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Combined effect of fuzzy logic controller and optimized voltage vector in torque ripple reduction of direct torque controlled permanent magnet synchronous motor

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Abstract. The Direct Torque Control (DTC) technique for Permanent Magnet Synchronous Motor (PMSM) has received increasing attention due to its simplicity and robust dynamic response compared with other control techniques. The classical switching table based DTC provides larger torque ripple and many techniques have been proposed in the literature to reduce torque ripple. Most of these are usually complicated and have more computational burden. It is mathematically proved that the voltage vector influences the electromagnetic torque of PMSM. Thus, by using the effective voltage vector combination in the switching table, the torque ripple can be minimized. The increment in the level of inverter provides 27 voltage vectors with different magnitudes, namely large, medium, small and zero. In the proposed DTC methods, 27 voltage vectors are allowed to form different groups of voltage vectors such as Large-Zero (LZ), Medium-Zero (MZ), Small-Zero (SZ), Large-Medium-Zero (LMZ), Large-Small-Zero (LSZ), Medium-Small-Zero (MSZ) and Large-Medium-Small-Zero (LMSZ). Based on these groups, the seven new switching tables are formulated and the conventional switching table is replaced by the proposed switching table. In the first stage, the switching tables are incorporated with the six sector based DTC methods which provide lesser torque ripple. The DTC method reduces the torque ripple with the maximum of 45.71% in comparison to the classical DTC. The accuracy of the reference torque magnitude also contributes to the torque ripple reduction. In the classical DTC method, the reference torque magnitude is calculated with the help of Proportional-Integral (PI) controller. In order to calculate the accurate reference torque magnitude, the Fuzzy-PI based controller is designed. The fuzzy-PI based methods minimized the torque ripple up to 61.93% for twelve sector based DTC method. The proposed DTC methods (with FLC and without FLC) are comparatively investigated with the classical DTC and existing literatures. It can be observed that the proposed DTC methods not only reduce the torque ripple, but also significantly reduce the flux ripple, average commutation frequency and improves the quality of stator current waveform compared with traditional and existing methods. Consequently, the effectiveness of the DTC method is justified by experimental results.

Keywords: AC drives, direct torque control, motion control, permanent magnet motor, power quality

1 Introduction

More or less 40 years ago, Blaschke proposed the concept of FOC for Induction Motor[3]. Since that time, the FOC has been dominating in the advanced AC drive market, even though it has a complicated structure. Fifteen years later, a new control technique for the Torque Control of Induction Motor was proposed by Takahashi and Nogushi as Direct Torque Control (DTC)[19]. Two years later Depenbrock presented another control technique named as Direct Self Control (DSC)[7]. The first follows Circular Trajectory and the latter follows Hexagon Trajectory. Both of them proved that it is possible to obtain a good and dynamic control of

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the torque without any sensor on the mechanical shaft. Thus, DTC and DSC can be considered as Sensorless type control technique.

The DTC scheme is normally preferred for low and medium power applications, whereas DSC scheme is chosen for high power applications. The DTC overcomes the drawbacks of FOC such as requirement of current regulators, co-ordinate transformations and PWM signal generators. DTC also provides high efficiency, high power/torque density and high reliability[6, 9, 15, 21]. Due to its simplicity, DTC allows a good torque control in the steady state and dynamic states.

On the other hand, the classical DTC, have some disadvantages and listed major disadvantages as follows: (1) high torque and current ripple; (2) difficulty to control torque at very low speed.

Most of the literature[1, 4, 8, 10, 11, 14, 16–18, 28] surveyed have analyzed classical DTC using two level inverter and all have presented high degree of torque ripple under dynamic conditions and this will reflect in speed and current too. In this article, the possibilities for minimization of torque ripple in the DTC is focused. The minimization of torque ripple is achieved by made improvement in the following areas, such as inverter, number of sector and switching table.

In the article, the possibilities for minimization of torque ripple in the DTC are focused. The torque ripple is reduced by an improvement in the following areas of the classical DTC, such as inverter, number of sector and switching table. In this research work, the torque ripple minimization is achieved by a simple modification in the classical DTC structure. That is, by eliminating two level inverter available in the classical DTC is replaced by three level Neutral Point Clamped (NPC) inverter. It has 27 voltage vectors, whereas only 8 voltage vectors are available with classical DTC. In 27 voltage vectors with different magnitudes, large (L) and medium (M) voltage vectors are six number in each, small (S) voltage vectors are twelve number and three number of zero (Z) voltage vectors.

Some of the literature[2, 5, 12, 13, 20, 23, 26] presents three level inverter with classical DTC, but it utilizes all the 27 voltage vectors to construct the switching table. The authors of paper [22] uses FLC for DTC of an induction motor. Here, the FLC is used to adjust the bandwidth of hysteresis torque controller. At present almost all the researchers are set the bandwidth of the hysteresis torque controller to zero. So, the FLC used in paper [22] will not significant in the reduction of torque ripple.

In this paper almost seven kind of DTC methods are proposed to reduce torque ripple. In the DTC method 1, all the voltage vectors such as large, medium, small and zero voltage vectors are used to construct a switching table, where as between DTC method 2 and DTC method 4, any three voltage vectors from the available four voltage vectors are utilized to construct a switching table. Any two voltage vectors are utilized to construct a switching table for the method between DTC 5 and DTC 7.

Thus on the basis of the experience of the authors, the fair comparison between all the DTC methods are presented in both steady state and dynamic conditions. The comparison is useful to indicate to the users which one of the method can be effectively utilized for various applications that today require torque control.

2 Factors affecting the torque of PMSM

2.1 Impact of voltage vector on torque

Contributions According to principle of DTC, electrical angle between stator and rotor flux vectors, δ can control the torque developed by the PMSM. In background, this can be achieved by controlling the voltage vector. Hence, the voltage vector is the prime controllable input variable in DTC. However, it is mandatory to develop a relation between torque developed by PMSM and voltage vector. The voltage and stator flux equations in stationary frame is expressed as

$$U_s = \frac{d\phi_s}{dt} + R_s\, i_s, \tag{1}$$

$$\phi_s = L_s\, i_s + \phi_r. \tag{2}$$

From Eqs. (1) and (2), we can get

$$L_s \frac{di_s}{dt} = U_s - R_s i_s - \frac{d\phi_r}{dt}, \tag{3}$$

$$L_s \frac{di_s}{dt} = U_s - R_s i_s - j\omega\phi_r. \tag{4}$$

The torque differentiation with respect to time ‘t’ is

$$\frac{dT_e}{dt} = \frac{3}{2}p\left\{\left(\frac{d\phi_s}{dt} \times i_s\right) + \left(\frac{di_s}{dt} \times \phi_s\right)\right\}. \tag{5}$$

Eqs. (1), (2) and (4) in (5), we can get

$$L_s \frac{dT_e}{dt} = \frac{3}{2}p\ \phi_r \times U_s - \frac{3}{2}p\omega\ \phi_r\ \times\ \phi_s - R_s\ T_e, \tag{6}$$

$$L_s \frac{dT_e}{dt} = T_{eI} + T_{eII} + T_{eIII}, \tag{7}$$

where,

ϕ_s, ϕ_r	:	Stator and Rotor flux vector.
U_s, i_s	:	Stator voltage and Current vector.
R_s, L_s	:	Stator resistance and Synchronous inductance.
p	:	Number of pole pairs.
T_e	:	Electromagnetic torque.

It can be seen from Eq. (6) the equation contains three components. The second component is negative and a function of speed. The third component is also negative and depends on stator resistance. The first component is always positive and depends on voltage vector. From this it is concluded that the non zero vector (active vector) always increases the torque developed and the zero vectors always decreases the torque developed.

2.2 Impact of reference torque on actual torque

In the conventional DTC, the reference torque is calculated from speed controller by comparing the actual speed with the reference speed. The PI controller is used in the speed controller. From the Eq. (6), it is observed that, the developed torque is also depends on the reference torque. In order to get accurate reference torque, a new FLC is designed and the same is combined with the existing PI controller.

3 Classical DTC method

Based on the errors between the reference and the actual values of torque and flux, it is possible to control directly the inverter switching states in order to reduce the torque and flux errors within the prefixed band limits. That is why this technique is called as *Direct Torque Control*. The block diagram of the classical DTC for PMSM is shown in Fig. 1. The basic principle of DTC is to select stator voltage vectors according to the differences between the reference and actual torques. The reference and actual value of the stator flux is processed through two level hysteresis comparator. If the error is positive, the magnitude of flux has to be increased and this is denoted as $d\phi_s = 1$. If the error is negative, the magnitude of the flux has to be decreased and this is denoted as $d\phi_s = 0$. The flux comparator conditions are given as,

$$d\phi_s = 1 \text{ for } |\phi_s| \leq |\phi_{sref}| - |\Delta\phi_s|, \tag{8}$$

$$d\phi_s = 0 \text{ for } |\phi_s| \geq |\phi_{sref}| + |\Delta\phi_s|. \tag{9}$$

The rotor reference speed is compared with the actual rotor speed and the error obtained is converted into reference torque by using suitable PI regulator. The reference and actual torque is processed through three level hysteresis comparator. If the error is positive, the magnitude of torque has to be increased and this is

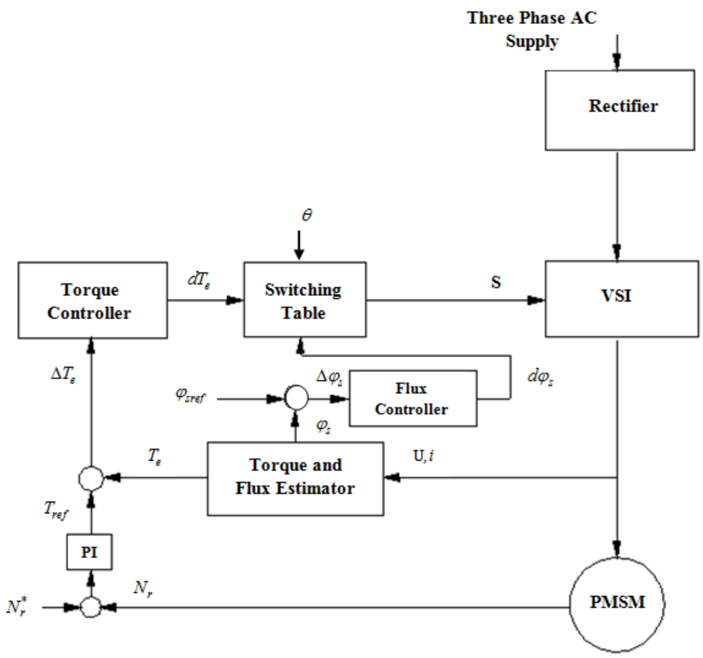

Fig. 1. Block diagram of the classical DTC

denoted as $dT_e = 1$. If the error is negative, the magnitude of torque has to be decreased and this is denoted as $dT_e = -1$. If the error is zero, the magnitude of torque has to be maintained constant and this is denoted as $dT_e = 0$. The torque comparator conditions are given as,

$$dT_e = 1 \text{ for } |T_e| \leq |T_{ref}| - |\Delta T_e|, \tag{10}$$
$$dT_e = -1 \text{ for } |T_e| \geq |T_{ref}| + |\Delta T_e|, \tag{11}$$
$$dT_e = 0 \text{ for } |T_{ref}| - |\Delta T_e| \leq |T_e| \leq |T_{ref}| + |\Delta T_e|. \tag{12}$$

Finally, most suitable voltage vectors are selected form the switching table based on the flux and torque errors for all the sectors.

4 Proposed DTC methods

The classical DTC uses two level inverter and produces only eight voltage vectors which includes six number of non zero vectors and rest of them are zero vectors. This does not allow smooth variation in the flux and torque. This could be one of the main reason for large flux and torque ripples. In this proposed DTC methods, the two level inverter is replaced by NPC three level inverter. Due to increment in the level of the inverter there are 27 voltage vectors are available to construct the switching table. In which six numbers of large voltage vectors (L), twelve numbers of small voltage vectors (S), three numbers of zero voltage vectors (Z) and remaining are medium voltage vectors (M). The inference from the section 3 is that the switching table plays an important role in the DTC technique. For proper switching table the best result can be obtained. The structure of the proposed method is shown in Fig. 2. In this proposed DTC methods, the available 27 voltage vectors are allowed to form different groups of voltage vectors such as two voltage vector combination (LZ or MZ or SZ), three voltage vector combination (LMZ or LSZ or MSZ) and four voltage vector combination (LMSZ). Based on these groups, a new effective switching table is proposed.

The Mamdani type FLC is designed and implemented in the speed controller to get accurate reference torque. In this paper, the FLC have two input variables and each input variables have seven membership functions. The 49 fuzzy rules are used to calculate the required reference torque.

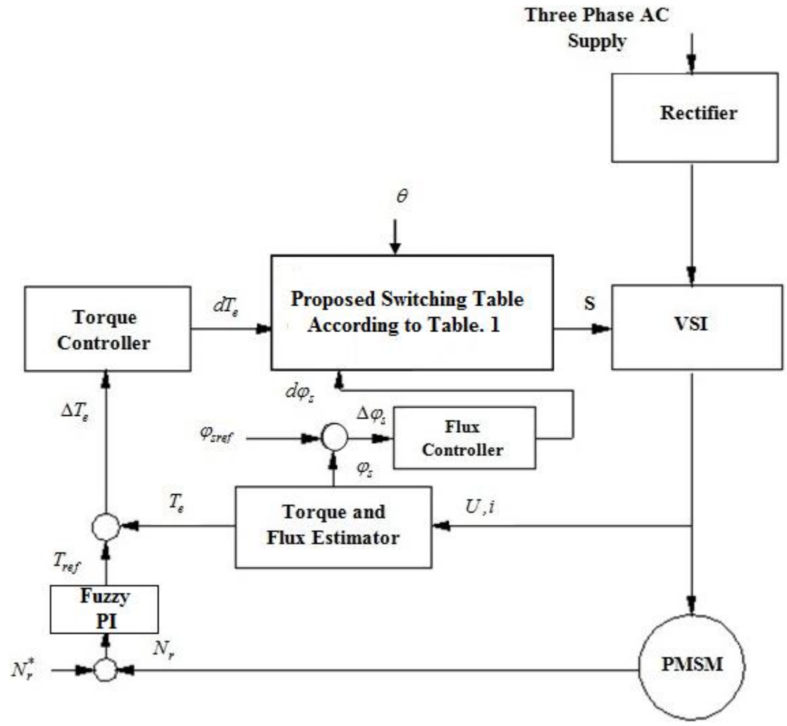

Fig. 2. Block diagram of the proposed DTC methods

The proposed DTC methods proves satisfactory results compared to classical DTC and existing literature. The Tab. 1 provides the technical idea of the proposed DTC methods. The classical DTC and proposed DTC method 5 (DTC 5) utilizes large and zero voltage vectors. The switching from zero voltage to large voltage increases the ripples in the flux and torque, harmonic content and stress across the switching devices. The Eq. (6) tells us that the large voltage vectors contributing to a torque in the same direction, which leads to large errors in the actual torque. This is true for small voltage vectors also. So, the classical DTC and DTC 5 presents large torque ripple, however DTC 5 takes the advantage of twelve sector, so presents slightly lesser torque ripple (refer Tab. 2).

Table 1. Technical difference among the classical and proposed DTC methods

Technique used	Classical DTC	Proposed DTC 1	DTC 2	DTC 3	DTC 4	DTC 5	DTC 6	DTC 7
Number of Sectors used	Six	Twelve	Twelve	Twelve	Twelve	Twelve	Twelve	Twelve
Inverter Level	Two	Three	Three	Three	Three	Three	Three	Three
Nature of Voltage Vectors available	LZ	LMSZ	LMSZ	LMSZ	LMSZ	LMSZ	LMSZ	LMSZ
Nature of Voltage Vectors utilized	LZ	LMSZ	LMZ	LSZ	MSZ	LZ	MZ	SZ

The switching table used in the proposed DTC method 2 (DTC 2), DTC method 3 (DTC 3) and DTC method 4 (DTC 4) uses three voltage vectors rather than two vectors in classical DTC and DTC method 5 (DTC 5), DTC method 6 (DTC 6) and DTC method 7 (DTC 7). The medium and small voltage vector act as a third voltage vector in three voltage vector based DTC. The smooth variation takes place in the torque, because of third voltage vector act as a intermediate voltage vector. The DTC 2, DTC 3 and DTC 4 presents lesser torque ripple, however DTC 3 and DTC 4 shows lower torque ripple compared to DTC, because of small voltage vectors.

From the experience of previous methods, the lesser torque ripples can be expected by combining small voltage vectors with any other voltage vectors. While selecting small voltage vectors, the following points can be noticed that, there are 12 small voltage vectors and these are exist in redundant pair i.e. six number of positive small vector and six number of negative small vector. So, the switching table is formed either by using positive small vector or negative small vector in order to balance neutral point potential. From the above discussions, it clear that the small voltage vector is identified to mitigate and solve the torque ripple problem. From the computer simulations and theory analysis, it can be observed that the proposed DTC methods can significantly reduces the flux and torque ripples and improves the quality of current waveform compared with traditional and existing methods. So, this ensures the safe operation of the entire system.

5 Simulation and results

The MATLAB/Simulink is used to perform the simulation for proposed DTC methods and classical DTC method. The machine parameters used in this paper is same as reported in the literature [24] and [25]. In this paper, the simulation results of classical DTC and all other proposed DTC methods were presented. For all the methods, the performance analysis and performance during external load disturbance was carried out.

5.1 Comparative study with existing work

First, the classical DTC and DTC 1 to DTC 7 without FLC will be carried out to show the effectiveness of the proposed DTC methods (with FLC). The proposed methods are also compared with existing work reported in [24] and [25]. The switching table used in this paper is different from [24] and [25] and the same is developed based on the Tab. 1.

Fig. 3 to Fig. 10 presents the responses at 1000 rpm with an external load of 3 Nm applied at 0.1 s for classical DTC and all other proposed DTC methods. From the top to bottom, the waveforms are stator current, torque, flux, rotor speed and the harmonic analysis of stator current, respectively. Form the Tab. 2, it is noticed that the torque ripple in all the proposed DTC methods are smaller than that of torque ripple in classical DTC.

For simplicity, the proposed DTC methods are classified into three categories. The first category (DTC 1) using four voltage vectors in their switching table. The category 2 (DTC 2, DTC 3 and DTC 4) using any three voltage vectors to form their switching table. In the third category (DTC 5, DTC 6, DTC 7), two voltage vectors used. It can be seen that the torque ripple of the DTC 5 is slightly lesser than that of classical DTC. This is because of both the methods utilizing two voltage vectors, such as large and zero voltage vectors (refer Tab. 1) in their switching table and the slight reduction in the torque ripple is due to sector increment and the usage of FLC in the DTC 5.In DTC 2, DTC 3 and DTC 4, three voltage vectors are used, in which DTC 2 and DTC 3 is formulated by adding small voltage vector with DTC 5. Compared with DTC 5, a lesser torque ripple reduction in DTC 2, where as a significant reduction in DTC 3. However, DTC 4 provides much lower torque ripple among three vector based DTC methods. From the above discussion, the three voltage vector based DTC can be significantly reduces the torque ripple as compared to classical DTC and existing DTC methods (refer Tab. 2). The two voltage vector based DTCs, such as DTC 5, DTC 6 and DTC 7, out of which, the DTC 7 exhibits better performance compared to DTC 5 and DTC 6. The key point in the DTC is that, the small voltage vectors contributing to a torque in the same direction and produces smaller torque ripple as compared to classical DTC, DTC 5 and DTC 6. One more important observation is that, if small voltage vector is included in the combination, lesser torque ripple can be resulted.

Tab. 2 provides quantitative comparison of the proposed DTC (with FLC) methods with all other existing DTC methods. The proposed DTC methods produces lesser torque ripple as compared to classical DTC and existing literature [24] and [25]. While comparing with the existing DTC methods [24] and [25], the proposed DTC 1, 4 and 7 provides lesser torque ripple. The Root Mean Square (RMS) torque ripple is followed in the literature [24], [25] and the same is followed in this paper also. The proposed DTC 7 gives torque ripple only 41.90 %, 62.44 %, 68.74 % of that of classical DTC, literature [24] and [25], respectively.

The average commutation frequency is calculated using the formula, = N/K/0.05, where, N is the total commutation instants of all the legs of the inverter used in the DTC methods during fixed period, e.g., 0.05 s in this paper and K is the switch number. The DTC 1, DTC 4 and DTC 7 provides lesser average commutation frequency compared to classical DTC and results reported in literature [24] and [25]. By comparing classical DTC and literature [24], the DTC 1, DTC 3, DTC 4, DTC 5 and DTC 7 has lower average commutation frequency. The proposed DTC 7 exhibits its better performance in terms of torque ripple and average commutation frequency.

Table 2. Technical difference among the classical and proposed DTC methods

Method	Without FLC			With FLC		
	f_{av}(Hz)	T_{ripple}(Nm)	% THD of Stator Current	f_{av}(Hz)	T_{ripple} (Nm)	% THD of Stator Current
Classic DTC	5.36 k	0.2004	6.73 %	5.77 k	0.1821	5.28 %
[24]	4.41 k	0.1222	5.85 %	–	–	–
[25]	3.22 k	0.1110	4.67 %	–	–	–
DTC 1	3.09 k	0.1107	6.27 %	4.03 k	0.0925	4.31 %
DTC 2	4.72 k	0.1677	5.91 %	7.55 k	0.1508	7.62 %
DTC 3	3.72 k	0.1296	4.66 %	4.67 k	0.1132	4.85 %
DTC 4	3.46 k	0.1135	5.21 %	4.24 k	0.1017	5.17 %
DTC 5	4.76 k	0.1934	6.20 %	4.71 k	0.1630	5.17 %
DTC 6	4.59 k	0.1499	12.05 %	7.17 k	0.1294	9.08 %
DTC 7	1.51 k	0.1088	6.98 %	2.39 k	0.0763	5.13 %

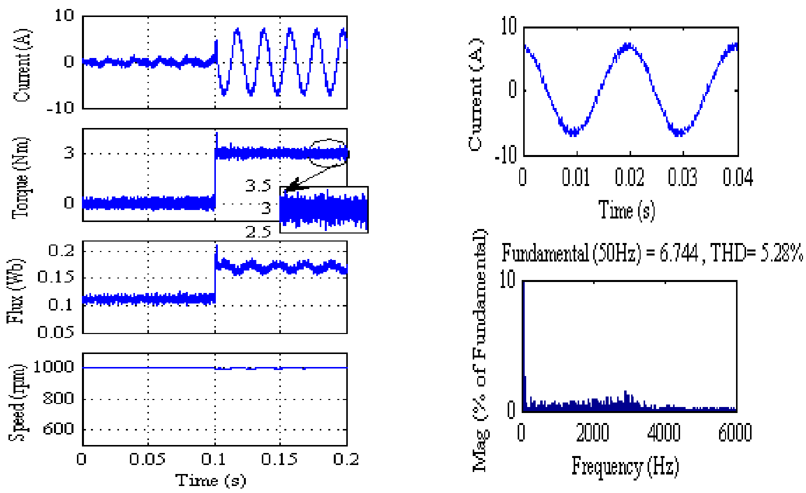

Fig. 3. Response of stator current, torque, flux and rotor speed at 1000 rpm with 3 Nm Load for Classic DTC

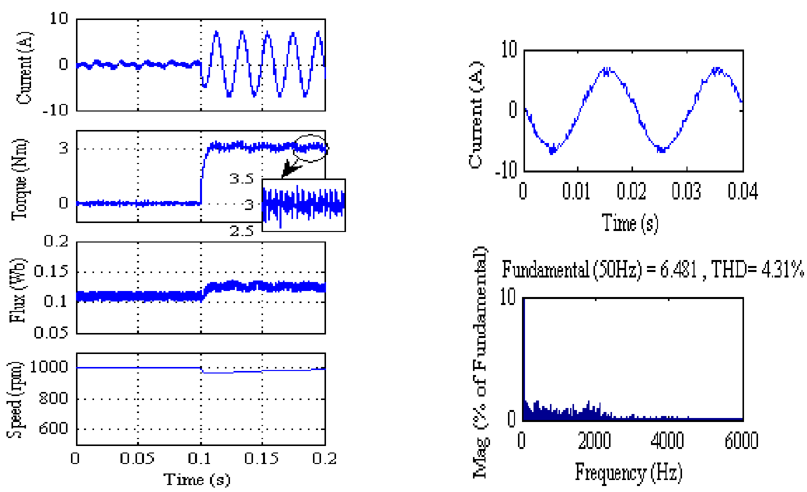

Fig. 4. Response of stator current, torque, flux and rotor speed at 1000 rpm with 3 Nm Load for DTC 1

The average commutation frequency of the DTC 1 is 4.03 kHz and for DTC 7 is 2.39 kHz, which is less than in literature [24] and [25].

The proposed DTC 1 has its average commutation frequency, only 69.84 %, 68.89 % and 86.30 % of that of classical DTC, existing DTC methods available in the literature [24] and [25], respectively. But, the average commutation frequency of the proposed DTC 7 is 2.39 kHz, which is less than in both the paper [24] and [25]. The proposed DTC 7 has its average commutation frequency, only 41.42 %, 40.85 % and 51.18 % of that of classical DTC, existing DTC methods available in the literature [24] and [25], respectively. This validates the superiority of the proposed DTC (with FLC) methods.

Even the DTC 1 to DTC 7 (without FLC) methods shows better performance compared to existing literatures. It can be seen that the current waveform is more sinusoidal and has less harmonic content in the proposed DTC methods as compared to existing methods. The Total Harmonic Distortion (THD) is calculated up to 6000 Hz. The dominant harmonics between 2000 Hz and 4000 Hz in proposed DTC method 1 and 3 are much lesser than as compared to other proposed methods and classical DTC method. It is seen that the stator current THD of the DTC 1 is 4.31 %, much lower than the 5.85 % and 4.67 % of the existing DTC methods available in the paper [24] and [25]. In the view of stator current THD, except DTC 2 and DTC 6, all other proposed DTC methods exhibits better performance, however except DTC 2 and DTC 6, all other proposed DTC methods provides lesser stator current THD compared to existing literature [24]. Fig. 11 provides the effectiveness of the proposed DTC methods over existing DTC methods. Similar conclusions are made for various operating point of the classical

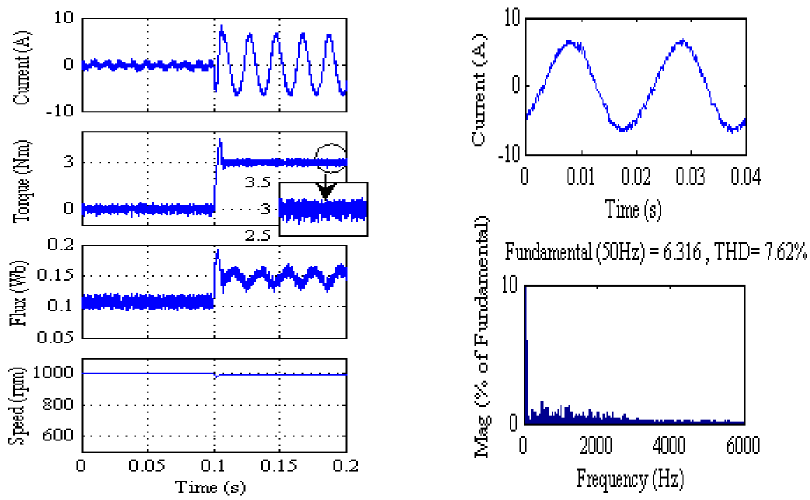

Fig. 5. Response of stator current, torque, flux and rotor speed at 1000 rpm with 3 Nm Load for DTC 2

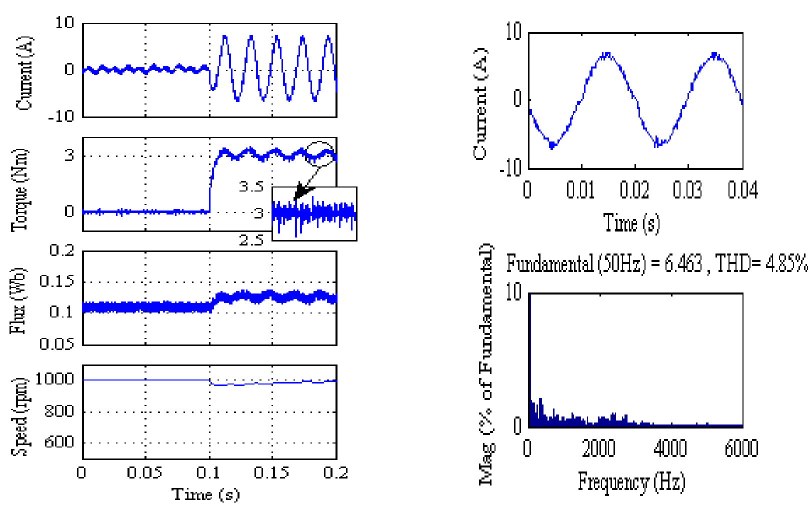

Fig. 6. Response of stator current, torque, flux and rotor speed at 1000 rpm with 3 Nm Load for DTC 3

DTC and proposed DTC methods with no load for an example. Due to page constraints, the waveform results are not listed here. However, the quantitative comparisons of the classical with proposed DTC methods

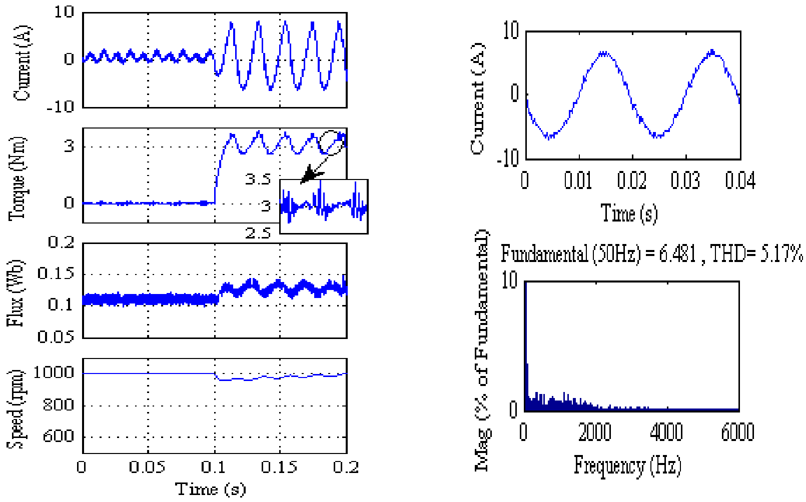

Fig. 7. Response of stator current, torque, flux and rotor speed at 1000 rpm with 3 Nm Load for DTC 4

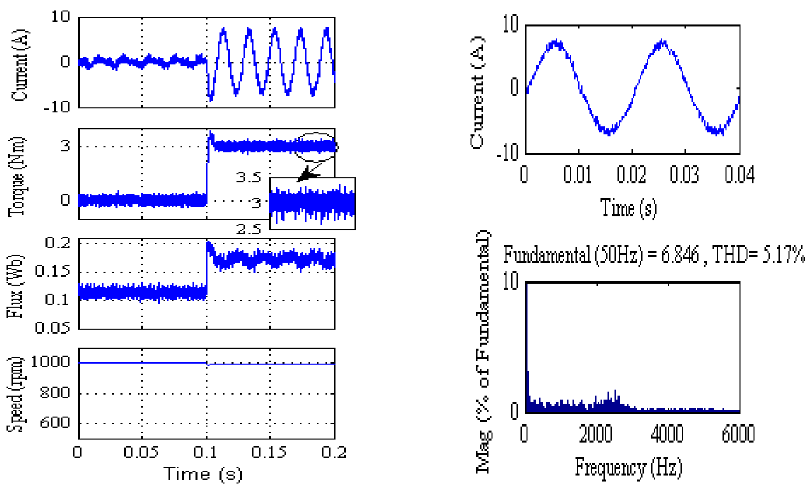

Fig. 8. Response of stator current, torque, flux and rotor speed at 1000 rpm with 3 Nm Load for DTC 5

(without FLC) and the classical with proposed DTC methods (with FLC) are shown in Fig. 12 and Fig. 13, respectively. This comparison is useful to indicate to the end users for various applications that today require torque control.

5.2 Response to external load disturbance

The responses to the external load disturbances are shown in Fig. 14 for classical DTC and DTC 1 to DTC 7, respectively. The motor is operated at a steady state with 2.5 Nm and 1000 rpm and then the load is suddenly removed in order to check the disturbance rejection capability of the classical DTC and proposed DTC methods (with FLC). The speed of the motor should be constant throughout the operation, even though there is any change in torque. It means that, in torque control, the motor should develop a required torque without reduction in speed.

In the proposed DTC methods with in a very short period, the motor speed returns to its original speed due to its fast torque response. It is observed that about 3.3 % peak speed increases for classical DTC and DTC 1. At the same time, about 3.0 % peak speed increases for DTC 3 and 6, where as 3.38 % peak speed increases for DTC 4. The smallest peak speed (0.3 %) increases for DTC 2 and DTC 5, at the same time, the highest peak speed (4.9 %) increased is seen from DTC 7. The above mentioned peak speed increases is observed when the load of 2.5 Nm is suddenly removed. However, almost all the DTC methods including classical DTC method takes same time to reach its original speed after the load is removed. This comparison informs that all the proposed DTC methods exhibiting its fast response of torque as compared to classical DTC. Even though the peak speed increases about 4.9 %, but takes lesser time to reach its steady state whereas the classical DTC takes same time to reach from its 3.2 % peak speed. However the classical DTC exhibits the best performance at the cost of larger torque ripple whereas all the proposed DTC methods provides lesser torque ripple and better performance in terms of disturbance rejection.

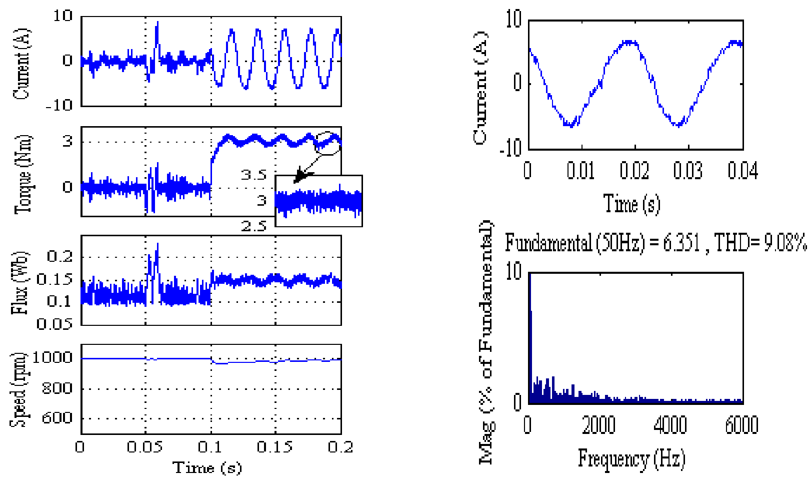

Fig. 9. Response of stator current, torque, flux and rotor speed at 1000 rpm with 3 Nm Load for DTC 6

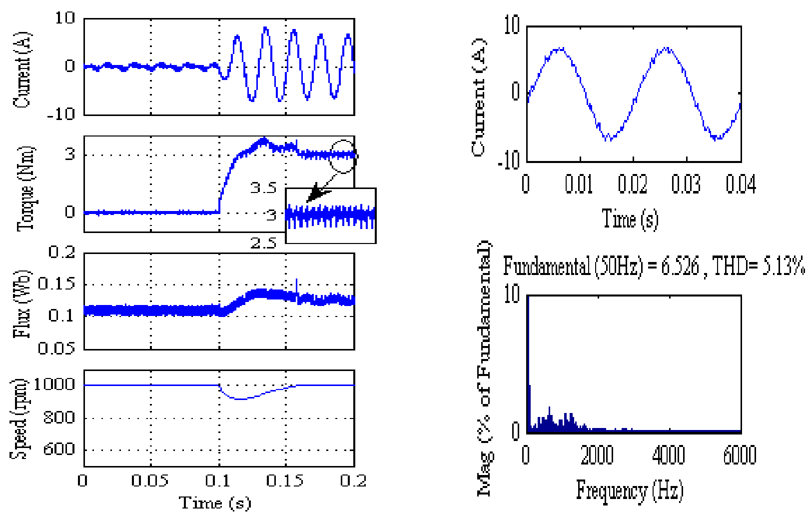

Fig. 10. Response of stator current, torque, flux and rotor speed at 1000 rpm with 3 Nm Load for DTC 7

6 Experimental results

Apart from the simulation results, the DTC methods are also experimentally tested to validate the effectiveness of the DTC methods. The control circuit arrangement of the system is the same as that in Fig. 2. The PMSM of 1 kW is used for both the experimental verification and numerical simulation. Fig. 15 shows the snapshot of the experimental arrangement for the DTC Methods. The three phase intelligent power module is developed with an insulated gate bipolar transistor, which is used for an inverter. A 200 V is maintained as DC link voltage both for numerical simulation and for the experimental setup. The gating pulses are generated in

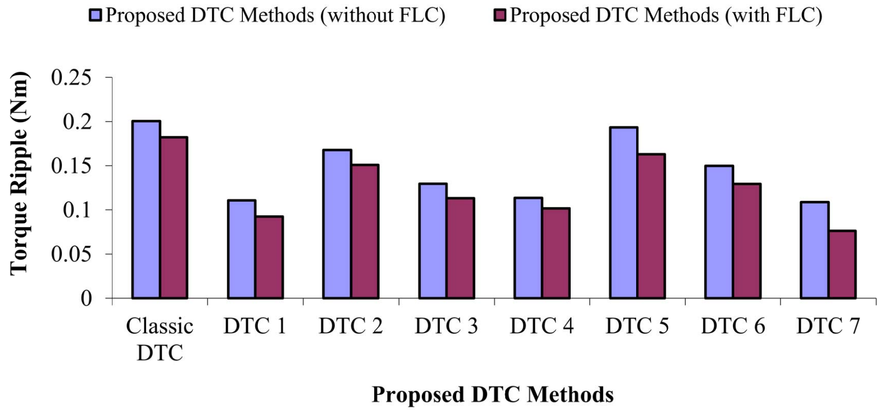

Fig. 11. Comparison of the torque ripple for classical DTC and Proposed DTC methods at the speed of 1000 rpm, load of 3 Nm

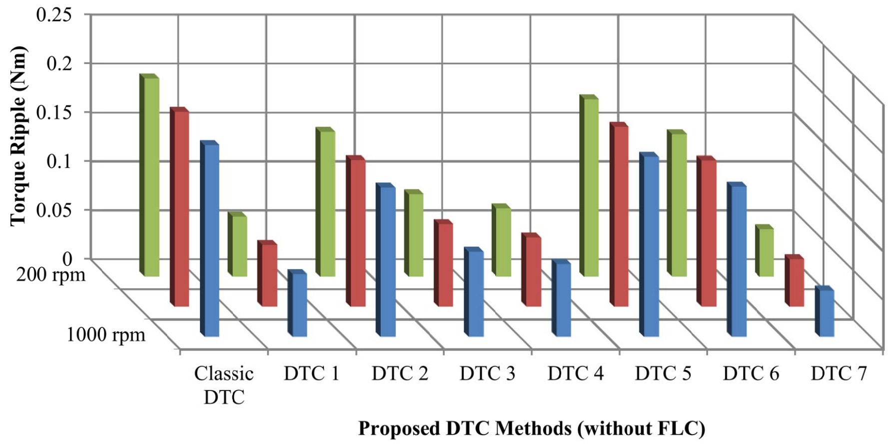

Fig. 12. Comparison of the torque ripple for classical DTC methods and Proposed DTC methods (without FLC) at various operating points

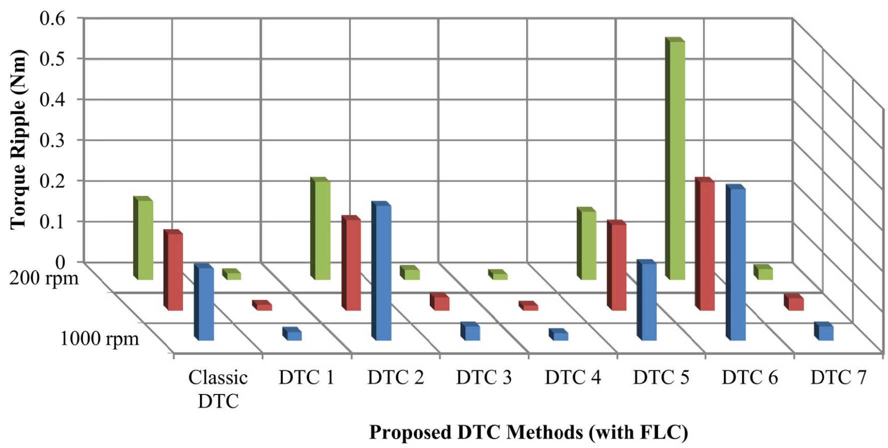

Fig. 13. Comparison of the torque ripple for classical DTC methods and Proposed DTC methods (with FLC) at various operating points

the SPARTAN 3A/3A DSP FPGA board and then sent to the three level NPC inverter. All the experimental results are captured using the Tektronix TDS 2004B and Agilent Technologies digital storage oscilloscope. To make the comparison fair, the same control circuit parameters are used in simulation and hardware setup.

Fig. 16 exhibits the load test performance of the DTC method at the speed of 1000 rpm with 3 Nm load torque. The figure contains the stator current, torque and speed of the motor from top to bottom. The figure shows the step change in torque from no load torque to 3 Nm load torque. Furthermore, it becomes clear that there is no decrement in the speed observed, even while increasing the load torque suddenly. This is because in DTC principle, if the load torque is applied, then the motor should satisfy the load torque demand. At the same time, it should not affect the motor speed. This means that, the motor should deliver the power, from zero torque to rated torque with constant motor speed.

The response to external load disturbance is illustrated in Fig. 17 for the stipulated DTC method. The motor is operated at a steady state of 1000 rpm with an external load of 2.5 Nm and then the external load is suddenly removed in order to check the disturbance rejection performance. It may be seen that the difference in the torque ripple throughout this operation is not much significant. It should also be noted that in a very short period, the motor torque steps up and returns to its reference value, due to the fast response of torque of the DTC method. The experimental results also prove the robustness of the DTC method against external load disturbance. Once again the DTC method has not shown any deviation in the speed throughout this operation. However, there is an increment in the stator current after applying the load torque of 2.5 Nm. Another aspect that is also noticed is that the stator current magnitude is decreased after removing load torque.

7 Important observations

Remark 1. The first observation is influence of number of sector on the torque ripple in DTC. The twelve sector DTC is capable of reducing torque ripple, but not that much significant.

Remark 2. A very simple and effective voltage vector combination is proposed in this paper, which can significantly reduces a torque ripple and distortion (THD) in the stator current. All the proposed DTC methods (without FLC) are capable of reducing torque ripple in DTC (Refer Tab. 2 and Fig. 12).

Remark 3. From the analysis, it can be concluded that, number of vector (two vector based or three vector based or four vector based) used in the group will not influence on the torque ripple of DTC. At the same time, the type of voltage vector (L or M or S or Z) will affect the torque ripple in greater extent.

Remark 4. The torque ripple is significantly reduced, if the small voltage vector combines with any other category of voltage vectors. The Small-Zero and Large-Medium-Small-Zero voltage vector combinations are identified as a effective voltage vector combination by theoretical and computer simulation analysis. This vector combinations are applicable for proposed DTC methods with FLC and without FLC.

Remark 5. In this paper, the classical DTC method and all the proposed DTC methods are comparatively investigated in the aspect of torque ripple, disturbance rejection performance during external load disturbance. By effective voltage vector combination, the torque ripple can be significantly reduced up to 61.93 % and 45.71 % in the proposed DTC method with FLC and without FLC, respectively, at the same time this is seen without degrading the steady state performance.

Remark 6. From the results indicated earlier, it is found that the torque ripple in the proposed DTC methods are less as compared to classical DTC method and existing literatures. All most, at all the operating points the classical DTC provides slightly higher torque ripple (refer Fig. 12 and Fig. 13). However, proposed DTC 1 and DTC 7 shows better performance in terms of torque ripple as compared to classical DTC, existing literatures [24], [25] and all other proposed DTC methods (refer Tab. 2).

Remark 7. The major drawback reported in the literature about the classical DTC is that the torque ripple during low speed is very high. But all the proposed DTC methods provides lesser torque ripple even in the low speed, where as the proposed DTC 1, DTC 4 and DTC 7 provides much lesser torque ripple among the classical DTC method, all other proposed DTC methods and results reported in existing literatures.

Remark 8. Once again all the DTC methods exhibits all most similar decelerating capability, however proposed DTC 1 and 3 provides lesser THD in the current waveform.

Remark 9. All the proposed and existing DTC methods shows good disturbance rejection characteristics at the cost of higher torque ripple except proposed DTC 1 and DTC 7.

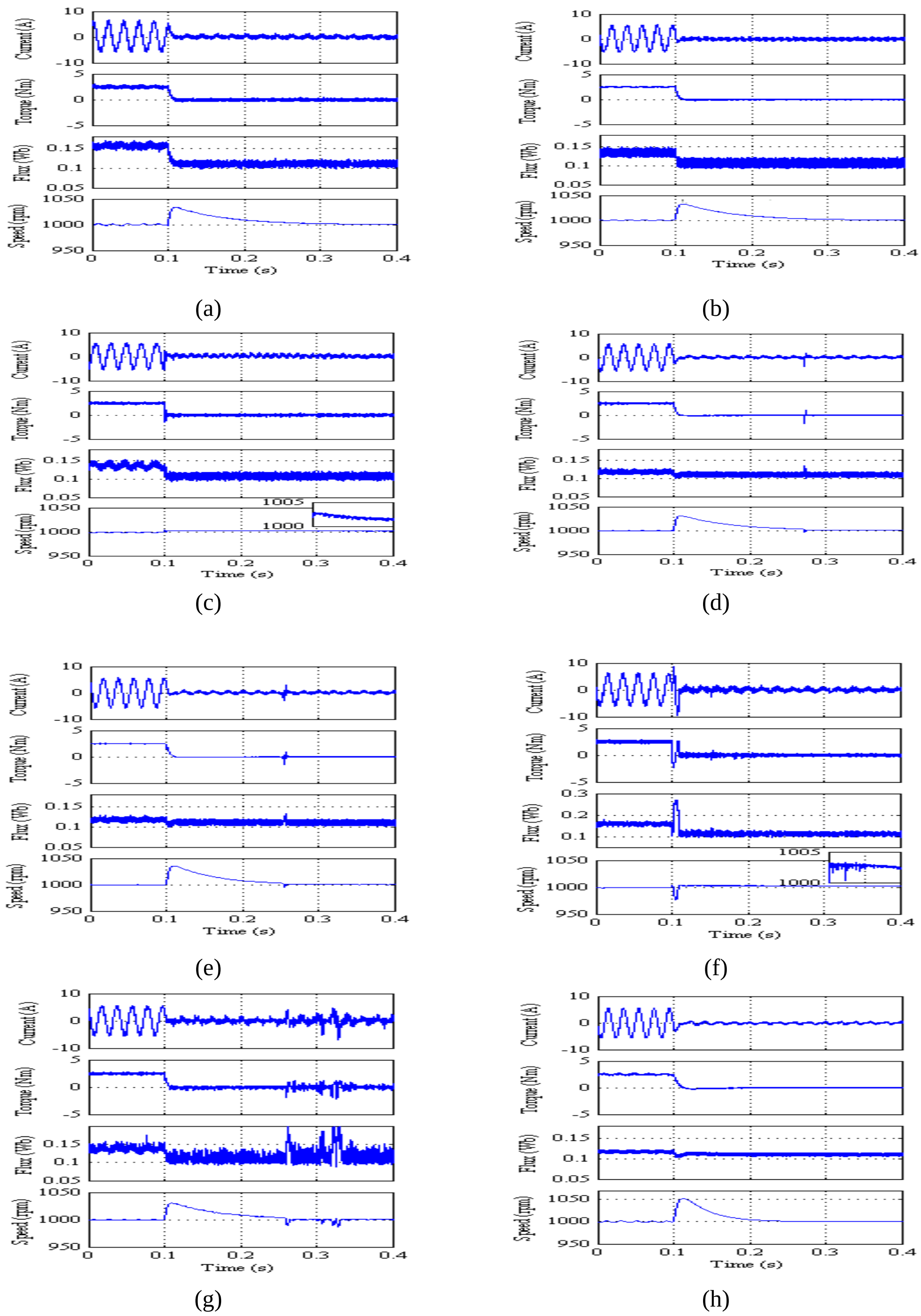

Fig. 14. Response to external load disturbance for: (a) Classical DTC; (b) DTC 1; (c) DTC 2; (d) DTC 3; (e) DTC 4; (f) DTC 5; (g) DTC 6; (h) DTC 7

Remark 10. The experimental results have proved that the DTC methods are capable of operating in a wide range of speeds without degrading the performance.

Remark 11. The experimental results prove that the DTC methods can achieve as excellent steady state performance and fast dynamic response. At the same time, it retains the merits of simplicity and robustness as found in classical DTC.

Fig. 15. Snapshot of the experimental arrangement

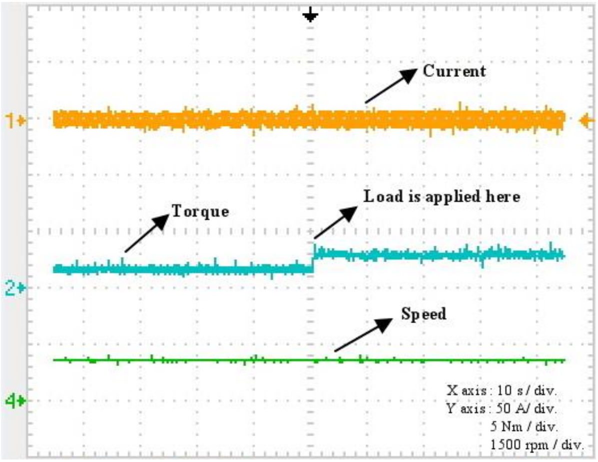

Fig. 16. Experimental results of the proposed DTC method at 1000 rpm with load torque of 3 Nm

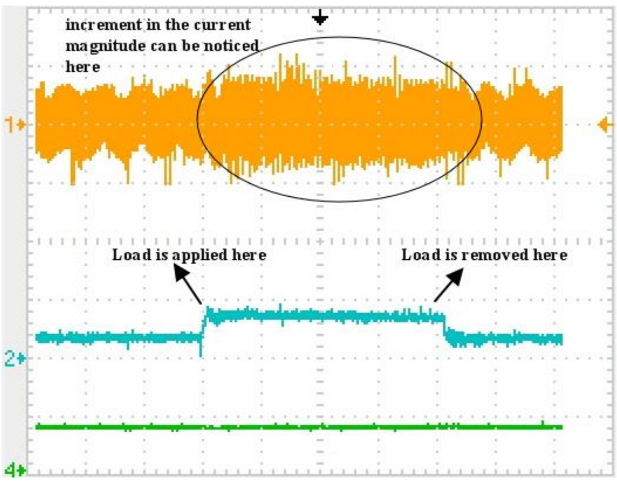

Fig. 17. Experimental results of the proposed DTC method during external load distrubance

Remark 12. The acoustic noise developed during the experimental investigations is a little higher. However, it is not that much audible compared to the noise observed during the experimental evaluation of the classical DTC method.

8 Conclusion

In this paper, the combined effect of FLC and a optimized voltage vector combination is investigated to minimize the torque ripple in DTC of PMSM drives. The new switching table, in which only any two (LZ, MZ, SZ) or three (LMZ, LSZ, MSZ) or four (LMSZ) voltage vectors are utilized. The performance of the proposed DTC methods (with FLC and without FLC) are comparatively investigated with classical DTC and existing literatures. The simulation results prove that the proposed DTC methods able to diminish the torque ripple at different operating points as compared to classical DTC. Consequently, the proposed DTC method has also gives excellent performance during external load disturbance operations. The proposed DTC methods also capable of reducing THD in the stator current. The settling time of the torque can be reduced if compared with the classical DTC method, furthermore, the related current ripple is also reduced. The proposed DTC methods also retaining the merits of simplicity and robustness as in classical DTC. This comparative study is our first stage work and this still lacks detailed experiments, and further efforts are needed to confirm the simulation results.

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