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MODELLING AND IMPLEMENTATION OF AN IMPROVED DSVM SCHEME FOR PMSM DTC

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Abstract: **A very widely used drive strategy for PMSM is the field oriented control (FOC), which was proposed in 1971 for induction motors (IMs). However, the FOC scheme is quite complex due to the reference frame transformation and its high dependence upon the motor parameters and speed. To mitigate these problems, a new control strategy for the torque control of induction motor was developed by Takahashi known as the direct torque control (DTC) and by Depenbrock as the direct self control (DSC). The basic direct torque control (DTC) scheme may cause undesired torque, flux and current ripples because of the small number of applicable voltage vectors. The control system should be able to generate any voltage vector, implying the use of space vector modulation (SVM) which complicates the control scheme. The discrete space vector modulation (DSVM) method was proposed for DTC to overcome this problem which replaces the simple switching table by several switching tables, to apply a combination of three voltage vectors in the same sampling period. In this paper, after a brief review of the primary concept of DSVM DTC technique, a new scheme of DSVM DTC for PMSM is proposed with a new set of switching tables taking into account the motor speed and the absolute values of torque and flux feedback errors. In one fixed sampling time interval, three vectors are applied to the motor including the two null vectors. Comparisons of the basic DTC and the improved DSVM DTC schemes are made based on the system performance and switching loss. For this purpose the DSVM technique uses prefixed time intervals within a sampling cycle to synthesize a higher number of voltage vectors than the basic DTC scheme. A set of switching table is carried out to minimize the torque error. An optimal vector selector is developed to reduce the switching loss and make the system more stable. The sampling period does not need to be doubled in order to achieve a mean switching frequency practically equal to that of the basic DTC scheme. For a comparable performance, the switching loss of the proposed scheme is less than that of the basic DTC method. The vector application sequence is investigated and an optimal algorithm is developed to reduce the switching loss and torque ripple. Simulation and experiments on the improved DSVM DTC are carried out and compared with those on the basic DTC scheme.**

Keywords: **Direct Torque Control, Discrete Space Vector Modulation, Field Oriented Control, Fuzzy Logic Controller, Permanent Magnet Synchronous Machine, Space Vector Modulation, Switching Table.**

I. INTRODUCTION

The permanent magnet synchronous motor (PMSM) has found wide applications due to its high power density (Compactness)., high efficiency, high torque-to-inertia ratio, and high reliability. A very widely used drive strategy for PMSM is the field oriented control (FOC), which was proposed by Blaschke in 1971 for induction motors (IMs) [1]. However, the FOC scheme is quite complex due to the reference frame transformation and its high dependence upon the motor parameters and speed. To mitigate these problems, a new control strategy for the torque control of induction motor was developed by Takahashi known as the direct torque control (DTC) [2] and by Depenbrock as the direct self control (DSC)[3]. The basic idea of DTC for induction motor is to control the torque and flux linkage by selecting the voltage space vectors properly, which is based on the relationship between the slip frequency and torque. It has been proven that the DTC scheme for induction motors could be modified for PMSM drive. Since it does not require any current regulator, coordinate transformation and PWM signal generator, the DTC scheme has the advantages of simplicity, good dynamic performance, and insensitivity to motor parameters except the stator winding resistance. Compared with the FOC, the major drawback of the DTC method is the large ripples of torque and flux linkage. The switching state of the inverter is updated only once in every sampling interval. The inverter keeps the same state until the output of the hysteresis controller changes state, resulting in relatively large torque and flux ripples. Another unwanted feature is the non-constant inverter switching frequency, which changes with the rotor speed, load torque and bandwidth of the two hysteresis controllers. In the past few years, many attempts were carried out to overcome these problems. Fixed switching frequency and reduction of torque ripple could be obtained by calculation of the stator flux vector variation required to exactly compensate the flux and torque errors. The control system should be able to generate any voltage vector, implying the use of space vector modulation (SVM) which complicates the control scheme. On the other hand, a discrete SVM (DSVM) method was proposed to improve the DTC scheme, which replaces the simple switching table by several switching tables, to apply a combination of three voltage vectors in the same sampling period [4]. The torque and flux ripple could be reduced with small calculation cost although the switching frequency of inverter is still variable. In this paper, the DSVM DTC of PMSM is reviewed and the choice of null-vectors and the vector selection sequence are modified to improve the performance and reduce the inverter switching loss. Comparisons of the basic DTC and the improved DSVM DTC schemes are made based on the system performance and switching loss. The novel DSVM DTC scheme is also experimentally tested and the results show improvements in both steady state and dynamic performance

II. PMSM MODEL AND DTC

The Permanent Magnet Synchronous Motor (PMSM) has numerous advantages over other machines that are conventionally used for ac servo drives. The stator current of the induction motor (IM) contains magnetizing as well as torque-producing components. The use of the permanent magnet in the rotor of the PMSM makes it unnecessary to supply magnetizing current through the stator for constant air-gap flux; the stator current need only be torque producing. Hence for the same output, the PMSM will operate at a higher power factor (because of the absence of magnetizing current).and will be more efficient than Induction Motor. The development of the PMSM was to remove the foregoing disadvantages of the Synchronous Motor by replacing its field coil, DC power supply and slip rings with a permanent magnet.

Model of the Permanent Magnet Synchronous Motor:

The two axes PMSM stator windings can be considered to have equal turn per phase. The rotor flux can be assumed to be concentrated along the d axis while there is zero flux along the q axis, an assumption similarly made in the derivation of indirect vector controlled induction motor drives. Also, rotor flux is assumed to be constant at a given operating point. There is no need to include the rotor voltage equation as in the induction motor since there is no external source connected to the rotor magnet and variation in the rotor flux with respect to time is negligible. The stator equations of the induction machine in the rotor reference frames using flux linkages are taken to derive the model of the PMSM. The rotor reference frame is chosen because the position of the rotor magnets determine independently of the stator voltages and currents, the instantaneous induced emf and subsequently the stator currents and torque of the machine. In Induction motor, the rotor fluxes are not independent variables, they are influenced by the stator voltage and currents and that is why any frame of reference is suitable for the dynamic modeling of the induction machine.

The well-known voltage equations in the rotor reference frame are as follows:

$$\upsilon_d = R_d\, i_d + \frac{d}{dt}\psi_d - \omega_r\psi_q \qquad (1)$$

$$\upsilon_q = R_q i_q + \frac{d}{dt}\psi_q + \omega_r\psi_d \qquad (2)$$

Where Rd and Rq are the quadrature and direct-axis winding resistances which are equal and be referred to as Rs is the stator resistance. To compute the stator flux linkage in the q and d axes, the current in the stator and rotor are required. The permanent magnet excitation can be modeled as a constant current source, $i_{f.}$ The rotor flux along d axis, so the d axis rotor current is $i_{f.}$ The q axis current in the rotor is zero, because there is no flux along this axis in the rotor, by assumption.

Then the flux linkage are written as

$\psi_d = L_d i_d + L_m I_f$ (3)

$\psi_q = L_q i_q$ (4)

Where Lm is the mutual inductance between the stator winding and rotor magnets Substituting these flux linkages into the stator voltage equations gives the stator equations:

$\upsilon_q = R_s i_q + \omega_r (L_d i_d + \psi_f) + \rho L_q i_q$ (5)

$\upsilon_d = R_s i_d - \omega_r L_q i_q + \rho (L_d i_d + \psi_f) R_d + L_d i_d$ (6)

$T_e = \frac{3}{2}(\psi_d i_q - \psi_q i_d)$ (7)

Which upon substitution of the flux linkages in terms of the inductances and current yields

$T_e = \frac{3}{2} P (\psi_f i_q + (L_d - L_q) i_q i_d)$ (8)

The implementation of Direct Torque Control System:

The basic DTC scheme is indicated in figure1, torque and flux signals are obtained from the estimator. These are regulated by using two hysteresis controllers. The hysteresis controllers outputs in turn switch the three inverter legs, applying a set of voltage vectors across the motor.

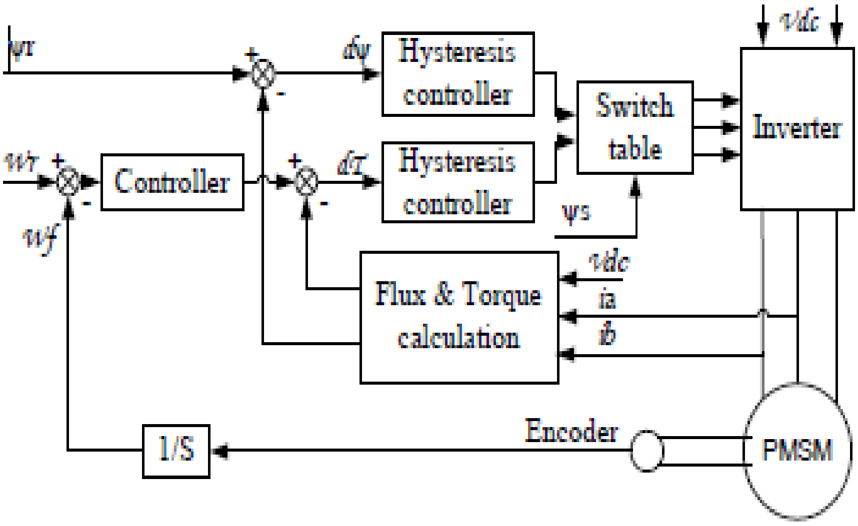


Fig. 1: Block Diagram for basic DTC of PMSM

In the DTC there are no extra sensors needed compared to FOC except the dc-bus voltage sensors. The continuous rotor position which is essential for torque control in the FOC is not required if the initial rotor position is known.

Flux and Torque Estimator:

Flux and torque estimator are used to determine the actual value of the torque and flux linkage. Into this block enters the VSI voltage vector transformed to the qd-stationary reference frame.

The stator flux linkage is estimated by taking the integral of difference between the input voltage and the voltage drop across the stator resistance as,

$\psi_d = \int (\upsilon_d - R_s i_d) \, dt$

$\psi_q = \int (\upsilon_q - R_s i_q) \, dt$ (9)

The flux linkage phasor is given by

$\psi_s = \surd(\psi_d^{2} + \psi_q^{2})$ (10)

In this block, the location of stator flux linkage (θ) is determined by the load angle (δ) i.e the angle between the stator and rotor flux linkage. The load angle must be known so that the DTC can choose an appropriate set of vectors depending on the flux location. The load angle can be determined by:

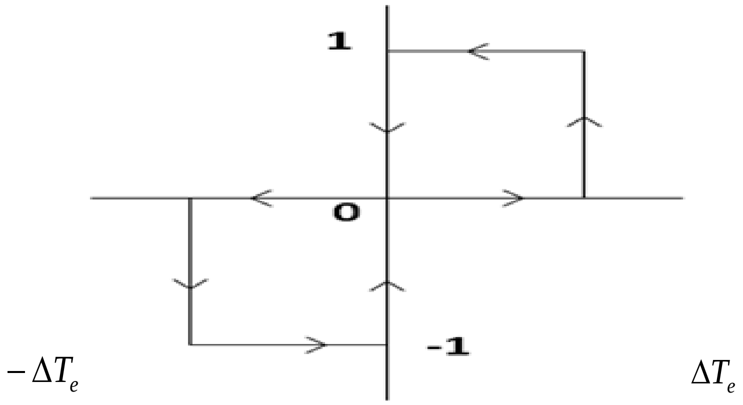
$$\delta=\tan^{-1}\frac{\psi d}{\psi q} \qquad (11)$$

The electromagnetic torque can be estimated with;

$$Te = \frac{3}{2} P\,(\psi_d\, i_q - \psi_q\, i_d) \qquad (12)$$

Torque and Flux Hysteresis Comparator:

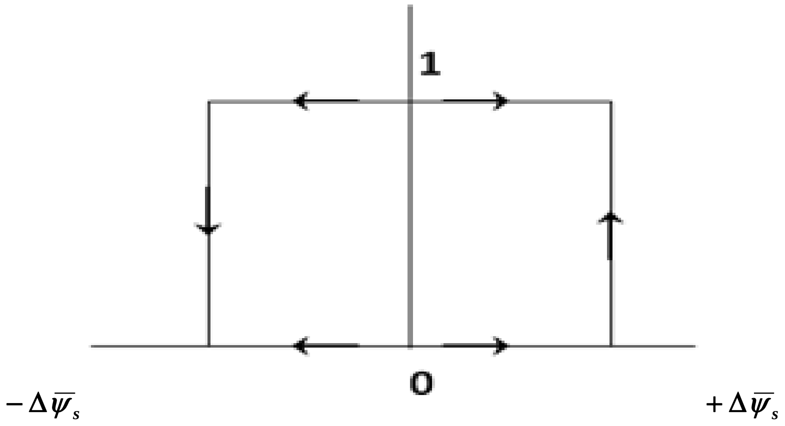
The estimated torque and stator flux linkage are compared with the reference torque and stator flux linkage. The difference between reference and estimated value is compared in this figure 2&3. If the actual torque is smaller than the reference value, the comparator output at state 1 or otherwise.



$$\text{If } T_e^* - T_e \ge \Delta T_e \quad \text{then } S_T = 1$$
$$\text{If } T_e \ge T_e^* \quad \text{then } S_T = 0$$

$$\text{If } T_e^* - T_e \le -\Delta T_e \quad \text{then } S_T = -1$$
$$\text{If } T_e \le T_e^* \quad \text{then } S_T = 0$$

Figure 2: 3-level torque hysteresis comparator



$$\text{If } \overline{\psi}_s \le \overline{\psi}_s^* - \Delta\psi_s \quad \text{then } S_\psi = 1$$
$$\text{If } \overline{\psi}_s \ge \overline{\psi}_s^* + \Delta\psi_s \quad \text{then } S_\psi = 0$$

Figure 3: 2-level flux hysteresis comparator

The control of the rotation of stator flux linkage (ψ_s):

When the zero voltage vectors are selected the stator flux linkage vector will be standstill in the position where it was and the electromagnetic torque will decrease rapidly. In a PMSM, however, the stator flux linkage is jointly determined by both the stator voltage and the rotor magnet flux. Since the permanent magnets rotate all the time, the stator flux linkage still exists even if the zero voltage vectors are used, and as a result, the zero voltage vectors will only cause the torque decrease slightly. An inverse voltage vector is normally selected to reduce the torque rapidly. The zero voltage vectors are not used for controlling the stator flux linkage. Thus ψ_s should always be in motion with respect to rotor flux linkage.

The electromagnetic torque can be controlled effectively by controlling the amplitude and rotational speed of the stator flux linkage. For counter-clockwise operation, if the actual torque is smaller than the reference, the voltage vector that keeps ψ_s rotating in the same direction are selected. The angle δ increases as fast as it can, and the actual torque increases as well. Once the actual torque is greater than the reference, the voltage vectors that keep ψ_s rotating in the reverse direction are selected instead of the zero voltage vectors. The angle δ decreases, and the torque decreases also.

By selecting the voltage vectors in this way, the stator flux linkage (ψ_s) is rotated all the time and its rotational direction is determined by the output of the hysteresis controller for the torque.

The switching table for controlling the amplitude and rotating direction of ψ_s is as below and is used for both directions of operations. In Table 1, φ and τ are the outputs of the hysteresis controllers for the flux linkage and torque, θ_1 - θ_6 denote the section of the space vector plane where the present flux linkage vector is located, V_1 - V_6 are the voltage vectors to be selected. This table formed the control strategy for DTC of PMSM.

If the φ = 1, then the actual flux linkage is smaller than the reference value. The same is true for the torque.

Table 1: The Switching table for Inverter

Flux ϕ	Torque τ	θ-Section (stator flux linkage position)					
		θ_1	θ_2	θ_3	θ_4	θ_5	θ_6
ϕ = 1	τ = 1	V_2(110)	V_3(010)	V_4(011)	V_5(001)	V_6(101)	V_1(100)
	τ = 0	V_6(101)	V_1(100)	V_2(110)	V_3(010)	V_4(011)	V_5(001)
ϕ = 0	τ=1	V_3(010)	V_4(011)	V_5(001)	V_6(101)	V_1(100)	V_2(110)
	τ=0	V_5(001)	V_6(101)	V_1(100)	V_2(110)	V_3(010)	V_4(011)

III. DISCRETE SPACE VECTOR MODULATION (DSVM)

Although this technique can clearly reduce the torque and flux ripples, more than six vectors directions are necessary to achieve a decoupled control of flux and torque of the machine. The simple switching table replaced by several switching tables, obtaining a combination of three voltage vectors into the same sampling period, which is called Discrete Space Vector Modulation(DSVM).

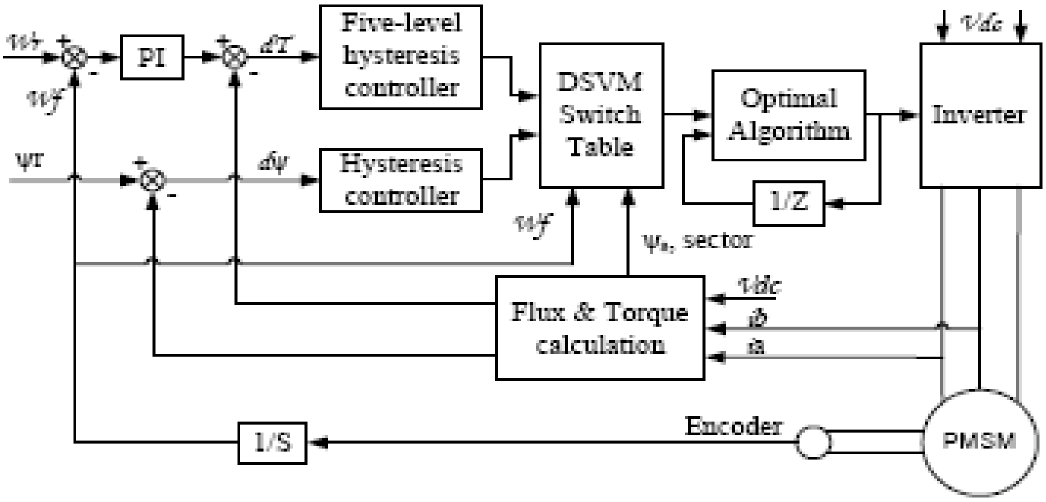


Fig 4: Block diagram of improved DSVM DTC scheme (proposed system)

Discrete SVM for DTC:

To reduce the switching frequency, algorithms based on discrete space vector modulation (DSVM) technique was developed, using prefixed time intervals within a cycle period. In this way a higher number of voltage space vectors can be synthesized compared to those used in the basic DTC technique. The increased number of voltage vectors allows the definition of more accurate switching tables in which the selection of voltage vectors is made according to the rotor speed, the flux error and the torque error. As shown in Fig. 5, three equal time intervals are used in one cycle period. In each sampling period the voltage vector is selected once only, as in the basic DTC scheme.

The advantage of using the DSVM technique is that one can choose among 19 voltage vectors instead of 5 of the basic DTC. On the other hand, at different speed ranges, the same vectors produce torque. Variations with quite different absolute values. This behaviour determines different torque ripple at low and high speeds. In the reported DSVM scheme, a set of new switching tables were established with the help of the multi-level torque hysteresis comparator and also considering the rotor speed range.

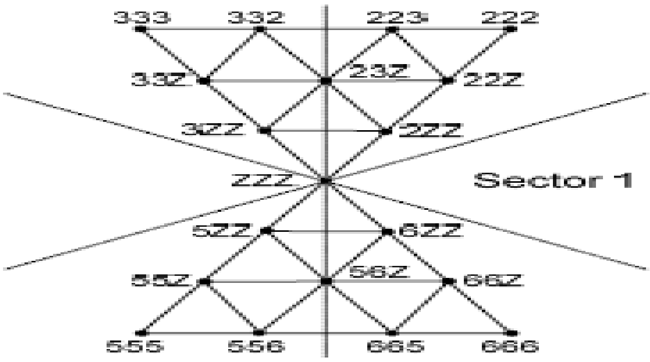


Fig. 5: Voltage Vectors Obtained by Using DSVM

Design of Fuzzy Logic controller:

Once fuzzy system is created using command line functions, can be directly embedded into SIMULINK using the **Fuzzy Logic Controller** block. In fuzzy Logic Controller design we relate the inputs with different rules for different membership functions.

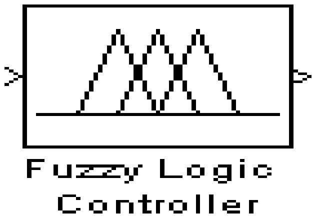


Fig 6: Fuzzy Logic Controller Block

IV. SIMULATION AND RESULT ANALYSIS

The simulation models are presented and the results are discussed. The PMSM parameter used in this project are given in Table 2.

Table 2: Parameter Values of PMSM used in Simulation

Resistance R (ohm)	0.4Ω
Inductance [Ld,]H	8.72 x10-3 H
Inductance [Lq,]H	22.8 x10-3H
Flux Induced by magnets[wb]	0.108
Inertia[Jkgm^2]	3.8 x10-3
Friction factor	0.1 x 10-4
Pairs of pole	4

Simulink block of the DSVM DTC for PMSM:

The simulink block for improved DSVM DTC scheme with fuzzy controller This method was proposed to improve the DTC scheme, which replaces the simple switching table by several switching tables to apply a combination of three voltage vectors in the same sampling period.

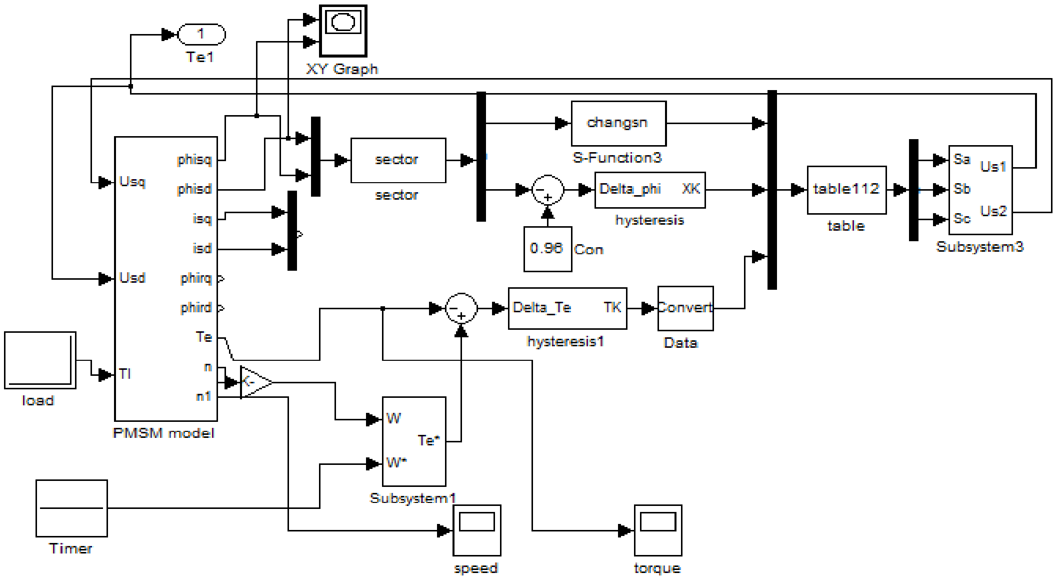


Fig 7: Simulink Block Diagram of DSVM DTC for PMSM

Simulation Results:

Matlab/Simulink models were developed to examine the basic SVM based Direct Torque Control for Permanent Magnet Synchronous Motor and improved Discrete Space Vector Modulation (DSVM) for Permanent Magnet Synchronous Motor. The waveforms are flux linkage, torque and speed respectively. The torque given is 10Nm to -10Nm and the stator flux linkage is set at the rated value 0.182Wb. Presents the comparison of basic SVM based DTC of PMSM and DSVM based DTC of PMSM performance at the same torque and flux. An appreciable reduction of torque and speed ripples has been obtained by using the DSVM technique.

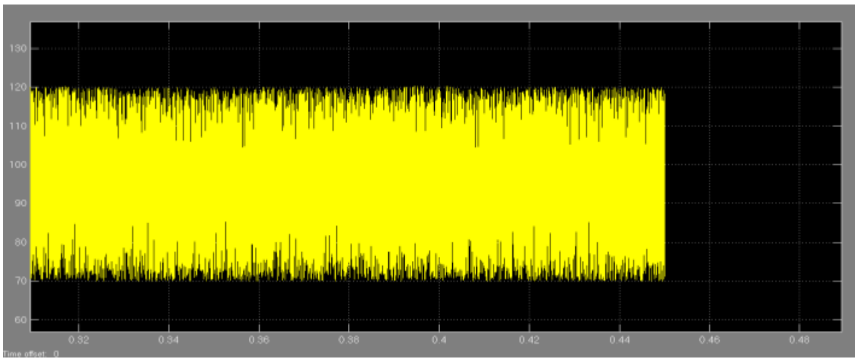


Fig 8:Steady state performance of basic DTC for PMSM with constant load at speed 100rpm.

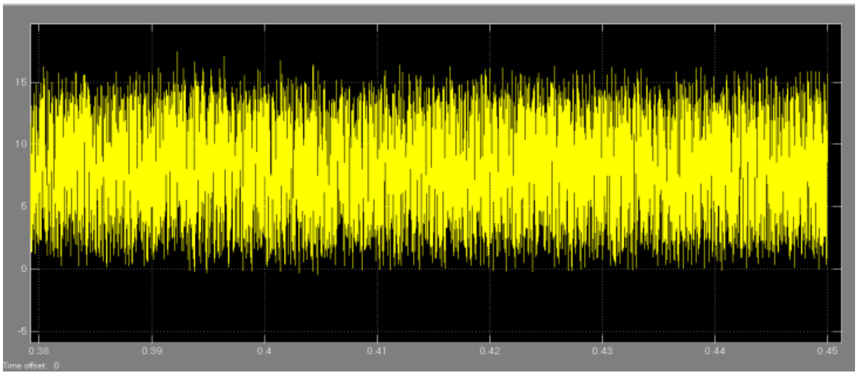


Fig 9:Steady state performance of basic DTC for PMSM with constant load at torque 10Nm.

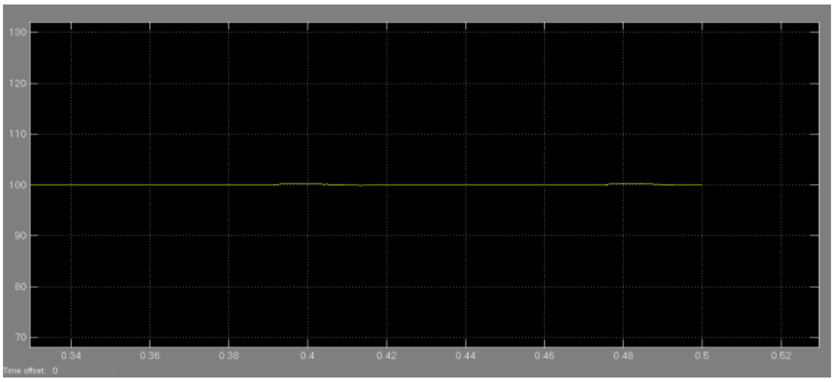


Fig 10:Steady state performance of DSVM DTC for PMSM with constant load at speed 100rpm.

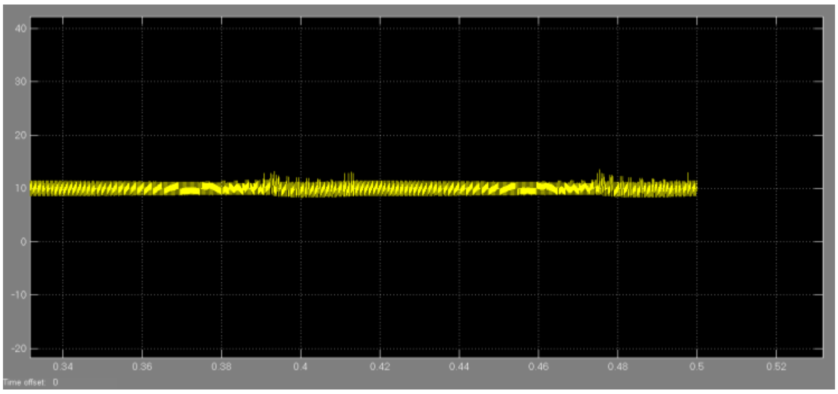


Fig 11:Steady state performance of DSVM DTC for PMSM with constant load at torque 10Nm.

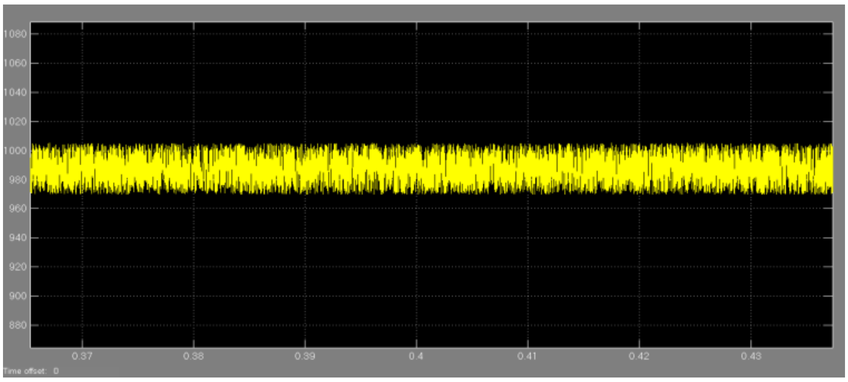


Fig 12:Steady state performance of basic DTC for PMSM with constant load at speed 1000 rpm.

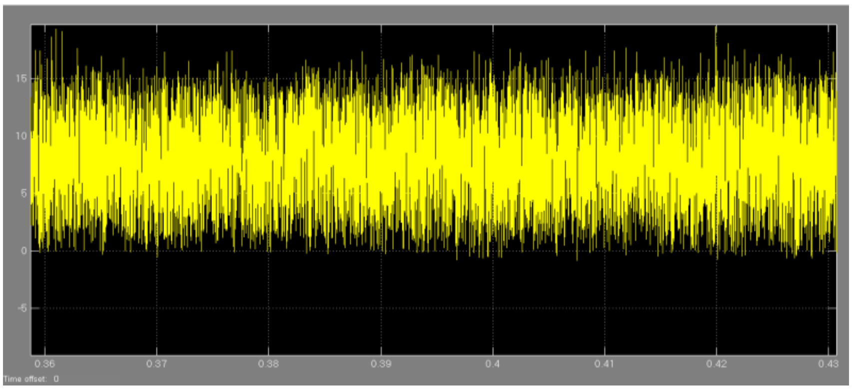


Fig 13: Steady state performance of basic DTC for PMSM with constant load at torque 10Nm.

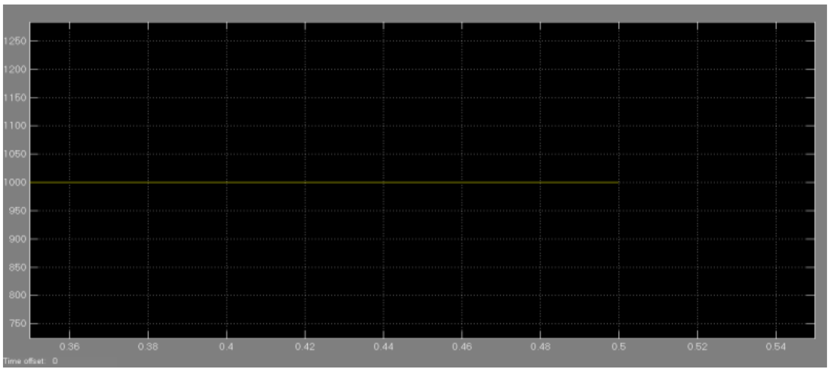


Fig 14 :Steady state performance of DSVM DTC for PMSM with constant load at speed 1000rpm.

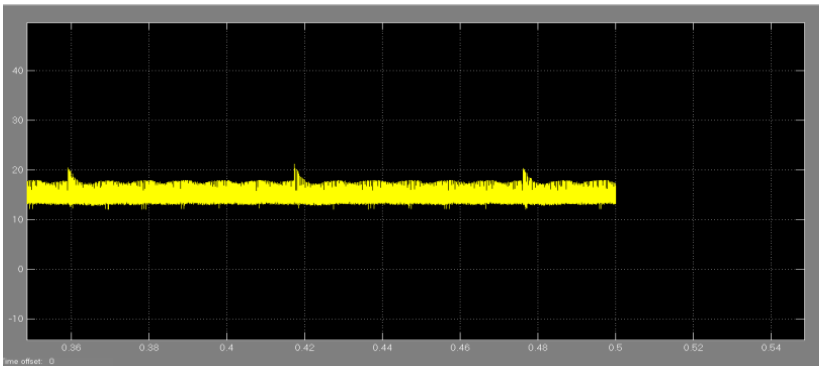


Fig 15:Steady state performance of DSVM DTC for PMSM with constant load at torque 10Nm.

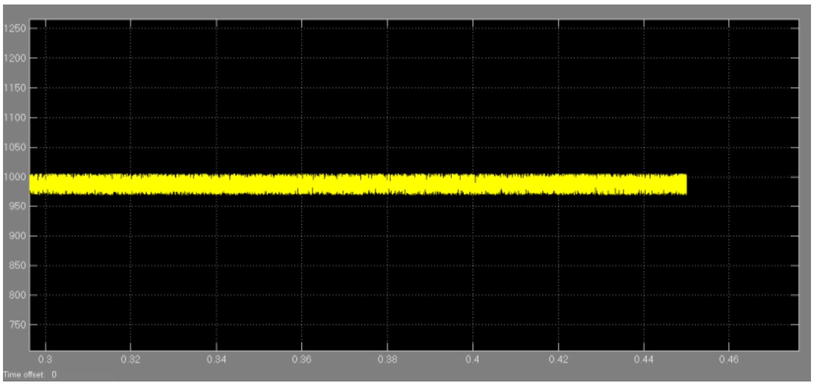


Fig 16:Performance of basic DTC for PMSM with variable load at speed 1000rpm and sampling period of 60µs.

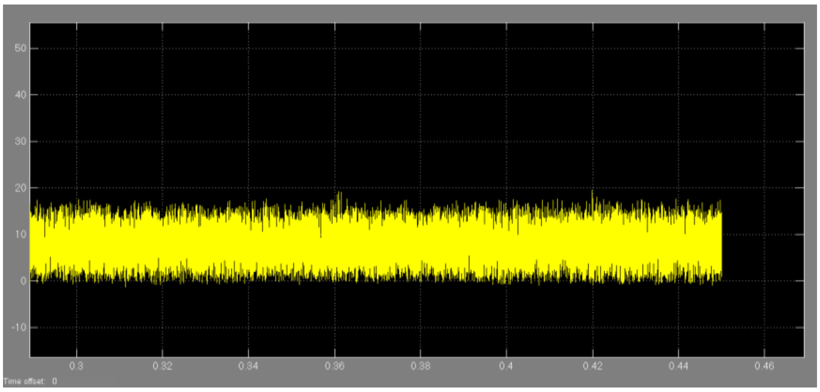


Fig 17:Performance of basic DTC for PMSM with variable load at torque 5Nm and sampling period of 60µs.

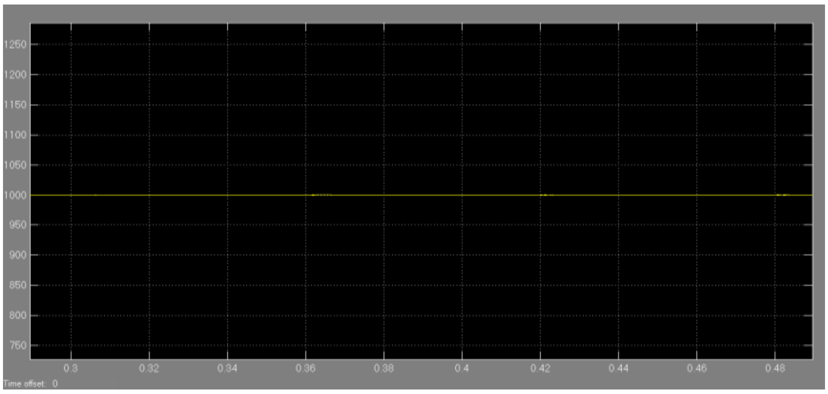


Fig 18:Performance of DSVM DTC for PMSM with variable load at speed 1000rpm and sampling period of 75µs.

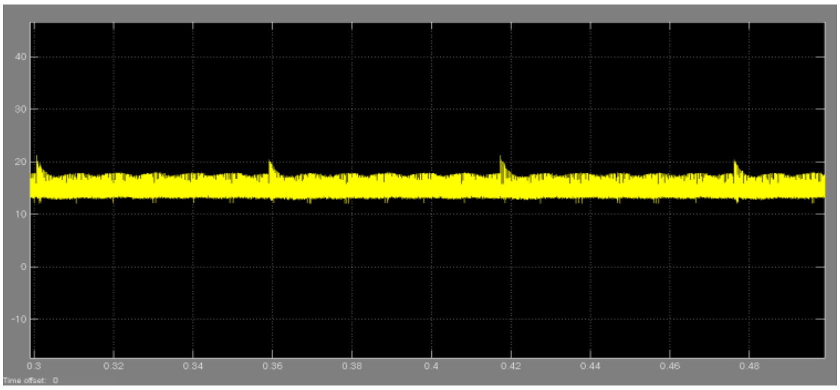


Fig 19:Performance of DSVM DTC for PMSM with variable load at torque 5Nm and sampling period of 75µs.

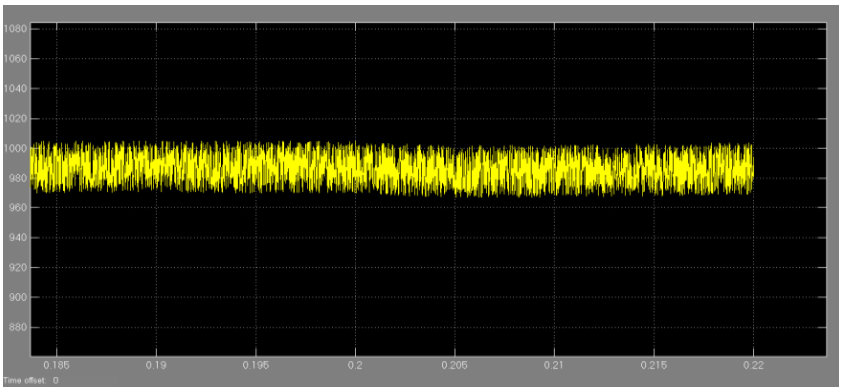


Fig 20:Performance of basic DTC for PMSM with variable load at speed 1000 rpm and sampling period of 60µs.

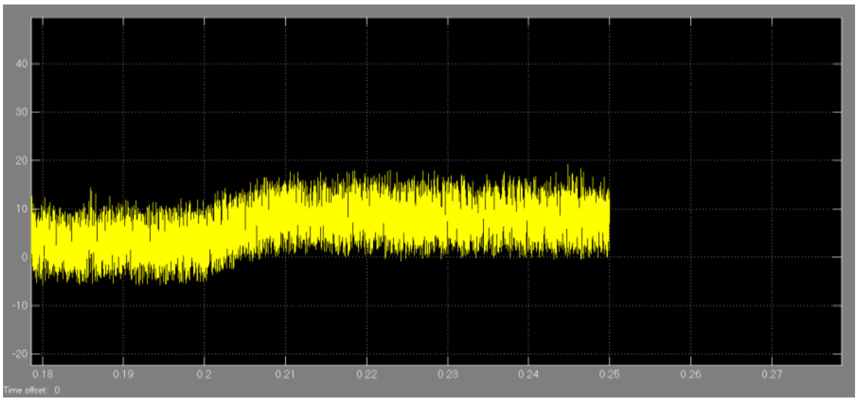


Fig 21:Performance of basic DTC for PMSM with variable load at torque 5Nm and sampling period of 60µs.

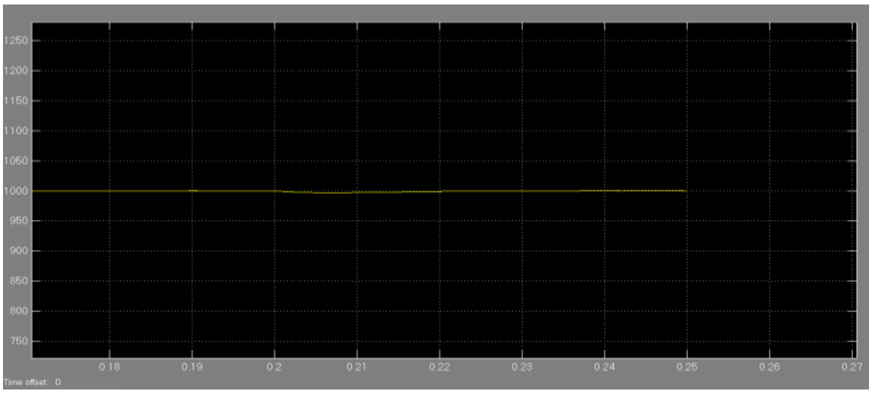


Fig 22:Performance of DSVM DTC for PMSM with variable load at speed 1000rpm and sampling period of 75µs.

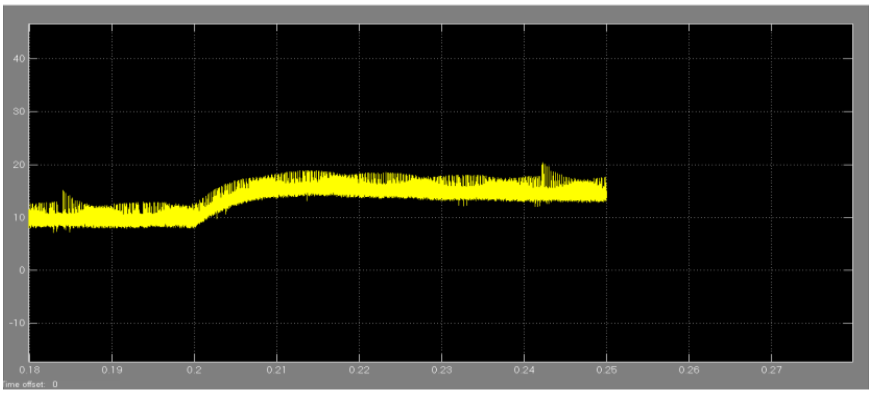


Fig 23:Performance of DSVM DTC for PMSM with variable load at torque 5Nm and sampling period of 75µs.

V. CONCLUSION

The DSVM DTC method is designed to modify the basic DTC control scheme to improve the performance of PMSM drive system with significant reduction of torque and flux ripples without using any complicated control algorithms. For this purpose the DSVM technique uses prefixed time intervals within a sampling cycle to synthesize a higher number of voltage vectors than the basic DTC scheme.

A set of switching table is carried out to minimize the torque error. An optimal vector selector is developed to reduce the switching loss and make system more stable. The sampling period does not need to be double in order to achieve a mean switching frequency practically equal to that of the basic DTC scheme.

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