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Efficient operation of deadbeat direct torque and flux control for IPMSM drives by minimizing copper losses

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Abstract. This paper presents copper loss minimization of an interior permanent magnet synchronous machine (IPMSM) drive using deadbeat direct torque and flux controller (DB-DTFC). With its constant switching frequency of DB-DTFC, the desired air-gap torque and stator flux can be achieved at the end of PWM sampling period. In this paper, a copper loss minimization DB-DTFC algorithm for an IPMSM is derived and demonstrated experimentally. Applying the presented DB-DTFC, the magnitude of stator flux linkage can be controlled while developing the commanded torque, such that copper losses of an IPMSM drive can be manipulated. The stator flux linkage that achieves minimum copper losses in an IPMSM over the given torque and speed operating space is presented. The effect of the proposed DB-DTFC algorithm is verified by analysing the efficiency maps of an IPMSM drive applying the copper loss minimizing stator flux linkage and a constant stator flux linkage.

1. Introduction

As demands of interior permanent magnet synchronous machines (IPMSMs) increases, operation of IPMSM drives efficiently becomes a critical issue. Different efficiency optimization methods for IPMSMs have been proposed.

Closed-loop current vector control (CVC) is used for most IPMSM drives for manipulation of torque of IPMSMs in a structure of an open-loop control [1-4]. Torque from an IPMSM is composed of both torque developed from magnet and reluctance torque [5,6]. Due to the reluctance torque term, the stator current vector reference for CVC is typically nonlinear with respect to command torque. Therefore, torque manipulation for current vector controlled IPMSM drives is not a simply extended algorithm of field oriented control. Instead, the stator current vector components are computed in a structure of an open-loop control (often a look-up table) to theoretically minimize losses for the desired torque. The feedforward loss minimization calculations can focus on losses occurred in a drive system such as iron losses, copper losses, switching losses and conduction losses, and so on. For example, the "maximum torque-per-ampere (MTPA)" method calculates the theoretical current vector combination that minimizes copper losses [1-4]. Copper loss minimizing current vector computations can be implemented with changing degrees of complexity, in which parameter adaptation and saturation can be included for improvement of the optimization [7]. The MTPA method is best used at low speed when iron losses are very low. During high speed operation, the maximum torque-per-voltage (MTPV) approach can be applied for iron loss minimization. For implementation of MTPA or

MTPV, a look-up table (LUT) is typically calculated and developed. However, LUTs result in a large program size. Alternative approaches have been investigated such as using fuzzy logic [8], polynomial approximations [9], or mathematical loss minimizing model techniques [10].

DB-DTFC is developed based on a well-established, discrete time, one step response control algorithm known as deadbeat control. DB-DTFC shares some features of the well-known direct torque control (DTC) algorithm. In both DB-DTFC and DTC, air-gap torque and stator flux linkage are the control state variables. However, DB-DTFC uses fixed frequency, space vector PWM whereas classical DTC uses a hysteresis controller. Therefore, smoother torque and stator flux linkage responses can be obtained with DB-DTFC. In terms of response speed, dynamic response tracks feasible torque and stator flux linkage commands in one PWM sample period due to the deadbeat control law [11] and it converges more quickly than the response using classical DTC.

This paper organized such that development of DB-DTFC for an IPMSM is briefly reviewed. The demonstration of DB-DTFC is presented using the derived DB-DTFC algorithm. Then losses related to the stator flux are presented because the proposed efficiency optimization method in this paper is achieved by controlling the magnitude of stator flux. In the following section, optimal stator flux that minimizes the copper losses of an IPMSM over the torque-speed space is presented. To verify the proposed control method, efficiency maps of the IPMSM are shown when the optimal stator flux and a constant stator flux are used. Additionally, the efficiency of the IPMSM is measured using a MTPA method. The efficiency of an IPMSM is evaluated via simulation and experiment.

2. A review of DB-DTFC for an IPMSM drive

The PMSM equation in the rotor reference frame can be written as a differential equation of stator flux linkage vectors as equation (1) [12]. The equation can be written using notation of d-q complex vector where $\boldsymbol{f}_{dq} = f_d + jf_q$ [5].

$$\mathbf{v}_{dqs}^{r} = r_s\,\mathbf{i}_{dqs}^{r} + \frac{d}{dt}\boldsymbol{\lambda}_{dqs}^{r} + j\omega_r\,\boldsymbol{\lambda}_{dqs}^{r} \tag{1}$$

where $\lambda_{ds}^{r} = L_d\, i_{ds}^{r} + \lambda_{pm}$ and $\lambda_{qs}^{r} = L_q\, i_{qs}^{r}$

The air-gap torque equation of PMSM is developed as equation (2) in the structure of the stator current vectors, which comprises of the reluctance torque and the magnet torque.

$$T_{em} = \frac{3P}{4}\left(\left(L_d - L_q \right) i_{ds}^{r}\, i_{qs}^{r} + \lambda_{pm}\, i_{qs}^{r} \right) \tag{2}$$

The discrete time form of the PMSM's state equation is derived from equation (1) and rearranged as equation (3). Equation (4) is the air-gap torque equation of a PMSM in a discrete time. T_S is a sampling time.

$$\lambda_{dqs}^{r}(k+1) = \lambda_{dqs}^{r}(k) + v_{dqs}^{r}(k)\,T_s - \left(\frac{R_s}{L_s} + j\omega_r \right)\lambda_{dqs}^{r}(k)\,T_s + \frac{R_s}{L_s}\lambda_{pm}\,T_s \tag{3}$$

$$T_{em}(k) = \frac{3P}{4}\left((L_d - L_q)\, i_{ds}^{r}(k)\, i_{qs}^{r}(k) + \lambda_{pm}\, i_{qs}^{r}(k) \right) \tag{4}$$

By combining equations (3) and (4), an expression of the change in torque can be developed,

$$\Delta T_{em}(k) = T_{em}(k+1) - T_{em}(k) \tag{5}$$

This equation can be rewritten as equation (6), in a form of the linear relationship between the d axis and q axis stator voltage (volt-sec.) vectors with the commanded change in torque, $\Delta T_{em}(k)$.

$$v_{qs}^{r}(k)\,T_s = M\, v_{ds}^{r}(k)\,T_s + B \tag{6}$$

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where,

$$M = \left(\frac{(L_q - L_d)\, \lambda_{qs}^r(k)}{(L_d - L_q)\, \lambda_{ds}^r(k) + L_q\, \lambda_{pm}} \right)$$

$$B = \left(\frac{L_d\, L_q}{(L_d - L_q)\lambda_{ds}^r(k) + L_q \lambda_{pm}} \right) \left[\frac{4\Delta T_{em}}{3P} - \frac{\omega_r T_s}{L_d\, L_q} \left((L_q - L_d)\, (\lambda_{ds}^r(k)^2 - \lambda_{qs}^r(k)^2) - L_q \lambda_{ds}^r(k)\, \lambda_{pm} \right) \right.$$

$$\left. - \frac{R_s\, T_s\, \lambda_{qs}^r(k)}{L_d^2\, L_q^2} \left((L_q^2 - L_d^2)\, \lambda_{ds}^r(k) - L_q^2\, \lambda_{pm} \right) \right]$$

Using equation (6), numerous stator voltage (volt-sec) vectors can be computed to achieve the commanded change in torque over the next PWM sampling time.

Among the multiple stator voltage (volt-sec) selections, a constant stator flux linkage solution is derived in this paper as follows. The voltage drop across a stator resistor is treated as being negligible and the cross-coupling stator flux linkage term in equation (3) is decoupled. Then the discrete time stator flux linkage equation is approximated as equation (7).

$$\lambda_{dqs}^r(k+1) = \lambda_{dqs}^r(k) + v_{dqs}^r(k)\, T_s \tag{7}$$

Numerous stator flux linkage options exist when stator voltage is not near its limits. For the case of constant stator flux linkage magnitude, the stator flux linkage can be derived as equation (8).

$$|\lambda_{dqs}^r(k+1)|^2 = \left(\lambda_{ds}^r(k) + v_{ds}^r(k)\, T_s\right)^2 + \left(\lambda_{qs}^r(k) + v_{qs}^r(k)\, T_s\right)^2 \tag{8}$$

Here, stator flux linkage magnitude at the next sample time is developed by voltage (volt-sec) vectors that stay on the stator flux linkage circle. By substituting equation (6) into equation (8), the stator voltage (volt-sec) vectors for the constant stator flux linkage case are written as

$$v_{ds}^r(k)\, T_s = \frac{-X_1 \pm \sqrt{X_1^2 - (M^2+1)\, X_2}}{M^2 + 1} \tag{9}$$

where $X_1 = M\, \lambda_{qs}^r(k) + \lambda_{ds}^r(k) + MB$, $X_2 = B^2 + 2B\lambda_{qs}^r(k) + \lambda_{ds}^r(k)^2 + \lambda_{qs}^r(k)^2 - \lambda_s^*(k)^2$

$$v_{qs}^r(k)\, T_s = M\, v_{ds}^r(k)\, T_s + B \tag{10}$$

Figure 1 shows the block diagram of the implemented DB-DTFC system.

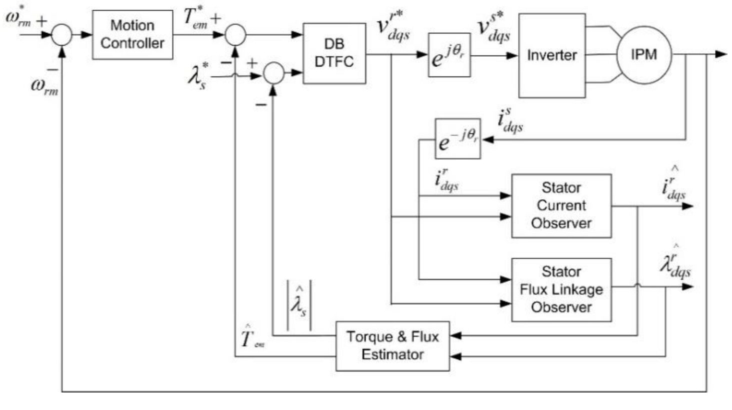


Figure 1. A block diagram for the implemented DB-DTFC system.

3. Copper loss minimizing DB-DTFC for an IPMSM

Based on the DB-DTFC algorithm derived, a DB-DTFC solution can be represented graphically as figure 2.

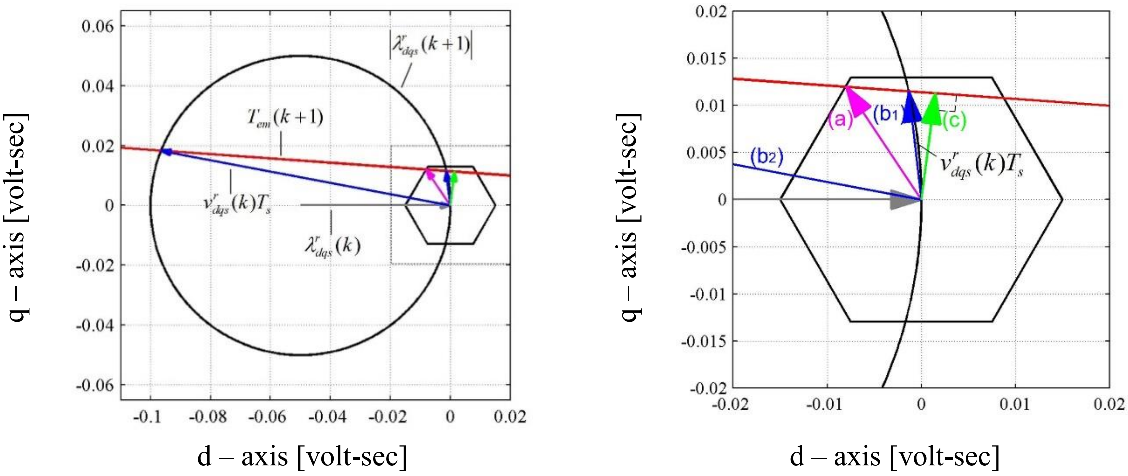


Figure 2. Graphical representation of DB-DTFC voltage solution for IPMSMs.

After aligning the stator flux linkage vector with the d axis, the torque line developed in equation (10) and stator flux circle from equation (8) are shown at one operating condition. Under the operating condition, three feasible stator voltage (volt-sec.) vectors are shown in figure 2 as an example. All three stator volt-sec. vectors result in the torque command at next sample time. When stator volt-sec. vector (a) is chosen, the magnitude of the stator flux linkage is decreased at the next PWM sample time. The minimum stator volt-sec. vector that yields the torque command is (c) in figure 2 and it results in an increase of the stator flux linkage magnitude at next PWM sample instant.

- Constant Stator Flux Linkage Solution

Two stator volt-sec. vectors (b_1 and b_2), will produce the circular constant stator flux linkage plot in figure 2. Both stator volt-sec. vector solutions can be obtained from equations (9) and (10), however they are not both feasible. The hexagon in figure 2 represents the volt-sec. limits of the inverter. As known, the maximum volt-sec. of the hexagon is 2/3 of the DC link voltage. The stator volt-sec. vector b_1 is within the volt-sec. hexagon is feasible.

- Copper loss minimizing DB-DTFC

The losses in an IPMSM are copper losses, iron losses, stray losses, mechanical losses, and inverter losses. The mechanical losses are due to friction and winding and the inverter losses consist of switching losses and conduction losses. Stator flux does not directly affect the mechanical losses and has only a secondary effect on the inverter losses. In this paper, only copper losses in an IPMSM are considered.

The copper losses are due to the stator resistance in an IPMSM and are given as

$$P_{cu} = |i_{dqs}|^2 R_s = (i_{ds}^2 + i_{qs}^2) R_s \tag{11}$$

Copper losses are a function of the stator current as seen in equation (11). Stator flux linkage can be directly manipulated via the stator current as shown in equation (1). Therefore, copper losses can be manipulated by stator flux control. The minimum stator current yields the minimum voltage production in a motor drive. Therefore, selecting the minimum stator volt-sec. vector (c) in figure 2 is one of possible solutions that minimize copper losses an IPMSM each PWM period. Since the volt-sec. vector (c) is perpendicular to the torque line developed in equation (10), d and q axis stator voltages (volt-sec.) have the following relationship.

$$v_{qs}^{r}(k)\ T_s = -\frac{1}{M}\ v_{ds}^{r}(k)\ T_s \tag{12}$$

By substituting equation (12) into equation (10), the stator voltage (volt-sec) vectors for the minimum stator voltage case are written as equations (13) and (14).

$$v_{ds}^{r}(k)\ T_s = -\frac{MB}{M^2+1} \tag{13}$$

$$v_{qs}^{r}(k)\ T_s = \frac{B}{M^2+1} \tag{14}$$

Reviewing a copper loss model in IPMSM's, one can conclude that copper losses are functions of the stator flux. Therefore, copper losses in IPMSM's can be manipulated by controlling the stator flux, which can be done in each PWM period using DB-DTFC.

4. Simulation and experimental results

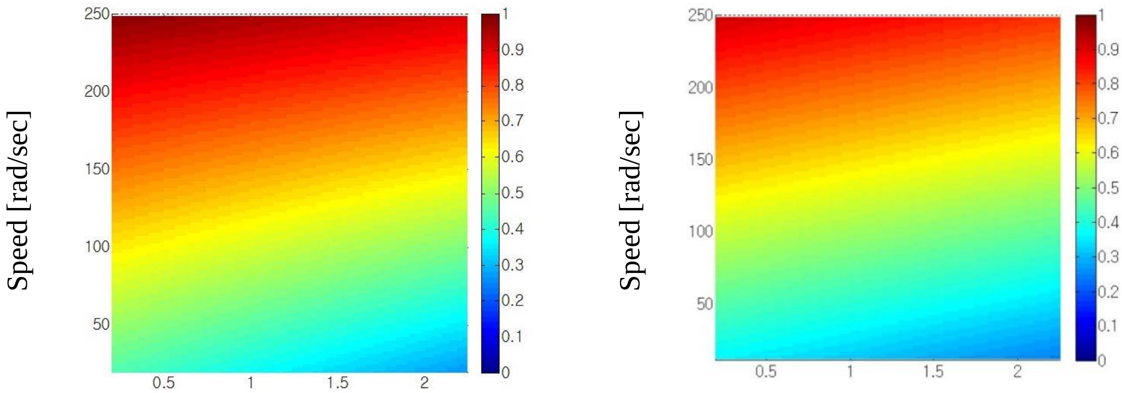
In order to apply the simulations for solving ARPCO problem by WPA are implemented using Matlab R2012b on a Windows 7 Professional Intel i5-3210M CPU 2.5GHz 8GB RAM.

An optimal stator flux surface that should yield minimum loss and maximum efficiency over a full speed and torque operating space can be theoretically calculated for the lab test stand IPMSM based on IPMSM state equations, IPMSM parameters, and loss models. For this paper, only a copper loss model in an IPMSM is applied. The efficiency of the IPMSM test machine is shown with simulation and experiment results in this paper.

- Simulation Results

The calculated optimal stator flux surface is shown in figure 3, as well as the optimal stator flux which yields maximum efficiency exists at each torque-speed operating point. It is observed that the optimal stator flux command slightly increases as the load torque increases and decreases as speed of IPMSM increases. Efficiency maps of the IPMSM using a constant stator flux command, 0.1[v-sec], and the optimal stator flux are shown in figure 3.

In figure 3, the efficiency using the optimal stator flux command is higher than the efficiency using the constant stator flux command at the overall torque-speed operating space. In both cases, the IPMSM is driven efficiently at low torque and high speed operating space.



(a) Torque [Nm] (b) Torque [Nm]

Figure 3. Simulation results of efficiency map of an IPMSM using (a) optimal stator flux command and (b) constant stator flux command.

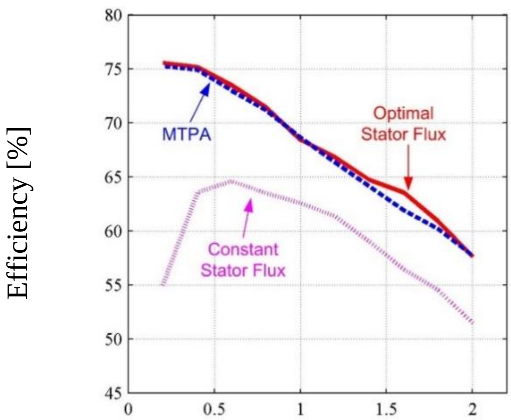
- Experimental Results

The specification of the test IPMSM is summarized in table 1.

Table 1. Specification of IPMSM specifications.

R_S	1.5 Ω
L_d	5.5 mH
Lq	12.5 mH
λpm	0.121 Volt-sec
Jp	1.0 kg·m^{2}x10^{-4}
T_S	100 μ-sec
Poles	4
Rated Torque	2.23 Nm
Rated Speed	6200 rpm

During the experiment the input power to the IPMSM is measured through a Voltech PM300 power analyzer and the output power of the IPMSM is calculated from torque and speed data. The efficiency of the IPMSM is measured at two different speeds, which are 0.31 [pu] and 0.92 [pu] of the rated speed of the IPMSM test machine. At each speed condition, the torque of the IPMSM is increased from 0 to 2 [N.m]. 0.11 [v-sec] (0.91 pu) is applied as a constant stator flux command during the experiment. The efficiency of the IPMSM is measured experimentally using the constant stator flux command and the optimal stator flux command for the DB-DTFC system. The MTPA strategy is used for the CVC system when the efficiency is measured. The experimental results at steady state are shown in figure 4.



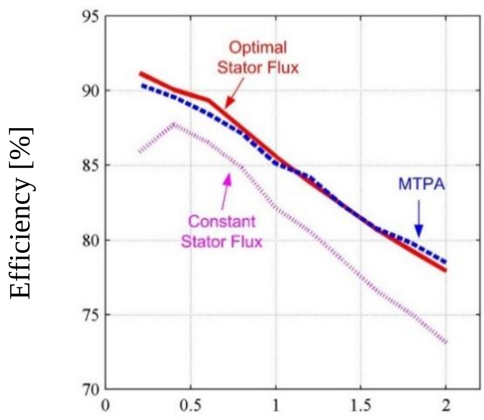
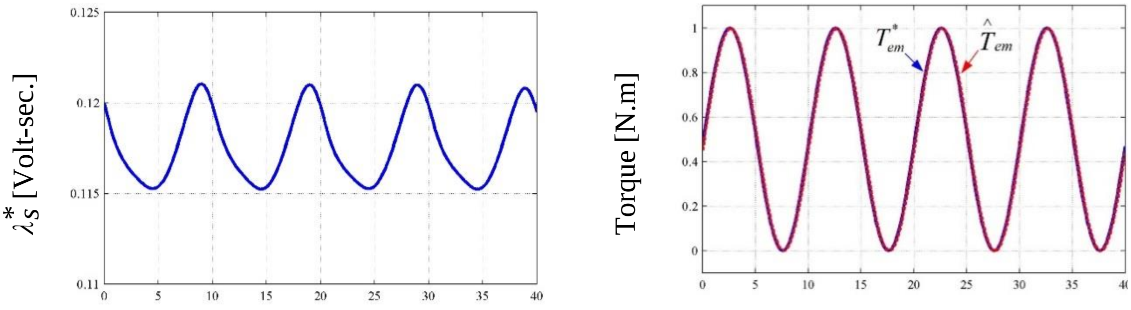


Figure 4. Experimental results of efficiency of an IPMSM at a) ω_{rm} = 0.31 [pu] and b) ω_{rm} = 0.92 [pu].

In figure 4, the efficiency of the IPMSM is increased using the optimal stator flux command as opposed to using the constant stator flux command. In both cases, the efficiency is higher at low torque and high speed. This result corresponds well to the simulation. It is also investigated from the experiment that the efficiency of the IPMSM using the optimal stator flux command and the MTPA method is approximately the same, as would be expected since the results in this paper have only included copper losses.

In addition to steady state, the efficiency of the IPMSM is also measured at dynamic state. A sinusoidal signal is commanded in torque to investigate the optimal stator flux command that achieves minimum stator voltage as torque command varies. The torque command is changed from 0 to 1 [N.m] with 100 Hz frequency. The experimental results of the stator flux command and the torque are shown in figure 5.



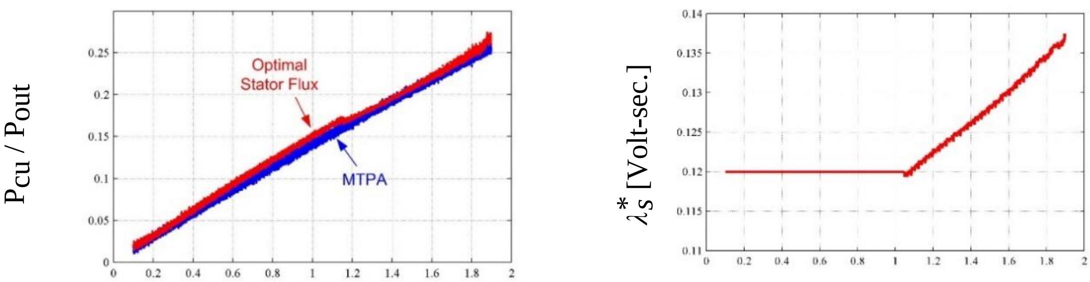
(a) Time [milli-sec.] (b) Time [milli-sec.]

Figure 5. Experimental results the optimal stator flux command and the torque in an IPMSM with a sinusoidal torque command. Experiment Setting: ω_{rm}= 0.49 [pu] = 80 [rad/sec], T_S=100 [μ-sec] .

As seen in figure 5, the estimated air-gap torque tracks the torque command very well. The stator flux command varies as the torque changes from 0 to 1 [N.m]. The experimental results show that DB-DTFC commands the stator flux that minimizes the stator volt-sec. vector at each PWM sampling time.

The rate between copper losses and output power of the IPMSM is measured by increasing the torque command linearly from 0 to 2 [N.m]. By investigating the rate between copper losses and output power of the IPMSM, the portion of copper losses in the IPMSM can be observed indirectly in a given torque range.

As shown in figure 5, the stator flux command becomes lower than the permanent magnetic flux of the IPMSM which is 0.121 [Volt-sec] when the torque is lower than 1 [N.m]. When the stator flux command is too lower than the permanent magnetic flux of the IPMSM, the negative d-axis stator current increases to weaken the stator flux command. Increasing the stator current causes an increase of copper losses in the IPMSM. Therefore, DB-DTFC with the constant stator flux linkage solution is partially applied during the experiment. The constant stator flux linkage solution is used when the torque is from 0 to 1 [N.m] and the minimum voltage solution is used when the torque is 1 to 2 [N.m]. By combining two solutions, the copper loss minimization strategy of DB-DTFC is developed. The experimental results of the rate between copper losses and output power of the IPMSM and the optimal stator flux command used to achieve copper loss minimization are shown in figure 6.



(a) Torque [N.m] (b) Torque [N.m]

Figure 6. Experimental results of a rate between copper losses and output power of an IPMSM and the optimal stator flux command used to achieve copper loss minimization with DB-DTFC Experiment Setting: ω_{rm}= 0.49 [pu] = 80 [rad/sec], T_S=100 [μ-sec] .

It is investigated from the experimental results that the rate between copper losses and output power of the IPMSM using DB-DTFC with the copper loss minimization solution and CVC with the

MTPA strategy is approximately the same at a given operating condition. In addition, the rate between copper losses and output power of the IPMSM increases as the torque command increases. From the observation, it is concluded that the efficiency of the IPMSM decreases as torque increases. This result corresponds to the simulation result and the experimental results at steady state.

5. Conclusions

Copper loss minimization at each PWM sampling time of an IPMSM using DB-DTFC is proposed and evaluated in this paper. The DB-DTFC control algorithms for a constant stator flux solution and a copper loss minimizing solution are derived mathematically and graphically. The corresponding discrete time model for an IPMSM is developed. Optimal stator flux that yields the minimum copper losses of an IPMSM is determined with simulation. The simulation results of the IPMSM efficiency maps are shown when the optimal stator flux and a constant stator flux are used. The efficiency of the IPMSM is measured experimentally using the optimal stator flux and a constant stator flux at the DB-DTFC system and the MTPA strategy is applied at the CVC system. The copper loss minimization strategy for the IPMSM using DB-DTFC is proposed by combining the constant stator flux solution and the minimum stator voltage solution. It is verified that the copper losses in an IPMSM can be manipulated with proposed copper loss minimization solution at each PWM sampling time in this paper.

Acknowledgments

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