# Reducing both Torque and Flux Ripple in the DTC of IPMSM by Incorporating Duty Cycle Calculation Method and Dithering Technique

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**Abstract**
**The Direct Torque Control (DTC) of Interior Permanent Magnet Synchronous Motor (IPMSM) offers simple structure and fast torque response. The conventional Switching Table-based DTC (ST-DTC) presents some disadvantages like high torque and flux ripple and also variable switching frequency. This paper investigates the improved ST-DTC strategies to reduce both torque and flux ripple in DTC of IPMSM with emphasis on structure simplicity and fast dynamics. New switching table with only two active vectors for each sector is introduced and the torque control hysteresis band is replaced by duty cycle calculation unit. For flux ripple reduction, conventional hysteresis-based controller is replaced by simple dithering technique. The duty cycle calculation unit is implemented to operate on each selected vector with the aim of torque ripple RMS minimization. The increase of switching frequency in ST-DTC because of delay in torque and flux estimation process, actually, is not possible; even when hysteresis bands are sufficiently diminished. This paper incorporates the combination of duty cycle modulated DTC and dithering technique to enlarge switching frequency. It therefore provides smoother waveform concurrently for the motor torque and the flux. In the proposed method waveform comparison structure for duty cycle calculation is used; hence, the merits of classical ST-DTC, such as fast dynamic and simple structure, are mostly preserved.**

**Keywords: direct torque control, duty cycle, ripples reduction, switching table.**

**Nomenclature**

| | |
|---|---|
| $\mathbf{i}_s$ | Stator current vector |
| $L_s$ | Stator winding inductance |
| $R_s$ | Stator winding resistance |
| $T_e$ | Electromagnetic torque |
| $\mathbf{u}_s$ | Stator voltage vector |
| $\boldsymbol{\psi}_r$ | Rotor flux vector |
| $\boldsymbol{\psi}_s$ | Stator flux vector |

## 1. Introduction

A simple and fast motor control structure-mainly based on waveform comparison instead of complex analytical equation solution known as direct torque control (DTC)-has been introduced by Takahashi and Noguchi [1] and Depenbrock [2] in the mid of 1980s. The DTC approach is also developed for PMSMs in 1990s [3]. It is known that the DTC provides very fast torque response and low parameter dependency; however, conventional Switching Table-based DTC (ST-DTC) presents some disadvantages such as high flux and torque ripple, high stator current, total harmonic distortion (THD), and variable switching frequency. Thus, various methods have been proposed to overcome such problems and drawbacks.

A very common way to minimize the torque and flux ripple to obtain constant switching frequency is incorporating space vector modulation (SVM) in the DTC known as DTC–SVM [4]. The DTC-SVM falls into two groups based on voltage references determination methods. In the first group, the decoupled voltage references were obtained in the synchronously rotating reference frame first; and then, transformed to the stationary reference frame using the rotary coordinate transformation [5]. In the second group, the voltage references were obtained directly from the incremental stator flux vectors in the stationary reference frame without coordinate transformation [6]. Although, the new DTC-SVM represents a great deal of advantages, it reduces the robustness and dynamic

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performance of the original DTC [7]. Recently model- based predictive torque and flux (MPTF) control is used to improve conventional DTC performance in [8-9].

Calculating duty cycle of the selected voltage vectors from switching table to reduce torque ripple in DTC of Induction Motor (IM) is discussed in [10]. There are varieties of the methods to predict duty cycle. The duty ratio calculation methods for both PMSM and IM differ in the optimization aims. Introducing duty cycle control in the MPTF control reduces torque and flux ripples. Conventional MPTF controllers employ the optimized voltage vectors during the sampling period and this is one of the causes of torque and flux ripples. Hence, by applying duty ratio to selected voltage vectors, the torque and flux ripples can be minimized, significantly. Recently, duty control-based MP-DTC is proposed in [11-12], where analytical calculations are used to minimize torque and flux ripples. In [12], for calculating the optimal duty ratio, only torque ripple is considered; hence, the flux ripple is increased.

A new method is proposed in [13] to reduce both torque and flux ripple. The main problem with their method is the need of two switching tables, one for transient and another for steady state condition. The duty cycle calculation method is complicate and parameter dependent, too. In [14], three methods for obtaining duty cycle are compared and a new simple strategy is proposed to reduce complexity and parameter dependency. New duty-cycle-based method to reduce both torque and flux ripple using three active vectors, and, one null vector; is carried out in [15]. Although, the introduced method for torque ripple reduction is simple and has less parameter dependency, for flux ripple reduction; it is still complex and more parameter dependent. Direct torque control was extended to Matrix Converter (MC) fed induction machines (MC-DTC) in 2001 [16]. Since the MC-DTC can control not only torque and flux of the motor but also input power factor, it has been developed rapidly in the last decade [17-20]. An improved DTC strategy using duty cycle optimization is proposed for matrix converter (MC)-based PMSM drive system in [21]. This method is characterized by low torque ripple, and fixed switching frequency.

Increasing of switching frequency with the dithering technique for torque and flux ripple reduction is proposed in [23]. Very fast digital implementation requirement and variable switching frequency in transient condition are the main problems. In [24], a new torque controller-based on the dithering method has been introduced. It can be implemented with medium speed digital systems and presents more stable switching frequency. But in this method, dynamic performance of torque response and inherent robustness of conventional DTC is a bit lost.

In this paper, a new switching table, containing only two active vectors in each sector is proposed. These two active vectors are selected on the basis of only flux hysteresis band. Then, torque hysteresis block is replaced by duty cycle calculation unit. The duty cycle calculation unit is implemented to operate on selected active vectors to minimize the RMS of the torque ripple. For selected active vectors the duty cycle unit applies active vectors for the calculated time duration and zero vectors for the rest of switching period. The duty cycle unit-which is based on the basic logic circuits-is easy for digital implementation and has simple structure; hence, it preserves the structure simplicity of original ST-DTC. It is known that the zero vectors have no significant effect on stator flux, so duty cycle modulation technique that applies duty cycle to both of the two active vectors, simultaneously, cannot be effective enough for the flux ripple reduction. Applying high frequency triangular signal to the flux controller hysteresis block input known as dithering technique, increases the number of applied vectors in each sampling period. The dithered signal, in addition to regulating the duty ratio between two active vectors, increases the switching frequency; therefore, the duty cycle modulation unit can apply zero vectors before torque goes higher up-because of the delay in estimation process. The proposed method also eliminates the variables contributing to the current harmonics. To study the performance of proposed scheme Matlab, Simulink model of IPMSM drive is developed.

## 2. The Machine Model

### 2.1. IPMSM Equations

Machine equations in the stationary reference frame for interior PMSM can be written, using complex vectors, as follows [5]:

$$\mathbf{u}_s = R_s\mathbf{i}_s + \frac{d\boldsymbol{\psi}_s}{dt} \qquad (1)$$

$$\boldsymbol{\psi}_s = L_s\mathbf{i}_s + \boldsymbol{\psi}_r \qquad (2)$$

$$T_e = \frac{3}{2}p\,\mathbf{Im}\{\boldsymbol{\psi}_s^* \times \mathbf{i}_s\} \qquad (3)$$

**Table 2.**The voltage vectors effects on motor torque and flux

| | | |
|---|---|---|
| $\boldsymbol{\psi_s} \uparrow$ | $T_e \uparrow$ | $\boldsymbol{u_{n+1}}$ |
| $\boldsymbol{\psi_s} \downarrow$ | $T_e \uparrow$ | $\boldsymbol{u_{n+2}}$ |

**2.2. The DTC Basics**

The basic structure of DTC for IPMSM drive is shown in Figure 1. It has a simple structure, where no frame transformation required, and only stator resistance information is used to estimate the stator flux and motor torque.

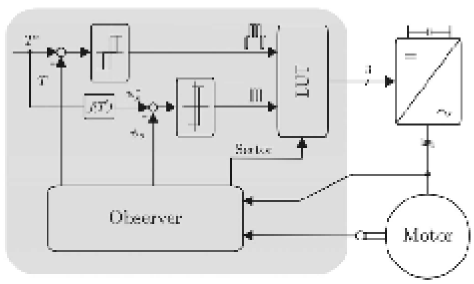



**Figure 1**. Conventional Hysteresis Based DTC [7]

The voltage vector table of conventional DTC for flux and torque regulation is shown in Table 1.

**Table 1.**Voltage vector for Conventional DTC [1]

| $H\_\psi_s$ | $\mathbf{H\_T_e}$ | Selected Vector |
|---|---|---|
| 1 | 1 | $u_{n+1}$ |
| 1 | -1 | $u_{n-1}$ |
| 0 | 1 | $u_{n+2}$ |
| 0 | -1 | $u_{n-2}$ |

The hysteresis controllers regulate torque and flux in their hysteresis band. A combination of two hysteresis controllers determines the voltage vectors at each instant. At every sampling period torque and flux hysteresis bands should be touched by their error signals; however, due to the feedback and dead-time delay, the controlled signals (torque and flux) usually exceed their hysteresis bands. This phenomenon decreases the switching frequency and increases the THD of the stator current.

## 3. The Proposed DTC

The objective of the proposed method is to increase the number of voltage vectors in one switching cycle of the fundamental frequency. Composition of the duty cycle calculation method and the simple dithering technique reduces torque and flux ripple and the THD of stator currents. New switching table with two active vectors is used and their effects on the motor torque and flux are shown in Table 2. Since these vectors are selected by means of the flux hysteresis controller, the torque hysteresis band can be eliminated.

### 3.1. Torque Ripple Minimization

The derivative of torque can be written as follows [14]:

$$\frac{dT_e}{dt} = \frac{1}{L_s}\left(-R_sT_e - \frac{3}{2}p\omega Re\{\psi_s \times \psi_r^*\} - \frac{3}{2}pIm\{u_s \times \psi_r^*\}\right) \quad (4)$$

The slopes of torque for two applied active vectors during $t_1 and\ t_2$ , according to the Figure 2.a and equation (4), can be calculated as follows [15]:

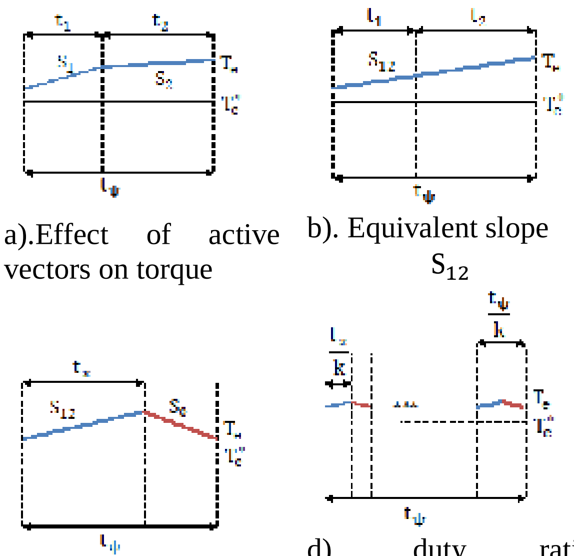
$$S_1 = \frac{1}{L_s}\left(-R_sT_e - \frac{3}{2}p\omega Re\{\psi_s \times \psi_r^*\} - \frac{3}{2}pIm\{u_{n+1} \times \psi_r^*\}\right) \quad (5)$$

$$S_2 = \frac{1}{L_s}\left(-R_sT_e - \frac{3}{2}p\omega Re\{\psi_s \times \psi_r^*\} - \frac{3}{2}pIm\{u_{n+2} \times \psi_r^*\}\right) \quad (6)$$

The above vectors increase the torque value. It is known that null vector decreases (In Counter Clockwise direction) the torque and has no significant effect on flux. Equation (7) shows the effect of zero vectors on torque change [13-15].

$$\frac{dT_e}{dt} = \frac{1}{L_s}\left(-R_sT_e - \frac{3}{2}p\omega Re\{\psi_s \times \psi_r^*\}\right) \quad (7)$$

Because the switching table contains two active vectors-which are selected with flux controller-the total time duration of these vectors $(t_1 + t_2)$ is the period of flux controller output pulse $(t_1 + t_2 = t_\psi)$. Hence, duty cycle calculation unit applies active vectors for calculated the time duration, and, null vectors for the rest of the $t_\psi$.




a).Effect of active vectors on torque

b). Equivalent slope $S_{12}$

c).duty ratio calculation for one flux cycle

d). duty ratio calculation for $\frac{1}{k}$ flux cycle

**Figure 2.** Duty cycle calculation for selected active vectors

It is useful to define $S_{12}$ as equivalent slop of two active vectors (Figure 2.b) [14]:

$$S_{12} = \frac{S_1 t_1 + S_2 t_2}{t_\psi} \tag{8}$$

Torque ripple RMS value for Figure 2.c can be written as follows [14-15]:

$$T_{e_{ripple}}^2 = \frac{1}{t_\psi}\left(\int_0^{t_x}\left(S_{12}t + T_e^* - T_e^i\right)^2 dt + \int_{t_x}^{t_\psi}\left(S_0 t - S_0 t_x + S_{12} t_x + T_e^* - T_e^i\right)^2 dt\right) \tag{9}$$

Increasing hysteresis controller output pulse frequency by means of dithering ( $F_{\psi-new} = k * F_{\psi-old}$ ) applies more voltage vectors which should be selected in each cycle of fundamental frequency. So, the torque ripple RMS expression for ($t_\psi$/k) can be rewritten as (10):

$$T_{e_{ripple}}^2 = \frac{1}{t_{\psi k}}\left(\int_0^{t_{xk}}\left(S_{12}t + T_e^* - T_e^i\right)^2 dt + \int_{t_{xk}}^{t_{\psi k}}\left(S_0 t - S_0 t_{xk} + S_{12} t_{xk} + T_e^* - T_e^i\right)^2 dt\right) \tag{10}$$

Where $t_{xk} = t_x/k$ and $t_{\psi k} = t_\psi/k$ (11)

By taking the derivative of equation (10) with respect to $t_{xk}$ and setting the result to zero, optimum value for the time duration of active vectors to minimize the torque ripple RMS is obtained:

$$t_{xk} = \frac{2\left(T_e^* - T_e^i\right)}{2S_{12} - S_0} + \frac{-S_0 t_{\psi k}}{2S_{12} - S_0} \tag{12}$$

According to [15], assume:

$$2S_{12} - S_0 = cte = C \tag{13}$$

$$-S_0 t_{\psi k} \propto \left(\psi_s^* - \psi_s^i\right) \tag{14}$$

then $t_{xk}$ can be re-written as follows:

$$t_{xk} = \left|\frac{2\left(T_e^* - T_e^i\right)}{C}\right| + \left|\frac{\left(\psi_s^* - \psi_s^i\right)}{C}\right| = \left|\frac{E_T}{C_T}\right| + \left|\frac{E_\psi}{C_\psi}\right| \tag{15}$$

Where $C_T$ and $C_\psi$ are two positive constants [13-15] that can be tuned very easily. For proposed duty cycle method implementation, it is possible to compare calculated time duration with a triangular wave that its amplitude and period are equal to $t_{\psi k}$. (Figure 3)

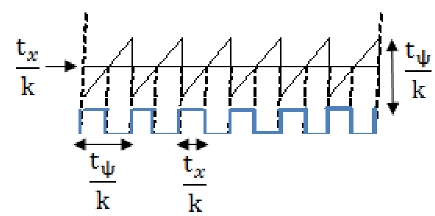



**Figure 3.** Implementation of proposed duty cycle method

Therefore, the duty ratio of output pulse is:

$$\frac{t_{on}}{T} = \frac{\frac{t_x}{k}}{\frac{t_\psi}{k}} = \frac{t_x}{t_\psi} = D \tag{16}$$

From Figure 4, the operation of duty cycle unit is understood. In any sector (n), the output of switching table is one of two $u_{n+1}$ or $u_{n+2}$ vectors and null vectors are inserted by duty cycle unit. For having a more symmetrical waveform at the output of inverter, vector $u_0$ and $u_7$ are applied together.

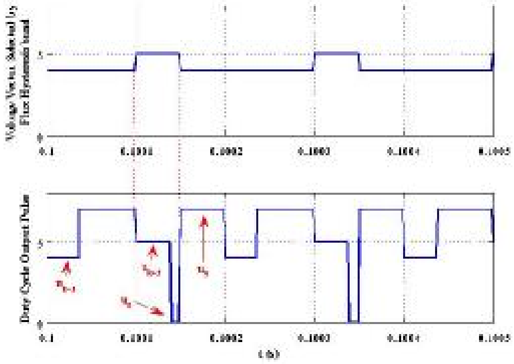


**Figure 4.** Operation of duty cycle unit

The process of duty ratio calculation is very simple and $F_{\psi-new}$ can be set to a constant value, using dithering technique for flux controller.

### *3.2. Dithering technique*

By superposing high frequency triangular waveform, on the stator flux error, the switching frequency of inverter (that mostly relies on flux controller output) is increased and; hence, more voltage vectors are applied in one cycle, which improves the waveform quality of motor currents. The schematic of proposed method is shown in Figure 5. In the proposed method, the frequency of dithered signal is set to 10 kHz, which makes duty cycle calculation process easier, and can be implemented with a medium-speed digital signal processor.

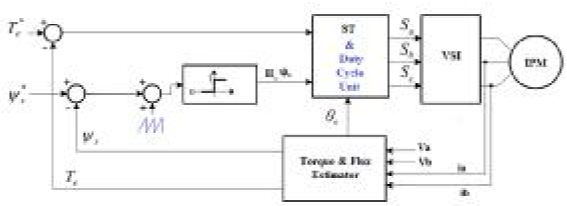



**Figure 5.** Proposed DTC schematic

## 4. Simulation Results

To study the performance of the proposed scheme, Matlab Simulink model of IPMSM drive has been developed. The inverter is characterized by a DC link of 300V. For the purpose of calculation of the objective function, sampling time of $20\mu s$, $40\mu s$ *and* $80\mu s$ are used. The switching frequency of the modified DTC is almost constant and only depends on flux hysteresis controller frequency, but, it has a little variation when speed changes. The IPM motor parameters for simulation study are shown in Table 3.

**Table 3.** The machine parameters

| Parameters | Value |
|---|---|
| P | 2 |
| $R_s$ | 5.8 Ω |
| $L_d$ | 0.0448 H |
| $L_q$ | 0.1024 H |
| $\psi_m$ | 0.533 (Wb) |
| $T_{e\_rated}$ | 6 (Nm) |
| $\omega_{rated}$ | 1260 (rpm) |
| $P_{rated}$ | 1 kW |

The calculated duty ratio in different loads and speeds is shown in Figure 6. By multiplying this duty ratio to $t_\psi$ value, the calculated time duration for active vectors is achieved. Then, this duty cycle is compared with the triangular wave shown Figure 3, for implementation. The effects of load and speed changes on duty cycle are shown in Figure 6. From top to bottom, the curves belong to stator current (A), rotor speed (rad/sec), torque (Nm), and duty cycle(s), respectively.

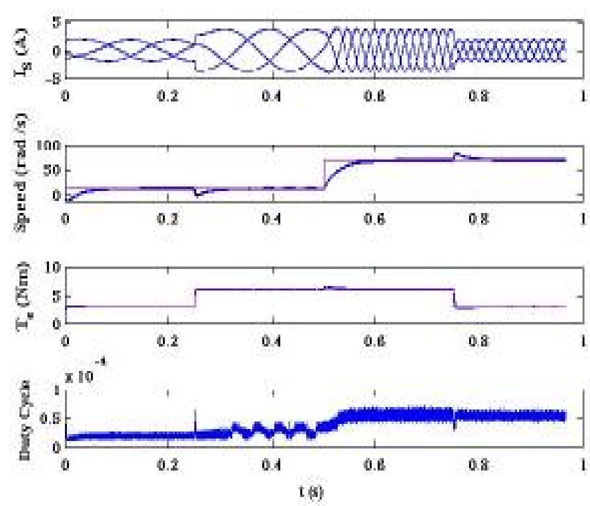
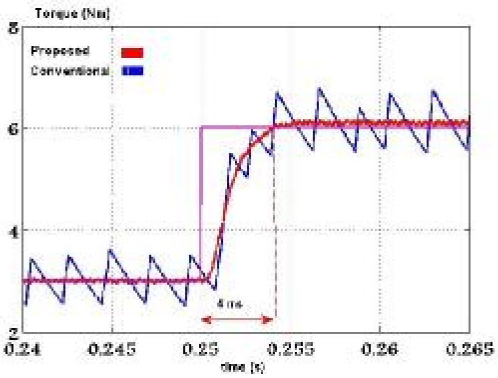
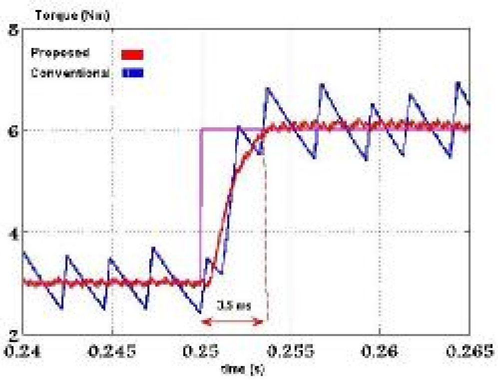


**Figure 6.** Calculated duty cycle in different loads and speeds

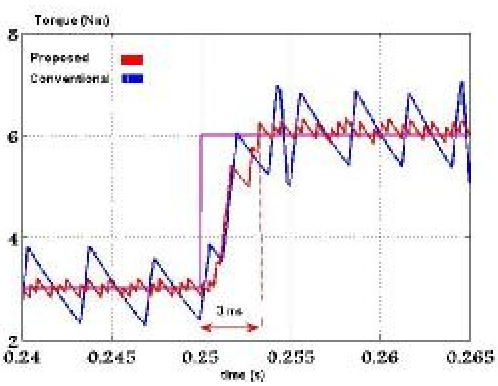
Torque ripple and dynamic of the proposed DTC are compared with that of conventional DTC one, at the speed of $\omega_{rated}/10$ during a step load changes between $T_{e_{rated}}/2$ and $T_{e_{rated}}$. The simulation results for three sampling periods are shown in Figure 7. For conventional DTC, the switching table presented in [1] is used. There is an average ripple reduction of 61% for the torque in the proposed controller compared to the conventional controller.




a). $T_{sp} = 20\ \mu s$




b). $T_{sp} = 40\ \mu s$

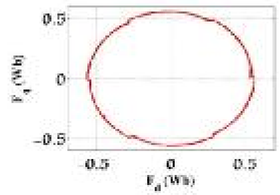



c). $T_{sp} = 80\ \mu s$

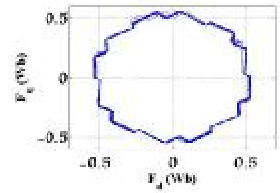
**Figure 7.** Torque ripple and dynamic comparison in the proposed and conventional DTC at $\omega = 0.1*\omega_{rated}$ for three different sampling times. $\Delta\psi/\psi_{rated} = 0.1$ , $\Delta T_e/T_{e\_rated} = 0.1$

The results of Figure 7 show that the proposed DTC has very small torque ripple, especially at low sampling time values of $20\mu s$ and $80\mu s$. Moreover, the presented method is as fast as conventional DTC. In the high sampling period, (80 us) because of delay in estimation, the torque ripple increases. This delay causes the selected active vector to remind more than optimized time duration calculated by duty cycle modulation unit on motor's terminals according to (12).

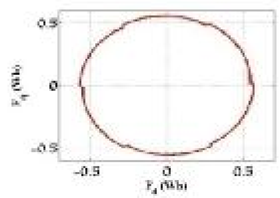
In the proposed method for flux ripple reduction, dithering technique is used, which increases switching frequency; hence, provides more smooth trajectory for motor stator flux according to (1).



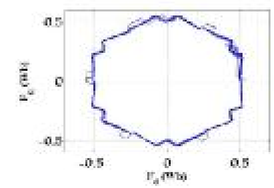
a). Proposed DTC, at $\omega_{rated}$



b). Conventional DTC, at $\omega_{rated}$

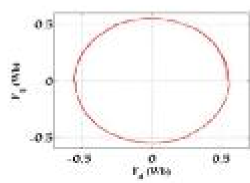


c). Proposed DTC, at $\omega_{rated}/2$

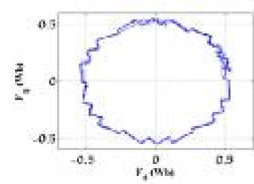


d). Conventional DTC, $at\ \omega_{rated}/2$

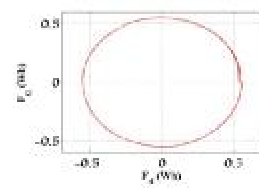
**Figure 8**. Stator flux at $T_{sp}$ =



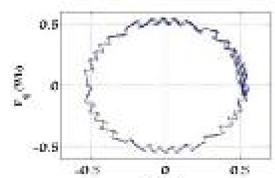
a). Proposed DTC, at $\omega_{rated}/4$



b). Conventional DTC, at $\omega_{rated}/4$



c). Proposed DTC, at $\omega_{rated}/10$



d). Conventional DTC, at $\omega_{rated}/10$

**Figure 9**. Stator flux at $T_{sp} = 20\mu s$, and $T_e = T_{e\_rated}$. $\Delta\psi/\psi_{rated} = 0.1$, $\Delta T_e/T_{e\_rated} = 0.1$

Stator flux comparison results show that the proposed method has good influence on the flux ripple reduction at various speeds. Figures 8 and 9 show the standard deviation of the stator flux of both the conventional and proposed methods with different speeds. It can be seen that for lower speed ranges, the flux ripple of the proposed method are smaller than those of the conventional method. To be specific, in the condition of $\omega$=126 r/min and $T_L$=6 Nm, the values of flux ripple of the conventional and proposed methods are 0.018 Wb and 0.0055 Wb, respectively. For higher speed ranges, the flux ripples are increased in the proposed method, as the duty cycle becomes close to 1 with larger back-EMF. Nevertheless, the flux ripples of the proposed method are also reduced, effectively.

The proposed method also presents low current THD. Comparison between the conventional and the proposed DTC is given in Figure 10. More detailed comparisons between these two methods for three different sampling times and various motor speeds are given in Table 4.

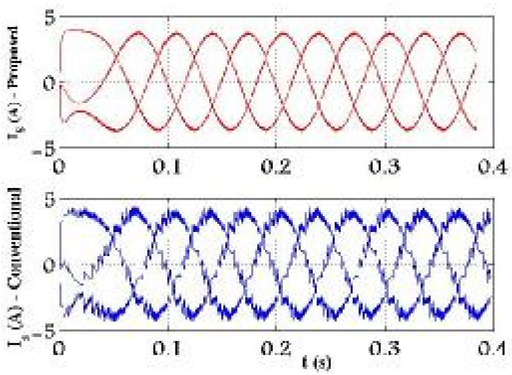



**Figure 10.** Stator current in the conventional and the proposed method. $T_{sp} = 20\ \mu s$, $\omega = \omega_{rated}/4$, $THD_P = 1.34\ \%$, $THD_C = 9\ \%$, and $\Delta\psi/\psi_{rated} = 0.1$ , $\Delta T_e/T_{e\_rated} = 0.1$

**Table 4.** Detailed THD% comparison between the conventional and the proposed method $\Delta\psi/\psi_{rated} = 0.1$ , $\Delta T_e/T_{e\_rated} = 0.1$

| | $\omega_{rated}/10$ | $\omega_{rated}/4$ | $\omega_{rated}/2$ | $\omega_{rated}$ |
|---|---|---|---|---|
| Prop. | 1.3 % | 1.34 % | 2.14 % | 2.9 % |
| Conv. | 7.7 % | 9 % | 8.95 % | 9.2 % |

$T_{sp} = 20\ \mu s$,

| | $\omega_{rated}/10$ | $\omega_{rated}/4$ | $\omega_{rated}/2$ | $\omega_{rated}$ |
|---|---|---|---|---|
| Prop. | 1.71 % | 2.26 % | 3.13 % | 4.0 % |
| Conv. | 8.35 % | 10.25 % | 9.65 % | 11.5% |

$T_{sp} = 40\ \mu s$

| | $\omega_{rated}/10$ | $\omega_{rated}/4$ | $\omega_{rated}/2$ | $\omega_{rated}$ |
|---|---|---|---|---|
| Prop. | 4.40 % | 4.48 % | 6.83 % | 7.27 % |
| Conv. | 12.40 % | 12.10 % | 12.49 % | 13.4 % |

$T_{sp} = 80\ \mu s$

According to the results, compared with the conventional DTC, the proposed DTC shows superiority in reducing torque and stator flux ripples under different loading, rotating speeds, and sampling conditions. It is also obvious from THD values that the stator current of the proposed control system is more sinusoidal.

It is useful to compare the results of the proposed method to that of the conventional method when flux and torque hysteresis bands are equal to zero. In this case, because of the delay in estimation process, although the hysteresis bands are diminished, sufficiently; because of delay in estimation process according to [23]; flux and torque ripple and the THD of stator currents are still high compared to that of the proposed method. The results are shown in Figure 11.

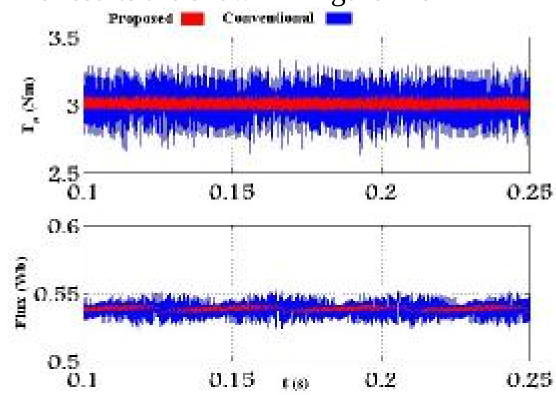



**Figure 11.** Torque and flux ripple in $\Delta\psi/\psi_{rated} = 0.0$ , $\Delta T_e/T_{e\_rated} = 0.0$, $T_{sp} = 20\ \mu s$

Table 5 Summarizes the improvements achieved by the proposed DTC in terms of stator current THD with the conventional DTC when hysteresis bands are diminished.

**Table 5.** Detailed THD% comparison between the conventional and the proposed method $\Delta\psi/\psi_{rated} = 0.0$ , $\Delta T_e/T_{e\_rated} = 0.0$

| | Proposed | Conventional |
|---|---|---|
| Speed | $\omega_{rated}/4$ | $\omega_{rated}/4$ |
| THD | 2.17 % | 5.47 % |
| $T_{sp}$ | 20 µs | 20 µs |

## 5. Conculsion

In this paper, a modified DTC algorithm for IPMSM is investigated and detailed comparisons between the proposed and the conventional hysteresis-based DTC in different sampling periods (20 us – 80 us) and rotor speeds (10 % - 100 % of rated speed) with step changes in motor load (50% - 100% of rated load), are presented. The proposed method aims to reduce torque ripple, flux ripple and stator currents THD by enlarging of the switching frequency and setting duty cycle for active vectors. The proposed DTC has more stable switching frequency (about 10 kHz) and low torque and flux ripple compared to that of dithering technique without losing dynamic and robustness of conventional DTC. It also has a simple structure and is easy to implement in comparison to the duty cycle modulation method. The simulation results show that this method also decreases stator currents THD.

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