Online Torque-Flux Estimation Based Nonlinear Torque and Flux Control Scheme of IPMSM Drive for Reduced Torque Ripples

Mohammad Nasir Uddin¹, Senior Member, IEEE, and Md. Mizanur Rahman², Member, IEEE

Abstract – In order to have direct and better control of reducing the torque/flux ripples of interior permanent magnet synchronous motor (IPMSM), this paper presents an online torque and flux estimation based nonlinear torque and flux control (NTFC) scheme of IPMSM drive considering motor electromagnetic developed torque and stator air-gap flux linkage as virtual state variables. For conventional nonlinear controller the d-q axis currents (i_d, i_q) are considered as state variables that indirectly controls the torque/flux which may not be suitable for high performance drives. On the other hand, conventional direct torque and flux control (DTFC) scheme suffers from significant torque ripples. The proposed work overcomes the major drawback of both the conventional nonlinear and DTFC schemes through the significant reduction in torque ripples. Stability of the proposed drive is also demonstrated through Lyapunov’s stability criterion and global asymptotic stability is assured through the application of criterion supported by Barbalat’s lemma. Reduced torque ripples and robustness of the proposed NTFC scheme is validated through comparative simulation and experimental results with classical nonlinear controller and DTFC based IPMSM drive. The proposed NTFC scheme achieves the lowest possible torque ripples in steady-state at different operating conditions.

Keywords— Interior permanent magnet motor, nonlinear torque and flux control, torque ripples minimization and real time implementation.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>v_d, v_q</td>
<td>Stator voltages; d-and q- axis components.</td>
</tr>
<tr>
<td>i_d, i_q</td>
<td>Stator currents; d-and q- axis components.</td>
</tr>
<tr>
<td>L_d, L_q</td>
<td>Stator inductances; d-and q- axis components.</td>
</tr>
<tr>
<td>R_s</td>
<td>Stator per phase resistance.</td>
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<tr>
<td>ψ_d, ψ_q</td>
<td>Stator flux and rotor magnetic-flux linkage.</td>
</tr>
<tr>
<td>P</td>
<td>Motor pole pairs number.</td>
</tr>
<tr>
<td>ω_r</td>
<td>Actual rotor speed.</td>
</tr>
<tr>
<td>ω</td>
<td>Electrical speed of the rotor (ω=Pω_r)</td>
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<td>k_ω, k_T</td>
<td>Speed error and torque error.</td>
</tr>
<tr>
<td>k_ψ</td>
<td>Stator flux linkage error.</td>
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<td>ψ_d, ψ_q</td>
<td>Stator flux linkages; d-and q- axis components.</td>
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<tr>
<td>T_e, T_L</td>
<td>Motor electromagnetic developed and load torque.</td>
</tr>
<tr>
<td>J, B_m</td>
<td>Rotor inertia and Friction damping coefficient.</td>
</tr>
<tr>
<td>T_e, ψ'</td>
<td>Command torque and stator flux linkage.</td>
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</table>

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I. INTRODUCTION

Advancements and expanded accessibility of rare magnetic material such as, neodymium-iron-boron (high-energy alloy), researchers put high attention in the control of interior permanent magnet synchronous motor (IPMSM) as it offers high torque-current ratio, greater flux weakening capability, high efficiency, high power factor, low noise and robustness [1,2]. Traditionally, vector control (VC) and direct torque and flux control (DTFC) schemes have been widely used for ac motor drives. The DTFC offers fast transient response, less parameter dependence and it does not need the pulse-width modulation (PWM) as compared to vector control scheme [3]. On the other hand, DTFC suffers from variable switching frequency, high torque ripples and flux distortion which degrade the performance of the drive systems at low speed operation [4,5]. To overcome the torque/flux ripples of classical DTFC some inverter control algorithms were developed [6-11]. In classical DTFC inverter states are selected directly based on the errors from torque, flux hysteresis comparators and stator flux linkage position where torque and flux are two control variables [8]. In [9] authors reported a topology to obtain constant switching frequency where two waveform (triangular) generators, two comparators and PI controllers are used. But, the reported DTFC scheme still suffers from high torque ripples in steady state. Incorporating large number of active voltage vectors (non-zero) and using modified DTFC table, authors in [10] proposed a novel DTFC but torque ripple increases for a delay of one sample instant in the torque sensor. In [11] authors proposed a novel eighteen-sector based DTFC scheme but the reported work suffers from high torque ripples in steady-state.

Conventional PID controllers are most popular for ac motor drives due to its simplicity and easy implementation, but it is sensitive to parameter variations. To overcome the shortcomings of classical PID controllers, adaptive backstepping based nonlinear controllers are proposed for ac drives [12-15]. In [16] authors reported adaptive backstepping based nonlinear controller by considering i_d and i_q as control state variables to expand the operating speed limit utilizing reluctance torque. However; the motor air-gap flux linkage was not estimated as a virtual control variable and hence, the controller didn’t have direct control on the flux and consequently, couldn’t minimize the torque ripples in steady-state.

To provide an effective solution of reducing the torque/flux ripple of IPMSM drive with faster speed response, this paper presents an online torque-flux estimation based
nonlinear torque and flux control (NTFC) scheme of IPMSM drive where motor electromagnetic developed torque and air-gap flux linkage are considered as virtual control variables. The robustness of the proposed drive is achieved by online estimation of q-axis inductance. In addition, stability of the control law state variables of the proposed drive is demonstrated through Lyapunov’s stability criterion. The global asymptotic stability is also assured through the application of criterion supported by Barbalat’s lemma. The effectiveness of the proposed NTFC scheme of IPMSM drive is verified by real-time test on a DSP board DS1104 for a laboratory 5-hp motor. The performance of the proposed drive is compared with conventional nonlinear controller, DTFC and VC schemes to verify the effectiveness in terms of torque ripple minimization. Results obtained from both simulation and experiment confirm that the proposed NTFC scheme maintains lower torque ripples from low speed to the rated speed with robustness as compared to the classical nonlinear controller, VC and DTFC schemes.

II. IPMSM MODEL AND PROPOSED NTFC SCHEME

Considering sinusoidal induced EMF with no damper winding on rotor and negligible core losses, state model of an IPMSM drive is derived from synchronous machine can be obtained by [17,27] as follows:

\[
\begin{align*}
\frac{d}{dt} i_d &= \frac{1}{L_d} [v_d - R_d i_d + P \omega_r L_d i_q ] \\
\frac{d}{dt} i_q &= \frac{1}{L_q} [v_q - R_q i_q - P \omega_r L_d i_d - P \omega_m \psi_m] \\
\frac{d}{dt} \omega_r &= \frac{1}{J_r} [T_e - T_L - B_m \omega_r] \\
\frac{d}{dt} \omega_m &= v_d - R_s i_d \\
\frac{d}{dt} \psi_q &= v_q - R_q i_q \\
\psi_s &= \psi_d^2 + \psi_q^2
\end{align*}
\]

Usually, \( i_q \) is controlled to control the motor speed while \( i_d \) is maintained zero to make controller development easier. However, with this assumption motor cannot be operated above rated speed as reluctance torque is zero that also restricts the optimal motor performance [15]. A well-known technique, maximum torque per ampere (MTPA) and flux weakening (FW) based d-axis current controller is developed by most of the researchers to expand the operating speed of the motor [17-18]. Fig. 1 shows the conventional DTFC scheme of IPMSM drive where motor electromagnetic developed torque and stator air-gap magnetic flux linkage are the control variables. Because of direct control of the torque/flux the computational speed of DTFC is faster than that of the conventional VC scheme. But, with the conventional DTFC scheme command flux is maintained constant at the rated value and the conventional scheme also suffers from high torque ripples owing to discrete nature of voltage vector selection. Due to nonlinear nature and variations of dynamic operating conditions, motor parameters are not constant. Therefore, considering both the advantageous features of nonlinear controller and conventional DTFC scheme, online torque-flux estimation based NTFC scheme is proposed by considering the motor electromagnetic developed torque and stator air-gap flux linkage as virtual control variables as shown in Fig. 2. The development of the proposed NTFC scheme is briefly discussed in section II-A. Command control input voltages \((v_{ds}, v_{ql})\) in Fig. 2 are developed through virtual control of torque and flux based on Lyapunov’s stability criteria. Then, PWM logic signals are generated for the inverter switches whereas the conventional DTFC uses the look-up table to trigger the inverter switches.

A. Torque-Flux control variable based NTFC Controller

Motor actual speed converges to the command speed. The speed error dynamic is specified as:

\[ e_\omega = \omega - \omega_r \]

where: \( e_\omega \) = speed error and \( \omega_r \) = speed reference.

Fig. 1: Schematic of the conventional DTFC based IPMSM drive.

Fig. 2: Block diagram of the proposed NTFC based IPMSM drive.

Then, from (3), and (8) one can get:

\[ e_\omega = \omega - \frac{1}{J} (B_m \omega_r + T_L - T_e) \]

where: \( e_\omega \) = rate of change of speed error (error dynamic). To fulfill the speed tracking objectives, derivative of the initial Lyapunov function, \( V = \frac{1}{2} e_\omega^2 \), given by:

\[ V = e_\omega e_\omega = \frac{1}{J} (B_m \omega_r + T_L - T_e) \]
To ensure the stability of (10), $T_L$ and $\psi_L$ is identified as virtual control variable. The stabilizing function $T_L$ and $\psi_L$ are selected such that (10) becomes negative semi-definite. Command motor electromagnetic developed torque and stator air-gap flux are chosen as:

$$T'_e = B_m\omega_r + T_L + k_\omega\epsilon_{eo} \text{ and } \psi' = \psi_{ref}$$

(11)

where, $k_\omega$ is closed-loop feedback gain and $T'_e$ is the command motor electromagnetic developed torque. Substituting the values back into (10) the Lyapunov’s function becomes:

$$V = -k_\omega\epsilon_{eo}^2$$

where negative semi-definite condition is achieved by selecting $k_\omega > 0$. For proper tracking, corresponding error variables are defined as:

$$e_T = T'_e - T_e \text{ and } e_{\psi} = \psi' - \psi$$

(12)

Derivatives of the error dynamics are defined as:

$$e'_T = T'_e - T_e \text{ and } e'_{\psi} = \psi' - \psi$$

(13)

From the derivative of motor command electromagnetic developed torque:

$$T'_e = \frac{1}{j}(B_m-k_\omega)J(T_e - T_L - B_m\omega_r)$$

(14)

The derivative of motor actual electromagnetic developed torque:

$$\dot{T}_e = \frac{3}{2}P\left[\psi_d\frac{d}{dt}(i_q) + \psi_d i_q \psi_d \frac{d}{dt}(i_d) - \psi_q i_d\right]$$

(15)

Substituting the values of $T'_e$ and $\dot{T}_e$ in torque error derivative (equation 13):

$$e'_T = \frac{(B_m-k_\omega)}{J}(T_e - T_L - B_m\omega_r) - \frac{3}{2}P\left[\psi_d\frac{d}{dt}(i_q) + \psi_d i_q \psi_d \frac{d}{dt}(i_d) - \psi_q i_d\right] + P\omega_r\psi_m] + \frac{3}{2}P\left[i_d - \frac{\psi_q}{L_q}i_q\right] + \frac{3}{2}P\left[i_d - \frac{\psi_q}{L_q}\right] - k_\omega J \epsilon_{eo}$$

(16)

Similarly, stator air-gap flux linkage error dynamics are derived from (5), (6) and (7) as:

$$e'_{\psi} = \psi' - \psi = 2\psi_dR_qi_d + 2\psi_qR_qi_q - 2\psi_d\epsilon_{eo} - 2\psi_q\epsilon_{eo}$$

(17)

The values of load torque ($T_L$) and magnetic flux constant ($\psi_m$) varies with different operating conditions. Therefore, $T_L$ and $\psi_m$ is estimated adaptively. Due to magnetic saturation of the rotor core, the air gap flux linkage changes, which mainly affects the value of q-axis inductance ($L_q$) thus the value of $L_q$ should be estimated online in order to achieve the desired tracking objectives. The estimation of unknown parameters can be done by exploiting the features of adaptive backstepping approach [19-22]. Therefore, corresponding error variables are given by:

$$\dot{T}_L = T'_L - T_L + \dot{\psi}_m = \dot{\psi}_m - \psi_m \text{ and } L_q = \dot{L}_q - L_q$$

(18)

where, $\dot{T}_L$, $\dot{\psi}_m$, and $\dot{L}_q$ are estimated values of load torque, magnetic flux constant coefficient and q-axis inductance, respectively. A new Lyapunov’s function is defined as:

$$V_1 = \frac{1}{2}\left[\epsilon_{eo}^2 + \epsilon_{eo}^2 + \epsilon_{\psi}^2 + \frac{1}{\phi_1}\dot{\psi}_m^2 + \frac{1}{\phi_2}\dot{\psi}_m^2 + \frac{1}{\phi_3}\dot{L}_q^2\right]$$

(19)

The speed error, motor electromagnetic developed torque and stator air-gap flux is modified to incorporate the estimated load torque and magnetic flux constant as:

$$\dot{T}_e = B_m\omega_r + T_L + k_\omega\epsilon_{eo} \text{ and } \psi' = \psi_{m}$$

(20)

$$e_{eo} = \frac{1}{j}(T_L - k_\omega\epsilon_{eo})$$

(21)

The derivative of new Lyapunov function is:

$$V_1 = \epsilon_{eo}^2 + \epsilon_{eo}^2 + \epsilon_{\psi}^2 + \frac{1}{\phi_1}\dot{\psi}_m^2 + \frac{1}{\phi_2}\dot{\psi}_m^2 + \frac{1}{\phi_3}\dot{L}_q^2$$

(22)

To establish the global asymptotic stability of the drive, control voltages $v_d$ and $v_q$ are chosen from (22) by setting the terms multiplied with the torque ($e_T$) and flux ($e_{\psi}$) errors to zero so that the derivative of the Lyapunov’s function ($V_1$) becomes negative definite.

$$v_d = \frac{1}{\psi_L\psi_m}\left[2\psi_B(B_m - k_\omega)J(T_e - T_L - B_m\omega_r) - \psi_3\dot{\psi}_m^2\right]$$

(23)

$$v_q = \frac{1}{\psi_L\psi_m}\left[2\psi_B(B_m - k_\omega)J(T_e - T_L - B_m\omega_r) - \psi_3\dot{\psi}_m^2\right]$$

(24)

where, $k_\omega$, $\psi_B$ and $k_T$ are closed-loop feedback constants and $\phi_1$, $\phi_2$, $\phi_3$ are adaptive gains. Substituting (23) and (24) into (22), parameters are predicted online based on adaptive backstepping can be defined as:

$$\dot{T}_L = \phi_1\left[\epsilon_{eo} - \frac{2e_T}{j}(B_m - k_\omega)\right]$$

(25)

$$\dot{\psi}_m = \phi_2\epsilon_{T}\omega_r L_d$$

(26)

$$\dot{L}_q = \phi_3\epsilon_{T}\omega_r L_d$$

(27)

Based on command voltages as defined in (23) & (24) and update laws from (25) to (27), the Lyapunov derivative in (22) can be shown to be negative semi-definite with bounded state variable as:

$$V_1 = -k_\omega\epsilon_{eo}^2 - k_T e_T^2 - k_\psi \epsilon_{\psi}^2$$

(28)

Three criterion of Barbalat’s lemma principle is used to establish asymptotic stability of the controller [23-24], and
then applied to the (27). Validity of the conditions is checked as:

(a) (19) cannot be less than zero; it is lower bounded.
(b) (28) is negative semi-definite and less than or equal to zero.
(c) (28) is a continuous function of time as it is a bounded function.

Then: \( V_i \to 0 \) as \( e_\omega \to 0 \). Consequently, control laws are validated and global asymptotic stability of the proposed system is verified.

The losses in the semiconductors can be classified into two categories, namely switching losses (switch turned on or off loss) and conduction losses (due to ohmic resistance). These losses depend on the applied voltage, the commutated current and the semiconductor characteristics [25]. In the conventional DTFC scheme, the selected voltage vector applies for the whole switching period, irrespective of the magnitude of the torque error which results variable switching frequency with higher torque ripples. Therefore, switching losses is higher in conventional DTFC scheme. Also in the conventional DTFC, torque and flux ripple is higher as no any voltage source inverter (VSI) states are capable to generate exact voltage vector from the switching table required to make zero both the electromagnetic developed torque error and the stator flux linkage error [26]. In the proposed NTFC topology, switching losses are minimized utilizing the optimal transfer ratio and inverter is switched to keep the torque and flux error to zero.

**III. SIMULATION RESULTS**

Simulation of the proposed online torque-flux estimation based NTFC scheme of IPMSM drive is carried out using MATLAB/Simulink software. The motor parameters used in simulations are given in Table I. Sample results are presented below.

Speed and torque simulated responses of the conventional DTFC and proposed online torque-flux estimation based NTFC scheme of IPMSM drive for a command speed of 183 rad/s and 19.1 Nm load (rated condition) are shown in Figs. 3(a) and 3(b), respectively. At rated conditions, motor torque ripples are reduced drastically while provides faster speed response for the proposed NTFC as compared to the traditional DTFC scheme as shown in Fig. 3. The speed, torque and flux error dynamics for the proposed NTFC scheme of IPMSM drive are gradually merged to zero, as shown in Figs. 4(a), 4(b) and 4(c), respectively that validates the global (asymptotic) stability of the system. The balanced operation of the drive system is established through the line currents demonstrated in Fig. 4(d).
It is clearly seen from Figs. 5(a) and 5(b) that, the online estimated load torque and motor air-gap magnetic flux linkage values are same or near the actual/nominal values given in the Table-I as the adaptive controller estimates the values based on changing operating condition. Simulated speed and developed torque responses of the proposed NTFC scheme of IPMSM drive for increase of command speed from 50 to 183 rad/s at rated load is shown in Fig. 6. It is found from Fig. 6 that the proposed NTFC scheme has better dynamic performance (low torque ripples) from low speed to the rated speed while there are negligible speed ripples. The ability to withstand the sudden disturbances is also tested for a sudden change of load at a command speed of 183 rad/s, which is shown in Fig. 7. The load is suddenly increased from 14 Nm to 19.1 Nm at t=2.5 seconds. Although there is a small deviation of speed with change of load but it converges within minimum time to the command speed. The proposed NTFC scheme maintains lower torque ripple that is confined to a small bandwidth without any abrupt peak as shown in Fig. 7. Figs. 8 show the comparative dynamic performance analysis of the proposed NTFC scheme with the classical VC scheme for increase in load (4~19 Nm) in a step of 5 Nm at 183 rad/s. From Fig. 8 (b), it is seen that developed torque for the proposed NTFC scheme is confined to small bandwidth whereas conventional VC scheme contains higher torque ripples in steady state. Thus, the proposed NTFC scheme exhibits the lowest torque ripples as compared to both conventional VC and DTFC schemes. Figs. 9(a)-9(d) show the performance of the proposed NTFC scheme of IPMSM drive for motor parameter variations as magnetic saturation, loading conditions and temperature fluctuations alters the motor parameters that affect the effective drive performance. When $L_q$ is decreased by 25%, proposed drive maintains low torque ripples with negligible speed variations. If stator resistance, motor inertia and friction constants are doubled due to operating conditions, the proposed drive still maintains reduced torque ripple while speed follows the command speed.
Fig. 8: Simulated speed and developed torque responses for a step change of load (4→19 Nm) in a step of 5 Nm at 183 rad/s: (a) conventional VC scheme, and (b) proposed NTFC scheme.

Fig. 9: Simulated speed and developed torque responses of the proposed NTFC for parameter variations: a) $L_q \rightarrow 0.75L_q$, b) $R_s \rightarrow 2R_s$, c) $J \rightarrow 2J$, and d) $B_m \rightarrow 2B_m$.

Performance of the proposed NTFC scheme is also compared to the conventional PI based speed and hysteresis current regulator based field oriented control scheme. Fig. 10 shows such comparison for ramp changes in motor load at rated speed. Load is initially 50% of rated value and then increased to 75% from t=1.0 seconds to t=1.5 seconds, finally the load is reduced to 25% from t=2.5 seconds to t=3.0 seconds. Initially, the PI controller was tuned and hence the starting performance was similar to the proposed NTFC scheme but the performance of the PI controller deteriorates as the load changes. Due to the adaptive nature the proposed NTFC scheme is able to recover from load disturbances more rapidly, and with less overshoot and undershoot than that of the PI controller.

Fig. 10: Speed response comparison of PI based field oriented control and proposed NTFC scheme.
IV. EXPERIMENTAL RESULTS

The digital-signal processor (DSP) board DS1104 is used to implement the online torque-flux estimation based proposed NTFC scheme of IPMSM drive in real-time for a laboratory 5-hp motor [28]. Figure 11 shows the experimental set-up of the complete system. An optical encoder is used to sense the rotor position and using encoder interface the signal is fed to the DSP board. Then numerical differentiation is used to compute the motor speed from rotor position angles. Two phase currents $i_a$ and $i_b$ are measured by Hall-effect current sensors with current and frequency range of 0–200 A and 0–250 KHz, respectively. The other phase current is determined by balanced currents as generator neutral is not grounded. Finally, firing pulses are generated through the control algorithms and fed to the driver circuit of IGBT inverter. A dc-machine is used as generator to adjust the load. A real-time model of the proposed NTFC scheme is developed and loaded to the DSP board. The sampling frequency of 10 kHz is found suitable for real-time implementation of the proposed NTFC scheme. For conventional DTFC the computational time is less than the proposed NTFC since the traditional scheme does not require any co-ordinate transformation, current regulators, and SVM based PWM pulse generation. Thus, the sampling frequency for conventional DTFC could increase up to 15 kHz. However, for fair comparison sampling frequency of 10 kHz was used for all the control techniques. Sample experimental tests are presented below.

The starting speed responses of the conventional d-q axis current control variable based nonlinear controller and the proposed torque-flux estimation based NTFC scheme of IPMSM drive at a command speed of 120 rad/s and 50% rated load is shown in Figs. 12(a) and 12(b), respectively. It is clearly seen that in the case of conventional nonlinear controller motor speed can follow the command speed but it has higher overshoot whereas with proposed NTFC scheme based motor can follow the command speed without any overshoot and steady-state error. Speed and developed torque responses of the proposed drive are shown in Fig. 13 at low speed of 90 rad/s and 10% rated load conditions. At light load condition the proposed drive maintains low torque ripples without any significant torque peak which verifies steady-state torque ripple minimization capability of the proposed drive. Fig. 14(a) shows the steady-state speed and torque responses at a command speed of 140 rad/s and 50% rated load conditions. It is found that, the torque ripple is maintained lower without any abrupt peak which verifies the simulation results. Corresponding d-q axis current responses for the proposed online torque-flux estimation based NTFC scheme of IPMSM drive is shown in Fig. 14(b). As the d-axis current is negative, it can contribute to utilize the reluctance torque of the motor.
The robustness to the parameter variation (magnetic saturation) of the proposed NTFC scheme of IPMSM drive is validated experimentally and shown in Fig. 15. It is clearly seen that if $L_q$ is changed from $L_q \rightarrow 0.75L_q$ the speed follows the command speed of 100 rad/s while maintains low torque ripples at 25% rated load condition. Online estimation of $R_s$ can be incorporated but the controller will be more complicated especially, in real-time implementation as compared to the advantage gained by doing that. Moreover, the stator resistance does not change that much as compared to that of the inductance parameter with changes in operating conditions. Therefore, in this work $R_s$ is considered constant at its nominal value for real-time.

Figure 16 demonstrates the comparative dynamic performance analysis of the proposed NTFC scheme with the classical VC and DTFC scheme at a command speed of 100 rad/s and 50% rated load condition. It is found that, the classical VC and DTFC has higher torque ripples which degrades the performance of the industrial drive system, whereas, proposed NTFC reduces torque ripples significantly. Therefore, the proposed NTFC is superior to the classical VC and DTFC regarding the torque ripples minimization of the drive. Balanced operation of the proposed drive is verified by the line currents shown in Fig. 17. This also provides distinct information that all hypothesis used for reference frame conversion are verified in real-time. Thus, the effectiveness of the proposed NTFC based IPMSM drive is validated at various operating conditions in real-time.

![Fig. 14: Experimental steady state responses of the proposed NTFC based IPMSM drive at a command speed of 140 rad/s and 50% rated load: (a) speed and developed torque, and (b) $d$- and $q$-axis current responses.](image1)

![Fig. 15: Experimental speed and torque response of the proposed NTFC based IPMSM drive at a command speed 100 rad/s and 25% rated load when $L_q$ is changed from $L_q \rightarrow 0.75L_q$.](image2)

![Fig. 16: Torque responses for a command speed of 100 rad/s and 50% rated load: (a) conventional PI based VC, (b) conventional DTFC, and (c) proposed NTFC.](image3)

![Fig. 17: Balanced line currents of the proposed drive.](image4)
V. CONCLUSION

An online torque-flux virtual control variable based NTFC scheme for IPMSM drive has been presented in this paper. Advantageous features of both classical nonlinear controller and conventional DTFC scheme have been utilized for the proposed controller development. For direct torque ripples minimization in steady state, a nonlinear controller has been developed considering motor electromagnetic developed torque and stator air-gap flux linkage as virtual control variable where stability of the control laws is verified through Lyapunov’s stability criterion supported by Barbalat’s lemma. Reduced torque ripples condition was verified both in simulation and real-time under different speed and load conditions. Performance of the proposed NTFC scheme has been compared with the classical VC and DTFC scheme of IPMSM drive. In terms of torque ripple minimization, faster load disturbance elimination capability and excellent parameter variation handling capability, the proposed NTFC based IPMSM drive is found preferable to the conventional nonlinear, VC and DTFC schemes. Thus, the proposed online torque-flux estimation based NTFC scheme of IPMSM drive has been found as a probable contender for industrial drives.

### Table-I: IPMSM Parameters

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<th>Label</th>
<th>Parameter</th>
<th>Value with units</th>
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<tr>
<td>$P_{rated}$</td>
<td>IPMSM rated power</td>
<td>3.7 kW</td>
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<tr>
<td>$V_{rated}$</td>
<td>Rated rms voltage</td>
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<tr>
<td>$I_{rated}$</td>
<td>Rated current</td>
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<td>$f_{rated}$</td>
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<td>$\omega_r$</td>
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### REFERENCES


Authors’ Biography:

Mohammad Nasir Uddin (S’98-M’00-SM’04) received the B.Sc. and M. Sc. degrees both in electrical & electronic engineering from Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh, and the Ph.D. degree in electrical engineering from Memorial University of Newfoundland, Canada in 1993, 1996, and 2000, respectively.

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