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PERFORMANCE ANALYSIS OF DIRECT TORQUE CONTROL OF PERMANENT MAGNET BRUSHLESS DC MOTOR

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ABSTRACT

This paper recommends the direct-torque control (DTC) for Permanent Magnet Brushless DC Motor **(**BLDC) motor drives. DTC is unique productive techniques utilized in factor frequency drives to control BLDC motor. This control strategy interduce numerous focal points like quick torque response, no need of organize change and less reliance on the rotor parameters. The predictable flux magnitude and torque are related to their set values. The torque set value is created from the produced signals at speed controller (PI controller). The PI parameters tuning are imperative to DTC system to enhance the performance of the system at low speeds. This article presents the performance analysis simulation of BLDC drive utilizing PI controllers and assessed under different load disturbances influences in the MATLAB/Simulink program. Simulated results are displayed, and it is verified that the DTC control system decrease torque swell and a quicker dynamic response .

Key words: BLDC Motor, Direct-torque control, PI controller, Dynamic response

الملخص العربى

يوصي هذا البحث بالتحكم المباشر في عزم الدوران (DTC) لمحرك التيار المستمر ذى المغناطيس الدائم بدون فرشPMBLDC وهي تقنيات تحكم فريدة تستخدم في مغيرات السرعة. تثير إستراتيجية التحكم هذه العديد من النقاط المحورية مثل الاستجابة السريعة لعزم الدوران ، وتقليل الاعتماد على متغيرات العضو الدوار. فى هذه الطريقة يتم استنباط قيم المجال المغناطيسى وعزم الدوران من الإشارات المنتجة في وحدة تحكم السرعة التناسبي والتكامليPI ومقارنتها بقيمهما المحددة مسبقا. يعد ضبط معاملات PI أمرًا ضروريًا لنظامDTC لتحسين أداء النظام خاصة عند السرعات المنخفضة. كما قدم هذا البحث محاكاة تحليل الأداء لمحرك BLDC باستخدام وحدات التحكم PI وتقييمها في ظل تأثيرات اضطرابات الحمل المختلفة في برنامج MATLAB / Simulink تم عرض النتائج المحاكية ، وتم التحقق من أن نظام التحكم DTC ينتج عزم دوران باستجابة ديناميكية سريعة اثناء التحميل.

الكلمات الداله: محرك التيار المستمر ذى المغناطيس الدائم بدون فرش ، مغيرات السرعة ، نظام التحكم التناسبي والتكاملي ،التحكم المباشر في عزم الدوران

1-INTRODUCTION

The BLDC motors are normally PM-synchronous machines that are well supplied by dc voltage. Permanent magnet BLDC motors have wide assortment of favorable circumstances like higher speed ranges, higher proficiency, and better speed versus torque characteristics. Likewise, it has an imperative preferred standpoint is that the proportion of torque conveyed to the measure of machine is higher, and this adds to its handiness regarding space and weight thought. The PM BLDC drives are used in the enterprises, particularly in the zones of apparatuses creation, air transportation, drug, purchaser and modern robotizations, etc. As of late numerous examinations have been created to discover diverse answers for the PM BLDC drive control having the highlights of fast and exact torque response, decrease of the intricacy of field-oriented control algorithms [1-3]. There are a few strategies to shift the speed of a BLDC motor over a wide range. Procedures for control of current incorporate vector control, predictive-control and direct-torque control. The most present-day procedure is direct torque control approach (DTC). In the DTC control method, no need of organize change and less reliance on the rotor parameters. The regular PI (proportional, integral) control strategy is generally utilized in motor control system because of the straightforward control structure and effectiveness of plan. In the current paper, numerous calculations have been recommended for the DTC control. The eight voltage-vector changing plan is by all accounts reasonable just for fast activity of the motor while at low speed the six voltage-vector exchanging plan, maintaining a strategic distance from the two zero voltage-vectors, is by all accounts proper for the PM BLDC drives [1, 4-6]. The voltage vector system utilizing exchanging table is generally investigated and marketed, in light of the fact that it is basic in idea and simple to be executed. The stator fluxes linkages are determined from voltage and current models PM BLDC drive. The DTC is progressively drawing interest on account of the end of rotor position sensor, straightforwardness of its structure, dumping of the present controllers and characteristic postponements. The magnitude and frequency of controlled variables are considered. In the controlling of vector, amplitude and position of a controlled vector of space are considered.

2-MATHEMATICAL MODELING OF THE PM BLDC DRIVE

The motor considered in the following analysis is an interior PM BLDC motor which composed of three phase stator windings and a PM rotor. The phasor diagram of PM BLDC motor in d-q axis is indicated in figure1.

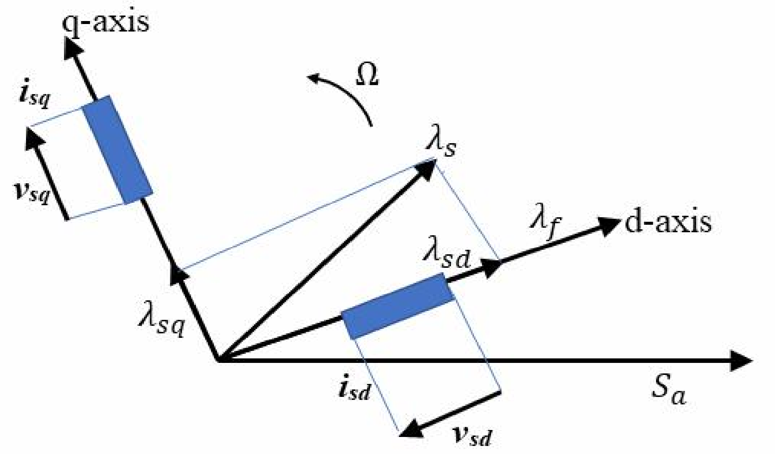

Fig. 1. Model of PM BLDC motor in d-q axis

The voltage equations in a synchronous reference frame can be derived as follows:

$$v_{sd} = R_s.i_{sd} + \frac{d\lambda_{sd}}{dt} - \omega.\lambda_{sq} \quad (1)$$

$$v_{sq} = R_s.i_{sq} + \frac{d\lambda_{sq}}{dt} - \omega.\lambda_{sd} \quad (2)$$

Where the direct and quadrate axis flux linkages are:

$$\lambda_{sd} = L_{sd}.i_{sd} + \lambda_f \quad (3)$$

$$\lambda_{sq} = L_{sq}.i_{sq} \quad (4)$$

The induced electromagnetic torque of the motor can be estimated as follows:

$$T_e = \frac{3}{2}p[\lambda_f.i_{sq} + (L_{sd} - L_{sq}).i_{sd}.i_{sq}] \quad (5)$$

The motor motion equation can be simply described by the following:

$$T_e - T_r = J.\frac{d\Omega}{dt} + B.\Omega \quad (6)$$

With:

Ω: mechanical speed of the BLDC motor

ω: electric rotation's speed.

p: Number of pairs of poles.

J: moment of inertia.

B: viscous friction coefficient.

T_e: induced electromagnetic torque,

T_r: Resistive torque.

λ_f: magnetic field produced by the permanent magnet.

λ_{sd}: stator d-axis magnetic flux, λ_{sq}: stator q-axis magnetic flux,

L_{sd}: stator d-axis inductance, L_{sq}: stator q-axis inductance,

R_s: stator winding resistance,

i_{sd}: stator d-axis current,

i_{sq}: stator q-axis current

3- DTC CONTROL TECHNIQUE OF PM BLDC MOTOR:

Since the methods proposed DTC for induction machines in the middle of 1980's [9, 11], over one decade has passed. The simple idea of DTC for induction machine is slip control, which is created on the relationship between the slip and induced electromagnetic torque [2]. In the 1990's, DTC for PM BLDC machines was developed [7, 8]. Associated with Rotor Field Oriented Control, the DTC has numerous points of interest, for example, less machine parameter reliance, less complex usage and faster unique torque response. There is no current controller required in DTC, because it is attributed to chooses the voltage space vectors as indicated by the blunders of flux linkage and torque. The most widely recognized approach to complete the DTC is switching table and hysteresis controller, as in [8, 10].

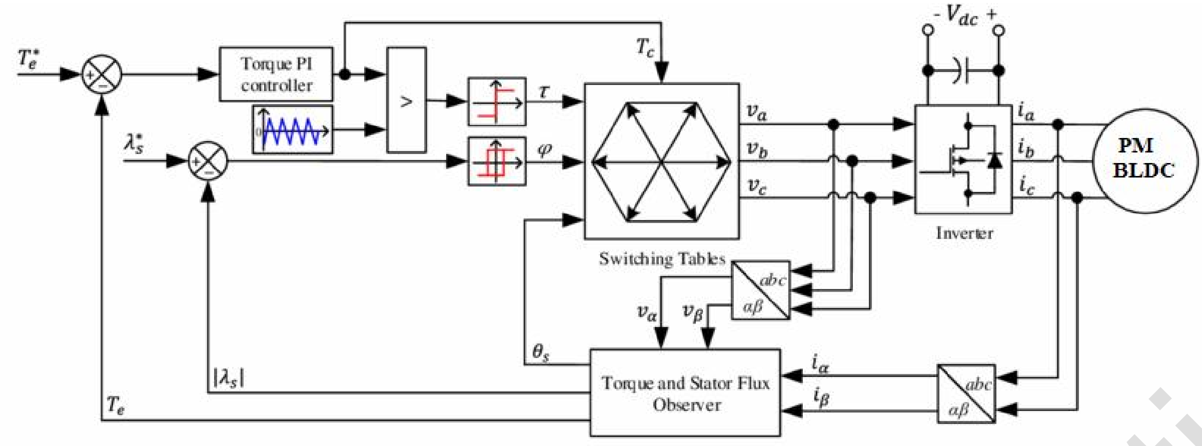

Fig. 2. Schematic of DTC BLDC drive.

Typically, a DC-bus voltage sensor and two current sensors are required for the leakage flux and induced torque observer. Speed sensor isn't important for torque and flux control. The switching condition of the voltage source inverter (VSI) is refreshed in each sampling time.

Inside each sampling time interim, the inverter preserves the state until the output situations of the hysteresis controller change. In this way, the switching frequency is usually not settled, it changes with the rotor speed, load and data transfer capacity of the speed and torque regulators. As control DTC is a vectorial control, it is important to have those components of the currents and stator voltages of the PM BLDC motor. One thus breaks up the three stator currents i_{sabc} and the three stator voltages v_{sabc} into components direct ($v_{s\square}$) and quadratic ($v_{s\square}$) such as:

$$\begin{bmatrix} v_{s\alpha} \\ v_{s\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -0.5 & -0.5 \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} \tag{7}$$

Since the model of the PM BLDC motor is expressed in the reference mark (d-q), a passage of the two-phase system (α-β) to the two-phase system (d-q) proves to be essential:

$$\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} = \begin{bmatrix} cos(\theta) & sin(\theta) \\ -sin(\theta) & cos(\theta) \end{bmatrix} . \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} \tag{8}$$

For flux estimator the stator electric equations of PM BLDC motor, in the reference mark (α-β) are given by:

$$V_{s\alpha} = R_s . i_{s\alpha} + \frac{d\lambda_{s\alpha}}{dt} \tag{9}$$

$$V_{s\beta} = R_s . i_{s\beta} + \frac{d\lambda_{s\beta}}{dt} \tag{10}$$

where:

$$\hat{\lambda}_{s\alpha} = \int_0^t (V_{s\alpha} - R_s . i_{s\alpha}) . dt \tag{11}$$

$$\hat{\lambda}_{s\beta} = \int_0^t (V_{s\beta} - R_s . i_{s\beta}) . dt \tag{12}$$

$$\hat{\lambda}_s = \hat{\lambda}_{s\alpha} + j . \hat{\lambda}_{s\beta} \tag{13}$$

For higher speeds, one neglects the voltage drop the equations become:

$$\hat{\lambda}_{s\alpha} = \int_0^t V_{s\alpha} . dt \tag{14}$$

$$\hat{\lambda}_{s\beta} = \int_0^t V_{s\beta} . dt \tag{15}$$

$$\lambda_s = \sqrt{\lambda_{s\alpha}^2 + \lambda_{s\beta}^2} \tag{16}$$

And the induced electromagnetic torque is given by:

$$T_e = \frac{3p}{2}(\lambda_{s\alpha}.i_{s\beta} - \lambda_{s\beta}.i_{s\alpha}) \quad (17)$$

The basic control algorithm of DTC consists of two independent hysteresis comparators producing the error signal of stator leakage flux and induced electrical torque. A two-level hysteresis flux comparator and a three levels hysteresis torque comparator compare the actual values to the reference values produced by flux and torque reference which produced by controllers. Depending on the output from the two hysteresis controllers [5], the optimum switching logic selects one of the six voltage vectors and two zero voltage vectors generated by VSI [8]. Also, in order to keeping stator leakage flux and electromagnetic torque within the limits of two hysteresis boundaries. The control switches of VSI is depicted from Fig.3. The angle of the stator leakage flux vector is used to regulate the voltage sector.

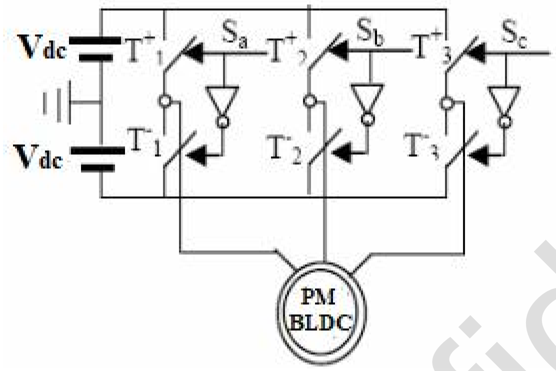

Fig. 3 Control switches of the inverter

The switches of the (VSI) as shown in (Fig.3) must be well-ordered so maintain the flow and the couple of the machine. The stator voltage can be represented as a vector in the form:

$$V_s = \sqrt{\frac{2}{3}}.V_{dc}.(S_a + S_b.e^{j\frac{2\pi}{3}} + S_c.e^{j\frac{4\pi}{3}}) \quad (18)$$

Where (S_a, S_b, S_c) represent the logical state of the 3-switches; (S_i = 1) means that upper switch is closed, and lower switch is open ($V_i = +V_{dc}$) and (S_i = 0) mean that the upper switch is opened, and the lower switch is closed ($V_i = - V_{dc}$). One will thus be seeking to control flow and the couple via the choice of the vector of voltage which will be completed by an arrangement of the switches. As we have 3- switches, there are thus ($2^3 = 8$) possibilities for the V_s vector. The two vectors (V_1 and V_8) correspond to the null vector: (S_a,S_b,S_c) = (0,0,0) and (S_a,S_b,S_c) = (1,1,1).

Table 1: different configuration from the interrupters

S_c	S_b	S_a	T_1		T_2		T_3		V_s
			T^+_1	T^-_1	T^+_2	T^-_2	T^+_3	T^-_3	
0	0	0	Off	On	Off	On	Off	On	V_1
0	0	1	On	Off	Off	On	Off	On	V_2
0	1	0	Off	Off	On	Off	Off	On	V_4
0	1	1	Off	On	On	Off	Off	On	V_3
1	0	0	On	Off	Off	On	On	Off	V_6
1	0	1	Off	Off	Off	On	On	Off	V_7
1	1	0	Off	On	On	Off	On	Off	V_5
1	1	1	On	Off	On	Off	On	Off	V_8

Six non-zero vectors (V_1–V_6) shape the axes of a hexagonal as represented in the figure 4 and feed current to the motor. The angle between any contiguous two non-zero vectors is 60 degrees. In the meantime, two-zero vectors (V_0 and V_7) are at the origin and shall apply zero-voltage to the load. The eight vectors are called the basic space vectors and are denoted by (V_0, V_1, V_2, V_3, V_5, V_6, and V_7). By assuming the stator leakage flux vector is placed on the sector 1 of the d-q plane, V_1, V_2, V_6 could be chosen to exceed the stator leakage flux vectors as depicted from Fig.4. Contrarywise, V_3, V_4, V_5 could be chosen to decrease the stator leakage flux vector. The zero (null) voltage vectors does not affect the stator flux vector. Voltage vectors are chosen to control the torque also. In general, V_2 and V_3 vectors are chosen to rise the torque and V_5 and V_6, vectors will reduce the torque.

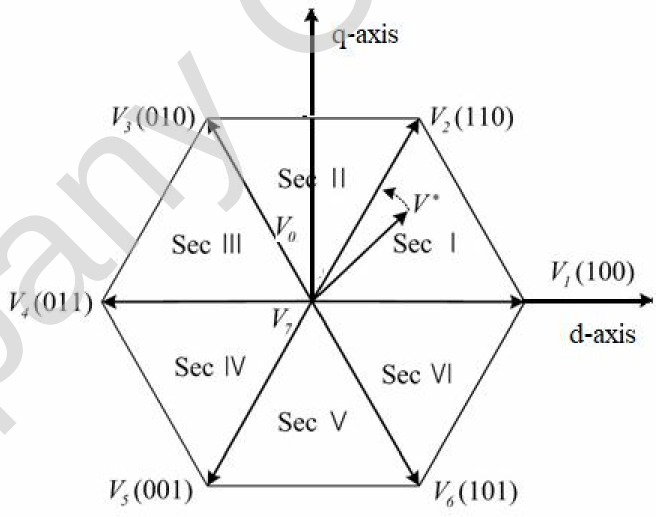

Fig.4. Voltage vectors and sectors of detection

To get very good dynamic behavior, the optimal of a corrector with hysteresis with two navels seems to be the simplest solution and best improved to the studied control. Definitely this type of controller, one can easily control and maintain the end of vector flux λ_s in a circular ring.

The applied awareness of order DTC is generally done on charts DSP, FPGA or with microcontrollers [12] having one period of sampling for the period 0 to τ, the voltage vector chooses does not change where allows, starting from the equations (14), (15) and (16) to write:

$$\hat{\lambda}_{s\alpha} = \int_0^{\tau} V_{s\alpha}.dt = V_{s\alpha}.\tau \quad (19)$$

$$\hat{\lambda}_{s\beta} = \int_0^{\tau} V_{s\beta}.dt = V_{s\beta}.\tau \quad (20)$$

$$\hat{\lambda}_{s} = \hat{\lambda}_{s\alpha} + j.\hat{\lambda}_{s\beta} = V_{s}.\tau \quad (21)$$

The track of the vector flow λ_s is thus given by the selected vector of voltage V_i the Fig.5 shows the sequence of the voltage vectors maintaining flow in a crown thickness equal to the width of hysteresis.

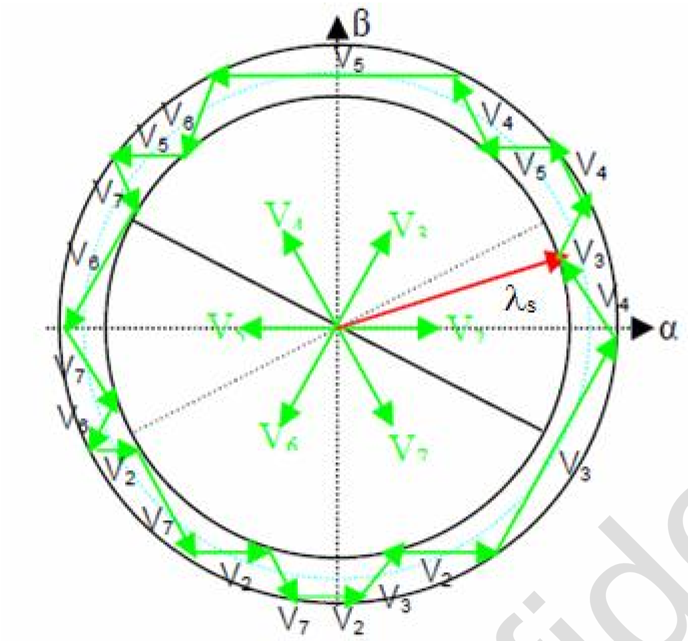

Fig.5. Sequence of the voltage vectors

4-SIMULATION AND RESULTS:

Here the MATLAB/Simulink model of the PM BLDC motor is developed rendering to the d-q model. In the simulation, the stator magnetic flux amplitude value is expected to be the same as the value of the PM flux.

Table 2: Motor parameters

Parameter	Value
VSI dc bus voltage	36V
number of poles	4
Stator resistance R_s	0.25 Ω
PM flux λ_f	0.2 Wb
d-axis inductance L_{sd}	3.34 mH
q-axis inductance L_{sq}	3.58 mH
Moment of inertia J	0.001469kgm2

The figure 6 presents the simulink block diagram of the DTC of the PM BLDC motor in the reference mark d-q. The i_{sd} and i_{sq} currents, also v_{sd} and v_{sq} voltages are subjected to Clark transformation in order to get the components ($i_{s\alpha}$, $i_{s\beta}$, $v_{s\alpha}$ and $v_{s\beta}$). Those components are applied has a block of estimator of couple and flow as well as the detector of sector. Those values are calculated thereafter are compared with reference to be included in correctors of hysteresis to 2 and has 3 levels, to introduce its errors into a table of commutation which functions by report sector to produce the pulses of the inverter which will produce the voltage three-phase current. Subsequently which will be transformed into co-ordinates d-q, the output voltages v_{sd} and v_{sq} are applied in average values at the boundaries of the phase's stator of the PM BLDC motor.

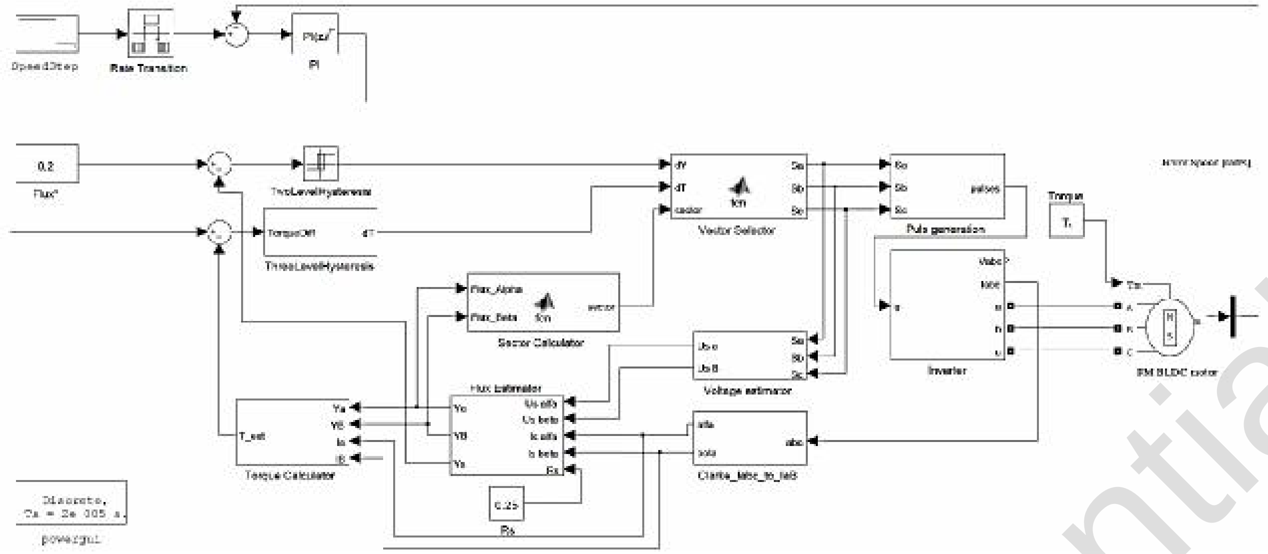

Fig. 6. Simulink Blocks for the simulation of the DTC for the PM BLDC motor

In the performed simulation, certain stator flux and torque references are compared to the values calculated in the driver and errors are sending to the hysteresis comparators. The flux and torque comparators outputs are used in order to regulate the appropriate voltage vector and stator flux space vector. Vector of Locus of stator flux linkage at 1500 rpm illustrated in Figure 7. The simulated value of current is predictable from the estimated torque which is derived from the mathematical model and motor parameters such as phase voltage and phase currents as shown figures (8-16).

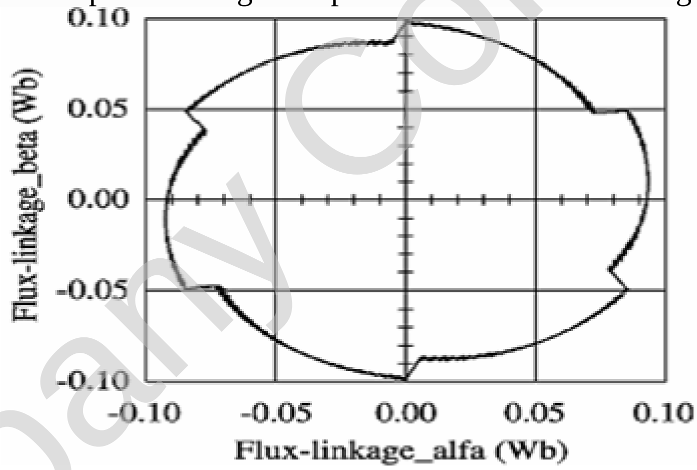

Fig. 7. Simulated results for Locus of stator flux linkage at 1500 rpm.

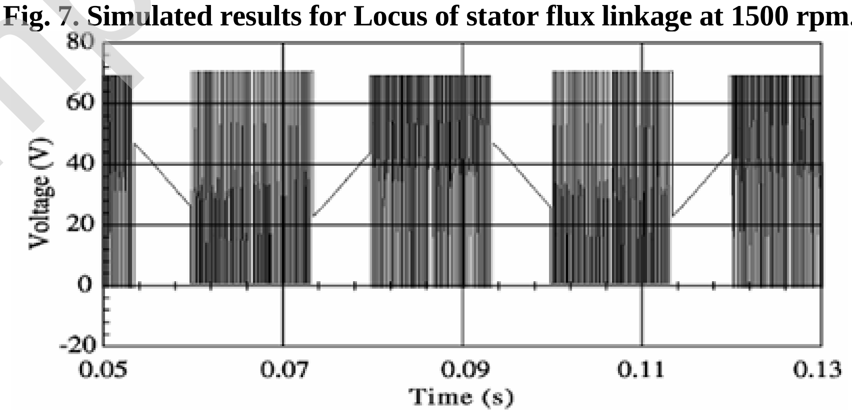

Fig. 8. Simulated results for output VSI Phase-to-ground voltage at 1500 rpm.

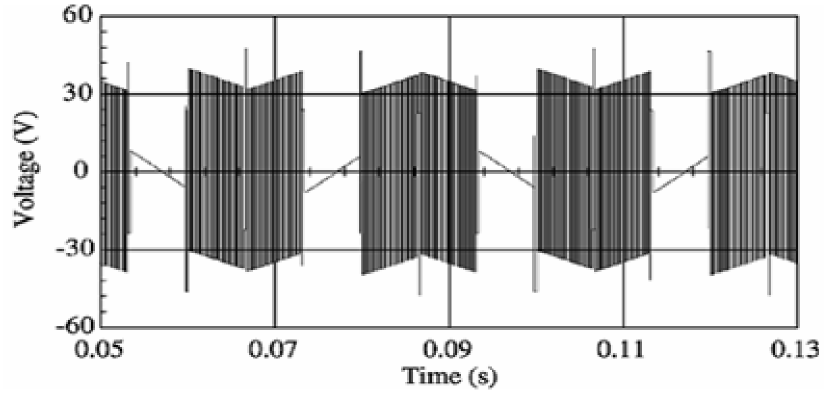

Fig. 9. Simulated results for output VSI Phase voltage at 1500 rpm.

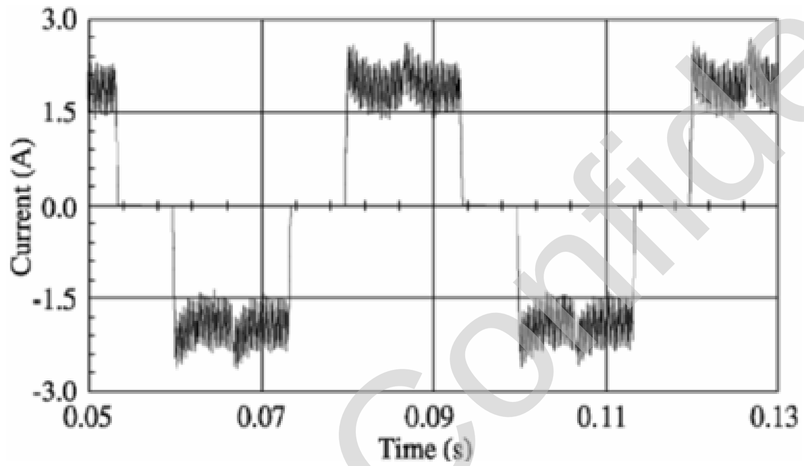

Fig. 10. Simulated results for stator Phase current at 1500 rpm.

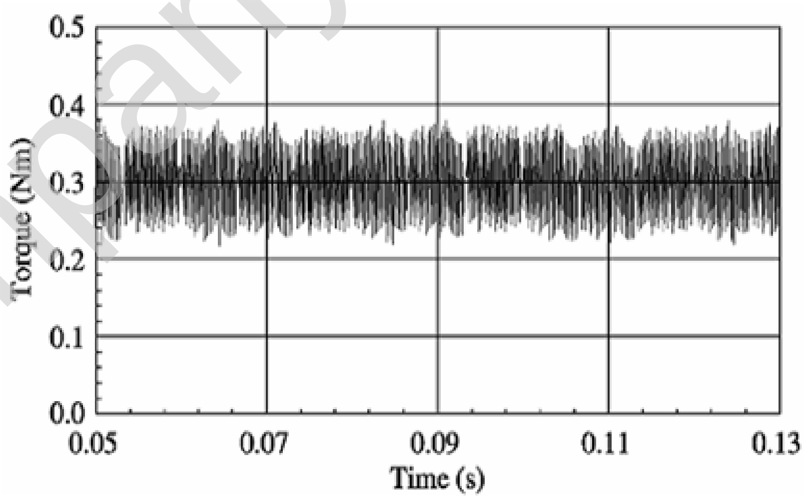

Fig. 11. Simulated results for motor electromagnetic torque at 1500 rpm.

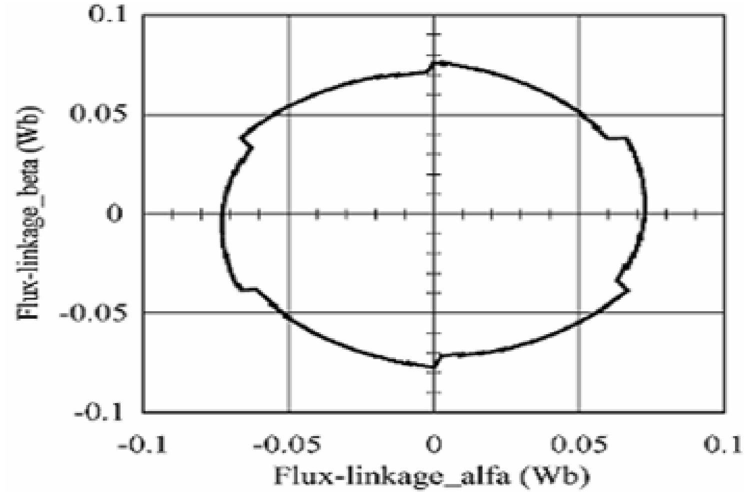

Fig. 12. Simulated results for Locus of stator flux linkage at 500 rpm.

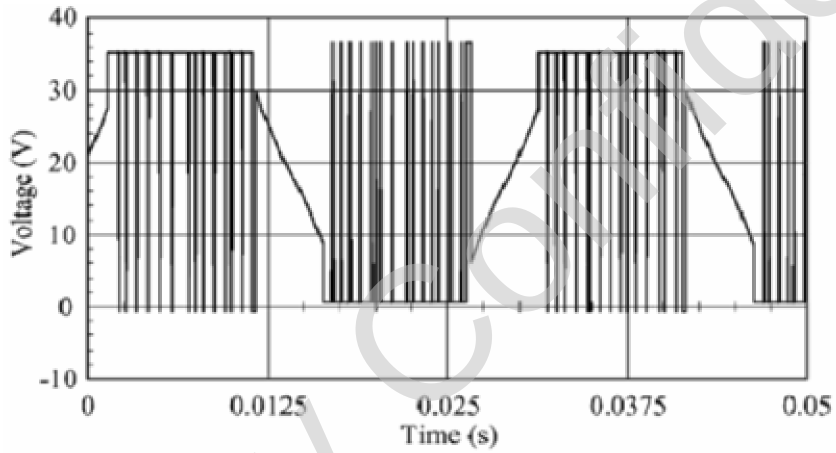

Fig. 13. Simulated results for VSI Phase-to-ground voltage at 500 rpm.

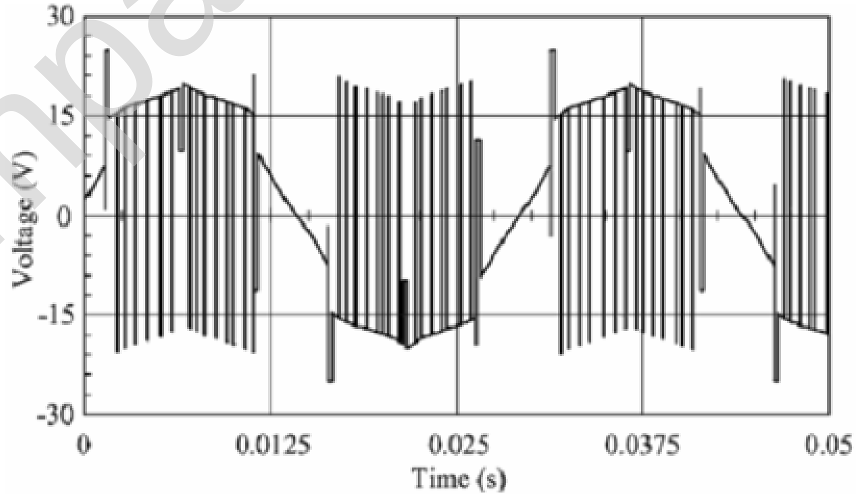

Fig. 14. Simulated results for output VSI Phase voltage at 500 rpm.

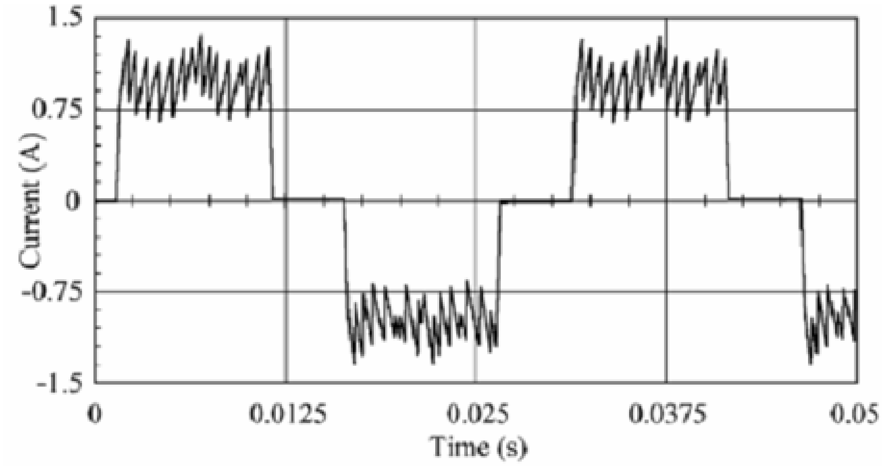

Fig. 15. Simulated results for stator Phase current at 500 rpm.

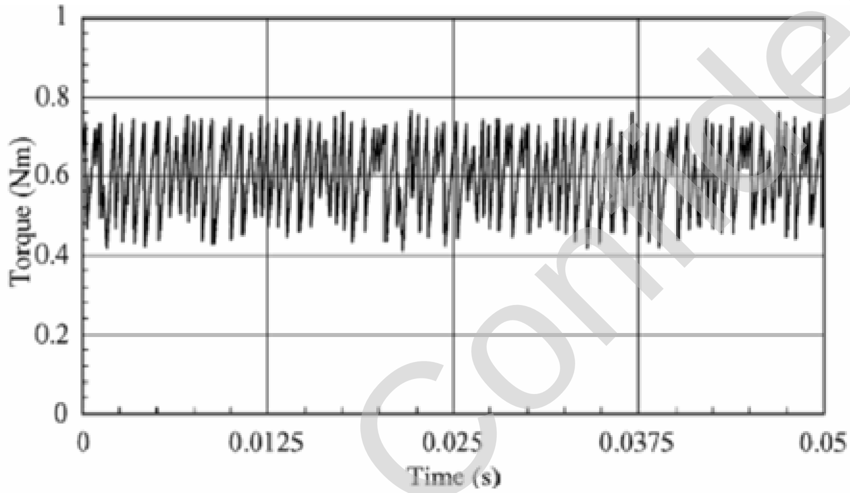

Fig. 16. Simulated results for motor electromagnetic torque at 500 rpm.

The algorithm employed in DTC of BLDC motor has occasioned in the optimal selection of kp, ki values. This technique has finally improved the dynamic performance of the BLDC motor when compared with that of PI controller-based DTC of BLDC motor. The phase-phase voltage and currents at 500 rpm are shown in fig 14 and 15 respectively. The phase-current waveform is shown only one phase of the motor. The currents are in square waveforms but exhibits ripples at the steady state.

The torque –time characteristics at 500 rpm is shown in fig .16. The results show that the normal speed control will not get the steady state till the end while direct torque control is reached stable position after some time.

The torque-time characteristics demonstrate that the direct torque control has great unique execution and decreased the torque ripples contrasted with the typical speed control. The phase to ground voltage is appeared in Fig.13. The voltage keeps up steady greatest incentive at each cycle.

5-CONCLUSION:

This paper interduce a modeling of PM BLDC motor under Matlab/Simulink. DTC has been implemented to a PM BLDC engine, and its utility has been approved by reproductions from the torque and flux. The estimation of torque and the portrayal of the inverter voltage vectors has been demonstrated that DTC is equipped for prompt torque control and, along these lines, of diminishing torque throbs and has the points of interest, for example, an ideal response time. It doesn't have mechanical sensors and affectability live with fasten the variety of specific parameters of the machine, it permits to acquire brilliant powerful exhibitions.

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