Dynamic torque response improvement of direct torque controlled induction motor

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Abstract. Induction motor is extensively being used with variable frequency drive (VFD) in variable speed service. Direct Torque control (DTC) of induction machines is simple compared to the Field oriented control (FOC). Although DTC has advantages there are some disadvantages like torque ripple is high, switching frequency is variable. This paper proposes a dynamic over modulation strategy which can be implemented in DTC to improve the dynamic response and to reduce the torque ripple. The objectives are achieved by switching voltage vector that produces the most tangential component to the circular flux locus. The principle advantage of the proposed technique is its effortlessness, since it requires a minor change to the conventional DTC-hysteresis-based structure. 80% reduction in torque ripple and 40% improvement in dynamic response are achieved in the proposed method compared to conventional method.

1. Introduction

In the recent generation DTC had gained huge consideration in industrial motor drive applications. Induction motors are renewed as work horses of the industry. Control of such drives can increase its performance and reliability. Different strategies had been implemented for control of induction motor. Basically the control achieved by implementing two techniques namely Stator control and Vector control. Vector control is subdivided into Field Oriented Control (FOC) and Direct Torque control (DTC). DTC is subdivided into Direct Self Control (DSC) and DTC-space vector modulation. The main distinction among DTC and DSC is the state of the way along which the flux vector is controlled, the previous way being quasi circular while the last is hexagonal with the end goal that the switching frequency of DSC is lesser than DTC. Stator flux optimization is done at low speeds both by utilizing desirable estimation of stator flux or optimizing command of stator flux [1]. With the view of achieving fast dynamic response voltage vector optimization is obligatory. It is done by reducing the error in steady sate conditions. The voltage vector which is tangential to the circular flux loci can be used to acquire quick transient reaction [2].

A hybrid FOC–DTC is actualized in which similar to FOC, the direct axis (d-axis) and quadrature axis (q-axis) errors in current can be straightforwardly controlled by fusing the DTC structure [3].

Variable switching frequency is the major drawback of DTC [4]. Current harmonics, flux ripple and torque ripple are the consequences of the variable switching frequency. CSF (constant switching frequency) DTC algorithm in which current harmonic spectrum is predictable as harmonics lie around
switching frequency whereas in conventional DTC it is unpredictable. Modification to the hysteresis controllers is done with the help of biasing the input utilizing triangular carrier wave whose frequency is same as the switching frequency. The CSF torque and flux controllers which have two digital outputs while the later has three achieve better dynamic response when actualized by proficient voltage vector selection algorithm. In DTC, constant switching frequency is obtained without the hysteresis controller and SVM [5]. Torque ripple is minimized by a two-way control algorithm of torque.

Algorithm based on fuzzy controller had been actualized to reduce the torque ripple. 98% torque ripple was decremented by switching either Zero or active vector in particular duty ratio. Optimal values of torque and flux ripple was attained in ANFIS-DTC.

In predictive control, the control variable status is calculated ahead and appropriate controller activity is processed. There is no time delay observed between the control and execution in predictive control. In predictive methodology ripple content in torque was reduced by controlling the increment or decrement in stator flux magnitude and angle.

2. Mathematical modelling of Induction motor

With respect to stationary reference frame, the induction machine model is expressed by the equations described below

\begin{align*}
V_s &= R_s I_s + \frac{d\varphi_s}{dt} \quad (1) \\
0 &= R_r I_r - j\omega_r \varphi_r + \frac{d\varphi_r}{dt} \quad (2) \\
\varphi_s &= L_s I_s + L_m I_r \quad (3) \\
\varphi_r &= L_s I_r + L_m I_s \quad (4) \\
T_e &= \frac{3}{2} p |\varphi_s| |I_s| \sin \delta \quad (5) \\
\varphi_{s,d}^s &= \int (V_{s,d}^s - I_{s,d}^s r_s) dt \quad (6) \\
\varphi_{s,q}^s &= \int (V_{s,q}^s - I_{s,q}^s r_s) dt \quad (7)
\end{align*}

Where \( R_s \) is the resistance of stator, \( R_r \) is resistance of rotor, \( \varphi_s \) is component of stator flux, \( \varphi_r \) is component of rotor flux, \( T_e \) is electromagnetic torque, \( p \) denotes the poles present where \( \delta \) is torque angle.

2.1. Conventional DTC
Figure 1. Schematic View of Conventional DTC [6]

The reference torque and stator flux references comparison is done with estimated values. Compared values of Torque are processed through the torque controller which has three level of output. Compared values of flux are processed through the flux controller which has two level output.

\[ H_T = +1 \text{ for } E_T > +HB_T \]  \hspace{1cm} (8)
\[ H_T = -1 \text{ for } E_T < -HB_T \]  \hspace{1cm} (9)
\[ H_T = 0 \text{ for } -HB_T < E_T < -HB_T \]  \hspace{1cm} (10)
\[ H_\phi = +1 \text{ for } E_\phi > +HB_\phi \]  \hspace{1cm} (11)
\[ H_\phi = -1 \text{ for } E_\phi < -HB_\phi \]  \hspace{1cm} (12)

The switching strategy is selected based on whether to ascend or descend the torque and stator flux position. The feedback values of torque and flux are estimated from the values of currents and voltages obtained from the machine. The sector in which flux vector \( \psi_s \) lies is calculated by the signal computation block. Six sectors are present. Each sector is spread over 60 degrees. Look up table receives the input signal \( H_\phi, H_T, \text{and } S(k) \) and applies the appropriate control voltage vector to the inverter. The main advantage of DTC i.e., decoupled control of torque and flux. Table 1 depicts the voltage vector to be switched during the conventional method.

**Table 1.** Conventional DTC Look-up Table [10]

| \( H_\phi \) | \( H_T \) | \( S_1 \) | \( S_2 \) | \( S_3 \) | \( S_4 \) | \( S_5 \) | \( S_6 \) |
|---|---|---|---|---|---|---|---|
| +1 | 0 | \( V_2 \) | \( V_3 \) | \( V_4 \) | \( V_5 \) | \( V_6 \) | \( V_7 \) |
| +1 | -1 | \( V_7 \) | \( V_0 \) | \( V_1 \) | \( V_2 \) | \( V_3 \) | \( V_4 \) |
| +1 | +1 | \( V_6 \) | \( V_5 \) | \( V_4 \) | \( V_3 \) | \( V_2 \) | \( V_1 \) |
| 0 | -1 | \( V_0 \) | \( V_7 \) | \( V_6 \) | \( V_5 \) | \( V_4 \) | \( V_3 \) |
| 0 | -1 | \( V_5 \) | \( V_6 \) | \( V_7 \) | \( V_1 \) | \( V_3 \) | \( V_4 \) |
| -1 | -1 | \( V_0 \) | \( V_5 \) | \( V_6 \) | \( V_7 \) | \( V_4 \) | \( V_1 \) |
2.2 Modified DTC

Dynamic over modulation scheme is used in case of modified DTC. The equivalent condition referred to dynamic over modulation occurs in case of Modified DTC when the output of hysteresis torque comparator produces a demand to continuous increase in the torque. In the meanwhile flux is controlled to trace the circular path with the help of two active voltage vectors.

When Torque demand suddenly shoots up which in turn results in large torque error, the torque comparator reciprocates that demands torque increment. As far now this won't provide the better dynamic response because two active voltage vectors are applied in transient state. Better response is achieved by switching only the voltage vector which is tangential.

In order to obtain an increment in the torque response $\delta$ is to be maximized. In the proposed process the voltage vector to be applied is chosen in such a way that it has largest tangential component during every sample period. Higher stator angular flux is achieved because one vector is switched.

Each sector is divided into two subsectors. Taking Sector 1 for example when the flux is located in subsector 1 the modification block produces an output of 0 and hence $V_{k+1}$ is selected. When it enters subsector 2 blocks produces an output value of 1 and $V_{k+2}$ is selected. By selecting the voltage vector continuously the stator flux goes on increasing and sometimes it may go out of bands which may consequently reduce the performance of stator flux and this can collapse the whole system as stator flux is always increased.

![Figure 2. Schematic View of Modified DTC [6]](image)

To avoid this stator flux is kept on check. If the stator flux crosses the band for $N_\phi$ consecutive times, modification process would be terminated.

Modifying block is activated only when there is increment in torque demand the equivalent condition occurs whenever reference torque alters the output of torque comparator for $N_\tau$ consecutive times the modifying block is activated. Algorithm used in modified method is depicted in figure 3.
Figure 3. Algorithm Implemented in Modified DTC [7]

3. Results

The entire system of figure 1 and figure 2 is tested in MATLAB SIMULINK platform. The load torque on the motor is varied as shown in the figure 4 and observation is done for various motor parameters. Simulation is carried out for Conventional DTC and Modified DTC in order for the comparison.

Figure 4 presents the reference speed and motor speed of conventional DTC whereas figure 5 presents the referenced speed and motor speed of Modified DTC. In both the cases the motor exhibits the superior performance with minimal fluctuation between each other.

Figure 4. Speed response of Conventional DTC
Table 2. Comparison of Torque ripple for Conventional and Modified DTC

| Torque reference (Nm) | Flux Reference (wb) | Conventional DTC | Modified DTC |
|------------------------|---------------------|------------------|--------------|
|                        |                     | Torque Ripple    | Ripple %     | Torque Ripple | Ripple %     |
| 50                     | 0.8                 | 55.47            | 110          | 5.64          | 11.2         |
| 100                    | 0.8                 | 58.05            | 58.5         | 6.38          | 6.38         |
| 150                    | 0.8                 | 56.06            | 37.3         | 9.28          | 6.18         |
| 200                    | 0.8                 | 61.98            | 30.9         | 14.24         | 7.12         |

Figure 5. Speed response of Modified DTC

Figure 6. Torque Response of Conventional DTC

Figure 7. Torque Response of Modified DTC

Figure 8. Stator Current in Conventional DTC
Table 2 represents the torque ripple comparison for conventional and modified method. From figure 8 it can be seen that for $0 \leq t \leq 1s$ no load current is obtained which is 40% of the rated current. For $1s < t < 1.5s$ load current is found as 52% of the rated current. Reference torque is given as 25% of the rated torque. For $1.5s < t < 2s$ load current is found as 65% of the rated current. Reference torque is given as 50% of the rated torque. For $2s < t < 2.5s$ load current is found as 75% of the rated current. Reference torque is given as 78% of the rated torque. For $2.5s < t < 3s$ load current is found as 95% of the rated current. Reference torque is given as 90% of the rated torque. Figure 6 represents the torque ripple obtained for conventional method and figure 7 represents the torque ripple obtained for modified method.

From figure 9 it can be seen that for $0 \leq t \leq 1s$ no load current is obtained which is 40% of the rated current. For $1s < t < 1.5s$ load current is found as 51% of the rated current. Reference torque is given as 25% of the rated torque. For $1.5s < t < 2s$ load current is found as 65% of the rated current. Reference torque is given as 50% of the rated torque. For $2s < t < 2.5s$ load current is found as 75% of the rated current. Reference torque is given as 78% of the rated torque. For $2.5s < t < 3s$ load current is found as 95% of the rated current. Reference torque is given as 90% of the rated torque. Dynamic Torque Response in Conventional and Modified DTC is represented by figure 10 and 11. It can be observed that the response time is improved from the conventional method and it is verified for different Quadrants of operation. Table 3 represents the comparison of dynamic torque response time for the conventional and modified methods.
**Table 3.** Dynamic Torque response comparisons for the Conventional and Modified DTC

| Torque Reference (Nm) | Conventional DTC (in ms) | Modified DTC (in ms) |
|-----------------------|--------------------------|----------------------|
| 50                    | 4.004                    | 6.860                |
| 100                   | 4.618                    | 6.161                |
| 150                   | 4.062                    | 6.771                |
| 200                   | 4.706                    | 6.873                |

**4. Conclusion**

Dynamic over modulation scheme whose complexity is less incorporated in Conventional DTC to achieve better dynamic response is presented in this paper. Voltage vector i.e. tangential to the circular flux loci is selected for time duration such that the angle is increased. The advantage of the proposed technique is its complexity is less because minor modification is done to the conventional method. Besides that improvement of dynamic response is obtained by the inclusion of flux error status modification block. The proposed scheme observed to minimize the torque ripple and maintain a superior performance under all operating conditions. A reasonable amount of torque ripple reduction and improvement of dynamic torque response confirms the success of suggested scheme.

**Appendix**

Design specification
- Power: 37 kw
- Voltage: 415V
- 3phase Frequency: 50HZ
- Speed: 1480 rpm
- Connection: Star Connected

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