Experimental Investigations on the Influence of Flux Control Loop in a Direct Torque Control Drive

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ABSTRACT

Accurate flux estimation and control of stator flux by the flux control loop is the determining factor in effective implementation of DTC algorithm. In this paper a comparison of voltage model based flux estimation techniques for flux response improvement is carried out. The effectiveness of these methods is judged on the basis of Root Mean Square Flux Error (RMSFE) and Total Harmonic Distortion (THD) of stator current. The theoretical aspects of these methods are discussed and a comparative analysis is provided with emphasis on digital signal processor (DSP) based controller implementation. Further the effect of operating flux on the performance of induction motor drive in terms of dynamic response, torque ripple and efficiency of operation is carried out. The proposed investigations experimentally validated on a test drive.

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1. INTRODUCTION

In a DTC induction motor drive, a decoupled control of torque and flux can be achieved by two independent control loops for torque and flux [1]-[3].The steady state as well as the dynamic performance of the drive is closely related to the efficient implementation of these two control algorithm. There are few well-known methods to estimate these parameters. Most of them are voltage model based [3], where the flux and torque are estimated by sensing stator voltage and current. The methods based on voltage models are most preferable for sensor less drives since these methods are less sensitive to the parameter variations and does not require motor speed or rotor position signals. However, the estimation of stator voltage when the machine is operating at low speed introduces error in flux estimation which also affects the estimation of torque and speed in case of sensor less drive [4]-[11].

In a conventional DTC drive the basic voltage model based flux estimation is carried out by integrating the back emf of the machine. A pure integrator has the following limitations.

1. Any transduction error in measured stator current due to offset introduces DC component and hence results in integrator saturation.
2. Integration error due to incorrect initial values.

A commonly employed solution is to replace a pure integrator with a low pass filter [12] [13], however it is achieved at the expense of deteriorated low speed operation of the drive, when the operating frequency of the drive is lower than the cut off frequency of the low pass filter.

Flux estimation based on the current model is most suitable for low speed operation [14] [15], however it is a parameter dependent method, which require rotor speed or position. Thus parameter independent operation, which makes a DTC drive more robust and reliable compared to a FOC drive ,gets affected when current model based flux estimation is implemented .

Most of the available literature on flux estimation and its influence on the performance of an induction motor drive is primarily focused on sensor less field oriented controlled drives [5]-[11].The available literature on DTC drives too are mainly confined to performance enhancement in terms of torque ripples. Since the steady state as well as dynamic performance of a DTC drive is greatly affected by the flux control loop which in turn depends upon flux estimation algorithm. In this paper a comprehensive study on voltage model based flux estimation algorithm from the perspective of their impact on the flux response of the drive, in terms of flux ripples and stator current harmonics is carried out. In a DTC drives a conventional way to set the flux reference is to use the nominal flux (which depends upon the rated voltage or the DC link voltage and the base speed of the drive) for speeds lower than thebase speed, and a flux reference inversely proportional to the rotor speed above the base speed (flux weakening). However, this solution is not an energy efficient solution especially when the drive is subjected to a varying load condition with periods of full and part loadings. In a DTC drive the ripples in torque are also increased due to non-optimal selection of the reference flux under variable load torque demand.

This paper investigates the performance of a DTC drive in terms of stator current harmonics and root mean square flux ripples under the influence of voltage model based flux estimation algorithm. The performance of the drive in terms of dynamic performance, torque ripples and energy efficiency with non-optimal selection of reference flux is also investigated.

2. VOLTAGE MODEL BASED FLUX ESTIMATION

2.1 Flux Estimation with Low Pass Filter

The stator flux components are computed by integration of the voltages in the stationary reference frame given by (1) - (4).

$$\lambda_{s\alpha} = \frac{1}{s}(E_{s\alpha}) \tag{1}$$

$$\lambda_{s\beta} = \frac{1}{s}\left(E_{s\beta}\right) \tag{2}$$

where

$$E_{s\alpha} = v_{s\alpha} - i_{s\alpha}R \tag{3}$$

$$E_{s\beta} = v_{s\beta} - i_{s\beta}R \tag{4}$$

Where $\lambda_{s\alpha}(k)$ and $\lambda_{s\alpha}(k-1)$ are flux linkage at the K th and (K-1) th sampling instant and Δt_s is sampling time step.A well-known solution to the dc-offset and initial value problem with a pure integrator is to replace it with a low pass filter (LPF) with an appropriate cut off frequency. The mathematical expression of the low pass filter with a cut off frequency of ω_c can be given by (5) and (6)

$$\lambda_{s\alpha} = \frac{1}{s+\omega_c}(E_{s\alpha}) \tag{5}$$

$$\lambda_{s\beta} = \frac{1}{s+\omega_c}\left(E_{s\beta}\right) \tag{6}$$

Where $\lambda_{s\alpha}(k)$ and $\lambda_{s\alpha}(k-1)$ are flux linkage at the K th and (K-1)th sampling instant. Which can be expressed in discrete form as shown by (7) and (8)

$$\lambda_{s\alpha}(k) = \frac{1}{1+\Delta t_s\omega_c}(\Delta t_s E_{s\alpha}(\mathrm{k}) + \lambda_{s\alpha}(\mathrm{k}-1\,)) \tag{7}$$

$$\lambda_{s\beta}(k) = \frac{1}{1+\Delta t_s\omega_c}\left(\Delta t_s\, E_{s\beta}(\mathrm{k}) + \lambda_{s\beta}(\mathrm{k}-1\,)\right) \tag{8}$$

The value of the cut-off frequency ω_c has to be judicially chosensince a cut-off frequency higher than operating frequency leads to flux distortion at low speeds.

2.2 Modified Low Pass Filter with Feedback Compensation.

The expression for the modified low pass filter with feedback compensation integration algorithm (Mod LPF) is given by (9).The method can be implemented as shown in Figure 1.

$$\lambda_s = E_s \frac{1}{s+\omega_c} + \lambda_s{}^{lim} \frac{\omega_c}{s+\omega_c} \quad (9)$$

The first part of the equation represents a low pass filter while the second part realizes a compensating feedback signal which is used to compensate the error in the output. The parameter $\lambda_s{}^{lim}$ in the second term of new integration algorithm is the output of a saturation block, which stops the integration when the output signal exceeds the reference stator flux amplitude. The value of $\lambda_s{}^{lim}$ can be obtained from the sine and cosine value of the angle obtained by integrating the stator angular frequency w_e given by (10) and (11).

$$\theta = \int w_e \mathrm{dt} \quad (10)$$

Where stator frequency can be given by

$$w_e = \frac{E_{s\beta}\lambda_{s\alpha} - E_{s\alpha}\lambda_{s\beta}}{|\lambda_s|^2} \quad (11)$$

The accuracy of the modified flux estimation algorithm thus is strongly dependent on the value of angle (θ) which can either be obtained from the stator frequency or from the flux components ($\lambda_{s\alpha}$, $\lambda_{s\beta}$) .At low speeds (low frequencies), accuracy of calculation is jeopardized by the large percentage of ripple in w_e . Hence, using the ratio of sin and cosine of angle (θ) based on the estimated flux components at low speeds leads to better results than the calculation based on electrical frequency.

The final expression of the Mod LPF for implementation on a discrete controller can be developed with the help of equations (12)-(16)

$$\lambda_s^{com} = \lambda_s{}^{lim} \frac{\omega_c}{s+\omega_c} \quad (12)$$

$$\lambda_{s\alpha}^{com}(k) = \frac{1}{1+\Delta t_s\omega_c}\left(\lambda_{s\alpha}^{com}(k-1) + \Delta t_s\omega_c\lambda_{s\alpha}{}^{lim}(k)\right) \quad (13)$$

$$\lambda_{s\beta}^{com}(k) = \frac{1}{1+\Delta t_s\omega_c}\left(\lambda_{s\beta}^{com}(k-1) + \Delta t_s\omega_c\lambda_{s\beta}{}^{lim}(k)\right) \quad (14)$$

$$\lambda_{s\alpha}(k) = \frac{1}{1+\Delta t_s\omega_c}\left(\Delta t_s E_{s\alpha}(k) + \lambda_{s\alpha}(k-1) + \lambda_{s\alpha}^{com}(k-1) + \Delta t_s\omega_c\lambda_{s\alpha}{}^{lim}(k)\right) \quad (15)$$

$$\lambda_{s\beta}(k) = \frac{1}{1+\Delta t_s\omega_c}\left(\Delta t_s E_{s\beta}(k) + \lambda_{s\beta}(k-1) + \lambda_{s\beta}^{com}(k-1) + \Delta t_s\omega_c\lambda_{s\beta}{}^{lim}(k)\right) \quad (16)$$

3. OPTIMAL FLUX OPERATION AND CONTROL

3.1 Optimal Operating flux

In a DTC dive the flux at which the motor operates depends upon the value of reference flux fed to the flux controller. The effect of reference flux or the operating flux on the performance of the drive is judged on the basis of the following parameters.

1. Drive efficiency
2. Ratio of maximum torque to stator current (Dynamic response)
3. Torque ripples

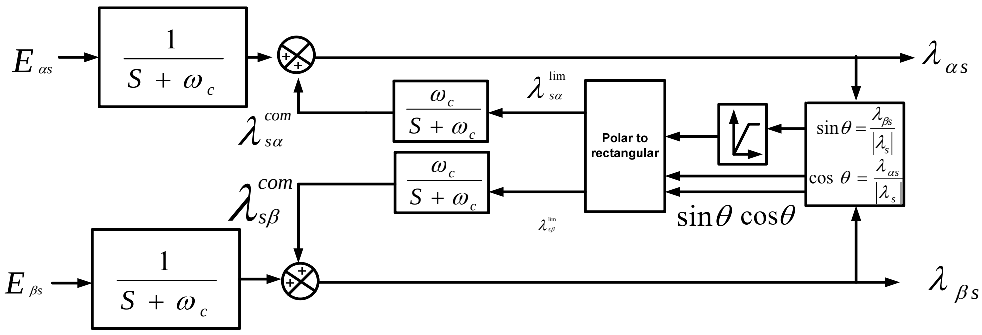


Figure 1. Modified low pass filter with feed back compensation.

The efficiency of the drive is a function of the operating conditions like speed load torque and nature of load. The iron loss increases at a higher value of operating flux when the drive is not subjected to its rated load torque. On the contrary if it is subjected to a flux lower than nominal flux, then reduction in iron losses is observed but at the expense of deterioration in torque capability of the drive. A drive operating at its rated load but operated at a reduced flux level suffers from higher ohmic losses due to high input power drawn

3.2 Torque Ripples

The torque ripples ΔT_ein conventional dtc drive can be considered as composed of two components.

$$\Delta T_{e1} = -T_e\left(\frac{1}{\tau_s} + \frac{1}{\tau_r}\right)\frac{\Delta t_s}{\sigma} \tag{17}$$

$$\Delta T_{e2} = P\,\frac{L_m}{\sigma L_s L_r}\left[\left(\overline{V_s} - j\omega_m\overline{\lambda_s}\right).j\overline{\lambda_r}\right]\Delta t_s \tag{18}$$

Where $\boldsymbol{\tau_s}$ and $\boldsymbol{\tau_r}$are stator and rotor time constant, $\boldsymbol{\Delta t_s}$ is the sampling period $\overline{\mathbf{V_s}}$ is the applied voltage vector and $\overline{\boldsymbol{\lambda_r}}$ is the rotor flux vector. From (18) it can be seen that the second component of torque ripple is a function of stator and rotor flux .One of the limitation of a DTC drive is that of torque ripples, and operating the drive at constant nominal flux for varying load torque conditions may further aggravate the problem of torque ripples. One of the possible solutions to overcome the problem of selection of optimal flux level from the point of view of efficiency of operation and torque ripple is to vary the flux depending on the load condition. A lower operating flux at reduced load torque level may result in decrement of torque ripples and at the same time improve the efficiency of the drive due to reduced iron losses. On the contrary operating the drive at nominal flux at rated load torque improves the dynamic response of the drive due to an increase in the peak torque to current ratio, which further improves the efficiency of the drive due to reduced ohmic losses.

4. RESULTS AND DISCUSSIONS

A test drive set up developed in the laboratory to validate the proposed investigation is shown in Figure 2. The experimental test drive setup consists of the following elements:

1) Machine unit; a 0.75 kW, 410 V, 50-Hz squirrel-cage induction motor with a shaft mounted tachogenerator for speed sensing coupled with dc generator for loading.
2) A power module with MOSFET based voltage source inverter with Hall Effect sensors and gate drive circuitry.
3) dSpace DS1104 control board.

The parameters of the motor for experimentation are as follows.

R_s=10.75 Ω,$R_r = 9.28\,\Omega$, $L_s = L_r = 51.9\,mH$, P=4 and $L_m = 479.9\,mH$. The sampling time of the DTC experiments is taken as 100 µs while the dead time for the switches is 5 µs. The value of torque and flux hysteresis comparator bandwidth is takes as 0.5 Nm and 0.005 wb. All experimental results are recorded using the Control Desk platform of dSpace DS1104.

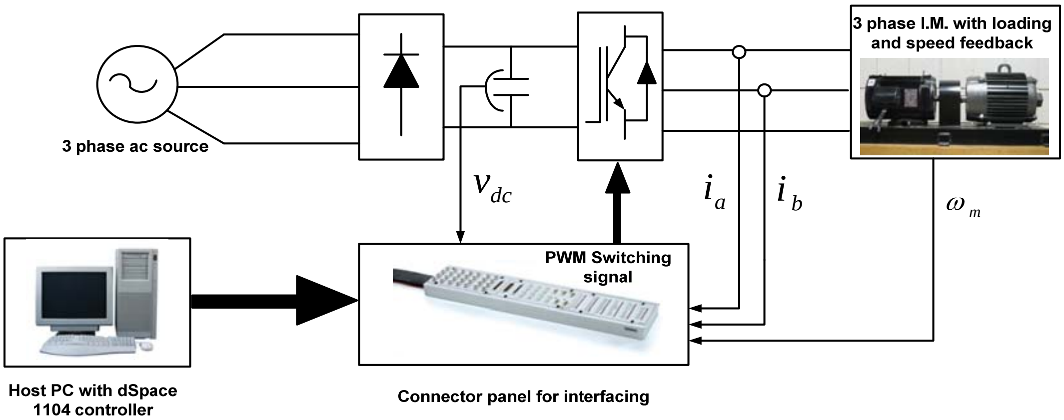


Figure 2. Experimental test drive set up.

4.1 Flux Estimation Analysis

The performance parameters to judge the effectiveness of the proposed integration algorithm are flux ripples and Total Harmonic Distortion (THD) of the stator current. The flux ripples can be mathematically expressed by Root Mean Square Flux Error (RMSFE) given by (19).

$$\text{RMSFE} \quad = \frac{1}{N}\sqrt{\sum_{k=1}^{N}\left(\lambda_s{}^{ref} - \lambda_s(k)\right)^2} \tag{19}$$

Where $\lambda_s(k)$ and $\lambda_s{}^{ref}$ are the estimated stator flux and reference flux at Kth and (K-1)th sampling instant and N is the number of data samples. The steady state flux ripples were studied for 100% and 30% loading of the machine at 90% rated speed. To judge the effectiveness of the flux estimation methods the test drive was operated with three different reference flux 0.6wb, 0.8wb and 1wb respectively. Furthermore to judge the low speed performance of the flux estimation algorithm the experimental DTC drive was operated at 20% of the rated speed.

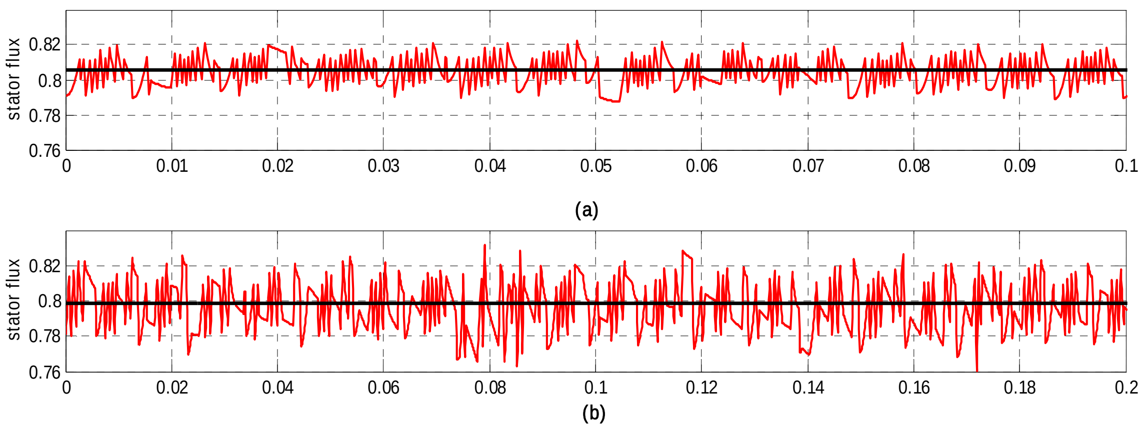


Figure 3. Experimentally obtained steady state flux response for low speed operation (20% rated speed) (a) Mod LPF (b) LPF

The comparison of low speed steady state flux response is shown in Figure 3. It can be verified from it that Mod LPF flux estimation algorithm shows minimum flux ripples in steady state condition. Table 1 shows the RMSFE calculated on the collected data samples of the estimated flux for 100% and 30 % loading, at 90% and 20% speed and with three different reference fluxes. The effectiveness of the Mod LPF flux estimation method in terms of flux ripples is validated from Table 1, where the RMSFE is the least for Mod LPF at all the operating flux and loading conditions during high as well as low speed operation . Since in the

Mod LPF method, the presence of the feedback loop with compensation has a tight control over flux ripples, hence the stator flux is confined within the boundaries of the limits imposed by the control algorithm.

The superiority of Mod LPF in terms of stator flux trajectory over the other flux estimation methods is validated from Figure 4(c), here a circular locus of the flux vector with least distortion is observed. Mod LPF method also improves the harmonic distortion in stator current, as verified from Figure 4 (a) and 4(b), which shows the harmonic spectrum of stator current for the two flux estimation methods. THD for different loadings and flux are summarized in Table 2.

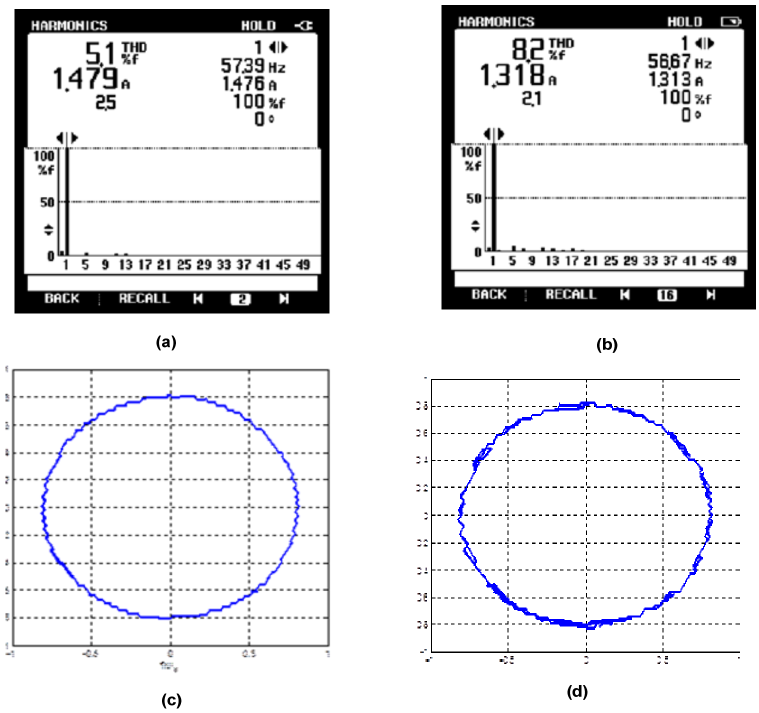


Figure 4. Stator current harmonics for 100% load and 0.8 wb ref flux.(a) Modified low pass filter (b) low pass filter, (c) Experimental Stator flux trajectory at 20% speed for Mod LPF integration algorithm (d) low pass filter integration algorithm

Table 1. RMSFE Comparison for Different Flux Estimation Algorithms.

INTEGRATION ALGORITHM	RMSFE (in percentage of ref Flux) at 90% rated speed						RMSFE at 20% speed	
	100% load			30% load			100% load	
	Refrence stator Flux			Refrence stator Flux			Refrence stator Flux	
	1 wb	0.8 wb	0.6wb	1wb	0.8wb	0.6wb	1 wb	0.8 wb
Mod. Low pass	1.02	1.24	1.77	1.03	1.2	1.62	.83	.9
Low pass	1.25	1.44	2.0	1.24	1.41	1.80	1.37	1.5

Table 2. THD of Stator Current at Different Loadings

INTEGRATION ALGORITHM	TOTAL HARMONIC DISTORTION (In percentage)					
	100% load			30% load		
	Refrence stator Flux			Refrence stator Flux		
	1 wb	0.8 wb	0.6wb	1wb	0.8wb	0.6wb
Mod. Low pass	8.3	5.1	3.3	8.9	9.5	7.3
Low pass	11.4	8.2	5.2	12.1	11.8	9.2

Figure 5 shows the comparison of stator flux dynamic response for a step change in reference flux (0.7 wb to 0.8 wb) at 500 rpm. From Figure 5(b) it can be clearly interpreted that the dynamic response of the Mod LPF flux estimation algorithm is the best compared to LPF. The stator flux tracks the reference flux with less distortion in Mod LPF method.

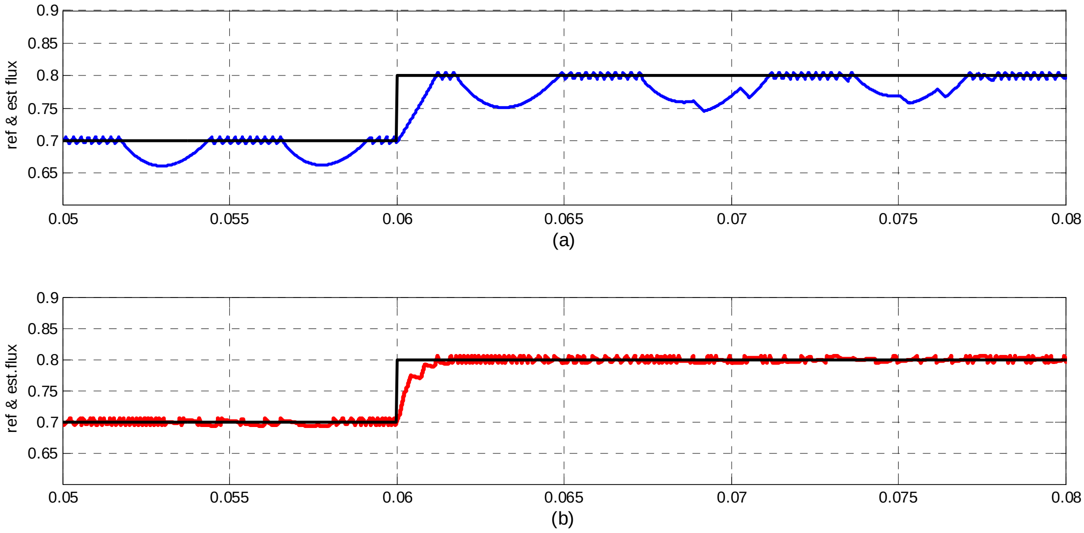


Figure 5. Dynamic response of estimated flux (a) LPF (c) Mod LPF

4.2 Optimal Flux Operation Analysis

The experimental test drive was operated at five different flux levels of 0.6, 0.7, 0.8, 0.9 and 1 wb respectively at constant load torque (30% loading). The input KVA and KVAR drawn by the motor were recorded. From Figure 6 it can be seen that the optimal operating flux lies between 0.8 and 0.85 wb at one third load torque.

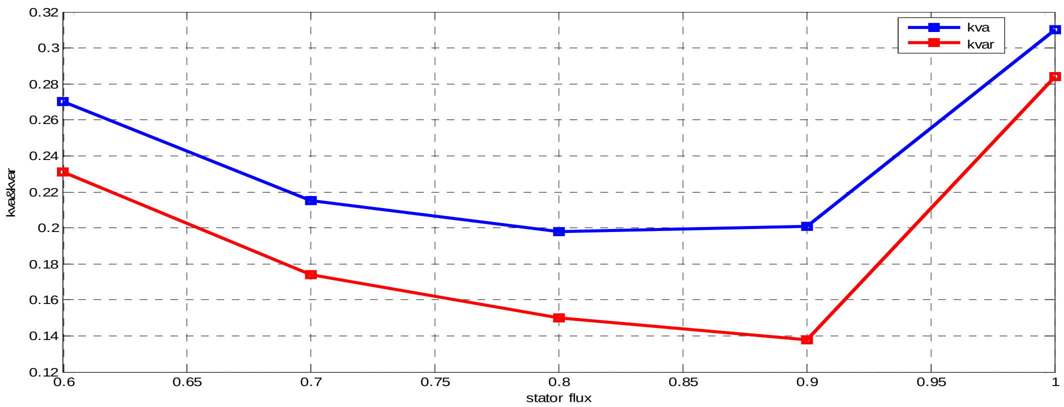


Figure 6. Variation of input power(Kva and Kvar) with operating flux at 30% load

The performance parameter to judge the dynamic response of the drive with energy efficient operation is maximum torque to current ratio.A higher value of this ratio signifies a high max torque (faster dynamic response) with reduced maximum current (reduced ohmic losses). From the simulation results shown in Figure 7 it can be concluded that deterioration in the dynamic response of the drive is observed at lower flux levels. From Table 4, which summarizes the results of Figure 7 it is verified that there is a considerable improvement in the torque capability of the drive at higher value of operating flux. The ratio of max torque to stator current at 0.7 wb is 2.205 Nm/amp while it is 1.12 Nm/amp at 0.5 wb which results in the improvement in dynamic response of the drive in terms of settling time (time to reach at set speed).

Table 3. Performance Parameters for Dynamic Response Analysis

Operating Flux	Peak torque to current ratio (Nm/amp)	Settling time (sec)
0.5 wb	1.12	0.5438
0.6 wb	1.18	0.247
0.7 wb	2.205	0.2

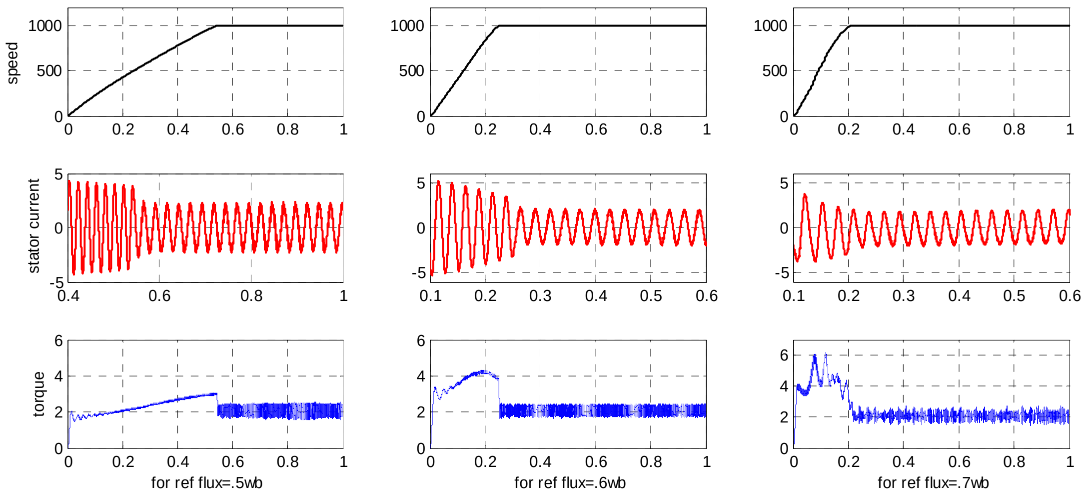


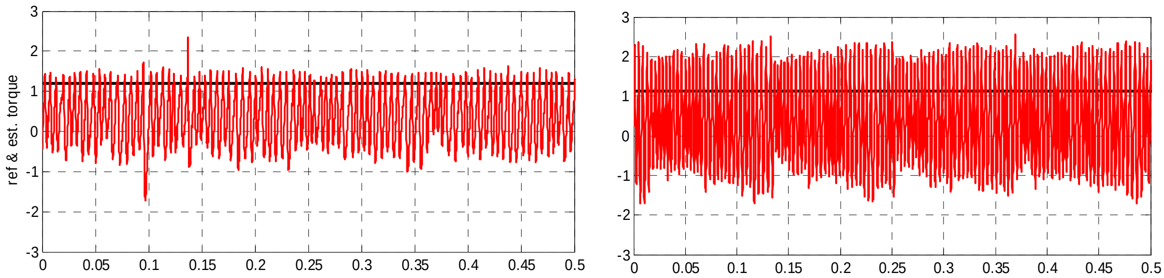
Figure 7. Comparison of dynamic response at operating flux of 0.5 wb,0.6 wb & 0.7wb .

4.3 Torque Ripple Analysis.

For the analysis of torque ripples at different flux and loading condition, the parameter to measure the ripples in torque can be given by root mean square torque error (RMSTE), which can be expressed by (20).

$$RMSTE = \frac{1}{N}\sqrt{\sum_{k=1}^{N}(T_e(k) - T_e^{avg})^2} \tag{20}$$

Where $T_e(k)$ and T_e^{avg} are the estimated torque at K sampling instant and calculated average torque respectively. The experimental drive was loaded at 100% and 50% of its rated load at 0.9 wb and 1 wb flux in torque control mode .From Fig.8 it is observed that the ripples in torque for a reference torque of 1.1Nm at 50% loading and 0.9 wb flux are less than the ripples at 100%loading and 1 wb operating flux. The calculated value of RMSTE on the collected experimental data at 0.9 wb flux and 50% loading is 1.0815 nm while it is 1.38 nm at 1 wb and 100% loading, resultingin a reduction of 27% in torque ripples .Thus the justification of not operating the drive at a constant nominal flux under varying load conditions from the perspective of steady state performance (torque ripples) is strengthened from the experimental results.



(a) (b)

Figure 8. Experimental Torque ripple comparison at 1.1 nm ref torque for (a) 0 .9wb ref flux at 50%load (b) 1 wb ref flux 100% load.

5. CONCLUSION

This paper presents an investigation on flux response by different voltage model based flux estimation algorithm in a DTC drive. Flux ripples and stator current harmonics are the considered performance parameters to judge the effectiveness of the estimation algorithm. The low pass filter with feedback compensation flux estimation method (Mod LPF) proved to be superior in terms of flux ripples and stator current harmonics at rated as well as low speed operation. Investigations on the influence of operating flux on the dynamic response, efficiency of operation and torque ripples is carried out extensively through simulation as well as experimentation. The energy efficient operation of a DTC drive depends upon the proper balance of iron and ohmic losses, which in turn depends upon the selecting an optimal operating flux, which should be load dependent. A high value of Peak torque to current ratio is obtained at a higher value of operating flux which improves the dynamic response of the drive at reduced input Volt-amperes. On the contrary reduction in torque ripples is observed at a reduced flux level, when the drive is not operating at its rated load. Thus a study on a DTC drive from the perspective of flux loop and its influence on drive efficiency, dynamic response, current harmonics and torque ripple is carried out extensively.

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