Sensorless Induction Motor Speed Control with Fast Dynamic Torque Control

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Abstract - **Vector control is employed in induction motor drives to provide a fast torque response. Various vector control methods have been proposed before, among which Direct Torque Control provides high dynamic performance with very simple control scheme. Basic DTC scheme is based on hysteresis control of flux and torque. The dynamic torque performance is very important in traction and electric vehicle applications. A method to achieve fastest dynamic performance by modifying the basic DTC scheme is discussed in this paper. This is achieved by applying a single voltage vector that produces the largest tangential flux component, at the time of torque dynamics. The modified method is used in sensorless speed control of induction motor. The new scheme was analysed using SEQUEL simulation tool.**

Keywords— **DTC, Dynamic Torque Response, Modified DTC, Sensorless Speed Control, SEQUEL simulation tool**

I. INTRODUCTION

Direct Torque Control scheme provides a decoupled control of torque and flux of induction machine. The scheme has a simple control structure and provides fast and good dynamic torque response. It also provides an indirect control of stator currents and voltages. This scheme was first proposed by Depenbrock in [2] and was termed as Direct Self Control (DSC). Later Takahashi and Noguchi introduced Direct Torque control method [3] which was a slight modification of DSC scheme. DTC has gained much popularity after its introduction due to its simple control scheme.

Basic DTC scheme is based on hysteresis control of torque and flux and has the disadvantages of high torque ripples and variable switching frequency. But the torque control was fast, as the torque and flux was controlled directly based on the estimated machine torque and flux. The researches done on DTC mainly focused on reducing torque ripples and achieving constant switching frequency. An analytical investigation on the ripples produced in torque and flux was done in [4]. The most popular variation of DTC of induction motor drives is one that based on SVM of inverter [5]. In DTC-SVM, a reference voltage is calculated or generated within a sampling period, which is synthesized using the space vector modulator. The SVM scheme provides a constant switching frequency and reduces torque ripples .But the controller scheme is complicated. A modulated hysteresis controller with constant switching frequency was proposed in [6]. In [7], PI controller was used for torque and flux control instead of hysteresis controllers. Variable hysteresis band was used to obtain a constant switching frequency in [8].

The newly introduced DTC schemes were able to achieve constant switching frequency with reduced torque ripples but on the expense of losing the simple controller structure. The basic DTC scheme can be used in low precision applications where the ripples in torque and flux can be ignored. The switching frequency can be limited by properly selecting the torque hysteresis band. The basic DTC scheme is capable to provide fast dynamic torque control. The dynamic torque performance is so important especially in traction and electric vehicle application. The dynamic torque response in DTC drive can be improved by efficiently utilizing the inverter DC-link voltage. The response can be made faster by using dynamic overmodulation of inverter.

This paper discusses a method to improve the torque response. The scheme is a modification of the basic hysteresis based DTC scheme, where the flux error status is modified before feeding to switching table. This is done to select only a single voltage vector during the dynamic torque condition. The voltage vector selected is such that it will produce the largest tangential flux component to the circular flux locus. Thus the method can provide fastest dynamic torque response while retaining the simple structure of basic DTC. This modified DTC is used for sensorless speed control of induction motor. Speed is estimated from the machine parameters and estimated torque.

II. DIRECT TORQUE CONTROL - PRINCIPLE

The electromagnetic torque developed in an induction motor is given below:

$$Te = \frac{3}{z}\mathbf{P|cps||is|smO'} \qquad (1)$$

where P is the number of pole pairs, cps is the stator flux, is is the stator current and 8 is the angle between stator flux and stator current. By keeping **|cps|** constant, the torque can be controlled by varying 8.

Consider the induction motor voltage equations **in** stationary reference frame;

$$VS = RSF_s + \frac{d<\{Js}{dt} \qquad (2)$$

$$0 = Rri. - jw.cpr + \frac{dcp\^}{at} \qquad (3)$$

From (2);

$$\frac{dcp_s}{dt} = \ldots \qquad (4)$$

Since the stator resistance drop is negligible (4) can be written as;

$$\frac{dcp_s}{dF} \qquad (5)$$

$$<(Js = \int Vs \, .dt \qquad (6)$$

From above equation it can be seen that by applying appropriate voltage space vector to motor the stator flux vector can be controlled.

A three-phase inverter schematic is shown in Fig.1. Based on the switching conditions it can have eight switching states. Out of which six produce active voltage space vectors and two states produce zero vectors.

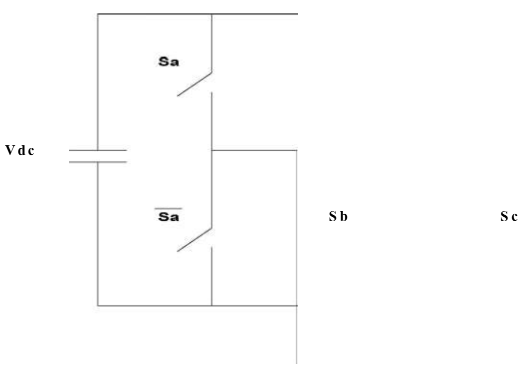


Figure 1. Three Phase Inverter schematic

Table. 1 shows the switching states and the voltage space vectors are diagrammatically represented in Fig.2.

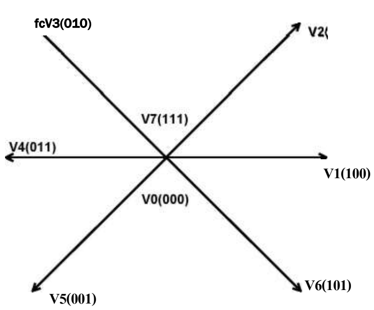


Figure 2. Voltage Space Vectors

TABLE I. INVERTER SWITCHING STATES

Sa	Sb	Sc	Vab	Vbc	Vca
0	0	0	0	0	0
0	0	1	+Vdc	0	-Vdc
0	1	0	0	+Vdc	-Vdc
0	1	1	-Vdc	+Vdc	0
1	0	0	-Vdc	0	+Vdc
1	0	1	0	-Vdc	+Vdc
1	I	0	+Vdc	-Vdc	0
1	I	1	0	0	0

The block diagram of basic hysteresis based DTC scheme is shown in Fig.3

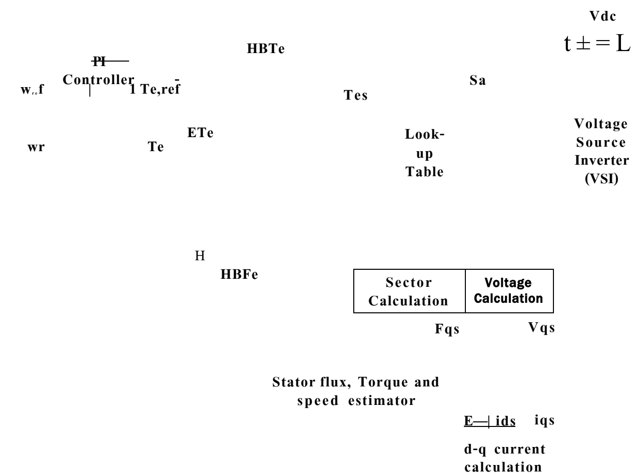


Figure 3. Basic DTC scheme

The flux, torque and speed estimation is done using the induction motor model in stationary d -q reference frame. The d and q axis voltages in stationary reference frame can be written as;

$$vJ_s = 3 \, Vdc(2Sa - Sb - Sc) \qquad (7)$$

$$V_{qs} - Vdc(Sb - Sc) \qquad (8)$$

$$<\{Jds - \int ds \qquad (9)$$

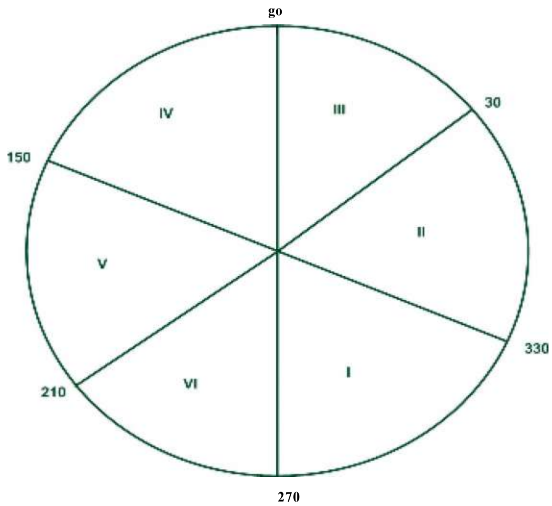
$$<(Jqs - \int * - qs \qquad (10)$$

Sa, Sb, Sc are the switching signals of inverter legs A, B and C.
The electromagnetic torque can be obtained using (11)

$$Te = -p((p_ds iqs - (Pqsids) \qquad (11)$$

and the speed $w_r = — f(Te\text{-}Tl)$ (12)

The above equations can be used to estimate torque, flux and speed. The stator flux vector of induction motor has a circular flux locus. The locus is divided into six sectors as



shown in Fig.4.

Figure 4. Flux locus and sectors

The speed estimated is compared with actual speed and error is fed to a PI controller to develop torque reference. The reference torque and actual torque are compared and error is fed to a three level hysteresis comparator to produce the torque error status Tes. The output of the hysteresis comparator will be 1, 0, or -1 based on Table.2.

TABLE II. TORQUE ERRORSTATUS Tes

Tes	Torque condition
1	Need to increase torque
0	to be maintained at same value
-1	Need to decrease

The flux error is also used to generate a flux error status Fes, by using a two level hysteresis comparator. It can have a status of 0 or 1 based on Table.3.

TABLE III. FLUX ERRORSTATUS Fes

Fes	Flux condition
1	Need to increase flux
0	Need to decrease flux

The error status along with sector information is fed to select appropriate switching signals Sa, Sb, Sc from the switching table. The switching table is formulated such that it will provide appropriate voltage vector based on whether the demand is to increase or decrease torque and flux.

A. Torque Control- during torque dynamics

A dynamic torque condition occurs when there is a sudden increase or decrease in speed demand due to acceleration or deceleration. Consider the situation of a sudden increase in speed. This will cause a demand for sudden increase in torque, resulting in dynamic torque condition. The torque error status bit Tes will be equal to 1 for the entire duration of dynamics i.e.; till the required speed level is attained. At the same time the flux error status Fes will switch between 0 and 1 to retain the circular flux locus, i.e.; to maintain the flux magnitude level constant.

The inverter will switch between two active voltage vectors at this time due to the change in flux error status. This will not guarantee quick torque response in the dynamic condition. To make the dynamic torque response fast the inverter must switch only a single voltage vector will increase the torque. The selected voltage vector should be such that it must produce the largest tangential flux component to circular flux locus so as to increase the torque. By using a single voltage vector for the entire duration of dynamic will put the inverter in overmodulation mode often referred to as dynamic over modulation.

III. MODIFIED DIRECT TORQUE CONTROL SCHEME

In the modified DTC scheme the dynamic overmodulation mode of inverter is used to achieve faster dynamic torque control. To select a single voltage vector for the entire torque dynamic period the flux error status Fes should be kept at a single value for this duration. The torque error status Tes will be having only a single value during this time. The status of flux error to be maintained is determined on the basis of location of flux.

Consider the situation of a demand for increase in torque and the flux vector lying in sector 1 and $a_k < 30°$ as shown in Fig.5. Let the motor rotation be counter clockwise.

To increase the torque the stator flux vector should advance in the counter clockwise direction. At this position of *qJs,* the voltage vector V I should be applied to increase the torque; since V I produces the largest tangential component to the flux locus as seen in Fig.5

Considering $a_k > 30°$ the location of flux vector and voltage components is shown in Fig.6. At this location of qJs, the voltage vector V2 has the largest tangential component to flux locus.

Hence the modified scheme should select V **1** when the location of flux is less than 30° inside a sector (in the direction of rotation) and should select V2 if location of flux vector is greater than 30°. This can be achieved by dividing the sector into two subsectors ass given below:

OS; a_k S; 30° subsector 1
30° S; ak S; 60° subsector 2

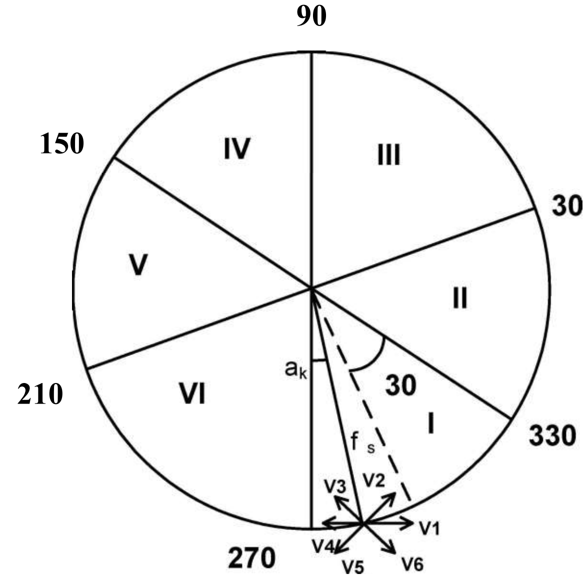


Figure **5.** Flux in subsector **I**

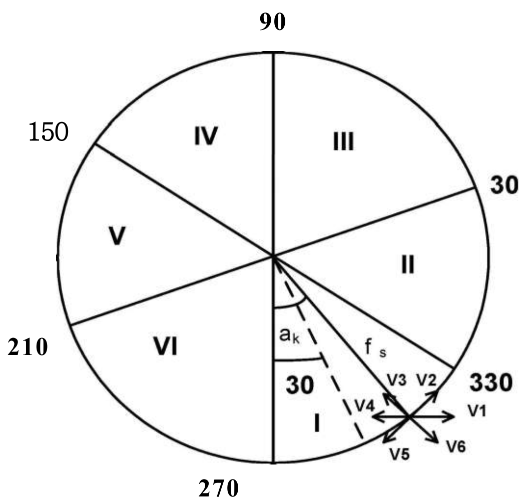


Figure **6.** Flux in subsector **2**

To select voltage vector VI it can be seen from the switching table that the Fes should be '1' and for selecting V2, the Fes should be '0'. Thus it can be concluded that Fes should be maintained at '1' if the flux is in subsector 1 and it should maintained at '0' if flux vector is in subsector 2 for the entire duration of torque dynamic.

Fig.7 shows the modified DTC scheme. The modification of flux error status block modifies the Fes during the torque dynamic as given below:

If ETe > 2HBTe, then

Fes+ = 1 if flux vector is in subsector 1
Fes+ = 0 if flux vector is in subsector 2

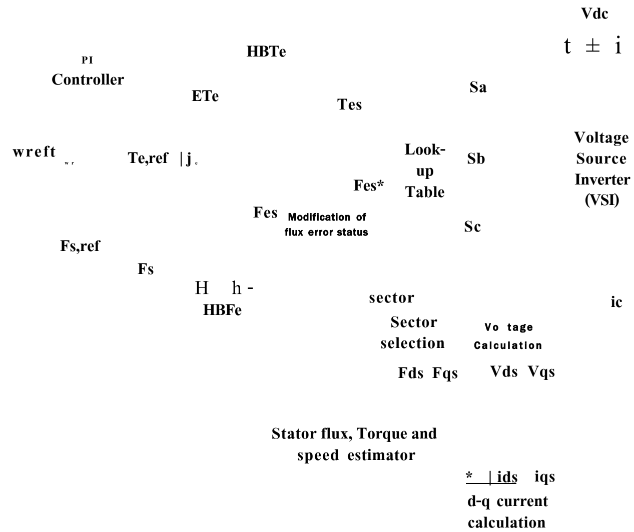


Figure **7.** Modified DTC Scheme

IV. SIMULATION RESULTS

Simulation of the modified DTC scheme was done using SEQUEL (Solver for circuit EQuations with User-defined Elements) simulation tool. The simulation of the basic DTC scheme is also done to compare the performance of the new scheme. The dynamic torque situation is evaluated by applying a step increase in speed from 100 rad/sec - 150 rad/sec with hysteresis band for torque controller as 1.013Nm and for flux controller as 0.016Wb. The PI controller parameters are Kp = Ki = 10 and Ti = 0.3. The simulation data is shown in Table.4

TABLE IV. SIMULATION PARAMETERS

Power	0.25hp
Vdc	615Volts
Rs	1.60680
Rr	1.60680
Us	9.6mH
Llr	9.6mH
Lm	241.9mH
J	0.25Kg-m^2
Speed Wr	157 rad/sec

Fig.8 - Fig.19 shows the simulation results.

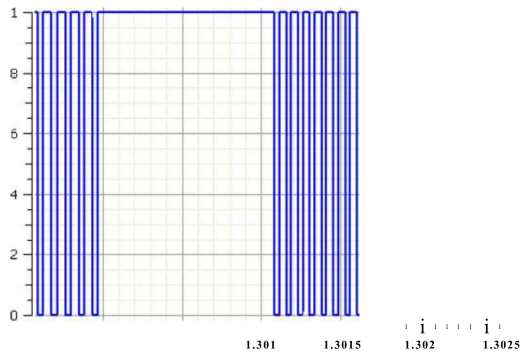


Figure 8. Torque error status - conventional DTC

1.3
time

Figure 9. Flux error status - conventional DTe

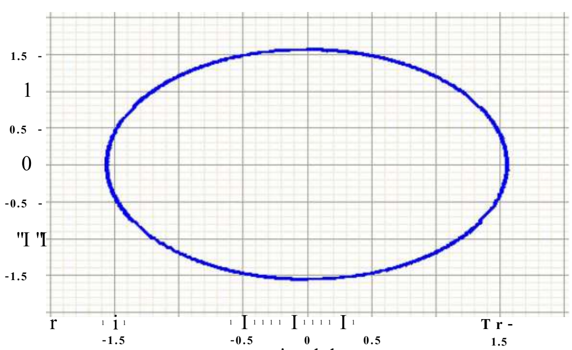


Figure 10. Flux locus - conventional DTe

1.6
1.4
1.2
1
0
1.298
1.299
1.3
1.301
psis_star
psis_est
time

Figure 11. Stator Flux- conventional DTe

1.3
1.302
time

Figure 12. Torque error status -Modified DTe

1.3
time

Figure 13. Flux error status - Modified DTe

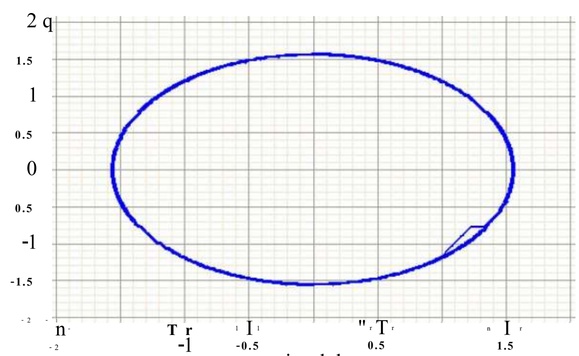


Figure 14. Flux locus - Modified DTe

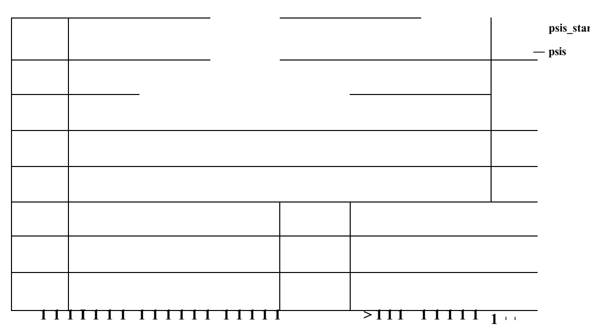


Figure 15. Stator Flux-Modified DTe

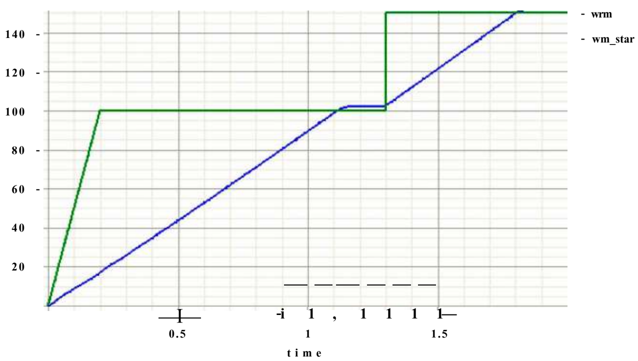


Figure 16. Speed Response -Modified DTC

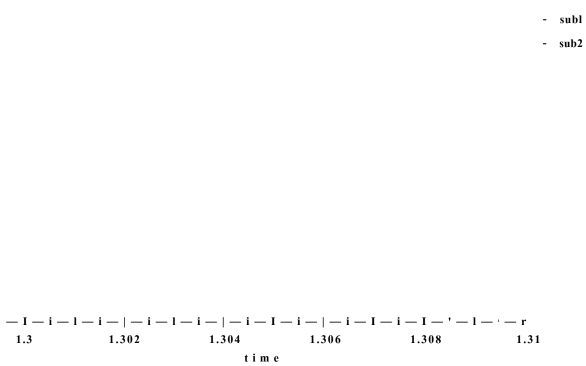


Figure 17. Flux Sub Sectors

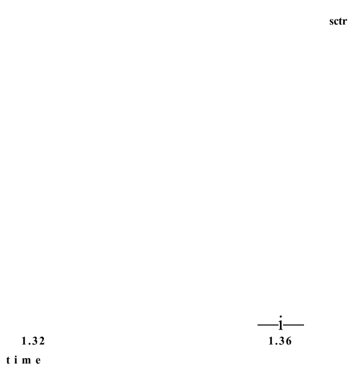


Figure 18. Flux Sectors

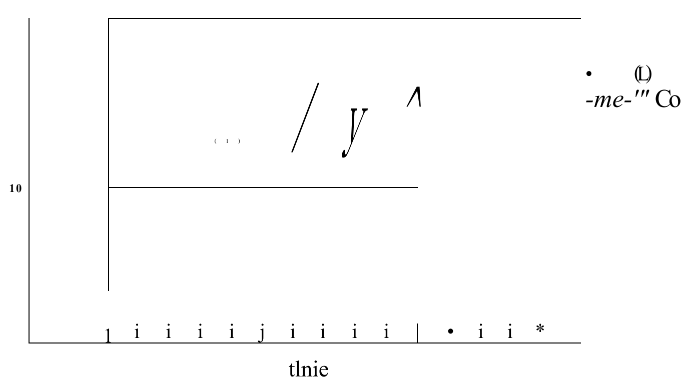


Figure 19. Torque Response

It can be seen from Fig. 18 and Fig. 17 that the flux location is at sector 1 and subsector 1 at the time of torque dynamic. The flux error status is maintained at 1 in the modified DTC as seen in Fig.I3. The torque response of conventional DTC scheme is shown by curve (2) in Fig. 19 and the torque response of modified DTC scheme is shown by curve (1) of Fig. 19. It can be seen from the figure that the modified DTC scheme has faster torque response that the basic DTC scheme.

V. CONCLUSION

The paper introduces a scheme to modify the basic hysteresis based Direct Torque Control scheme for improving the dynamic torque response. The modified scheme used a single voltage vector instead of switching between two voltage vectors during the entire dynamic torque period. The voltage vector to be selected is based on the location of stator flux within a sector. The scheme is used here for sensorless speed control of induction motor. Simulations of both basic and modified schemes for speed control were done in SEQUEL. The simulation results support the theoretical explanation given in this paper. Comparison between basic and modified scheme was done from the SEQUEL simulation results. The modified scheme was able to achieve fast control during torque dynamics while maintaining the simple structure of basic DTC.

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