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A New Direct Torque Control Scheme of an Induction Motor Using Duty Ratio Modulation

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Abstract – The direct torque control (DTC) scheme features a simple structure thanks to stator flux-oriented control. It has the advantage of robustness against motor parameters variation since only the stator resistance is involved in the control scheme. On the other hand, the disadvantage of DTC is large torque ripple. To reduce the torque ripple, many studies on DTC-space vector modulation (DTC-SVM) schemes, which modulate the duty ratio with a fixed switching cycle, have been proposed. However, there is the difficulty in obtaining the duty ratio for DTC-SVM. Hence, this paper proposes a new duty ratio selection and stator flux calculation methods for reducing torque ripple. Simulations and experiments were carried out to determine the validity of the proposed method. The proposed scheme has simplified the duty ratio command and achieved the same control performance as the conventional duty ratio modulation method without using the information of motor parameters.

Keywords: DTC (Direct Torque Control), DRM (Duty Ratio Modulation), Stator flux calculation, Torque ripple reduction, Fixed switching frequency

1. Introduction

Modern motor control schemes can be classified into two categories, which is field-oriented control (FOC) and direct torque control (DTC). The field-oriented control (FOC) method proposed in [1] is widely used in industry. FOC can be divided into stator flux-oriented control (SFOC), rotor flux-oriented control (RFOC), or air gap flux-oriented control depending on the flux referenced. The SFOC and air gap flux-oriented control methods are affected by interference between values in rotating coordinate systems. Therefore, the RFOC [2] became the most widely used.

Meanwhile, the switching table-based direct torque control (ST-DTC) method was proposed in [3]. Its simple control structure and reliance on the sole stator resistance as a motor parameter yielded a control performance that was robust against motor parameters variation.

The DTC method does not require a coordinate transformation. The DTC is characterized by a simple structure and quick response owing to the absence of the switching time calculation process for pulse width modulation (PWM). However, it suffers from drawbacks such as an irregular switching period and large ripples in torque and flux.

The conventional DTC method uses a hysteresis controller for torque and flux magnitude control, and directly generates voltage vectors using a switching table. The DTC method does not control the current directly; therefore, current waveform distortions may occur, producing a non-sinusoidal estimated flux waveform and increasing torque ripple. Many studies have been conducted to solve this torque ripple problem [4-8]. DTC-space vector modulation (DTC-SVM) [4-5] with a fixed switching frequency and the duty ratio modulation-DTC (DRM-DTC) [7-8] scheme have been proposed. In [4], a method to reduce the torque ripple through deadbeat DTC-SVM was proposed. This method determined the time required to apply two active vectors and one zero vector, as required for space vector modulation. This strategy results in a fixed switching period with reduced ripple in torque and flux, but requires an additional PWM time calculation process. Another type of DTC-SVM method was proposed in [5]. In [5], the voltage model for calculating the stator flux needed in the DTC scheme was applied to the FOC method, so that the widely used indirect FOC evolved into a direct field-oriented control (DFOC) method [6].

The DTC-SVM method uses flux linkage and torque as commands and the DFOC has become similar to this method, except that the d-axis and q-axis currents are used as the controller commands. However, the DTC-SVM method [4-5] lacks the control simplicity, which is typical of DTC.

On the other hand, the DTC method has been improved greatly after a torque ripple minimization technique with a fixed switching period was proposed in [7]. Furthermore, a simple method of implementing DRM, based on the existing DTC method of [7] with the use of PWM was presented in [8]. This DRM method, called PWM-DTC, uses PWM to modulate the duty ratio with a fixed switching period.

The method using the torque ripple slope in [7] requires

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the knowledge of many motor constants. The method of [7] was simplified by the schemes described in [8, 9] that omit the torque slope term. In [8, 9], the duty ratio was determined experimentally as a constant value. Therefore, in all the schemes in [7-9], the torque ripple affected the duty ratio determination. In [9], the torque ripple minimization method of [7] was applied to obtain a simple method for calculating the time during which the voltage vector has to be applied; this method is called DRM-DTC. The DRM technique based on conventional DTC put forth in [7] has showed excellent results and realized a new DRM-DTC technique. [10-12] proposed techniques of the torque ripple reduction through a separate controller that modulates duty ratio. However, when such a duty ratio modulator is inserted in the DTC controller, the overall system becomes complicated, so that the greatest advantage of direct torque control, which is simplicity, disappears.

Predictive control methods [13-14] require the knowledge of many motor parameters, in contrast to the simplicity of DTC, and it is difficult to ensure control performance. Therefore, this paper proposes a new method to re duce the torque ripple in the DTC method while maintaining its uniquely simple controller structure. The proposed method employs the symmetrical PWM used in [7-9] and proposes a stator flux estimation method reflecting the duty ratio and a simplified duty ratio equation for reducing torque ripple. Among many methods, the technique having the best control performance about reducing torque ripple is the RMS torque error DTC. However, this scheme sacrifices the benefits of the DTC due to use of many motor parameters. Hence, to overcome this problem, this paper presents a new duty-ratio modulation DTC that achieves a robust torque ripple reduction performance without use of motor parameters.

The reduction in torque ripple and the resultant performance improvement by the proposed method compared with the conventional DTC method were verified through simulations and experiments.

2. Dtc Scheme Based On Lookup Table

The DTC scheme performs motor control using the magnitudes of torque (T_e) and stator flux (λ_{dqs}) determined by Eqs. (1)-(4). Superscript s indicates stationary. Subscript d denotes value related to direct axis and q for quadrature axis. Subscript s and e for stator and electric, respectively. θ_{se} is the electric angle of stator flux, and λ_{se} denotes the electrical value of stator flux.

λ^s_{ds} and λ^s_{qs} are d- and q- axis component of stator flux in stationary reference frame, respectively. e^s_{ds}, and e^s_{qs} are stator back-emf in stationary d- and q- axis. Whereas, the DTC scheme only uses values in the stationary reference frame, so that there are no variables in the rotor flux reference frame written as superscript e.

Table 1. Lookup table of voltage vector selection for DTC scheme

$\Delta\lambda_s$	ΔT_e	Sector1	Sector2	Sector3	Sector4	Sector5	Sector6
1	1	$V_2(110)$	$V_3(010)$	$V_4(011)$	$V_5(001)$	$V_6(101)$	$V_1(100)$
	0	$V_7(111)$	$V_0(000)$	$V_7(111)$	$V_0(000)$	$V_7(111)$	$V_0(000)$
	-1	$V_6(101)$	$V_1(100)$	$V_2(110)$	$V_3(010)$	$V_4(011)$	$V_5(001)$
-1	1	$V_3(010)$	$V_4(011)$	$V_5(001)$	$V_6(101)$	$V_1(100)$	$V_2(110)$
	0	$V_0(000)$	$V_7(111)$	$V_0(001)$	$V_7(111)$	$V_0(000)$	$V_7(111)$
	-1	$V_5(001)$	$V_6(101)$	$V_1(100)$	$V_2(110)$	$V_3(010)$	$V_4(011)$

Table 2. v^s_{ds}, v^s_{qs} values corresponding to the selected voltage vector from the lookup table

v^s_{ds}, v^s_{qs}	V_1	V_2	V_3	V_4	V_5	V_6	V_0, V_7
v^s_{ds}	$\frac{2}{3}V_{dc}$	$\frac{1}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$	$-\frac{2}{3}V_{dc}$	$-\frac{1}{3}V_{dc}$	$\frac{1}{3}V_{dc}$	0
v^s_{qs}	0	$\frac{\sqrt{3}}{3}V_{dc}$	$\frac{\sqrt{3}}{3}V_{dc}$	0	$-\frac{\sqrt{3}}{3}V_{dc}$	$-\frac{\sqrt{3}}{3}V_{dc}$	0

The sector is identified by the stator flux angle (θ_{se}) in Eq. (4). The voltage vector to be applied to the motor is determined by referring to the lookup table (LUT) in Table 1 with the identified sector. The determined voltage vector was directly applied. The load phase voltage value applied to the motor through the controller was used as V^s_{ds} and V^s_{qs} in the digital signal processor (DSP), as shown in Table 2.

$$T_e = \frac{3}{2}\frac{P}{2}\left(\lambda^s_{ds} i^s_{qs} - \lambda^s_{qs} i^s_{ds}\right) \tag{1}$$

$$\lambda^s_{dqs} = \int e^s_{dqs} d\tau = \int \left(v^s_{dqs} - R_s i^s_{dqs}\right) d\tau \tag{2}$$

$$\left|\lambda_{se}\right| = \sqrt{\left(\lambda^s_{ds}\right)^2 + \left(\lambda^s_{qs}\right)^2} \tag{3}$$

$$\theta_{se} = \tan^{-1}\left(\lambda^s_{qs} / \lambda^s_{ds}\right) \tag{4}$$

The developed torque by the DTC method is relatively smooth, but the current waveform may not suitable if the load torque is small because large current distortions can occur. The performance of hysteresis controllers depends on the bandwidths of them, which were found experimentally. Even if the hysteresis bandwidth is appropriately set, the distortion in the current waveform becomes severe when the load torque is small, that is, when the magnitude of the current is small.

The distorted current waveform deteriorates the flux and torque estimation features, and the resultant torque ripple problem becomes more noticeable at the low speed operation. The flux can be estimated by using the voltage model or the current model. The DTC method uses the voltage model because it employs stator resistance as the only motor parameter and is therefore more robust against variation of motor constants. However, its flux estimation performance is not ideal because the counter-electromotive force at low speeds is small and the amount of noise becomes greater than the signals at the low speed operation condition. Therefore, in order to enhance the DTC performances, it is required to first have performance improvement of the DTC, which uses the voltage model, at low speed operation.

Furthermore, the torque ripple problem becomes more noticeable when applying speed control. This is because the DTC scheme consequently applies the necessary voltage vector to regulate torque and flux. Especially in the case of light load condition, the speed controller reduces the torque reference value after the motor speed has reached the desired value, but voltage vectors are still applied at the full duty ratio, resulting in a distorted current waveform at steady state.

3. Proposed duty Ratio-modulated Direct Torque Control

3.1 Proposed duty ratio modulation technique

In DTC, the fundamental concepts of the methods proposed for torque ripple reduction ([4,15,7]) are described by Eqs. (5)-(7), respectively. Where, T_s means the sampling time.

$$T_e\left[n+1\right] = T^*{}_e\left[n\right]$$

$$\frac{1}{T_s}\int_{nT_s}^{(n+1)T_s}\left(T_e - T_e^*\right)dt = 0 \qquad (6)$$

$$\frac{1}{T_s}\int_{nT_s}^{(n+1)T_s}\left(T_e - T_e^*\right)^2 dt \rightarrow min \qquad (7)$$

The deadbeat method, which was the first torque ripple reduction method proposed in [4], controls the torque in accordance with the reference torque in each control period, as shown in Eq. (5). Eq. (6) is known as the direct mean torque control method [15], which imposes that the mean torque error of one control period is zero. Eq. (7), as proposed by [7], is known as the root mean square (RMS) method, which minimizes the RMS value of torque error in each control period. The RMS method, which demonstrates excellent performance [16], determines the duty ratio by analyzing the torque ripple and finding the ripple slope s_1 and s_2. Then, the duty ratio was obtained by analyzing the slope of the torque ripple with the control period taken as the reference time through the motor equation, as expressed in Eq. (8) [7].

$$d = \frac{2\left(T_e^* - T_0\right) - s_2 T_s}{\left(2s_1 - s_2\right)T_s} = \frac{2\left(T_e^* - T_0\right)}{\left(2s_1 - s_2\right)T_s} - \frac{s_2 T_s}{\left(2s_1 - s_2\right)T_s} \qquad (8)$$

T_0 is the initial value of the torque in each control period. The implementation of motor control usually calculates the algorithm in each PWM interrupt period; therefore, the initial value of T_0 is equal to T_e sampled at the beginning of the PWM period. In Eq. (8), the first term requires a torque error value and s_1 and s_2 can be determined using the motor equation, as shown in Eqs. (9) and (10).

$$s_1 = -\frac{T_e}{\sigma\tau_{sr}} + \frac{3P}{4}\frac{L_m}{\sigma L_s L_r}\left[-v_{ds}^s\lambda_{qr}^s + v_{qs}^s\lambda_{dr}^s - \omega_m\left(\lambda_{ds}^s\lambda_{dr}^s + \lambda_{qs}^s\lambda_{qr}^s\right)\right] \qquad (9)$$

$$s_2 = -\frac{T_e}{\sigma\tau_{sr}} - \frac{3P}{4}\frac{L_m}{\sigma L_s L_r}\omega_m\left(\lambda_{ds}^s\lambda_{dr}^s + \lambda_{qs}^s\lambda_{qr}^s\right) \qquad (10)$$

where, $\sigma\tau_{sr} = \left(\frac{R_s}{\sigma L_s} + \frac{R_r}{\sigma L_r}\right)^{-1}$.

ω_m denotes the motor angular velocity. L_s, L_r, and L_m represent the stator inductance, rotor inductance, and mutual inductance, respectively.

When the switching frequency is high, that is, when the sampling period is very short, s_1 and s_2 can be considered as constant and so is $2s_1 - s_2$. Furthermore, because the reduction slope s_2 has a zero or negative value, a method reflecting the flux error while omitting the second term in Eq. (8) was proposed in [9]. The second term in Eq. (8) has T_s in both the numerator and denominator and, as s_1 and s_2 exhibit constant value in a steady state, this term can be considered as a small constant value and can be omitted. Therefore, in order to exclude the use of a motor constant, this paper proposes an equation that does not use the slope of torque ripple. The proposed duty ratio equation is written as

$$d = C_T\frac{\left|T_e^* - T_e\right|}{T_{rated}} + C_{offset} \qquad (11)$$

where, C_T and C_{offset} are proportionality constants found experimentally. C_{offset} can be omitted, and C_T and C_{offset} can be determined using Eqs. (9) and (10). The magnitudes of these constants were adjusted by speed range and load type.

3.2 Proposed Duty Ratio-Modulated Direct Torque Control

Fig. 1 shows the overall structure of the proposed DRM-DTC method. The method was carried out by converting the duty ratio into PWM by means of triangular waveform, as shown in Fig. 2.

To apply the sinusoidal PWM method, a symmetrical triangular waveform was used and the switching signals were applied by comparing the duty ratio with the triangular waveform. The DRM fixes the switching period based on the ST-DTC method. As the DRM applies a zero-vector similar to the sinusoidal PWM method, it generates an effect similar to the symmetrical space vector PWM method. For example, if the duty ratio is 0.3, as shown in Fig. 2, only 30% of the switching signals are fed when implementing the DRM by means of PWM. The final duty ratio for the application of the gate signal to the switching devices is in the range of 0-1.

The proposed stator flux integration when applying the duty ratio is expressed in Eq. (12), where d denotes the proposed duty ratio denoted in Eq. (11).

$$\lambda_{dqs}^{s}[n] = \lambda_{dqs}^{s}[n-1] + T_s\left(d \times v_{dqs}^{s}[n] - R_s i_{dqs}^{s}[n]\right) \qquad (12)$$

The idea of Eq. (12) is that the duty ratio is multiplied by the applied voltage in consideration of the time when the effective vector is used in the implementation of the fixed switching period DTC. In practice, the voltage vector is applied in each control period only for $d \times T_s$ seconds, which is the duty ratio multiplied by the sampling time T_s. If the DRM is not reflected in Eq. (2) corresponding to the stator flux calculation, the obtained stator flux value does

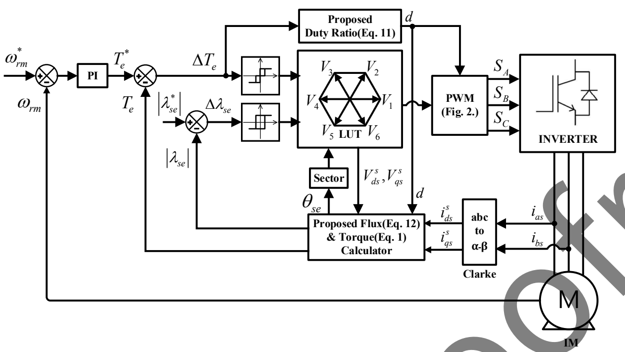

Fig. 1. The overall control block diagram of the proposed DRM-DTC scheme

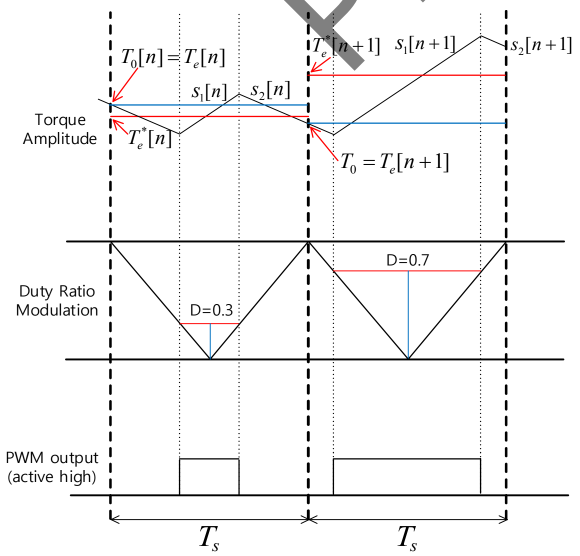

Fig. 2. The transient torque waveform and the PWM output signals in the proposed DRM-DTC scheme

not match the actual value. In the calculation of Eq. (1) for torque control, the magnetic flux is calculated to be larger than the actual value, and when the motor is controlled based on this, the generated motor torque becomes small.

When the stator flux value calculated does not match the actual value, it will have a significant effect on the DRM-DTC because Eq. (1) for calculating motor torque employs Eq. (2) in obtaining the stator flux. Any difference between the actual and calculated values of stator flux produces a difference between the actual and calculated motor torque. Therefore, both the magnitudes of stator flux and motor torque, which are the two control objectives in the DTC method, become different from the actual values. When operating under the medium load condition with a torque reduction scheme through DRM, the duty ratio is less than 1; thus, errors occur when obtaining stator flux with the conventional method. To solve this problem, the stator flux equation in Eq. (12) and the simplified duty ratio command of Eq. (11) that does not employ motor parameters are proposed in this paper. In Eq. (12), the stator flux can be determined accurately because the duty ratio range is 0–1 and the voltage vector is applied only for $d \times T_s$ seconds in each control period.

4. Verification

4.1 Simulation Results

Simulations were carried out to show the validity of the proposed method, which is based on a stator flux calculation method containing the DRM. Its effectiveness is demonstrated even without using the motor parameter. Figs. 3 and 4 show the results of the conventional stator flux detection scheme with the duty ratio equation of [7], whereas Fig. 5 displays the results of the proposed stator flux calculation method with the DRM-DTC scheme of [7].

Table 3 summarizes the specifications of the motor used in the simulations and experiments. The load torque commands for Figs. 3 and 4 are listed in Table 4, and the speed command is 800 [rpm]. The load was changed with light load (20% of rated torque), medium load (60%), rated

Table 3. Specifications of an induction motor used for simulations and experiments

Rated power[kW]	3.7	Rated speed[rpm]	1730
Rated current[A]	8.7	Rated torque[Nm]	20.42
No. of poles	4	Rated flux[Vs]	0.8
Stator resistance[Ω]	1.5	Rotor resistance[Ω]	0.5
Stator inductance[mH]	310	Rotor inductance[mH]	310
Mutual inductance[mH]	300	Inertia[kg-m^2]	0.025

Table 4. Load torque commands for the simulation of DTC

Time[sec]	0	5	10	15	20
T_L[Nm]	0	4.08	12.25	20.42	30.63

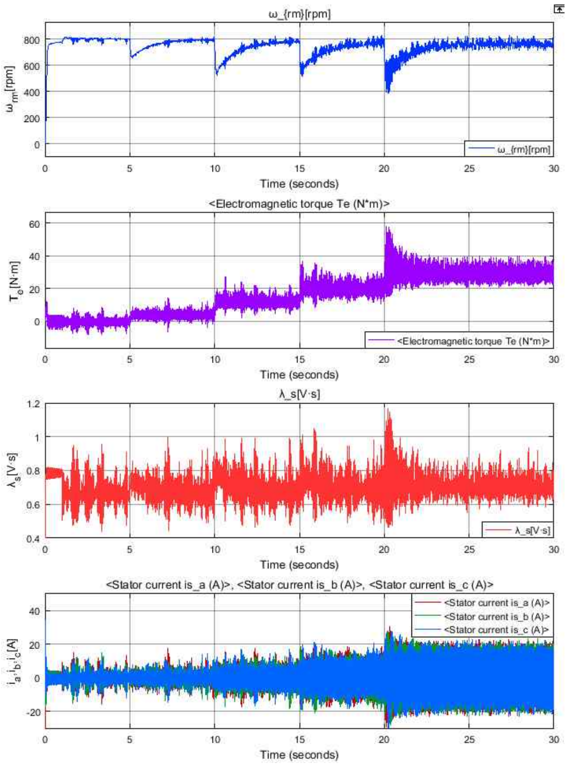

Fig. 3. Simulation waveforms done with the DRM-DTC scheme of [7] without consideration of duty ratio value in the stator flux calculation

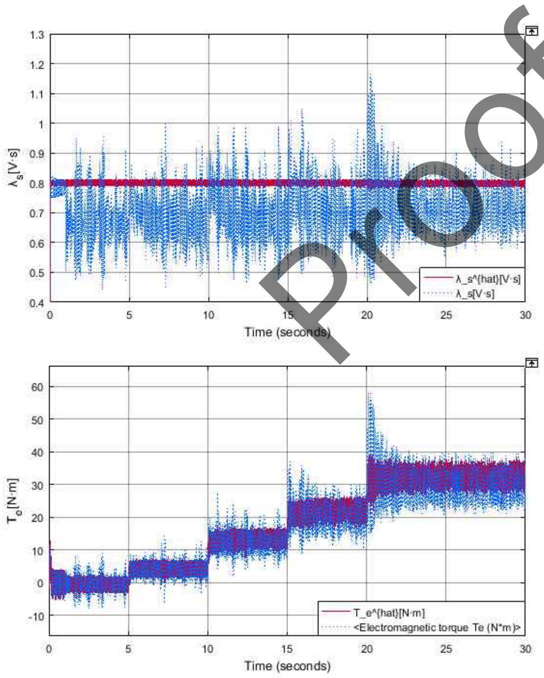

Fig. 4. Estimated and actual flux (upper figure), estimated and actual torque (lower figure) done with the simulation condition of Fig. 3

load, or maximum load (150%) condition.

In Fig. 3, the conventional stator flux calculation method was applied to the DRM-DTC of [7]. The duty ratio was

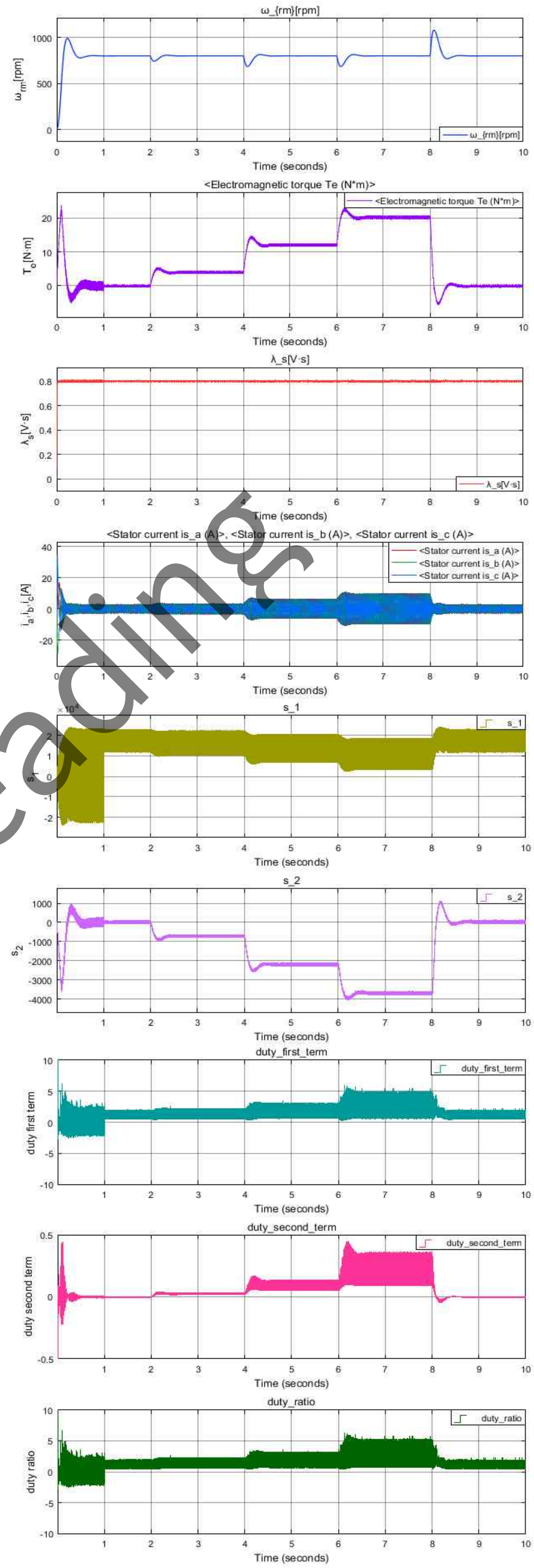

Fig. 5. Simulation waveforms done with DRM-DTC scheme of [7] with the proposed calculation method of stator flux

set to unity (i.e. full duty ratio) for the first 1 second of simulation for establishing the stator flux quickly. After 1 second, the DRM was carried out using Eq. (8). It is apparent that the conventional method cannot accurately obtain the stator flux value. From the top of the figure, the motor speed (ω_m[rpm]), motor torque (T_e[Nm]), stator flux magnitude $\left(|\lambda_s|[V \cdot s]\right)$, and phase currents ($i_a$, i_b, i_c[A]) are shown.

Fig. 4 illustrates the waveforms by comparing the calculated and actual values of the stator flux in Fig. 3. It can be seen from this figure that the calculated values of stator flux do not match the actual values. Since, the control is based on incorrect data, it results in non-sinusoidal current waveforms and large torque ripple. Fig. 5 shows the simulation waveforms when applying the proposed stator flux calculation method to the DRM scheme of [7]. From top to bottom, the motor speed, motor torque, stator flux, phase current, first and second terms of Eq. (8), and component corresponding to all of Eq. (8) are displayed.

The torque ripple in Fig. 5 is 0.7 [Nm]. The eighth waveform in Fig. 5 represents the second term in Eq. (8), which has a value of 0.1 or lower at the rated load or lower. Above the rated load, the duty ratio is already close to 1; thus, the effect of the second term of Eq. (8) is insignificant. In other words, compared to the first term, the second term is relatively small, such that the first term is mainly reflected in the final duty ratio.

Fig. 6 shows the simulation results of the proposed DRM-DTC method that does not use the motor parameters because Eq. (11) was employed. It should be noted that in the simulation results of Fig. 5, Eqs. (8)-(10) that include the motor parameters were used. On the other hand, in the simulation study for Fig. 6, the proposed stator flux calculation formula of Eq. (12) and the duty formula of Eq. (11) were employed.

The current waveform of the simplified DRM-DTC is very close to a sinusoidal waveform, and the torque ripple is very small at 0.5 [Nm] even without using the motor parameters in the duty ratio calculation. Furthermore, when the speed error becomes small after the transient state, the torque command decreases; when the torque error approaches zero, the motor operates more efficiently because the duty ratio becomes very small.

The two simulation results shown in Figs. 7 and 8 were conducted to compare the control performance corresponding to motor parameter variation. The modified motor constants are listed in Table 5. The controller has the motor parameter values in Table 3, whereas, the actual values are from Table 5. Parameter variations of 10% were assigned by considering magnetic saturation and heating.

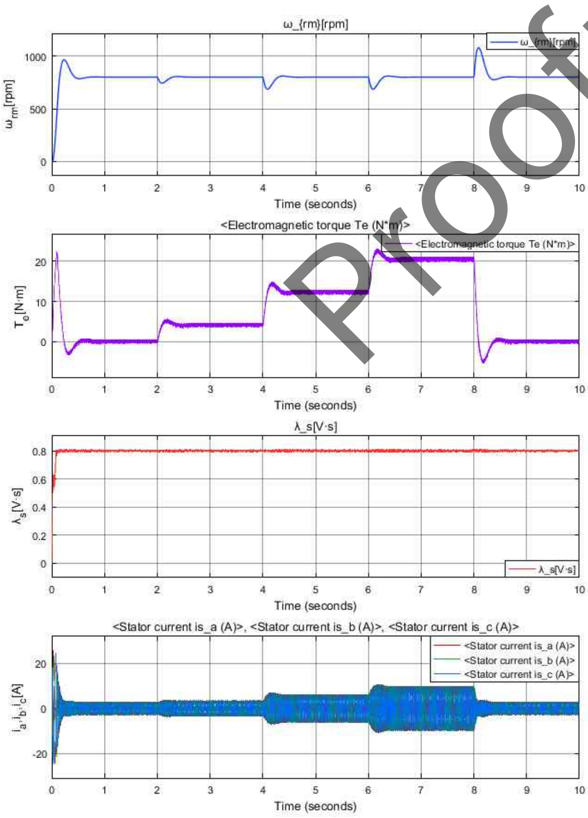

Fig. 6. Simulation waveforms of the proposed DRM-DTC scheme with the proposed stator flux calculation method and duty ratio formula of Eq. (11)

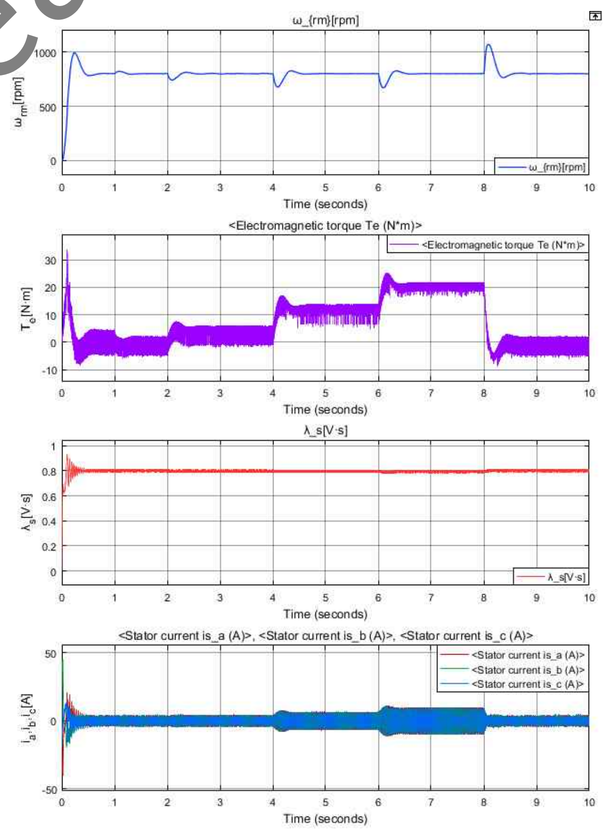

Fig. 7. Simulation waveforms obtained by the DRM-DTC scheme of [7] by applying only the proposed stator flux detection scheme when the actual motor values and those in controller are different

Table 5. Actual motor parameter values for the simulations shown in Figs. 7 and 8

Stator resistance[Ω]	1.65	Rotor resistance[Ω]	0.55
Stator inductance[mH]	335	Rotor inductance[mH]	331
Mutual inductance[mH]	330	No. of poles	4

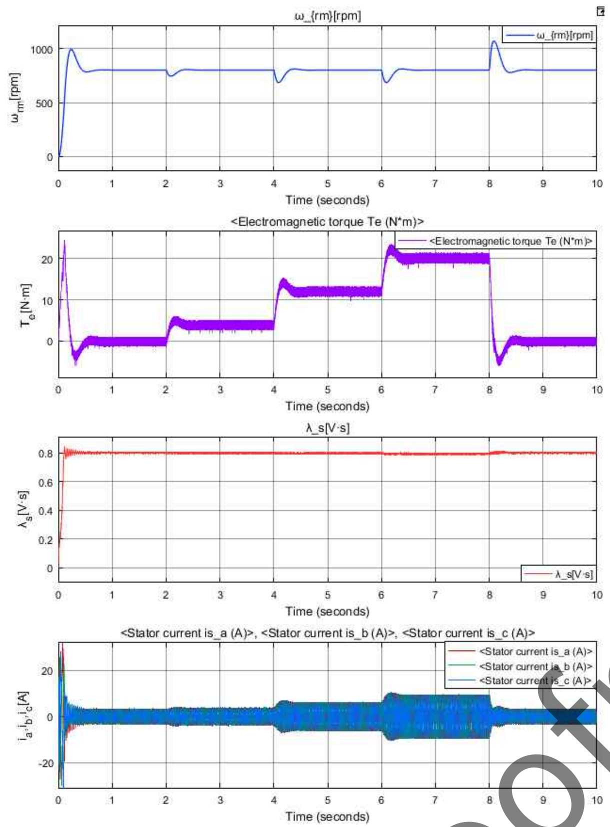

Fig. 8. Simulation waveforms carried out with the proposed DRM-DTC scheme having the discrepancy in actual motor parameters and those in the controller

Fig. 7 shows the simulation waveforms obtained by the duty ratio equation suggested in [7] with only use of the proposed stator flux calculation method as done in Fig. 5. Fig. 8 displays the simulation waveforms by applying both the proposed duty ratio equation and stator flux detection scheme, as done for Fig. 6.

Fig. 7 displays that the torque ripple increases compared to the ideal case shown in Fig. 5. From the figure, it can be seen that the technique of [7] is sensitive to the accuracy of the motor constants. In contrast, Fig. 8 illustrates small torque ripples owing to the characteristics of the proposed method without using the motor constant, unlike the conventional scheme. This suggests that the proposed method is robust against variations in motor parameters.

4.2 Experimental results

Fig. 9 shows the experimental setup. For the control, the DSP board, sensing circuit, gate drivers, and insulated gate bipolar transistors (IGBTs) were used in the experiment. The gate drivers and IGBTs of Semikron Inc. were used, and the proposed DTC method was implemented using the TMS320F28335 of Texas Instruments Inc. The switching frequency was 16 [kHz] and a proportional integral controller with a control period of 5 [msec] was used for speed control. The DC-link power supply was constructed by rectifying an alternating current power supply of 220 [V] at 60 [Hz]. The specifications used in the experiment were the same as those in Table 3.

Table 6. Speed commands used in the experiments of the proposed DRM-DTC for Fig. 10

Time[sec.]	0	1	2	3	4
Speed command[rpm]	200	400	600	800	1000

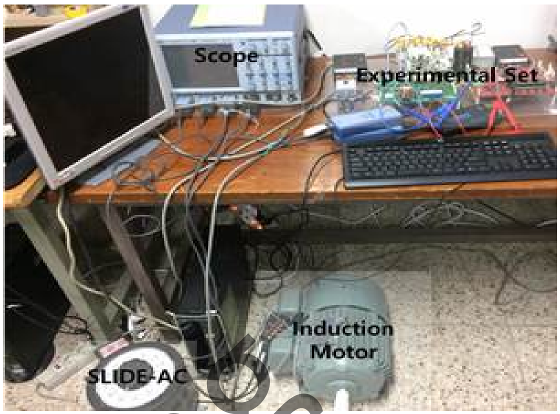

Fig. 9. Experimental setup.

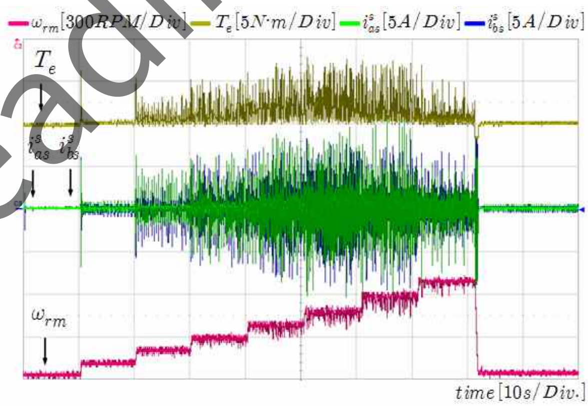

Fig. 10. Experimental waveforms of DTC without the proposed DRM scheme

Fig. 10 shows the experimental waveform without the proposed method. The selected voltage vector was applied after being multiplied by a constant duty ratio of 0.95 using the LUT, without performing DRM. The torque ripple was 3 [Nm], which is large and similar to the simulation waveforms displayed in Figs. 3 and 4. The speed commands of the experiments in Figs. 10 and 11 are shown in Table 6.

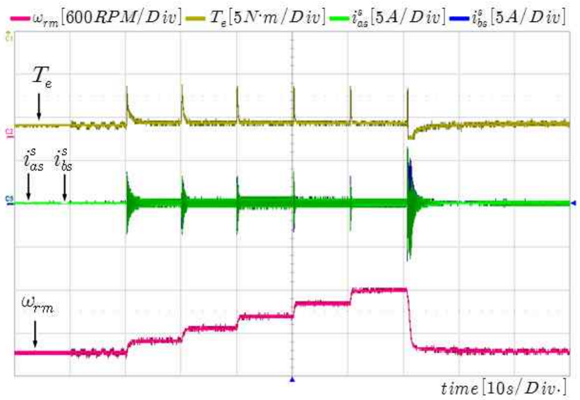

Fig. 11. Experimental waveforms obtained by the proposed DRM-DTC scheme

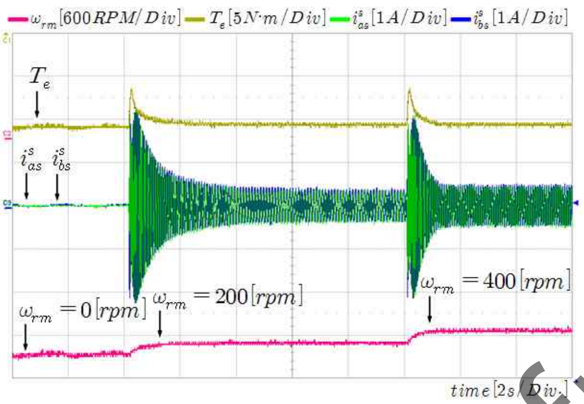

Fig. 12. Experimental waveforms of the proposed DRM-DTC scheme with speed variation from 200 to 400 rpm at light load condition

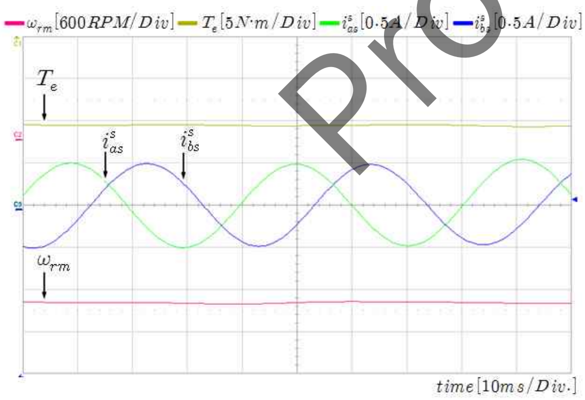

Fig. 13. Experimental waveforms by the proposed DRM-DTC at steady state with 600 rpm operation

Figs. 11-13 present the experimental waveforms of the simplified DRM-DTC based on the proposed stator flux integration method, taking into account the duty ratio. As can be seen from Figs. 11 and 12, the torque ripples are significantly smaller with the proposed method. Furthermore, in the medium-speed operating condition, the experimental current waveform in Fig. 13 is sinusoidal and the torque ripple decreases to 0.5 [Nm]. Therefore, these experimental waveforms demonstrate the validity of the proposed DRM-DTC method.

5. Conclusion

This paper proposed a stator flux calculation method that takes into account the duty ratio as well as a simplified duty ratio equation. The proposed DRM-DTC scheme achieved the same performance even though the complex conventional duty ratio equation is simplified. It has been demonstrated that the torque ripples can be reduced in the same manner with the proposed duty ratio equation, which does not use motor parameters. The distortions in the phase current waveforms significantly were decreased through the proposed torque reduction method, and the torque ripples were reduced by the same amount even without using motor parameters. The validity of the proposed control method was verified through simulations and experiments.

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References

[1] F. Blaschke, “The principle of field orientation as applied to the new transvector closed loop control system for rotating machines,” *Siemens Review*, vol. 39, no. 5, 1972, pp. 217-220.
[2] R. De Doncker and D.W. Novotny, “The universal field oriented controller,” *IEEE Trans. Ind. Appl.*, vol. 30, no. 1, pp. 92-100, Jan/Feb. 1994.
[3] I. Takahashi and T. Noguchi, “A new quick-response and high-efficiency control strategy of an induction motor,” *IEEE Trans. Ind. Appl.*, vol. 22, no. 5, pp. 820-827, Sep. 1986.
[4] T.G. Habetler, F. Profumo, M. Pastorelli, and L.M. Tolbert, “Direct torque control of induction machines using space vector modulation,” *IEEE Trans. Ind. Appl.*, vol. 28, no. 5, pp. 1045-1053, Sep./Oct. 1992.
[5] G.S. Buja and M.P. Kazmierkowski, “Direct torque control of PWM inverter-fed AC motors — A survey,” *IEEE Trans. Ind. Electron.*, vol. 51, no. 4, pp. 744-757, Aug. 2004.
[6] P.L. Jansen and R.D. Lorenz, “Observer-based direct field orientation: analysis and comparison of alternative methods,” *IEEE Trans. Ind. Appl.*, vol. 30, no. 4, pp. 945-953, July/Aug. 1994.
[7] J.-K. Kang and S.-K. Sul, “New direct torque control

of induction motor for minimum torque ripple and constant switching frequency," *IEEE Trans. Ind. Appl.*, vol. 35, no. 5, pp. 1076-1082, Sep./Oct. 1999.

[8] D.-H. Lee, Y.-J. An, and E.-C. Nho, "A High performance direct torque control scheme of permanent magnet synchronous motor," *in Conf. IEEE PEDS*, 2007, pp. 1361-1366.

[9] Y. Zhang and J. Zhu, "Direct torque control of permanent magnet synchronous motor with reduced torque ripple and commutation frequency," *IEEE Trans. Power Electron.*, vol. 26, no. 1, pp. 235-248, Jan. 2011.

[10] K.-K. Shyu, J.-K. Lin, V.-T. Pham, M.-J. Yang, and T.-W. Wang, "Global minimum torque ripple design for direct torque control of induction motor drives," IEEE Trans. Ind. Electron., vol. 57, no. 9, pp. 3148-3156, Sep. 2010.

[11] Y. Ren, Z. Zhu, and J. Liu, "Direct torque control of permanent-magnet synchronous machine drives with a simple duty ratio regulator," *IEEE Trans. Ind. Electron.*, vol. 61, no. 10, pp. 5249-5258, Oct. 2014.

[12] Y. Zhang and J. Zhu, "A novel duty cycle control strategy to reduce both torque and flux ripples for DTC of permanent magnet synchronous motor drives with switching frequency reduction," *IEEE Trans. Power Electron.*, vol. 26, no. 10, pp. 3055-3067, Oct. 2011.

[13] J.-K. Kang and S.-K. Sul, "Analysis and prediction of inverter switching frequency in direct torque control of induction machine based on hysteresis bands and machine parameters," *IEEE Trans. Ind. Appl.*, vol. 48, no. 3, pp. 1076-1082, June 2001.

[14] M. Pacas and J. Weber, "Predictive direct torque control for the PM synchronous machine," *IEEE Trans. Ind. Electron.*, vol. 52, no. 5, pp. 1350-1356, Oct. 2005.

[15] E. Flach, R. Hoffmann, and P. Mutschler, "Direct mean torque control of an induction motor," *in Proc. EPE*, 1997, vol. 3, pp. 672-677.

[16] F. Niu, B. Wang, A.S. Babel, K. Li and E.G. Strangas, "Comparative evaluation of direct torque control strategies for permanent magnet synchronous machines," *IEEE Trans. Power Electron.*, vol. 31, no. 2, pp. 1408-1424, Feb. 2016.

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