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A simple reluctance-based efficiency control strategy taking equivalent magnetic inductance into account for the switched reluctance motor drives

Wen-Nan Huang*, Ching-Cheng Teng

Department of Electrical and Control Engineering, National Chiao-Tung University, Hsin-Chu, Taiwan

Abstract

A novel method, the simple reluctance-based efficiency control for the switched reluctance motor drives, is proposed in this paper. This concept is realized by programming the ratio of current command to phase voltage, and to utilize the time-dependent derivatives of equivalent magnetic inductance obtained from reluctance-related opinion. The algorithms and computational procedures are derived and completed taking equivalent magnetic inductance into consideration. Simulation and experimental results demonstrated the validity of the capability for efficiency regulation of the proposed method.

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Keywords: Reluctance-based efficiency control; Switched reluctance motor; Equivalent magnetic inductance

1. Introduction

Switched reluctance motor (SRM), the electrical machine utilizing reluctance torque, is gaining acceptance in variable speed applications worldwide. In electrical machines-related research, one of the most challenging tasks is the complexity of implementing the efficiency control. Only a few have considered the efficiency improvement among the SRM drive studies carried out by a simple control strategy for ease of practical applications. In efficiency research, most efforts have been devoted to the SRM structure design as it can be clearly seen from Refs. [1–4], which is focused on the modified type and special design of motor phase number, flux path, and air gap parameters to achieve efficiency improvement. The circuit topologies for SRM drives are also taken to be the research topics in efficiency research, such as dual-decay converter, C-dump inverter, and modified $(n+1)$ switch converter, which are described in Refs. [5–7], respectively. Besides this, the current profile via switching angle control is also applied involving the efficiency-related research opinions [8]. We integrate the

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*Corresponding author. Tel.: +886-3-5914263; fax: +886-3-5820050.

E-mail address: wnhuang.ece88g@nctu.edu.tw (W.-N. Huang).

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considerations that originate from a motor model research, called reluctance-based model, to propose the reluctance-based efficiency control (RBEC) that makes use of the reluctance concept based on the equivalent magnetic inductance, without losing the conventional performance requirement in a simple way. RBEC is a novel current command decision method for adding the efficiency regulation capability in SRM drives.

2. Reluctance model

Eq. (1) expresses the voltage equation of SRM per phase

$$V_x = i_x R + \frac{\mathrm{d}\lambda_x}{\mathrm{d}t}, \tag{1}$$

where suffix x denotes phase expression; V, i, R, t, and λ denote phase voltage, phase current, resistance, specific time instant, and magnetic flux linkage, respectively. And, the magnetic flux linkage is equal to the product of equivalent magnetic inductance and current.

The definition of reluctance can be described as "magnetic resistance", being equal to the ratio of magneto-motive force to magnetic flux. For the characteristics of SRM, there is no doubt that the magnetic flux's highly related parameter, called equivalent magnetic inductance, can be taken as the basis of reluctance-based analysis. According to the topological and electromagnetic effect, it is known that the equivalent magnetic inductance will change with rotor position and phase current, which affects the SRM output directly.

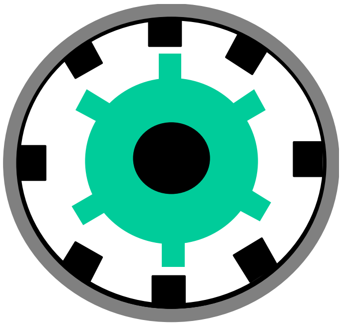

Fig. 1. A typical 8/6 SRM structure.

Fig. 1 shows the typical 8/6 SRM cross-sectional structure with stator and rotor pole numbers 8 and 6, respectively. Then, by D'Lamber's principle and magnetic co-energy concept, the output torque of SRM can be derived based on the energy balance from the following equation:

$$T_\mathrm{e} = \sum \frac{1}{2} i_x^2 \frac{\partial L_x}{\partial \theta}, \tag{2}$$

where T_e is the output torque. L and θ denote equivalent magnetic inductance and rotor angle, respectively. It is apparent that the torque is a function of reluctance force for the motive effect, which also means that the equivalent magnetic inductance is strongly involved.

3. Equivalent magnetic inductance-related estimation

From the description in Section 2, we realize that the equivalent magnetic inductance can be chosen as the desirable variable for further analysis of SRM drives. From Eq. (2), it can be figured out that the inductance and rotor angle are both important computation-needing parameters. Hence, we utilize a fuzzy neural network (FNN) scheme referred to Refs. [9,10] to approximately compute the partial derivatives of the inductance variation profile for SRM with respect to position and current, which is an unknown function.

The concept of computation is that the membership functions of the applied FNN are all differentiable. From this FNN structure, the derivatives of any order can be obtained by changing its membership functions. Therefore, the derivatives or partial differential computation of both equivalent magnetic inductance-related information and output torque for SRM can be obtained by this four-layer FNN, composed of input layer, linguistic term layer, rule layer, and output layer, which has established a dual computation network, with the learning rate and momentum parameter being 0.71 and 0.92 for succeeding estimation, as shown in Fig. 2. The comparison between FNN computation results

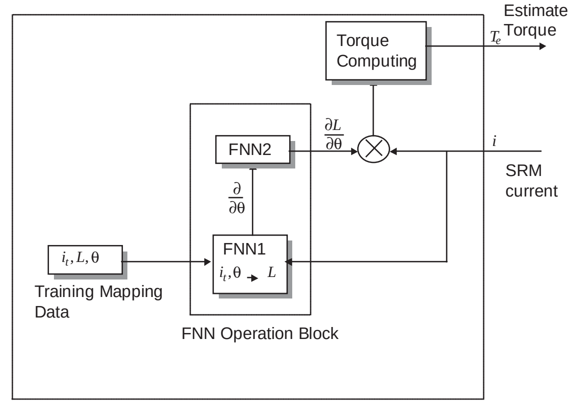

Fig. 2. The equivalent magnetic inductance and torque estimation scheme.

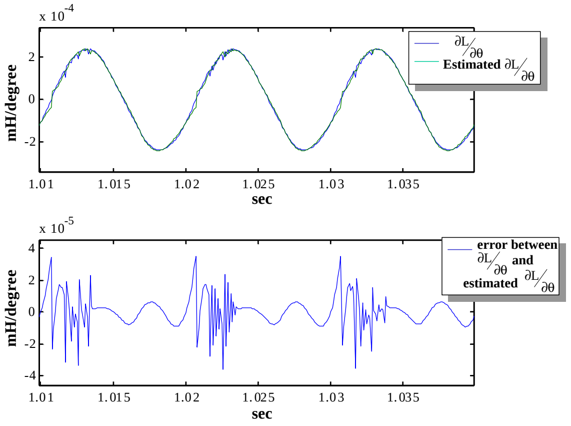

Fig. 3. The comparison of estimated and pre-measured equivalent magnetic inductance related partial differentials.

and pre-measured information, under rated speed and $\frac{1}{3}$ rated load, is shown in Fig. 3.

4. Reluctance concept of efficiency control strategy

The requirement for an easy and simple utilization of efficiency control motivates us to propose the core concept for RBEC. From Eq. (2), it can be derived one step further by the chain rule and specific time set to be

$$T_{\mathrm{e}} = \sum \frac{1}{2} i_x^2 \frac{\mathrm{d}L_x}{\mathrm{d}t} \frac{1}{W_{\mathrm{r}}}, \tag{3}$$

where W_{r} is the motor speed.

Eq. (3) can be rearranged by the SRM output power view, which is defined as the following relation relates to the product of torque and speed:

$$i_x^* = \sqrt{\frac{2P_{\mathrm{out}}}{K(\mathrm{d}L_x/\mathrm{d}t)}}, \tag{4}$$

where the superscript * is the expression for the command value. K is 1.027 or 0.1047 while the applied output power unit is (kgf · m · rpm) or (N · m · rpm), respectively.

From the definition of the input power for the SRM drives, which is the product of applied phase voltage and current, Eq. (4) can be further derived as

$$P_{\mathrm{in}(i_x^*)} = \sqrt{2}\sqrt{P_{\mathrm{out}}}\sqrt{\frac{1}{K(\mathrm{d}L_x/\mathrm{d}t)}}V_x. \tag{5}$$

Eq. (5) relates to input power (P_{in}) and output power (P_{out}), being a transformation to provide the basis for efficiency control. We apply the important concept and to derive Eq. (4) further to be Eq. (5), expressed as

$$\frac{i_x^*}{V_x} = 2\mathrm{Eff}^{*(i_x^*)} \frac{1}{K(\mathrm{d}L_x/\mathrm{d}t)}, \tag{6}$$

where $\mathrm{Eff}^{*(i_x^*)}$ is the desired efficiency that can be achieved under command current for the SRM drives.

In this paper, Eq. (6) has been derived from the reluctance-based view, being highly related to the equivalent magnetic inductance, with the capability of regulating the efficiency by appropriate programming of the ratio of the command current to the applied phase voltage. Based on the estimation information obtained from the FNN description in Section 3, the SRM drives can estimate the output torque and the inductance information. Then, by the reluctance model relevant derivation procedures and observation, we establish the RBEC scheme with a simple regulation method as shown in Fig. 4.

5. Simulation and experimental results

The experimental scheme and simulation concept for verifying the proposed RBEC strategy is

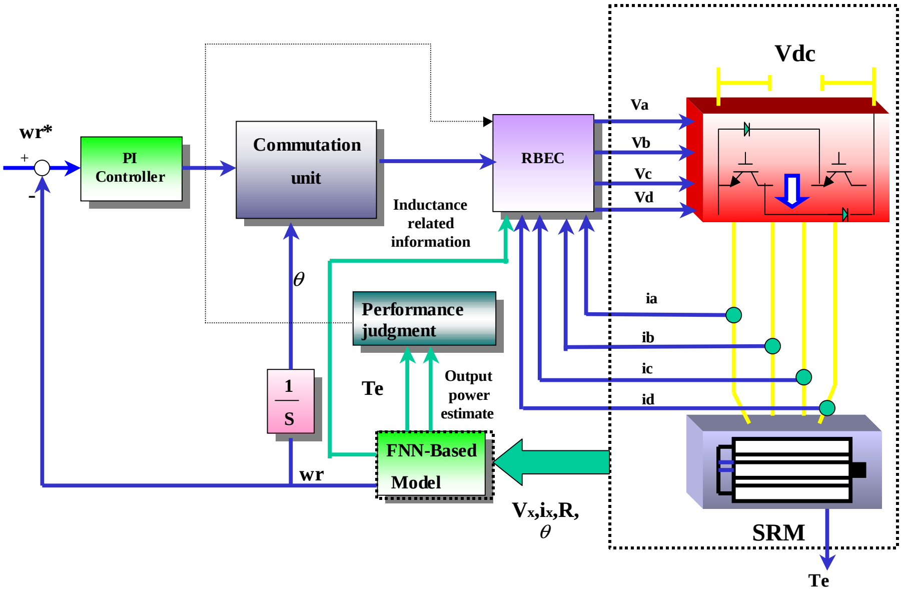

Fig. 4. The overall RBEC operation scheme.

Table 1
The applied SRM parameters

Phase (pole pair)	Rated voltage (power)	Rated speed
4 (8/6)	48 V (3HP)	6000 rpm
Inductance (aligned/unaligned)		Resistance
0.5382/0.0652 mH		0.0095 Ω

based on Fig. 4. The elementary controllers scheme we designed is the proportional-integration (PI) controller for speed control loop, and the hysteresis controller for current control loop, which we call conventional controller to regulate the current value by the appropriate error limit to trace the desired current value. The RBEC is constructed as an efficiency controller for SRM drives that utilizes both torque- and inductance-related parameters estimated by the FNN. Then, the reference current value is updated simultaneously by searching the optimum efficiency based on Eq. (6) that uses the equivalent magnetic inductance obtained from the weights of FNN updated. The related parameters of the applied SRM are listed in Table 1.

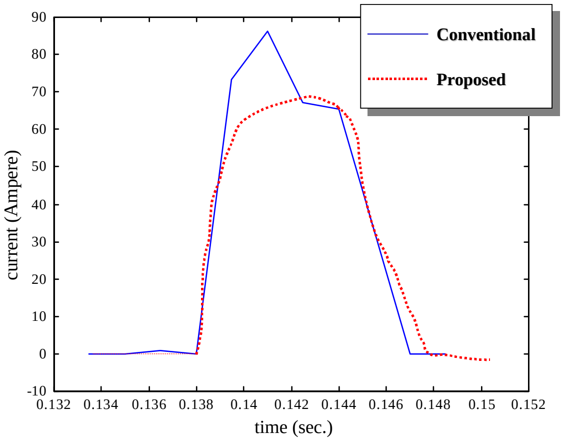

Fig. 5. The comparison of current profile of RBEC and conventional current control.

Fig. 5 shows the simulation results, the sampling time and speed command are set to be $\frac{1}{10{,}000}$ s and 1000 rpm, for the comparison of current profile for the conventional hysteresis control and RBEC. The area and profile of the current utilizing the RBEC are less and smoother than that by the conventional controller.

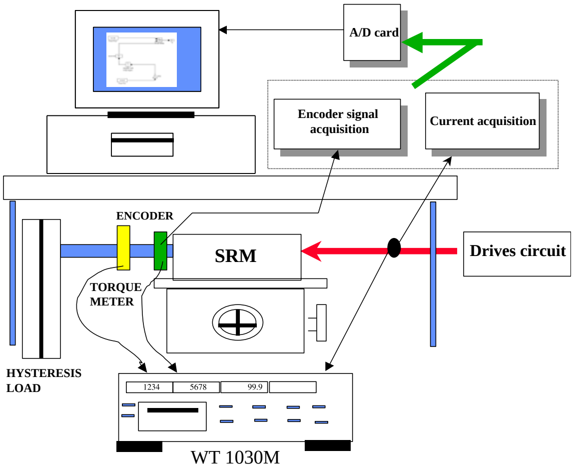

Fig. 6. The setup experimental scheme for RBEC verification.

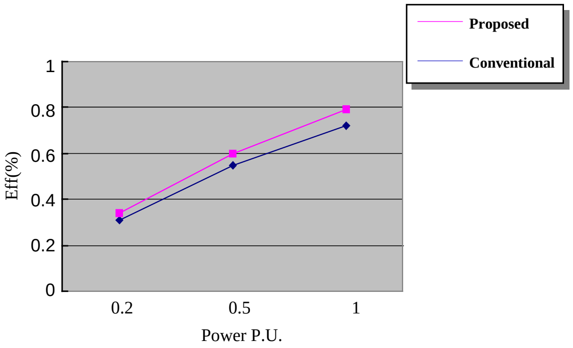

Fig. 7. The efficiency improvement of RBEC. See on-line figure for colour.

The hysteresis brake, chosen to be the load torque, and a developed PC-based SRM drives circuit with analog/digital card and interface circuit for information acquisition are applied for setting up the experimental platform, as shown in Fig. 6, and Fig. 7 shows the experimental results for the RBEC efficiency improvement of 3.5%, 5%, and 7.1% under ratio of 0.2, 0.5, and 1, rated power for SRM.

6. Conclusions

The main concept of RBEC is to apply the linking relation of equivalent magnetic inductance and reluctance for SRM to construct the simple efficiency control scheme. RBEC is realized for compensating the conventional current command to operate at the desired efficiency. A SRM driver is taken as an example to testify the feasibility of the RBEC method. Simulation and experimental results demonstrated the validity for equivalent magnetic inductance estimation at operational conditions and showed the applicability and effectiveness of the proposed strategy by efficiency improvement.

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