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A Loss Minimization Control Strategy for Direct Torque Controlled Interior Permanent Magnet Synchronous Motors

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ABSTRACT

The main objective of this a paper is to improve the efficiency of permanent magnet synchronous motors (PMSMs) by using an improved direct torque control (DTC) strategy. The basic idea behind the proposed strategy is to predict the impact of a small change in the stator flux amplitude at each sampling period to decrease electrical loss before the change is applied. Accordingly, at every sampling time, a voltage vector is predicted and applied to the machine to fulfill the flux change. The motor drive simulations confirm a significant improvement in efficiency as well as a very fast and smooth response under the proposed strategy.

Keywords: Direct Torque Control, Loss Minimization, Permanent Magnet Synchronous Motors

1. Introduction

The scarcity of primary energy resources and the ecological pollution crisis have made energy saving practices unavoidable. Since most generated electricity is consumed by electric motors, their loss minimization has attracted much attention recently. Although interior permanent magnet (IPM) motors are inherently efficient, their optimum efficiency is highly reliant on their control strategy [1]. Generally, there exist two control strategies for providing loss minimization of electrical machines i.e. online and offline strategies. In an online strategy, via a search procedure, a control variable changes continuously or step-wise so that the minimum input power to the motor is reached. Such a strategy is considered to be insensitive to machine parameters and it minimizes the total loss of both the machine and the drive [2-4]. However, it is slow; because the search period must be carried out in the steady state. Thus, in applications experiencing repetitive transient states, it may not result in considerable energy savings. In the offline strategy, based on the machine parameters and operating conditions, first a loss function is calculated offline, and then its minimization results in the form of an optimum control signal is applied to the machine as a command [5-6].

Compared to the vector control (VC) method, the direct torque control (DTC) method enjoys such advantages as lower dependency on machine parameters,

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faster dynamic response and no need for current controllers [7-8]. Loss minimization control can basically be integrated into any motor control method including VC or DTC. Many professionals have studied loss minimization of vector controlled PMSMs; while only a few researchers have paid attention to the loss minimization of direct torque controlled motors [9-11].

In this paper, a new loss minimization DTC method for IPM motors has been presented in which, the effect of any change in the stator flux linkage on electrical loss is foreseen. Subsequently, a well-chosen voltage vector will force the stator flux linkage in a way that it can reduce motor electrical loss. The structure of the paper is as follows. First, a machine model is presented in section 2. Then, in section 3, the electrical loss is derived as a function of the stator flux amplitude, the load angle and the operating point of the machine. The proposed method for electrical loss minimization is presented in section 4. The simulation results of applying the proposed loss minimization strategy to a typical machine and finally, the conclusions are presented in sections 5 and 6, respectively.

2. Machine model

Electrical loss mainly consists of copper loss as well as iron loss. In order to minimize the losses of IPM motors, a machine model incorporating these losses is needed. A steady state model of IPM motors in a d-q reference frame is shown in Fig. 1. Here, R_s and R_c stand for copper and iron loss resistances, respectively. Fig. 2 shows the vector diagram of a machine, where ψ_s, is the stator flux linkage, ψ_d and ψ_q are its d- and q-axis components, and δ is the load angle or the angle between the stator linkage flux and the permanent magnet flux.

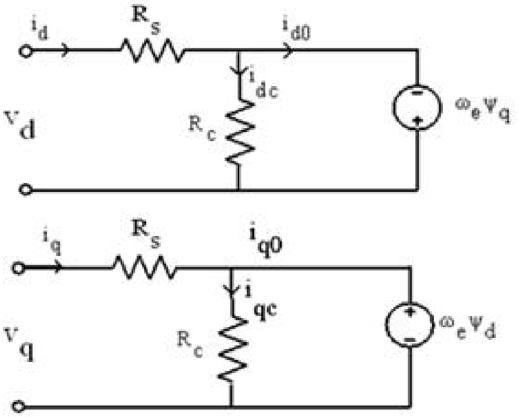

Fig. 1. A steady state model for PMSM.

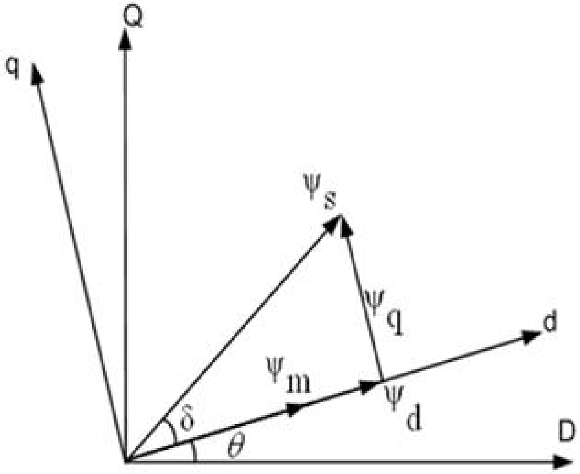

Fig. 2. Vector diagram.

3. Steady state electrical loss

In DTC, calculations are carried out in a stationary reference frame. By measuring the machine currents, the stator linkage flux and the electromagnetic torque are estimated. Thus, the nature of the DTC method dictates that the stator flux amplitude be the only control variable for handling electrical loss. Hence, the electrical loss function is directly derived as a function of stator linkage flux.

Considering Figs. 1 and 2, the steady state electrical loss function can be expressed as:

$$p_{loss} = \frac{3}{2}\frac{\left(\omega_e\psi_d\right)^2 + \left(\omega_e\psi_q\right)^2}{R_c} + \frac{3}{2}R_s\left(i_d^2 + i_q^2\right)$$
$$p_{loss} = \frac{3}{2}\frac{\left(\omega_e\psi_s\right)^2}{R_c} + \frac{3}{2}R_s\left(i_d^2 + i_q^2\right) \tag{1}$$

If ψ_s and δ are estimated, we can write:

$$i_d = i_{d0} + i_{dc} \quad , \quad i_q = i_{q0} + i_{qc} \tag{2}$$

$$i_{dc} = -\frac{\omega_e \psi_q}{R_c} = -\frac{\omega_e \psi_s \sin\delta}{R_c} \tag{3}$$

$$i_{dc} = \frac{\omega_e \psi_d}{R_c} = \frac{\omega_e \psi_s \cos\delta}{R_c} \tag{4}$$

$$i_{d0} = \frac{\psi_d - \psi_m}{L_d} = \frac{\psi_s \cos\delta - \psi_m}{L_d} \tag{5}$$

$$i_{q0} = \frac{\psi_q}{L_q} = \frac{\psi_s \sin\delta}{L_q} \tag{6}$$

The substitution of (3)-(6) into (2) yields i_d and i_q, then from (1) the loss function is obtained.

3.1 Load angle estimator

In DTC, at each sampling time, stator flux linkage and electromagnetic torque are estimated as follows:

$$\psi_D(k) = \{V_D(k-1) - R_s i_D(k)\}T_s + \psi_D(k-1) \tag{7}$$

$$\psi_Q(k) = \{V_Q(k-1) - R_s i_Q(k)\}T_s + \psi_Q(k-1) \tag{8}$$

$$\psi_S(k) = \sqrt{\psi_D^2(k) + \psi_Q^2(k)} \tag{9}$$

$$T_e(k) = \frac{3p}{2}\{\psi_D(k) i_Q(k) - \psi_Q(k) i_D(D)\} \tag{10}$$

Also, the electromagnetic torque can be expressed as:

$$T_e(k) = \frac{3p\psi_s}{4L_d L_q}[2\psi_m L_q \sin\delta(k) + (L_d - L_q)\psi_s \sin 2\delta(k)] \tag{11}$$

By estimating the electromagnetic torque from (10) and substituting it into (11), the load angle can be calculated. Since the direct solution of (11) is mathematically complicated, the load angle estimator is suggested.

Assuming that $\delta(k-1)$ is the previous step load angle, and $\delta(k-1)$ is sufficiently small (this can be achieved by choosing a small enough sampling time), we have:

$$\delta(k) = \delta(k-1) + \Delta\delta \tag{12}$$

$$T_e^*(k-1) = \frac{3p\psi_s}{4L_d L_q}[2\psi_m L_q \sin\delta(k-1) + (L_d - L_q)\psi_s \sin 2\delta(k-1)] \tag{13}$$

Replacing (12) into (11) we get:

$$T_e(k) = \frac{3p\psi_s}{4L_d L_q}[2\psi_m L_q \sin\delta(k) + (L_d - L_q)\psi_s \sin 2\delta(k)] \tag{14}$$

Expanding (14), for a small $\Delta\delta$ (sin($\Delta\delta$)=1 and cos($\Delta\delta$)=1), an acceptable estimate for load angle deviation is:

$$\Delta\delta = \frac{2L_d L_q}{3p\psi_s} \frac{[T_e(k) - T_e^*(k-1)]}{G(k-1)} \tag{15}$$

where:

$$G(k-1) = \psi_m L_q \cos\delta(k-1) + (L_d - L_q)\psi_s \cos 2\delta(k-1)$$

Fig. 3 shows a block diagram of the proposed load angle estimator. Thus, the block diagram of the electrical loss calculation will be similar to the one in Fig. 4.

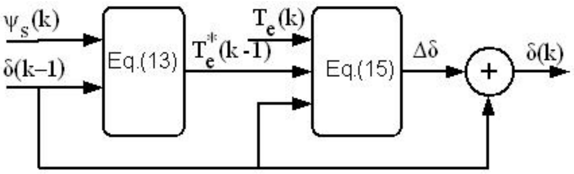

Fig. 3. The block diagram of proposed load angle estimator.

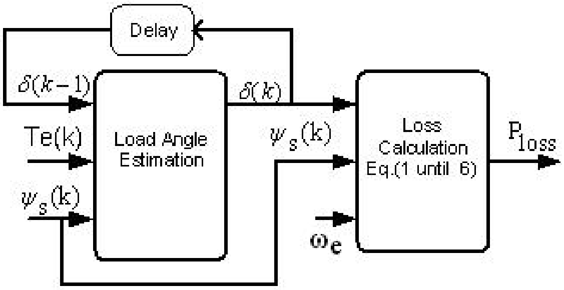

Fig. 4. The block diagram of IPM motors electrical loss calculation.

4. The proposed loss minimization strategy

4.1 The main idea

The main idea behind the proposed strategy is to predict the impact of a small change in the stator flux amplitude at each sampling period to decrease electrical loss before any change is applied. For this purpose, before any increase or decrease in stator flux, the effects of this change from the static model of the machine is predicted, and then the flux amplitude changes in a way that the electrical loss decreases a little. Repetition of this procedure would minimize electrical loss.

At every sampling time, it is assumed that the operating point of machine is constant. Therefore, electrical loss can be calculated from the steady state machine model. Although the operating point of a machine is considered to be constant, at each sampling time the previous operating point will be replaced by the new one. Since, in DTC, flux and torque controls are performed independently, after some time, torque and in turn, both the reference speed and the minimum loss will be achieved. For example, if the flux vector is located in the first zone and the electromagnetic torque becomes less than the reference torque, then, one of the voltage vectors V2 or V3 should be applied to machine, where V2 increases and V3 decreases the stator flux amplitude, respectively. In the proposed method, if the gradient of the loss function is positive, V3 will be chosen and if it is negative, V2 will be chosen (Fig. 5). Therefore, in each sampling period, our loss minimization algorithm will do the following:

- **a.** Measure the currents, voltages and speed of the machine.
- **b.** Estimate the instantaneous stator flux and electromagnetic torque.
- **c.** Choose a voltage vector that will compensate for the torque error and cause less loss provided that the operating point is constant.
- **d.** Apply this voltage for time Ts to the machine.

4.2 The proposed system's structure

A block diagram of the proposed method for DTC IPM motors loss minimization is shown in Fig. 6. In comparison with the conventional DTC method, the flux and torque hysteresis controllers are replaced by two comparators, while the switching frequency is held constant [12-13].

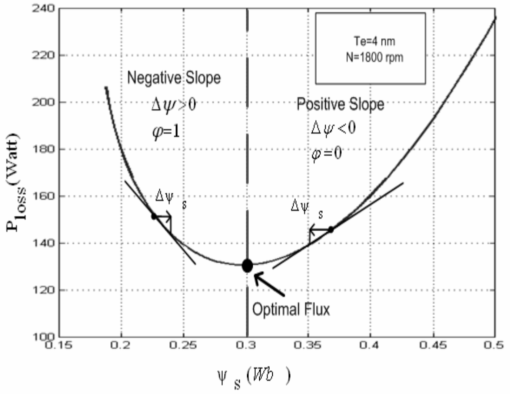

Fig. 5. Electrical loss curve versus flux amplitude.

In order to achieve speed control, the reference electromagnetic torque is applied to the motor through a simple PI controller.

In IPM motors with an estimated amplitude of $\psi_S(k)$ and its increment, $\psi_S(k)+\Delta\psi_S$, first, the machine loss for each flux is calculated. Then flags φ and τ are defined by (16) and (17) (Fig. 5).

$$\begin{aligned}&\text{if}\quad p_{loss}(\psi_S(k)+\Delta\psi_S)-p_{loss}(\psi_S(k))<0\rightarrow\\&\qquad\qquad\varphi=1\quad\text{(Increment Flux)}\\&\text{if}\quad p_{loss}(\psi_S(k)+\Delta\psi_S)-p_{loss}(\psi_S(k))>0\rightarrow\\&\qquad\qquad\varphi=0\quad\text{(Decrement Flux)}\end{aligned}\tag{16}$$

$$\begin{aligned}&\text{if}\quad T_{ref}<T_e\xrightarrow{\quad}\tau=1\quad\text{(Increment Torque)}\\&\text{if}\quad T_{ref}>T_e\xrightarrow{\quad}\tau=0\quad\text{(Decrement Torque)}\end{aligned}\tag{17}$$

Contrary to interior IPM motors, where the gradient of the loss function can not be calculated directly, in non salient-pole PMS machines, where $L_d=L_q=L_s$, the gradient of the loss function is straightforward [11]:

$$\frac{\partial p_{loss}}{\partial\psi_S}=A\psi_S+\frac{B}{\sqrt{1-\left(\frac{C}{\psi_S}\right)^2}}\tag{18}$$

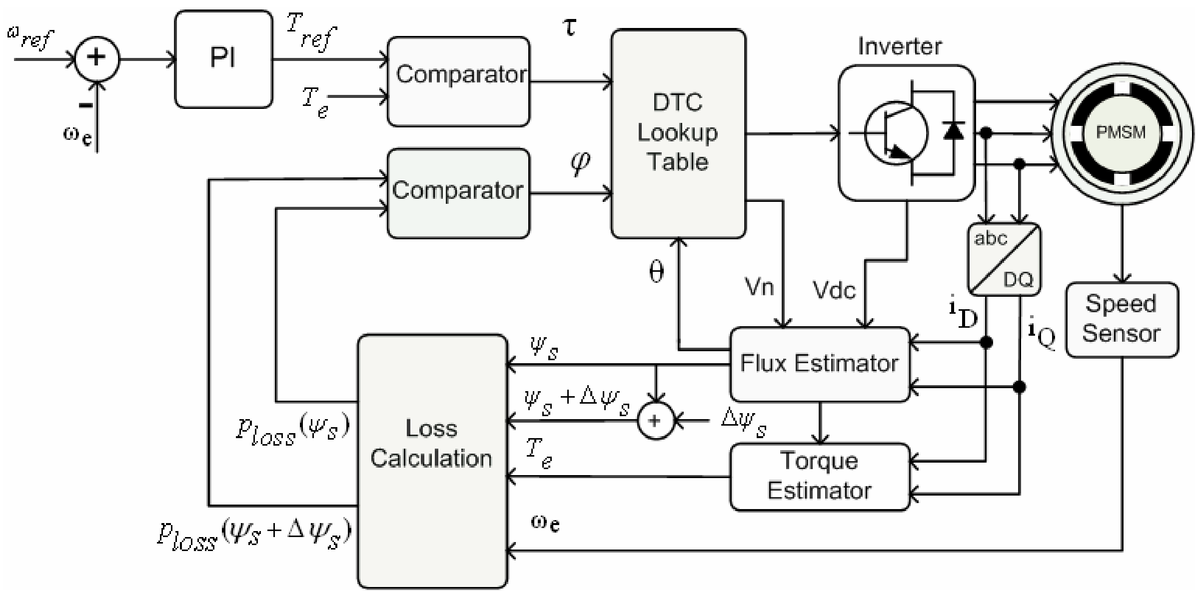

Fig. 6. A block diagram of the proposed loss minimization control method.

where the coefficients of A, B and C are dependent on machine parameters and operating conditions. Therefore the flag φ is expressed as follows:

$$\begin{aligned} &\text{if} \quad \frac{\partial p_{loss}}{\partial \psi_s} < 0 \longrightarrow \varphi = 1 \qquad \text{(Increment Flux)} \\ &\text{if} \quad \frac{\partial p_{loss}}{\partial \psi_s} > 0 \longrightarrow \varphi = 0 \qquad \text{(Decrement Flux)} \end{aligned} \tag{19}$$

The proposed switching look up table is shown in Table 1. It can be seen that the switching table is the same as the one used in the conventional DTC method.

Table 1. The switching table.

φ	τ	Region					
		1	2	3	4	5	6
1	1	V2	V3	V4	V5	V6	V1
	0	V6	V1	V2	V3	V4	V5
0	1	V3	V4	V5	V6	V1	V2
	0	V5	V6	V1	V2	V3	V4

4.3 Sampling time

As mentioned above, comparators are chosen instead of flux and torque controllers. Therefore, switching will be of constant frequency. As in the conventional DTC method, by reducing the sampling time, the flux and torque ripples are reduced. However, data processing should be done faster. Moreover, the higher the switching frequency, the higher the losses of the switches and the inverter. On the other hand, any increase in the sampling time will cause the ripples of the flux and torque to be increased.

The effect of switching time on flux and torque bandwidth has been examined [14]. If $\Delta\psi_s^*$ and ΔT_e^* define the permitted flux and the torque bandwidths respectively, and T_{s1} and T_{s2} are the maximum switching times so that neither the flux nor the torque violate their bandwidths, it can be written as:

$$T_{s1} = \frac{\Delta\psi_s^*}{V_s} = \frac{\Delta\psi_s^*}{\frac{2}{3}V_{dc}} \tag{20}$$

$$T_{s2} = \frac{\Delta T_e^* T_e}{T_0} \tag{21}$$

where T_e^* is the reference electromagnetic torque and T_0 is the time required to accelerate the motor from standstill to T_e^*. Therefore, the minimum sampling time will be given as:

$$T_s = \min(T_{s1}, T_{s2}) \qquad (22)$$

In this study, the sampling time is chosen to be $50\mu s$. Thus, with a voltage equal to $V_{dc} = 350$ V, the flux ripple and the maximum torque ripple will be 0.01 Wb and 0.1Nm, respectively. Compared with the nominal values of the machine, these flux and torque ripples are small.

4.4 Comparison with other minimization control strategies

In the online loss minimization control strategy a step change in the stator flux linkage of a machine is applied in the steady state repeatedly. The resulting change in the input power of the machine caused by the variation in stator flux is measured in a search for an optimal flux that corresponds to the minimum input power. In comparison, when the proposed loss minimization control method is used the effect of stator flux linkage variations on electrical loss are foreseen from the static model of the machine before the flux is changed. Also, the variations of the stator flux are small and applied within each time constant. Thus, the proposed method is very fast. On the other hand, it is different from the offline or model based loss minimization control strategy where the optimum value of the flux is obtained from a minimum loss function through a derivation of the loss function and solving a complicated algebraic equation. Compared to this, the optimum value of the flux will be obtained using a simple constraint which is the negation of the loss function gradient.

5. Simulation results

The specifications and parameters of an IPM motor are presented in Appendix A to be used in the simulation. The variations of the machine parameters during the simulation are ignored, and a sampling time is chosen to be $50\mu s$.

5.1 Comparison with the $i_d = 0$ control strategy

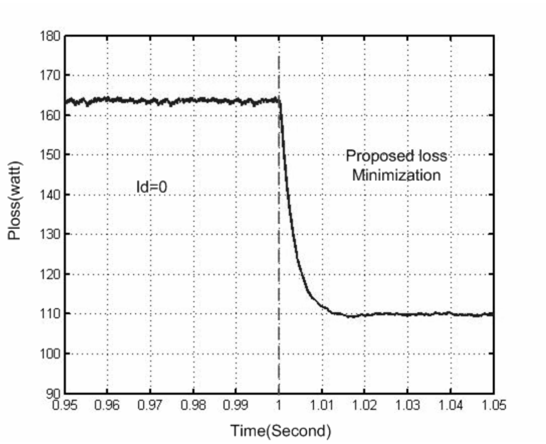

Fig. 7. The comparison of the electrical loss under $i_d = 0$ control and the proposed method (filtered).

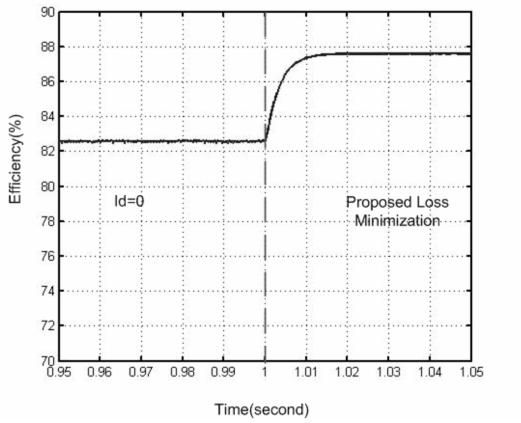

Fig. 8. The comparison of the machine efficiency under $i_d = 0$ control and the proposed method (filtered).

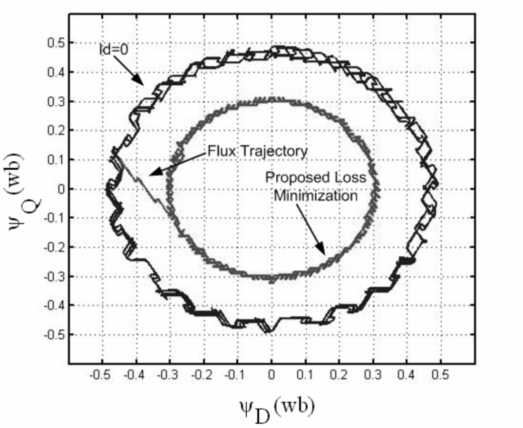

Fig. 9. The stator flux trajectories under both control methods.

Novel loss minimization methods are usually compared to the $i_d = 0$ control strategy under which the d-axis flux is the same as the magnet flux. In this study, the motor operates under the $i_d = 0$ control strategy under nominal conditions, (T_L =3.96 Nm and N=1800 Rpm). Under these conditions it can be shown that the amplitude of the stator flux is equal to $\psi_s = 0.4681$ Wb. Here, the control method is traditional DTC and the hysteresis band of both the flux and the torque are considered to be 10 percent of their nominal values. The electrical loss and efficiency of the machine under the $i_d = 0$ and the proposed control strategies are depicted in Figs. 7 and 8, respectively. It can be seen that under the proposed method the electrical loss decreases and the efficiency of the machine increases as much as 5 percent in comparison with those of the $i_d = 0$ control.

Fig. 9 shows the flux trajectories under the two control methods.

5.2 Dynamical response

Assume that the machine starts with a nominal torque (T_L =3.96 Nm) at t=1 second, when the nominal speed (N=1800 Rpm) is reached, the load torque of the machine decreases to T_L =1Nm. Under nominal torque and speed (T_L =3.96 Nm and N=1800 Rpm) and in the steady state, the electromagnetic torque will be equal to Te =4.1108Nm. The motor's speed, the electromagnetic torque, the minimized electrical loss and the optimum efficiency of the machine are shown in Figs. 10 to 13, respectively. It is clear from the figures that the proposed loss minimization DTC strategy makes the electrical loss minimization process very fast and smooth.

In Fig. 14, the trajectory of the stator flux upon the variation of the load torque at t=1 second, as it changes from an optimum steady state value to a new optimum value is shown. In fact, the simulation results show that the transient time in the proposed loss minimization control is less than 0.15 seconds.

6. Conclusions

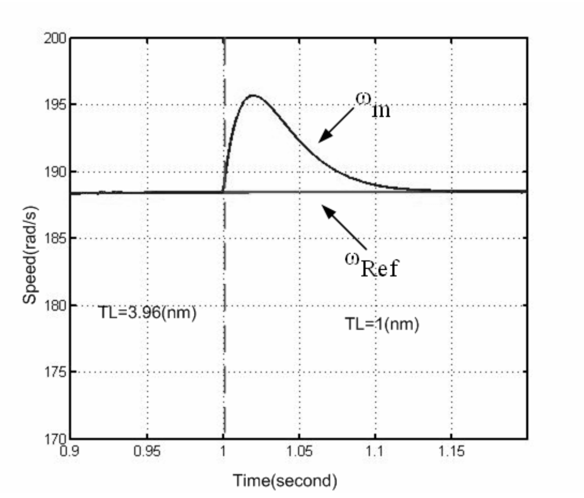

Fig. 10. The machine speed.

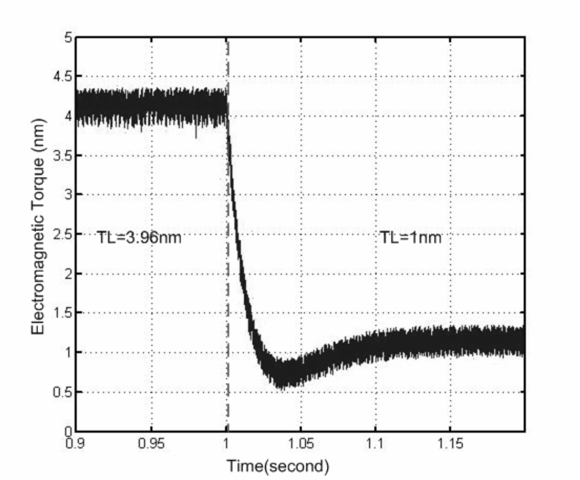

Fig. 11. The electromagnetic torque (unfiltered).

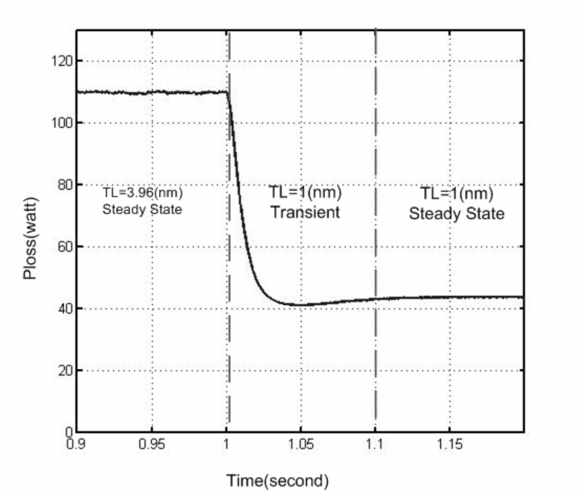

Fig. 12. The electrical loss (filtered).

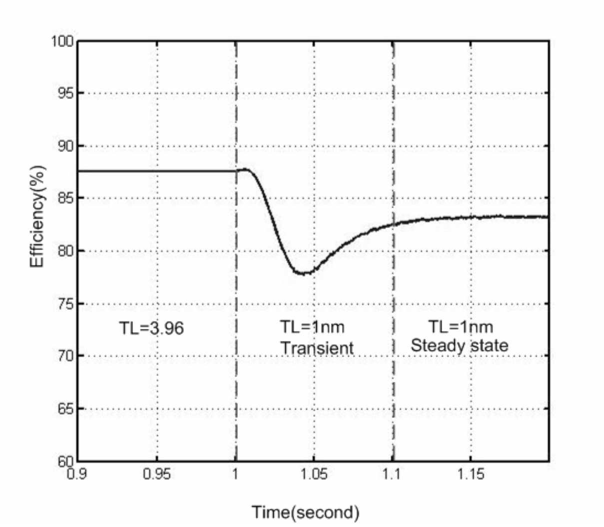

Fig. 13. The machine optimum efficiency (filtered).

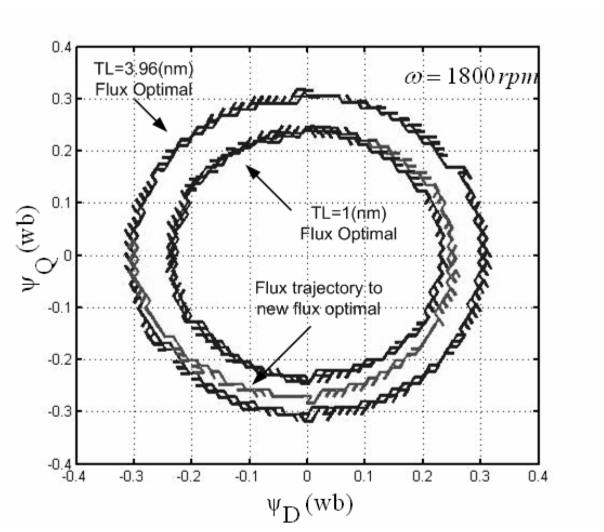

Fig. 14. The optimum flux trajectory upon the variation of load torque at t=1 second.

A new strategy was presented for the loss minimization of direct torque controlled IPM motors. This method integrates a novel loss minimization control strategy with a modified DTC. First, the copper and iron losses were derived as a function of the amplitude of the stator flux. Then, with a simple constraint used, a voltage vector is applied to the machine conducting the stator linkage flux towards the reduction of electrical loss. In order to illustrate the method, it was simulated on a typical IPM motor. The simulation results prove that the proposed method has a significant role in improving the machine's efficiency and reducing electrical loss. It also possesses a very acceptable dynamical response.

Appendix

Table 2. The specifications of the simulated IPM motor.

Nominal speed	1800 Rpm
ψ_m	0.314 Wb
L_d	42.44mH
L_q	79.57mH
Number of Pole pairs (P)	2
Nominal torque	3.96Nm
Inertia moment (J)	0.003
R_c	$330\,\Omega$
R_m	$1.93\,\Omega$
Friction Factor	0.0008

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Farzad Tahami was born in 1968, in Iran. He received a B.S. degree in Electrical Engineering from Ferdowsi University of Mashhad, Iran, in 1991, and a M.S., and a Ph.D. in Electrical Engineering from the University of Tehran, Iran, in 1993 and 2003, respectively. From 1991 to 2004, he was with Jovain Electrical Machines Co. (JEMCO), Iran, where he was the head of the R&D Department. Since 2004 he has been with the Department of Electrical Engineering at the Sharif University of Technology, where he is an assistant professor. His current fields of interest are electric motor drives, modern control theories applied to power electronics, resonant converters and vehicle system dynamics.