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High Efficiency Drive Technique for Synchronous Reluctance Motors Using a Neural Network

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ABSTRACT

A high efficiency drive technique for synchronous reluctance motors (SynRM) using a neural network (NN) is presented in this paper. High efficiency drive condition depends on the mathematical model of SynRM. A NN is employed as an adaptive model of SynRM. The proposed high efficiency drive technique does not require an accurate mathematical model of SynRM. Moreover, the proposed method shows robustness against machine parameter variations because the training algorithm of the NN is executed on-line. The usefulness of the proposed method is confirmed through experimentation.

Keywords: high efficiency drive, synchronous reluctance motor, neural network

1. Introduction

Synchronous reluctance motors (SynRM) have received much attention because of their simple and rigid structure [1-4]. However, the efficiency of SynRM drive is lower than that of the other types of ac motor drives [5]. For this reason, the high efficiency drive of SynRM is an important issue in energy conservation. There are various combinations of *d-q* axes currents that generate a certain output torque. Among them, an optimal combination of *d-q* axes currents that minimizes the electrical loss of SynRM exists. Such optimal *d-q* axes currents can be derived from the mathematical model of SynRM. Based on this concept, several methods to improve the efficiency of motor drive have been reported [6-7]. These methods require an accurate mathematical model of motor. Moreover, the performance of high efficiency drive declines due to parameter variations. An alternative method, which does not require the mathematical model of a motor, has been developed in [8]. In this method, a fuzzy controller is applied to the high efficiency drive. The problem of this method is that the design of fuzzy rules requires designer's experience and intuition. In [9], an optimal combination of *d-q* axes currents is searched so as to minimize input power. Although this method does not require any mathematical model of SynRM, a perturbation should be added to the *d*-axis current reference to search for an optimal operating point quickly.

Recently, a neural network (NN) has been applied to the field of motor drives, for example as an estimator of the state variables of an induction motor [10]. NN has the capability of identifying nonlinear functions after some training using only input-output data. Therefore, it is effective to use NN instead of an analytical model to solve several control and/or identification problems.

In this paper, a NN based high efficiency drive technique for SynRM is proposed. A NN is employed as

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an adaptive model of SynRM. The NN identifies the relationship between an optimal *d-q* axes current and torque reference. The training algorithm of NN is executed on-line by using a performance function, which consists of speed error and input power. These evaluate the speed control performance and the efficiency of SynRM, respectively. The proposed high efficiency drive technique does not require an accurate mathematical model of SynRM. Moreover, the proposed method shows robustness against machine parameter variations because the training of NN is executed on-line. The validity of the proposed scheme is demonstrated with experimental results.

2. Modeling and High Efficiency Drive Condition of SynRM

2.1 Modeling

The *d-q* axes equivalent circuits of SynRM considering stator iron loss are shown in Fig. 1. Since the iron loss resistance R_i is inserted in parallel with the inductance L and speed-emfs, armature currents (i_d, i_q) are divided into load currents (i_{dt}, i_{qt}) and iron loss currents (i_{di}, i_{qi}) as

$$\left.\begin{aligned} i_{dt} &= i_d - i_{di} \\ i_{qt} &= i_q - i_{qi} \end{aligned}\right\} \tag{1}$$

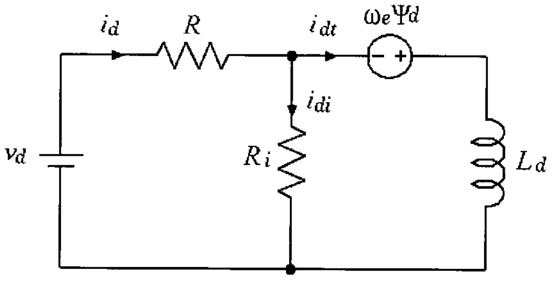
The steady state model of SynRM is satisfactory to evaluate the electrical loss. Since *d-q* axes iron loss currents are dc quantities, the transformer electromotive forces ($L_d di_{dt}/dt$, $L_q di_{qt}/dt$) in steady state condition are zero. Then, Iron loss currents are given as

$$\left.\begin{aligned} i_{di} &= -\frac{\omega_e \psi_q}{R_i} \\ i_{qi} &= \frac{\omega_e \psi_d}{R_i} \end{aligned}\right\} \tag{2}$$

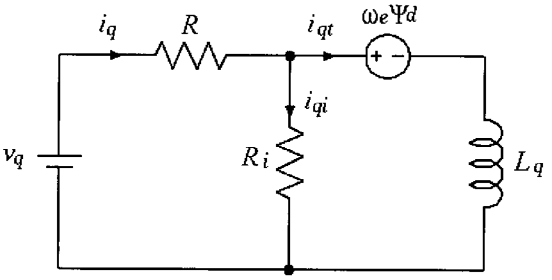
where ω_e is electrical angular velocity. Ψ_d and Ψ_q denote the *d-q* axes flux linkages and are represented as

$$\left.\begin{aligned} \psi_d &= L_d i_{dt} \\ \psi_d &= L_q i_{qt} \end{aligned}\right\} \tag{3}$$

The voltage equation of SynRM in a steady state condition is represented as



(a) *d*-axis



(b) q-axis

Fig. 1 d-q axes equivalent circuits

$$\left.\begin{aligned} v_d &= Ri_d - \omega_e \psi_q \\ v_q &= Ri_q + \omega_e \psi_d \end{aligned}\right\} \tag{4}$$

where v and R are armature voltage and armature resistance, respectively. Torque equation is given as

$$\begin{aligned} \tau_e &= P(\psi_d i_{qt} - \psi i_{dt}) \\ &= P(L_d - L_q) i_{dt} i_{qt} \end{aligned} \tag{5}$$

where P is the number of pole pairs.

2.2 High Efficiency Drive Condition

The efficiency of SynRM is represented as

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out} + P_L} \tag{6}$$

where P_{in} and P_{out} are the input and output power, respectively. P_L is the total loss of SynRM and is given as

$$P_L = P_c + P_i \tag{7}$$

where P_c and P_i are the copper loss and iron loss, respectively. From (6), the efficiency of SynRM is maximized when P_L is minimized under a certain output power (a constant torque and constant speed). The torque of SynRM depends on the product of *d-q* axes currents. An optimal combination of *d-q* axes currents exists such that the total loss of SynRM is minimized. Note that mechanical loss and stray load loss are neglected in the total loss of SynRM because mechanical loss is independent of the combination of *d-q* axes currents and stray loss is relatively small.

The copper loss and iron loss are given as

$$P_c = R(i_d^2 + i_q^2) \tag{8}$$

$$P_i = R_i(i_{di}^2 + i_{qi}^2) \tag{9}$$

Substituting (1) and (2) into (8) and (9) and using the torque equation indicated in (5) represent the total loss as

$$\begin{aligned} P_L = &\left\{R + \frac{\omega_e^2}{R_i}\left(1 + \frac{R}{R_i}\right)L_q^2\right\}\left\{\frac{\tau_e}{P(L_d - L_q)}\right\}^2 \frac{1}{i_{dt}^2} \\ &+ \left\{R + \frac{\omega_e^2}{R_i}\left(1 + \frac{R}{R_i}\right)L_d^2\right\}i_{dt}^2 + 2\frac{R}{R_i}\frac{\omega_e \tau_e}{P} \end{aligned} \tag{10}$$

The condition that minimizes the total loss P_L in steady state is given as

$$\frac{\partial P_L}{\partial i_{dt}} = 0 \tag{11}$$

The optimal *d*-axis load current that satisfies the condition (11) is derived as

$$i_{dt} = \sqrt[4]{\frac{A}{B}C} \tag{12}$$

At this point, substituting (12) into (5) gives the optimal *q*-axis load current as

$$i_{qt} = \sqrt[4]{\frac{B}{A}C} \tag{13}$$

In (12) and (13), variables *A*, *B*, and *C* are defined as

$$\left.\begin{aligned} A &= \frac{R}{\frac{\omega_e^2}{R_i}(1 + \frac{R}{R_i})} + L_q^2 \\ B &= \frac{R}{\frac{\omega_e^2}{R_i}(1 + \frac{R}{R_i})} + L_d^2 \\ C &= \left\{\frac{\tau_e^2}{P(L_d - L_q)}\right\}^2 \end{aligned}\right\} \tag{14}$$

Substituting (12) and (13) into (1) and rearranging (1) gives the optimal *d-q* axes currents as

$$i_d = \sqrt[4]{\frac{A}{B}C} - \frac{\omega_e}{R_i}\psi_q \tag{15}$$

$$i_q = \sqrt[4]{\frac{B}{A}C} + \frac{\omega_e}{R_i}\psi_d \tag{16}$$

Note that in the strict sense the condition $i_d = i_q$ does not give the maximum efficiency operating point of SynRM when iron loss exists although the condition gives the maximum efficiency of SynRM drive when the iron loss can be negligible.

3. Principle of High Efficiency Drive Using Neural Network

Fig. 2 shows the input power P_{in} versus *d-q* axes currents (i_d, i_q) under a certain load condition for various rotor speeds. As mentioned earlier, the output torque of SynRM depends on the product of *d-q* axes currents. In other words, there are a number of combinations of *d-q* axes currents to generate a certain torque. Since the copper loss and iron loss also depend on the combinations of *d-q* axes currents, the input power of SynRM can widely vary with *d-q* axes currents as shown in Fig. 2. Among them there is an optimal combination such that the input power of SynRM is minimized. Although the optimal *d-q* axes currents that give the maximum efficiency condition of SynRM have been derived theoretically in the previous section, it has two problems to realize the condition:

1) An accurate motor model is required,
2) Parameter variations should be compensated.

To overcome these problems, the high efficiency drive technique using a NN is developed. The NN identifies the optimal *d-q* axes currents on-line according to operating conditions.

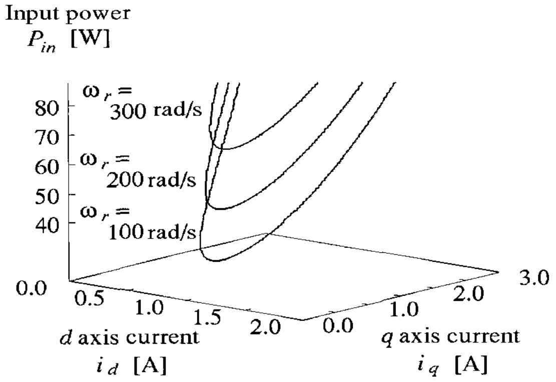


Fig. 2 Input power versus *d-q* axes currents under a certain load condition

Fig. 3 shows the configuration of the NN used in the proposed method. The NN consists of 1 input layer unit and 2 output layer units. The input is the torque reference τ_e^* and outputs are the *d-q* axes currents references (i_d^*, i_q^*). The number of hidden layer units is determined by trial and error. Although a number of hidden layer units generally make the performance of NN well, it increases computation time. From the viewpoints of both the degree of accuracy and computation time, the number of hidden layer units is determined as 4. The units of each layer are connected with interconnecting weights where w_{ji} denotes the weight from unit *i* to unit *j*. NN should be trained to adjust the interconnecting weights appropriately. The training algorithm utilized in this paper is the well-known error back propagation (EBP) rule. The performance function to be minimized is set as

$$E_P = (k_1 e_\omega + k_2 P_{in})^2 \tag{17}$$

where e_ω $(=\omega_r^* - \omega_r)$ is the speed error. The first term evaluates the speed control performance, while the second term evaluates the efficiency. The input power P_{in} can be calculated using the measured *d-q* axes currents and voltages as

$$P_{in} = v_d i_d + v_q i_q \tag{18}$$

The weights k_1 and k_2 are determined by the following procedure:

1) Initially, k_2 is set at zero.
2) Then, k_1 is determined so that speed error is within an acceptable value.
3) Finally, k_2 increases as far as the speed error within the acceptable value under the determined k_1 in step 2.

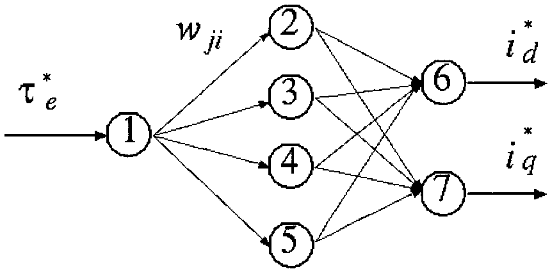


Fig. 3 Configuration of neural network

4. System Configuration

The system configuration of the proposed high efficiency drive is shown in Fig. 4. The torque reference τ_e^*, which is the input of NN, is obtained from the PI controller for speed control as

$$\tau_e^* = k_P e_\omega + k_I \int e_\omega dt \tag{19}$$

where k_P and k_I denote the proportional and integral gains, respectively. The optimal *d-q* axes current references (i_d^*, i_q^*) are determined by the NN according to torque reference. The interconnecting weights of NN are adjusted on-line so as to minimize the performance function in (17) with the EBP. The *d-q* axes currents are controlled so as to agree with their references, i.e., the optimal *d-q* axes currents. The outputs of current controller are the *d-q* axes voltage references (v_d^*, v_q^*). The voltage references are transformed into three-phase quantities and applied to SynRM via voltage source inverter.

5. Experimental Results

Some experimental results are provided to demonstrate the validity of the proposed high efficiency drive technique. The experimental system of the proposed technique is shown in Fig. 5. The system consists of a SynRM, torque transducer, DC generator, rotary encoder, voltage source inverter, and digital signal processor (TMS320C32). The specifications of the SynRM used in this system are listed in Table 1. The parameters for controllers and training algorithm of NN are listed in Table 2.

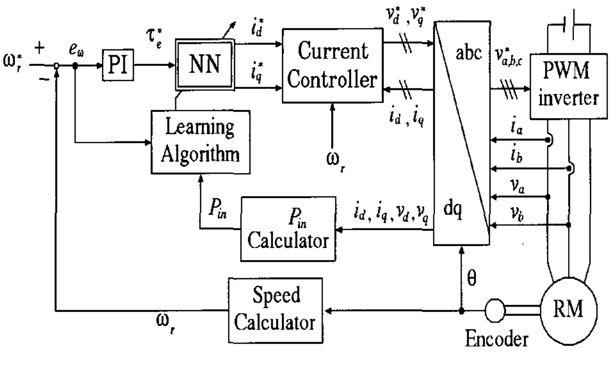


Fig. 4 System configuration

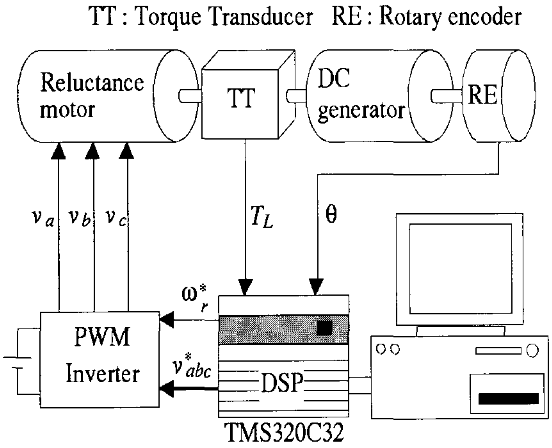


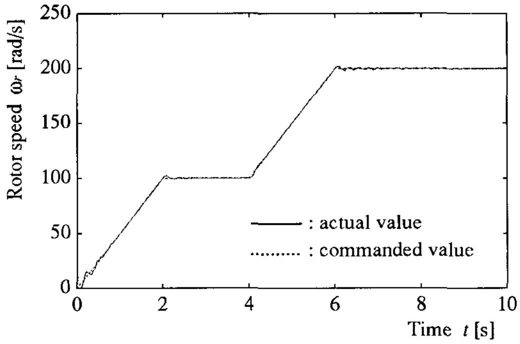
Fig. 5 Experimental systems

Table 1 Motor parameters

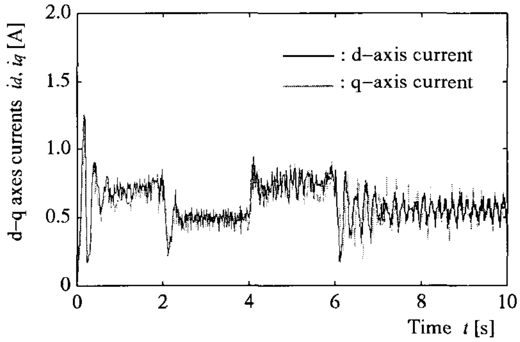
Rated power	P_n	150W
Rated voltage	V_n	200V
Rated current	I_n	1.2A
Rated speed	N_n	1800rpm
Armature resistance	R	12.75Ω
d-axis inductance	L_d	0.38H
q-axis inductance	L_q	0.12H
Number of pole pairs	P	2

Table 2 Control parameters

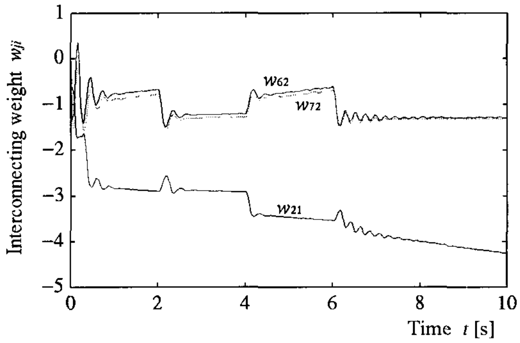
Sampling period	200μs
Switching frequency	10kHz
Proportional gain for speed ctrl.	0.2
Integral gain for speed ctrl.	0.5
Proportional gain for current ctrl.	10
Integral gain for current ctrl.	1000
Weight k_1	0.05
Weight k_2	0.0001
Learning rate for EBP	0.6
Inertia rate for EBP	0.2



(a) Rotor speed



(b) d-q axes currents



(c) Interconnecting weight

Fig. 6 Speed control performance of SynRM for ramp speed change

Fig. 6 shows the speed control performance of SynRM for ramp speed change. As can be seen from Fig. 6(a), speed control performance is acceptable. Fig. 6(b) shows d-q axes currents. The SynRM operates under $i_d \approx i_q$, i.e., high efficiency conditions when the effect of iron loss is negligible. Although d-q axes currents produce a ripple effect due to the switching of the inverter, the impact on torque generation is not an important issue because the frequency of the ripple is sufficiently high. Fig. 6(c) shows interconnecting weights w_{ji} of the NN indicated in Fig. 3 (ex. w_{21} denotes the interconnecting weight from unit 1 to unit 2). The initial values of the interconnecting weights are set randomly. Interconnecting weights varies according to operating condition.

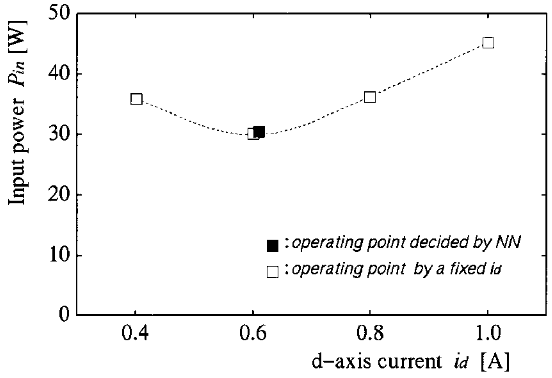


Fig. 7 Input power versus d-axis current at the operating point (100rad/s, 0.08Nm)

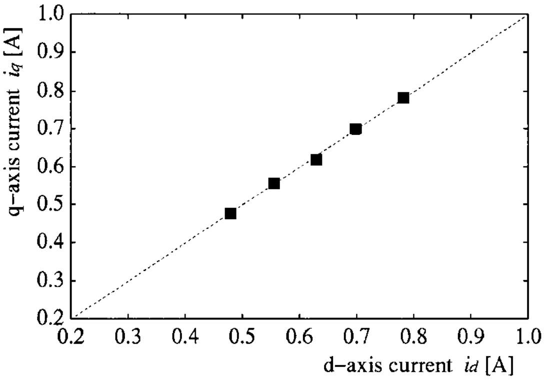


Fig. 8 The optimal combination of d-q axes currents determined by NN for various load condition at 100rad/s

Fig. 7 shows the characteristic of input power for d-axis current when SynRM rotates at operating point (100rad/s, 0.08Nm). It can be confirmed that the input power varies with the set of d-axis current even though the load condition is fixed. When the NN based high efficiency controller is applied to a speed control system, SynRM operates at minimum input power (the operating point is represented by the black square).

Fig. 8 shows the optimal combination of d-q axes current determined by NN for various load conditions at 100rad/s. The dashed lines means a condition of $i_d = i_q$. Since the optimal d-q axes currents almost lie on the $i_d = i_q$ condition, the effect of iron loss is not serious in this condition. Higher speed operation should result in a condition of $i_d \neq i_q$ though experimental results cannot be executed due to the existence of mechanical resonance. Nevertheless, the NN based high efficiency controller practically generates the optimal combination of d-q axes current on-line in this experimental result.

6. Conclusions

In order to improve the efficiency of SynRM, a high efficiency drive technique using a NN has been proposed. A NN is employed as an adaptive model of SynRM. The maximum efficiency drive of SynRM is accomplished easily without the use of an accurate mathematical model of SynRM. Moreover, since the training of NN is executed on-line, the proposed high efficiency method hardly suffers from parameter variations owing to a temperature change and saturation phenomenon.

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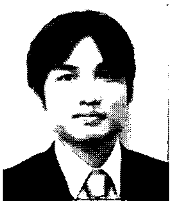

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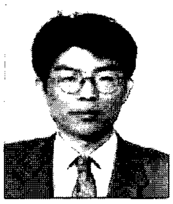

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