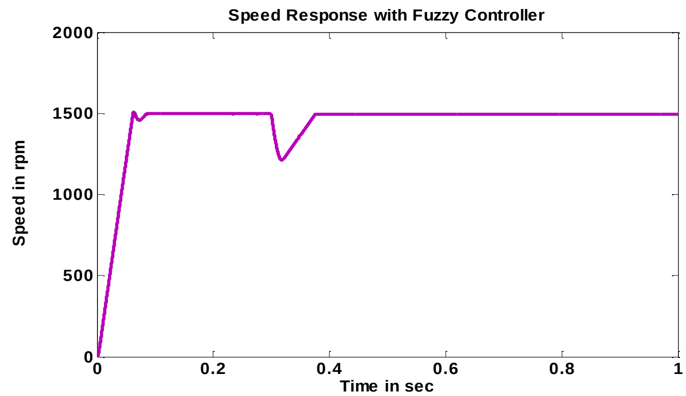

Fig 5: Speed response at no load and when load applied at t= 0.3 sec with CDTC

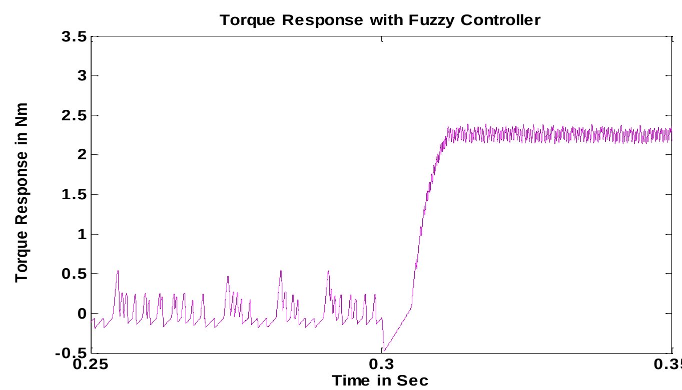

Fig 6: Torque response at no load and when load applied at t= 0.3 sec with CDTC

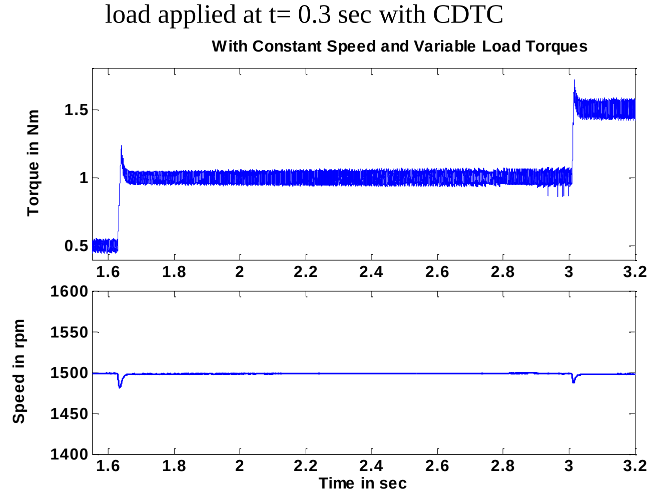

Fig 7 Speed and torque responses at constant speed and variable loads with CDTC

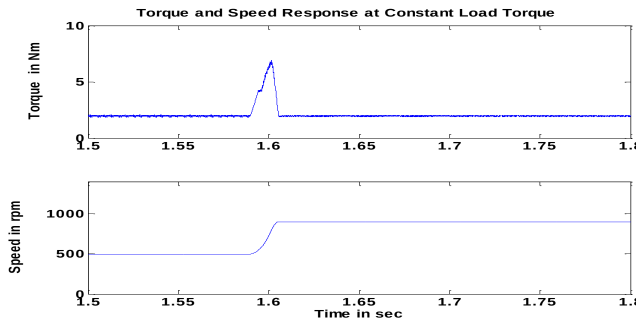

Fig. 8. Speed and torque responses at constant Load torque and variable set speeds with CDTC

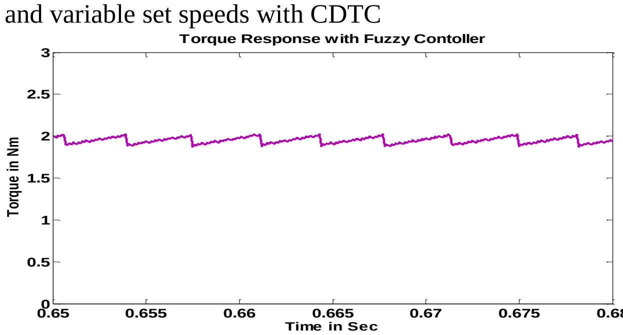

Fig. 9. Torque ripple analysis with CDTC with 3000rpm and 2.0 Nm

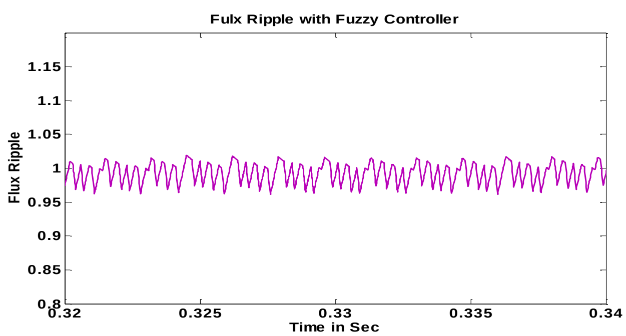

Fig. 10. Flux ripple analysis with CDTC with 3000rpm and 2.0 Nm

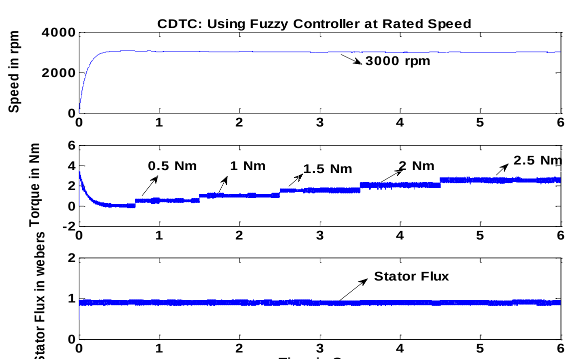

Fig. 11. Flux, electromagnetic torque and speed responses for 0.5 Nm to 2.5 Nm load with constant speed = 3000 rpm with CDTC

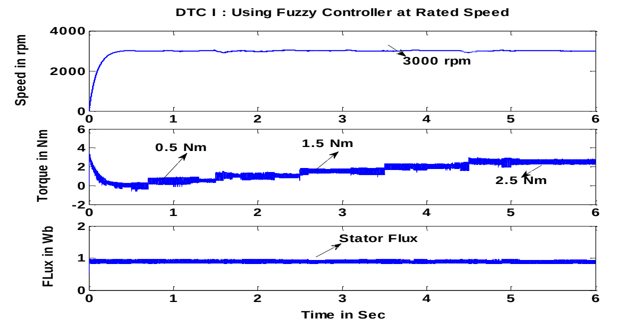

Fig.12. Flux, electromagnetic torque and speed responses for 0.5 Nm to 2.5 Nm load with constant speed = 3000 rpmwith DTC I

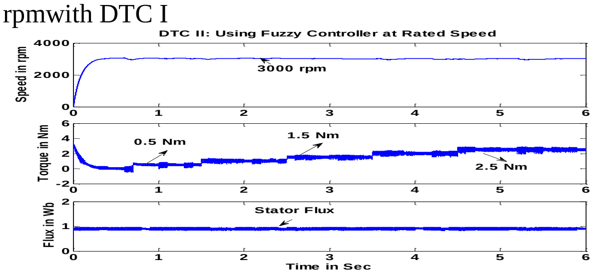

Fig.13. Flux, electromagnetic torque and speed responses for 0.5 Nm to 2.5 Nm load with constant speed = 3000 rpm with DTC II

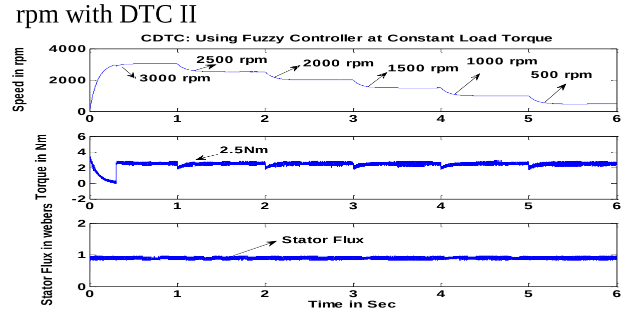

Fig.14. Flux, electromagnetic torque and speed responses for 3000 rpm to 500 rpm as set speeds with constant load = 2.5 Nm with CDTC

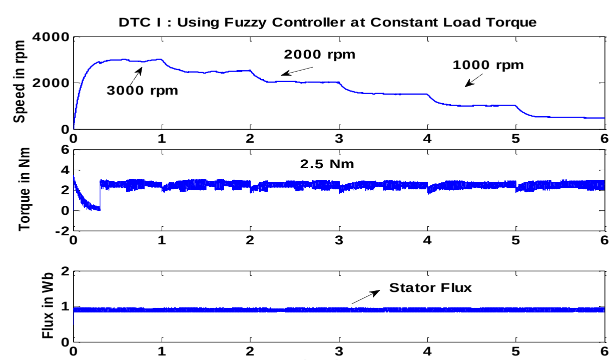

Fig.15. Flux, electromagnetic torque and speed responses for 3000 rpm to 500 rpm as set speeds with constant load = 2.5 Nm with DTCI

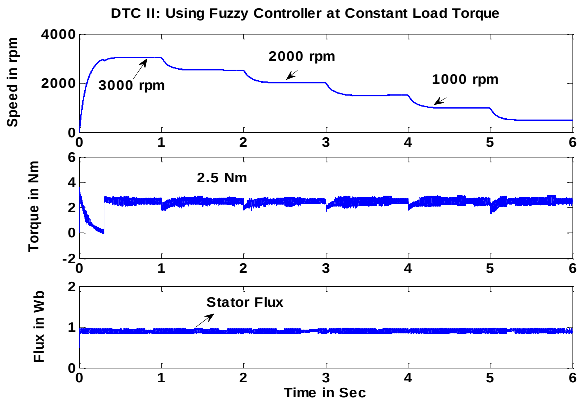

Fig. 16. Flux, electromagnetic torque and speed responses for 3000 rpm to 500 rpm as set speeds with constant load = 2.5 Nm with DTCII

Table 3: Torque Ripple, Flux Ripple, THD Analysis for Phase Cureents of the SPM drive using Fuzzy Controller with CDTC at rated speed= 3000 rpm

Time at which load is applied (sec)	Load Torque (Nm)	Torque Ripple (%)	Flux Ripple (%)	Phase Current (THD) %
0.7	0.5	35.3	10.4	2.63
1.5	1.0	14.2	8.2	3.82
2.5	1.5	12.4	7.98	2.52
3.5	2.0	10.2	6.81	1.49
4.5	2.5	9.3	6.2	1.52

Table 4: Torque Ripple, Flux Ripple, THD Analysis for Phase Cureents of the SPM drive using PI and Fuzzy Controllers with DTC I at rated speed= 3000 rpm

Time at which load is applied (sec)	Load Torque (Nm)	Torque Ripple (%)	Flux Ripple (%)	Phase Current (THD) %
0.7	0.5	31.5	11.42	4.8
1.5	1.0	24.7	9.1	4.12
2.5	1.5	19.2	10.02	3.12
3.5	2.0	18.8	9.21	3.21
4.5	2.5	12	8.12	2.9

Table 5: Torque Ripple, Flux Ripple, THD Analysis for Phase Cureents of the SPM drive using PI and Fuzzy Controllers with DTC II at rated speed= 3000 rpm

Time at which load is applied (sec)	Load Torque (Nm)	Torque Ripple (%)	Flux Ripple (%)	Phase Current (THD) %
0.7	0.5	48.2	9.21	3.12
1.5	1.0	22.13	8.08	4.23
2.5	1.5	16.38	7.68	2.81
3.5	2.0	13.45	7.1	2.54
4.5	2.5	13.18	5.02	1.98

5. FPGA Implementation of DTC Algorithm

Based on simulation analysis hardware implementation of a SPM using FPGA is carried out for the CDTC. Digital DTC algorithm is realized with Xilinx IST 10.1 simulator and implemented in Xilinx Spartan 3 FPGA board, Device: XC3S400, Pin package: PQ208. As already mentioned input to the FPGA board are flux error, torque error and the position of the flux vector (sector number). The flux error represents a two bit binary number (0 or 1 binary equivalent is 00 or 01) which are given to the pin numbers P39 and P40. The torque error represents a two bit binary number (0 or 1 or -1 binary equivalent is 00 or 01 or 11) which are given to the pin numbers P50 and P51. The sector number represents a three bit binary number (0 to 6).

The Direct Torque algorithm is designed and implemented by using Verilog HDL. In Fig. 17, the output represents the switching state of the inverter. Here the results obtained are when flux error is 1 and torque error is 1and the position of the flux vector is in sector 1 (From table.7) then the switching vector is V_1 i.e the switching states to the inverter are 100. After this switching state inverter switching state changes to V_2 (1 1 0) → V_3 (0 1 0)→V_4 (0 1 1) → V_5 (0 0 1) → V_6 (1 0 1) →V_1 (1 0 0) and so on until torque and flux commands are changes from the existing state. The block diagram of FPGA implementation of proposed CDTC for SPM Drive is given in Fig. 18. Switching states of the Inverter from sectors 1 to 3 is given in Fig. 19.

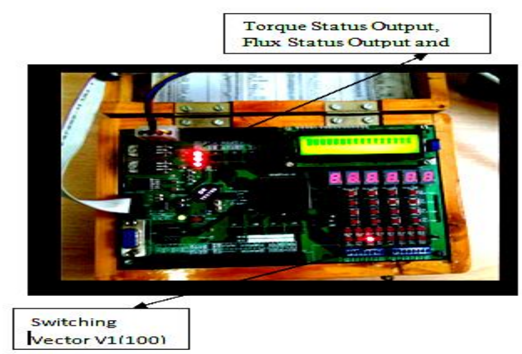

Fig.17. Digital DTC implementation on a Xilinx Spartan-3 FPGA board

The motor is fed with a two level three phase voltage source inverter which is implemented by a intellectual power module including gate drivers, six insulated IGBTs and protection circuits. The actual motor phase currents are measured by current sensors (current transformer) which is fed to the control computer through a 12 bit bipolar successive approximation ADC with 1micro sec speed. First only two motor phase currents are measured, as the motor neutral is isolated so only two sensors are required to measure phase currents. The rotor position is measured by means of QEP with 500 pulses per revolutions. To observe the load torque disturbances Spring balance load is coupled the shaft of SPM.

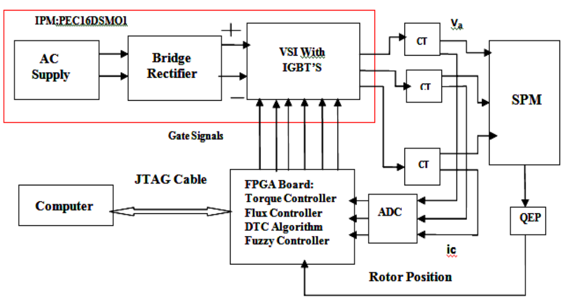

Fig.18. FPGA implementation of proposed DTC for SPM Drive

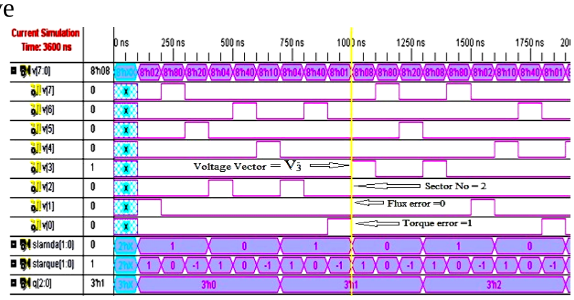

Fig. 19. Switching states of the Inverter from sectors 1 to 3

Table. 6. Selection of Voltage Vector from Torque and Flux Hysteresis Controllers

Sector No. (θ(N))		θ(1)	θ(2)	θ(3)	θ(4)	θ(5)	θ(6)
S_λ	S_T						
1	1	V_1	V_2	V_3	V_4	V_5	V_0
1	0	V_7	V_6	V_7	V_6	V_7	V_6
[illegible]	-1	V_5	V_0	V_1	V_2	V_3	V_4
0	1	V_2	V_3	V_4	V_5	V_0	V_1
0	0	V_6	V_7	V_6	V_7	V_6	V_7
0	-1	V_4	V_5	V_0	V_1	V_2	V_3

Table 7: Specification of SPM

Parameter Description	Value
Rated Output Power	800 W
Rated Speed	3000 rpm
Rated Voltage	230 V
Torque Constant +- 5%	0.455Nm/A
Voltage Constant +- 5%	31.8V/Krpm
Phase Resistance +- 5%	19.4 Ohms
Phase Inductance +- 5%	3.82mH
Electric Time Constant	5.6ms
Mechanical Time Constant	0.65ms
Rotor Inertia	1.16kgcm2

Fig. 20. Experimental Set up of the SPM Drive with FPGA Implementation

6. Experimental Results

Experiment is carried out with different sets of load torques and different sets of reference speeds. Experimental Set up of the SPM Drive with FPGA Implementation is represented in Fig 20. The electromagnetic torque response, stator flux response and reference speed responses are shown in Fig.21. Further It can be observed from these figures that, for a instantaneous change in the set point of the speed the tracking performance is very fast and accurate. The torque ripples are around 18 to 19% for SPM drive with the proposed DTC (CDTC) using Fuzzy controller with FPGA implementation for rated speed 3000rpm. Whereas with simulation results it is noticed from 7 to 10% Fig. 22 shows the torque ripple and flu**x** ripple for a refrence speed of 1000 rpm and for a load torque of 1.5 Nm. From the table 4, the THD of phase currents are 7.199% the THD of line voltage waveforms are 27.997 %; rms phase currents are 2.68A and rms phase voltage 103.8v.

From experimental results it is clear that the proposed DTC with Fuzzy controller for rated speed 3000rpm and for a load torque 2 Nm gives currents THD 4.%, where as torque and flux ripples are 19.54% and 13% respectively (table 6). The line voltage and phase current responses for rated speed 3000 rpm and load torque 2 Nm is given in Fig 23 and 24 respectively. The device utilization summary is given Table 8.

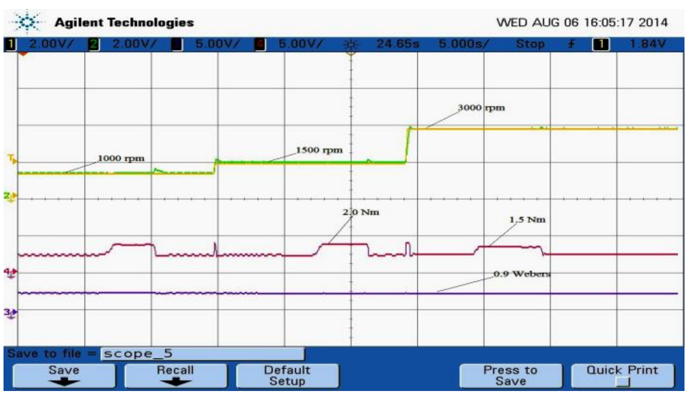

Fig. 21. Flux, electromagnetic torque and speed responses for 1000rpm ,1500 rpm and 3000 rpm

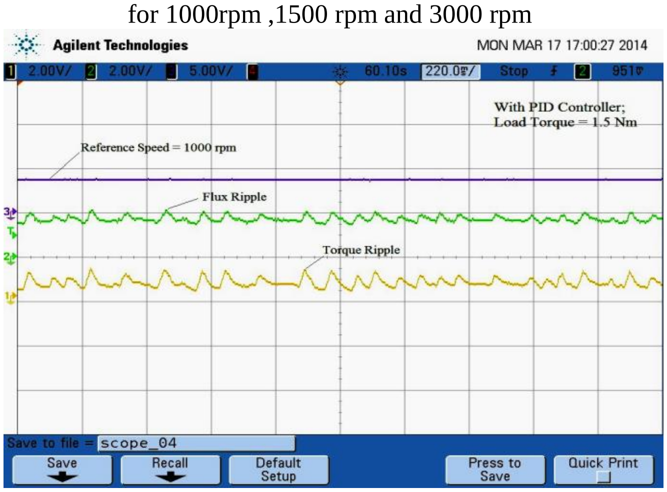

Fig. 22.Torque Ripple, Flux Ripple (refrence Speed 1000rpm, load torque 1.5 Nm)

Table.8 THD Analysis for Line Voltages and Phase Cureents

Load Torque (Nm)	Speed (rpm)	RMS value of Phase Currents	RMS value of Phase Voltages	THD for Phase Voltages (%)	THD for Phase Currents (%)	Torque Ripple (%)	Flux Ripple (%)
1.5	1000	2.68	103.80	27.997	7.199	24.03	17
	1500	2.62	123.99	15.238	3.910	19.12	
	3000	2.7	163	27.76	4.6	18.27	
2.0	1000	5.1126	110.02	22.679	4.7	22.16	13
	1500	5.1653	130.27	14.943	4.6	21.89	
	3000	5.2	173	28.56	4.019	19.54	

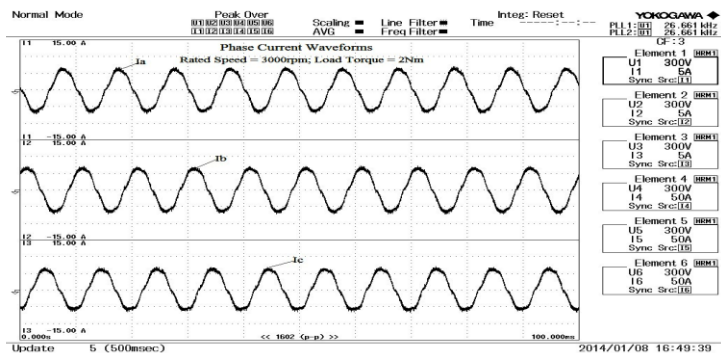

Fig. 23.. Phase current responses for reference speed 3000 rpm and load torque 2 Nm

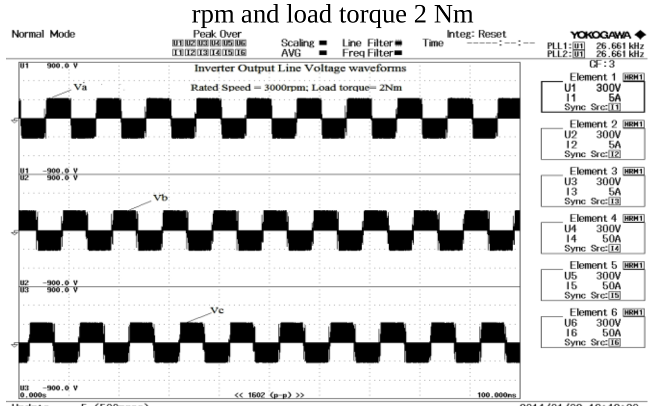

Fig. 24. Line Voltage responses for reference speed 3000 rpm and load torque 2 Nm

Table 9. Device utilization summary

Device Utilization Summary (Estimated Values)			
Logic Utilization	Used	Avaliable	Utilization
Number of Slices	5415	16640	32%
Number of Slice Flip Flops	3104	33280	9%
Number of 4 input LUTs	8943	33280	26%
Number of IOBs	56	519	10%
Number of GCLKs	3	24	12%
Number of DSP48s	66	84	78%
Xilinx XPower Analysis – Controller Design			
Total Power (in Watts)	0.056	-	-

7. Conclusion

The dynamic performance of the drive is tested with fuzzy controller up to the base speed with different sets of load torques with three different space vectors. The results showed better dynamic performance of SPM drive when using CDTC. Based on this analysis, in this paper FPGA implementation of Direct Torque Control for Permanent Magnet Synchronous by using Verilog HDL is carried out.

The high performance sensor less AC drives requires a fast digital realization of many mathematical operations concerning control and estimators, algorithms, which are time consuming. The modelling of the algorithm using FPGA need to be done only once so a lot of time is saved. Also control algorithm, when implemented in FPGA, can have a very short execution time due to the high degree of parallelism of its architecture. The proposed digital controller with simple design approach using Xilinx Spartan-3 FPGA board can provide better performance compared with existing controllers. Nowadays FPGAs are available at low – cost and hence a hardware configured controller using FPGA is effective in the reduction of torque and flux ripples. In particular, by virtue of the FPGA's re programmability, designers can keep changing and planning devices to cater to user's needs.

In this paper, FLC implementation of torque comparator for SPM is designed. Further FLC can be extended to flux comparator also. Implementation of FLC for flux and torque comparator reduces torque and flux pulsations to a great extent. This feature is more essential in many applications like electric power steering, which requires precise smooth control of steering.

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