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Implementation of Direct Torque and Indirect Flux Control of Bldc Motor

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Abstract : In this paper, the position-sensor less direct torque and indirect flux control of brushless dc (BLDC) motor with non sinusoidal back electromotive force (EMF) has been extensively investigated. In the literature, several methods have been proposed for BLDC motor drives to obtain optimum current and torque control with minimum torque pulsations. Most methods are complicated and do not consider the stator flux linkage control, therefore, possible high-speed operations are not feasible. In this study, a novel and simple approach to achieve a low-frequency torque ripple-free direct torque control (DTC) with maximum efficiency based on *dq* reference frame is presented. The proposed sensor less method closely resembles the conventional DTC scheme used for sinusoidal ac motors such that it controls the torque directly and stator flux amplitude indirectly using *d*-axis current. This method does not require pulse width modulation and proportional plus integral regulators and also permits the regulation of varying signals. Furthermore, to eliminate the low-frequency torque oscillations, two actual and easily available line-to-line back EMF constants (k_{ba} and k_{ca}) according to electrical rotor position are obtained offline and converted to the *dq* frame equivalents using the new line-to-line park transformation. Then, they are set up in the look-up table for torque estimation. The validity and practical applications of the proposed sensor less three-phase conduction DTC of BLDC motor drive scheme are verified through simulations and experimental results.

Keywords - Brushless dc (BLDC) motor, direct torque control (DTC), fast torque response, low-frequency torque ripples, Non sinusoidal back electromotive force (EMF), position-sensor less control, stator flux control, torque pulsation.

I. INTRODUCTION

The permanent-magnet synchronous motor (PMSM) and brushless dc (BLDC) motor drives are used extensively in several high-performance applications, ranging from servos to traction drives, due to several distinct advantages such as high power density, high efficiency, large torque to inertia ratio, and simplicity in their control [1]–[3].In many applications, obtaining a low-frequency ripple-free torque and instantaneous torque and even flux control are of primary concern for BLDC motors with non sinusoidal A great deal of study has been devoted to the current and torque control methods employed for BLDC motor drives. One of the most popular approaches is a generalized harmonic injection approach by numerical optimization solutions to find out optimal current waveforms based on back EMF harmonics to minimize mutual and cogging torque [4]. Those approaches limit Fourier coefficients upto an arbitrary high harmonic order due to calculation complexity [6].

This method provides advantages of the classical DTC such as fast torque response compared to vector control, simplicity (no PWM strategies, PI controllers, and inverse Park and inverse Clarke transformations), and a position-sensor less drive. As opposed to the prior two-phase conduction direct torque control methods used for BLDC motor [8], [9], the proposed DTC technique provides position- sensor less drive that is quite similar to the one used in conventional DTC scheme and also controls the stator flux indirectly using *d*-axis current. Therefore, flux weakening operation is possible. Coordinate transformations are done by the new line-to-line Park transformation that forms a2 × 2 matrix instead of the conventional 2 × 3 matrix. Therefore, rather than three line-to-neutral back EMF waveforms, which are not directly available in the motor easily accessible two line-to-line back EMF constants (k_{ba} (θ_{re}) and k_{ca} (θ_{re})) are obtained offline and converted to the *dq* frame equivalents(k_d (θ_{re}) and k_q (θ_{re})). Then, they are stored in a look-up table for the torque estimation. The electrical rotor position is estimate during winding inductance and stationary reference frame stator flux linkages and currents. Since the hysteresis controllers used in the proposed DTC scheme are not fast controllers like PI, they can easily regulate not only constant, but also the varying references (torque and flux). Simulation and experimental results are presented to illustrate the validity and effectiveness of the sensor less three-phase conduction DTC of a BLDC undergoes a corresponding change.

II. PROPOSED LINE-LINE AND PARK TRANSFORMATION

Since the balanced systems in *dq*-axes reference frame do not require a zero sequence term, first line-to-line Clarke transformation from the balanced three-phase quantities is derived and, then the line-to-line Park transformation forming a 2 × 2matrix instead of a 2 × 3 matrix for three-phase systems can be obtained in the following. Using some algebraic manipulations, the original Clarke transformation forming a 2 × 3 matrix excluding the zero sequence term can be simplified to a 2 × 2 matrix as follows:

$$[T_{LL}] = \begin{bmatrix} \frac{-1}{3} & \frac{-1}{3} \\ \frac{\sqrt{3}}{3} & \frac{\sqrt{3}}{3} \end{bmatrix} \qquad (1)$$

which requires only two input variables X_{ba} and X_{ca} where $X_{ba} = X_b - X_a$ and $X_{ca} = X_c - X_a$. X represents machine variables such as currents, voltages, flux linkages, back EMFs, etc. To obtain the line-to-line Park transformation forming a 2×2 matrix, the inverse of the original Clarke transformation matrix $[T_{\alpha\beta}]$ is required. Since the zero-sequence term is removed, $[T_{\alpha\beta}]$ matrix is not square anymore, but it is still singular and therefore, pseudo inverse can be found in the following:

$$[T_{\alpha\beta}]^+ = [T_{\alpha\beta}]^T ([T_{\alpha\beta}][T_{\alpha\beta}]^T)^{-1} \text{………} \qquad (2)$$

where $[T_{\alpha\beta}]^+$ and $[T_{\alpha\beta}]^T$ are the pseudo inverse and transpose of the original Clarke transformation matrix $[T_{\alpha\beta}]$, respectively. Here *abc* to *ba–ca* transformation can be represented as follows:

$$[T_{\alpha\beta}]^+[T_{\alpha\beta}]\begin{bmatrix}X_a\\X_b\\X_c\end{bmatrix}=[T_{\alpha\beta}]^+[T_{LL}]\begin{bmatrix}X_{ba}\\X_{ca}\end{bmatrix} \text{……….} \qquad (3)$$

After (3) is expanded and multiplied by the original 2×3 Park transformation matrix in both sides, algebraic manipulations lead to simplifications using some trigonometric equivalence. Therefore, the following 2 × 2 line-to-line Park transformation matrix form is obtained:

$$\begin{bmatrix}X_d\\X_q\end{bmatrix}=\frac{2}{3}\begin{bmatrix}\sin(\Theta-\frac{\Pi}{6}) & -\sin(\Theta+\frac{\Pi}{6})\\ -\cos(\Theta-\frac{\Pi}{6}) & \cos(\Theta+\frac{\Pi}{6})\end{bmatrix}\begin{bmatrix}X_{ba}\\X_{ca}\end{bmatrix} \text{…..} \qquad (4)$$

Unlike previous two-phase conduction DTC of BLDC motor drive techniques, which are proposed in [8] and [9], this method uses DTC technique with three-phase conduction, therefore, flux-weakening operation as well as a much simpler sensor less technique can easily be achieved. Compared with the two-phase conduction DTC scheme, this DTC method differs by its torque estimation and voltage vector selection table which is similar to the one used for DTC of PMSM drives explained in [10].

For machines with surface-mount magnet rotor (BLDC) stator flux linkages in rotor *dq* reference frame can be written as

$$\varphi_{qs}^r=L_s i_{ds}^r+\varphi_r' \sum_{n=1}^{\infty}(K_{6n-1}+K_{6n+1})\sin(6n\Theta_r)\text{……} \qquad (5)$$

$$\varphi_{ds}^r=L_s i_{qs}^r+\varphi_r' \sum_{n=1}^{\infty}(K_{6n-1}-K_{6n+1})\cos(6n\Theta_r)+\varphi_r'\text{…………………………….} \qquad (6)$$

where ϕ_r is the peak value of the fundamental rotor magnetic flux linkage of the BLDC motor, the coefficients $K6n-1$ and $K6n+1$ represent the odd harmonics of the phase back EMF other than the third and its multiples. $K6n-1$ equals $[\sin(6n-1)\sigma]/[(6n-1)3\sin\sigma]$, and $K6n+1$ can be depicted as $[\sin(6n+1)\sigma]/[(6n+1)3\sin\sigma]$. σ is the angle between zero-crossing and phase back EMF, where it becomes flat at the top. Fundamental peak value of the rotor magnet flux linkage ϕ_r equals $(4ke/\sigma\pi)\sin\sigma$, where k_e is the line-to-neutral back EMF constant.

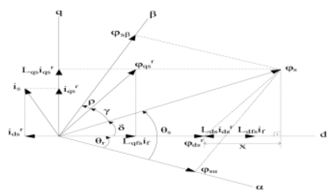


Fig. 1. Rotor and stator flux linkages of a BLDC motor in the stationary $\alpha\beta$-plane and synchronous *dq*-plane

The phasor diagram for stator flux linkage vectors in BLDC motor can be drawn in the rotor *dq* and stationary ($\alpha\beta$) reference frames as shown in Fig. 1, where $L_{ds} = L_{qs} = Ls$ and $L_{dqs} = L_{qds} = 0$. L_{dqs} and L_{qds} are the mutual inductances between *d*- and *q*-axis. L_{dsf} and L_{qsf} are the mutual inductances between *dq*-axes and permanent magnet (PM), respectively, and *if* is the equivalent current generated by PM. In Fig. 1, unlike PMSM with sinusoidal back EMF synchronous reference frame flux linkages ϕ_{ds}^r and ϕ_{ds}^r vary with time, therefore, stator flux amplitude ϕ_s is not constant anymore. γ, ρ, and δ in Fig. 1 can be obtained, respectively, as

$$\Upsilon = \sin^{-1}\left(\frac{L_{qs} i_{qs}^r}{\varphi_{qs}^r}\right)+\cos^{-1}\left(\frac{L_{qs} i_{qs}^r}{\varphi_s}\right)-\frac{\Pi}{2} \qquad (7)$$

$$\rho=-\left(\Theta_s+\Upsilon-\frac{\Pi}{2}\right) \qquad (8)$$

$$\delta=\frac{\Pi}{2}-\cos^{-1}\left(\frac{L_{qs} i_{qs}^r}{\varphi_s}\right) \qquad (9)$$

Moreover, *x* in Fig. 1 can be expressed as

$$x=\varphi_{qs}^r\cos\left[\sin^{-1}\left(\frac{L_{qs} i_{qs}^r}{\varphi_{qs}^r}\right)\right] \qquad (10)$$

The electromagnetic torque *Tem* estimation algorithm can be Derived for a balanced system in *dq* reference frame by equating the electrical power absorbed by the motor to the mechanical power produced ($Pi = Pm = Tem\omega m$) as follows:

$$T_{em} = ((3P)/(4\omega_{re}))\times (e_q(\theta_{re})\, i_{ds}^r + e_d(\theta_{re})\, i_{ds}^r)$$

$$= ((3P)/4)\times (k_q(\theta_{re})\, i_{ds}^r + k_d(\theta_{re})\, i_{ds}^r) \qquad (11)$$

where P is the number of poles, ω_{re} is the electrical rotor speed, $e_q(\theta_e)$ and $e_d(\theta_e)$, i_{ds}^r and i_{qs}^r, $k_q(\theta e)$, and $k_d(\theta_e)$ are the *dq*axes back EMFs, currents, and back EMF constants according to the electrical rotor position, respectively. As it can be noticed that the right-hand side equation in (11) eliminates the speed term in the denominator which causes problem at zero and near zero speeds.

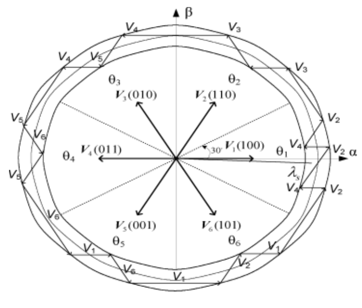


Fig. 2. Dodecagon trajectory of stator flux linkage in the stationary $\alpha\beta$-plane.

III. CONTROL OF STATOR FLUX LINKAGE AMPLITUDE

The stator flux linkage equations of a BLDC motor can easily be represented in the stationary reference frame similar to PMSM. During the sampling interval time, one out of the six voltage vectors is applied, and each voltage vector applied during the predefined sampling interval is constant, then the stator flux estimation for BLDC motor can be written as

$$\varphi_{s\alpha} = V_{s\alpha}\, t - R_s \int i_{s\alpha} dt + \varphi_{s\alpha}(0)$$

$$\varphi_{s\beta} = V_{s\beta}\, t - R_s \int i_{s\beta} dt + \varphi_{s\beta}(0) \qquad (12)$$

where $\phi_{s\alpha}$ (0) and $\phi_{s\beta}$ (0) are the initial stator flux linkages at the instant of switching. If the line-to-line back EMF constant k_{LL} is roughly known, and let say the rotor is brought to zero position (phase a), initial stator flux linkages at startup can be obtained by integrating the back EMF in which the ideal trapezoidal is assumed. Therefore, approximate initial starting flux values at zero position can be obtained as

$\phi_{s\alpha}$ (0) = $2kLL\pi/(3\sqrt{3})$ and $\phi_{s\beta}$ (0) = 0. (13)

Since BLDC motor does not have sinusoidal back EMF, the stator flux trajectory is not pure circle as in PMSM. It is more like a decagonal shape as shown in Fig. 2. Thus, direct stator flux amplitude control in a BLDC motor is not trivial as in PMSM such that rotor position varying flux command should be considered. However, this is a complicated way to control the stator flux linkage amplitude. Therefore, in this study, instead of $|\phi_s|$ itself its amplitude is indirectly controlled by *d*-axis current. In the constant torque region, i^r_{ds} is controlled as zero, and in the flux-weakening region it is decreased for a certain amount depending on the operational speed to achieve maximum torque. As a result, in this study, stator flux linkage amplitude is indirectly kept at its optimum level, while the motor speed is less than the base speed.

Table I
Switching Table For DTC Of BLDC Motor Using Three-Phase Conduction

φ	τ	$\theta(1)$	$\theta(2)$	$\theta(3)$	$\theta(4)$	$\theta(5)$	$\theta(6)$
$\varphi=1$	$\tau=1$	$V_2(110)$	$V_3(010)$	$V_4(011)$	$V_5(001)$	$V_6(101)$	$V_1(100)$
	$\tau=-1$	$V_6(101)$	$V_1(100)$	$V_2(110)$	$V_3(010)$	$V_4(011)$	$V_5(001)$
$\varphi=1$	$\tau=1$	$V_3(010)$	$V_4(011)$	$V_5(001)$	$V_6(101)$	$V_1(100)$	$V_2(110)$
	$\tau=-1$	$V_5(001)$	$V_6(101)$	$V_1(100)$	$V_2(110)$	$V_3(010)$	$V_4(011)$

The switching table for controlling both the amplitude and rotating direction of the stator flux linkage is given in Table I. where the output of the torque hysteresis comparator is denoted as τ , the output of the flux hysteresis comparator as ϕ, and the flux linkage sector is denoted as θ. The torque hysteresis comparator τ is a two valued comparator; $\tau = -1$ means that the actual value of the torque is above the reference and out of the hysteresis limit and $\tau = 1$ means that the actual value is below the reference and out of the hysteresis limit. The same logic applies to the flux related part of the control (*d*-axis current). The one out of six voltage space vectors is selected using lookup table in every sampling time to provide fast rotation of stator flux linkage vector. Therefore, fast torque and flux responses are obtained in a predefined hysteresis bandwidth, which limits the flux amplitude.

IV. Estimation Of Electrical Rotor Position

Electrical rotor position θ_{re} , which is required in the line-to line Park transformation and torque estimation algorithm can be found by

$$\theta_{re} = \tan^{-1}\left(\frac{\varphi_{s\beta} - L_s\, i_{s\beta}}{\varphi_{s\alpha} - L_s\, i_{s\alpha}}\right) \qquad (14)$$

motor with varying stator flux linkage amplitude as shown in Fig. 2. The second algorithm in [12], which is the modified integrator with an amplitude limiter To solve the common problems for integrators, a special integration algorithm for estimating the stator flux linkage proposed in [12] is used in this study. Although the method in [12] is designed for sine wave systems, the algorithm is still applicable to a BLDC is used for the stator flux linkage estimation. The maximum amplitude of the stator flux linkage reference approximated as $2kLL\pi/(3\sqrt{3})$ is set for the limiter when the motor speed is less than the base speed.

V. Results And Discussions

The drive system shown in Fig. 3 has been simulated in order to demonstrate the validity of the proposed three-phase conduction DTC of a BLDC motor drive scheme using line-to-line machine model. The sampling interval is 15 μs. The magnitudes of the torque and flux hysteresis bands are 0.001 N·m and 0.001 Wb, respectively. The dc-link voltage *V*dc equals 40√ 2V. Appendix I shows the specifications and parameters of the BLDC motor. In Fig. 4, the possibility of the flux-weakening region operation is simulated when i^r_{ds} is changed from 0 to −5 A. As it can be seen in Fig. 4 that the shape of stator flux linkage trajectory is kept same, however, its amplitude is smaller compared to the initial case, which means that the flux in the machine is weakened to obtain maximum possible torque above the base speed. It is concluded that in the proposed control scheme flux weakening operation is viable by properly selecting the *d*-axis current reference as in PMSM drives. As a result, there is no need to use position-varying stator flux linkage amplitude $|\phi_s(\theta_{re})|$ as a reference, which is complicated to obtain especially in the flux-weakening region.

Fig. 5 shows the *dq* frame back EMF constants according to the electrical rotor position ($kd(\theta_{re})$ and $k_q(\theta_{re})$), which are set up in the look-up tables for torque estimation both in simulation and experiment. The feasibility and practical features of the proposed three phase conduction DTC of a BLDC motor drive scheme have been evaluated using an experimental test-bed, as shown in Fig. 6. The same conditions are used as in simulation.

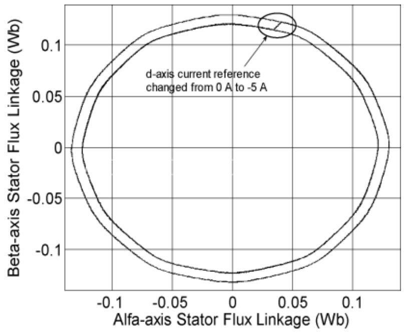


Fig 4. Indirectly Controlled Stator Flux Linkage Trajectory Under The Sensor Less Three-Phase Conduction Dtc Of A Bldc Motor Drive When i^r_{ds} Is Changed From 0 To −5 A Under 0.5 N·M Load Torque.

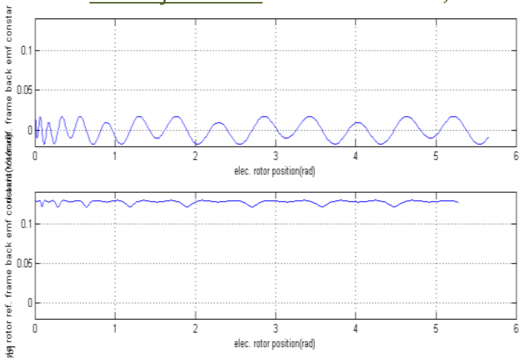
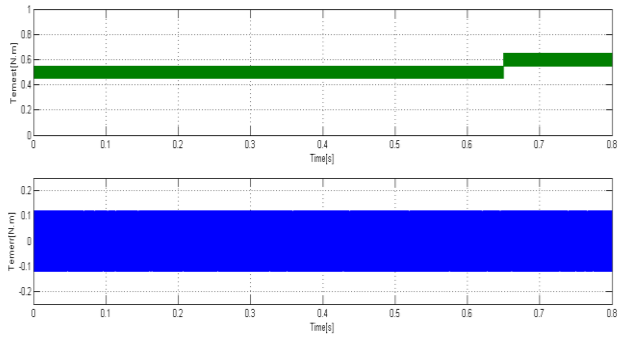
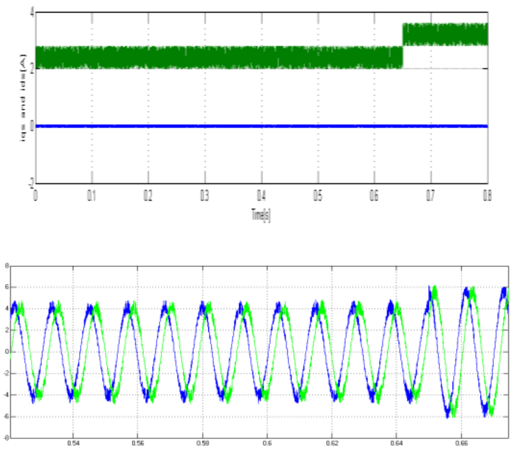


Fig. 5. Actual *Q*- And *D*-Axis Rotor Reference Frame Back Emf Constants Versus Electrical Rotor Position ($K_d\,(\Theta_{r\,E})$ And $K_q\,(\Theta_{r\,E})$



(a)



(b)

Fig.7. Steady state and transient behavior of (Top) estimated electromagnetic torque, (bottom) error between reference and estimated electromagnetic torque. (b) (Top) *q*-axis stator current and *d*-axis stator current and (bottom) *ba*–*ca* frame currents when i_{ds}^{r} = 0 under 0.5 N·m load torque.

Implementations of steady state and transient torque, torque error, *q*- and *d*-axis rotor reference frame stator currents, and line-to-line current responses of the proposed DTC of a BLDC motor drive scheme are demonstrated in Fig. 7(a) and (b), respectively, under a 0.5 N·m load torque condition. The torque reference is changed abruptly from 0.52 to 0.65 N·m at 0.65 s. It is seen in Fig. 7(a) (top) that fast torque response is obtained and the estimated torque tracks the reference torque closely. The reference torque value in the experimental test is selected a little bit higher than the load torque to compensate the friction of the total experimental system such that the rotor speed is kept at steady-state level (30 mechanical rad/s). The torque error between reference and estimated electromechanical torque is shown in the bottom part of Fig. 7(a). The high frequency ripples observed in the torque and current can be minimized by properly selecting the dc-link voltage and torque hysteresis band size. The $\alpha\beta$-axes stator flux linkages are estimated using (12) in which the $\alpha\beta$-axes voltages are measured using a dc-link voltage sensor and the estimated position of the stator flux linkage vector θ_s . The motor is initially locked at zero position (phase a) for proper starting. Fig. 8 shows the experimental results of the indirectly controlled stator flux linkage locus by controlling the *d*-axis rotor reference frame current at 0 A when 0.5 N·m load torque is applied to the BLDC motor.

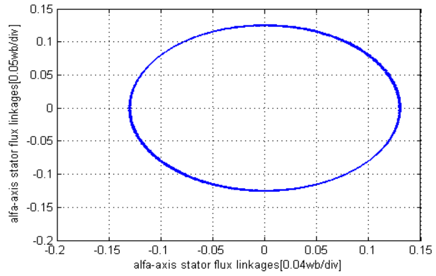


Fig. 8. Experimental indirectly controlled stator flux linkage trajectory under the sensor less three-phase conduction DTC of a BLDC motor drive when i_{ds}^{r*}=0 at 0.5 N·m load torque.

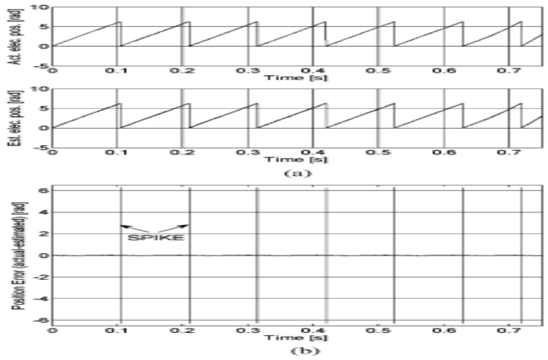


Fig. 9. (a) Steady state and transient behavior of the actual and estimated electrical rotor positions from top to bottom, respectively and (b) error between actual and estimated electrical rotor positions under 0.5 N·m load torque.

In Fig. 10, the flux-weakening operation is evaluated under1.1926 N·m load torque. Fig. 10(a) shows the high speed operation when i_{ds}^{r*} = 0. The desired speed is dropped from 540electrical rad/s to 513.5 electrical rad/s and oscillations in speed and torque are observed, as shown in Fig. 10(a). This result shows that the desired torque can only be obtained at lower speed when flux is not weakened. However, in Fig. 10(b), i_{ds}^{r*} is decreased to −4.51 A and the speed is controlled in the desired level quite well. The dc-link voltage is 115 V and the base speed for that voltage is 500electrical rad/s.

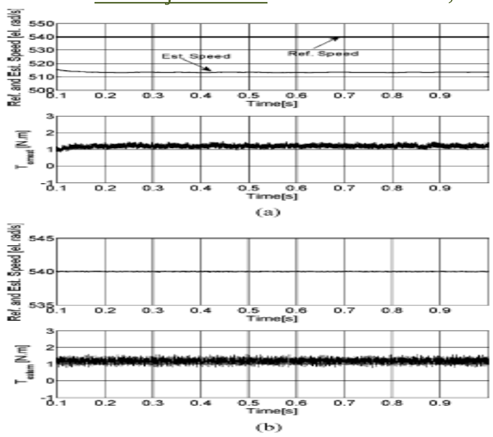


Fig.10.Steady-state flux-weakening behavior of the actual speed and estimated electromechanical torque, respectively, (a) when i_{ds}^{r*}= 0 and (b) when i_{ds}^{r*} = −4.51 A under 1.1926 N·m load torque at 540 electrical rad/s desired speed (*V*dc link = 115 V).

VI. CONCLUSION

This paper has successfully demonstrated application of the proposed position-sensor less three-phase conduction DTC scheme for BLDC motor drives that is similar to the conventional DTC used for sinusoidal ac motors where both torque and flux are controlled, simultaneously. This method provides advantages of the classical DTC such as fast torque response compared to vector control, simplicity (no PWM strategies, PI controllers, and inverse Park and inverse Clarke transformations), and a position-sensor less drive. It is shown that the BLDC motor could also operate in the flux-weakening region by properly selecting the *d*-axis current reference in the proposed DTC scheme.

Since the actual back EMF waveforms are used in the torque estimation, low-frequency torque oscillations can be reduced convincingly compared to the one with the ideal-trapezoidal waveforms having 120 electrical degree flat top. A look-up table for the three-phase voltage vector selection is designed similar to a DTC of PMSM drive to provide fast torque and flux control.

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BIOGRAPHIES

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