Minimization of Losses in Permanent Magnet Synchronous Motors Using Neural Network

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Abstract

In this paper, maximum efficiency operation of two types of permanent magnet synchronous machine drives, namely: surface type permanent magnet synchronous machine (SPMSM) and interior type permanent magnet synchronous machine (IPMSM), are investigated. The efficiency of both drives is maximized by minimizing copper and iron losses. Loss minimization is implemented using flux weakening. A neural network controller (NNC) is designed for each drive, to achieve loss minimization at different speed and load values. Data for training the NNC are obtained through off-line simulations of SPMSM and IPMSM at different operating conditions. The accuracy and fast response of each of the NNC is proved by applying sudden changes in speed and load and tracking the NNC output. The drives' efficiency obtained by flux weakening is compared with the efficiency obtained when setting the d-axis current component to zero, while varying the angle of advance " φ " of the PWM inverter supplying the PMSM drive. A NN is also designed, and trained to vary φ following the derived control law. The accuracy and fast response of the NN controller is also proved.

1. Introduction

The Permanent magnet synchronous motors PMSM offers several advantages, namely: a high torque-to-inertia ratio and an excellent power factor, since the copper losses are confined to the stator. In addition, for the same delivered mechanical power, a PMSM needs a smaller line current value, which is favorable for the design of the electronic power converter feeding this drive. However, the need to save energy still exists to develop an efficient drive. Several control methods have been proposed to minimize the losses of PMSM drives [1-7].

In the previous work, no attempt was done to apply Neural Network (NN) controllers for maximum efficiency operation of PMSM drive. In this paper, a loss minimization strategy is developed to minimize copper and iron losses in e (SPMSM), and (IPMSM) drives. The proposed strategy is based on the air-gap flux weakening, where the value of the d-axis stator current component that leads to minimum losses is first derived for IPMSM and SPMSM drives. To achieve

fast response with minimum losses within wide speed range, flux weakening is implemented using neural networks (NN). The advantages of the NN lie in its learning character, as well as in its ability to deal with nonlinearities. Also the efficiency of the PMSM drive is deduced when setting the d-axis stator current component to zero while varying the angle of advance " α " of the PWM inverter supplying the PMSM drive. The value of α that allows maximum efficiency is derived as function of speed and load, and a NN controller is designed and tested to implement this scheme.

2. Loss Minimization Model of Interior PMSM

The steady state model of the IPMSM is derived from the d and q-axes per-phase equivalent circuit shown in Fig. (1):

$$V_q = R_s i_q + \omega_s L_d i_{od} + \omega_s \lambda \quad (1)$$

$$V_d = R_s i_d - \omega_s L_q i_{oq} \quad (2)$$

The electric torque is given by:

$$T_e = 1.5 P [\lambda i_{oq} + (L_d - L_q) i_{od} i_{oq}] \quad (3)$$

And the equation for motor dynamics is:

$$T_e = T_L + B \omega_r + J p \omega_r \quad (4)$$

The main losses of the PMSM are the copper and iron losses. Referring to the general equivalent circuit of the PMSM given in Fig.(1), the copper losses are given by:

$$P_{cu} = R_s i_d^2 + R_s i_q^2 \quad (5)$$

While the iron losses are given by:

$$P_{fe} = \omega_s^2 * \lambda_o^2 / R_c \quad (6)$$

Where, λ_o is the air gap flux.

Eq.(6) could be written as:

$$P_{fe} = \omega_s^2 * [(\lambda + L_d i_{od})^2 + (L_q i_{oq})^2] / R_c \quad (7)$$

Adding equations (5) and (7), and

differentiating with respect to i_{od} , gives:

$$\partial P_L / \partial i_{od} = i_{od} [R_s + (\omega_s^2 * L_d^2 / R_c)] + i_{oq} * \partial i_{oq} / \partial i_{od} [R_s + (\omega_s^2 * L_q^2 / R_c)] + (\omega_s^2 * \lambda * L_d / R_c) \quad (8)$$

From the electric torque equation (3), the current i_{oq} is:

$$i_{oq} = T_e / 1.5 * P [\lambda + (L_d - L_q) i_{od}] \quad (9)$$

Hence $\partial i_{oq} / \partial i_{od}$ is derived as:

$$\partial i_{oq} / \partial i_{od} = -[(L_d - L_q) * T_e / 1.5 * P [\lambda + (L_d - L_q) i_{od}]]^2 \quad (10)$$

Substituting (10) into (8) and equating the result to zero, gives the optimum d-axis stator current i_{dop} that leads to minimum losses at a given steady state speed and torque:

$$i_{dop} = 1.5 P^* L^* \{ [(R_s * R_c) + (\omega_s^2 * L_q^2)] / [(R_s * R_c + \omega_s^2 * L_d^2)] \} i_{oq}^3 - \{ [\lambda * \omega_s^2 * L_d^2] / [R_s * R_c + \omega_s^2 * L_d^2] \} \quad (11)$$

Loss minimization condition for voltage controlled schemes is obtained by substituting eq.(11) into equations (1) and (2) and using the supply voltage V_s as:

$$V_s = \sqrt{(V_d^2 + V_q^2)} \quad (12)$$

To prove the existence of minimum losses as speed varies, the total losses are plotted versus V_s at variable speed and constant torque in Fig.(2).

2. Network Controller for Loss-Minimization in IPMSM

3.1 Control Scheme

The control scheme to implement loss minimization in IPMSM is shown in Fig. (3). In such scheme, a PI controller is used to calculate i_q^* from the difference between the torque command and the actual torque. The inputs to the proposed NN are i_q^* and the rotor speed ω_r . The output of the NN is i_{dop} , which is used with i_q^* to calculate the 3-phase currents, in current controlled schemes, or the 3-phase voltages in the voltage-controlled scheme.

3.2 Neural Network (NNI) Controller for IPMSM

In order to establish the neural network model, the interconnected weights and biases are trained according to an existing input/output pattern. This pattern is obtained from the simulation results of the described loss minimization control strategy, i.e. off-line training. After many trials, a 3-layer NN with two input neurons, 2- hidden layer neurons, and one output neuron gave the required error goal after few epochs. The trained output of NNI is compared with i_{dop} calculated from the condition of minimum losses, and the results given in Fig.(4) as function of rotor speed. The slight difference between the two values of current proves the accurate tracking of the current value required for loss minimization.

In order to verify the fast response of the established NNI loss minimization controller, sudden step change in the drive speed is imposed at constant load torque, and the calculated power loss at this operating point is plotted versus time in Fig.(5a), while the existing power loss after applying NNI controller is plotted in Fig.(5b) for clarity. The corresponding fast change in the output of NNI as the speed changes proves the fast response of the neural network output, which assures that minimum losses are obtained at different operating conditions. This fact is further proved by applying a step change of load torque and plotting the expected power loss with that obtained after applying NNI.

Results shown in Fig.(6) assures the fast response of the designed NNI.

3. Loss Minimization Model of Surface SPMSM

In the case of SPMSM drive, $L_d = L_q = L_s$, where L_s is the stator inductance. Hence, the iron loss equation (7) reduces to

$$P_{fe} = \omega_s^2 * [(\lambda + L_s i_{od})^2 + (L_s i_{oq})^2] / R_c \quad (13)$$

and the electric torque reduces to:

$$T_e = 1.5 P \lambda i_{oq} \quad (14)$$

Adding copper and iron losses and differentiating with respect to i_{od} gives:

$$\partial P_L / \partial i_{od} = R_s i_{od} + (L_s \omega_s^2 \lambda) / R_c + (\omega_s^2 L_s i_{od}) R_c \quad (15)$$

Equating (15) to zero leads to the following expression for the optimum d-axis current at a given speed and torque:

$$i_{dop} = (L_s \omega_s^2 \lambda) / (R_s R_c + \omega_s^2 L_s^2) \quad (16)$$

4. Neural Network Controller for Loss-Minimization in SPMSM

4.1 Control Scheme

Due to the simpler expression for optimal d-axis current given in (16), and the independency of i_{dop} on the q-axis current component, the PI controller used with IPMSM drive is canceled. Instead the q-axis current is directly calculated from the command torque, which is used as one of the inputs of the neural network controller for SPMSM drive (NNS).

4.2 Neural Network (NNS) Description

An off line trained neural network NNS is designed for loss minimization in SPMSM. The inputs to the NNS are the drive speed, and the load torque (which determines the q-axis component of the stator current). The output of the network is the optimal value of d-component of stator current i_{dop} . The input/output pattern used to train NNS is obtained from the simulation results of the described loss minimization control strategy. A 3-layer NN with two input neurons, 2- hidden layer neurons, and one output neuron gave the required error goal after few epochs. The trained output of NNS is compared with i_{dop} calculated from the condition of minimum losses, and the results given in Fig.(7) as function of rotor speed. The slight difference between the two values of current proves the accurate tracking of the current value required for loss minimization.

In order to verify the fast response of the established NNS loss minimization controller, a step change of load torque is applied to the SPMSM, and NNS output current plotted in Fig.(8). Results prove the fast response of the designed NNI. This fact is further proved by applying a sudden step change of 30 rad/sec to the speed command at constant load torque, and NNS

output plotted versus time in Fig.(9), The corresponding fast change in the output of NNS as the speed changes proves the fast response of the neural network output, which assures that minimum losses are obtained at different operating conditions.

5.Operation At $i_d=0$

5.1 Equation Derivation

The d-component of the stator current is set to zero, and another approach is used to allow the PMSM to operate with minimum winding losses. This approach depends on variation of the inverter angle as the speed and load varies to achieve minimum losses. To determine this optimum angle in an analytical manner, i_d is set to zero in equations (1)-(3) leading to the following voltage and torque equations:

$$V_q = V_i \cos \varphi = R_s i_{oq} + \omega_s \lambda \quad (17)$$

$$V_d = -V_i \sin \varphi = -\omega_s L i_{oq} \quad (18)$$

The electric torque is given by:

$$T_e = 1.5 P \lambda i_{oq} \quad (19)$$

Where L

= L_q for IPMSM drive, and $L=L_s$ for SPMSM drive

It is clear that with this constraint and for steady state operation at a required load torque, the quadrature axis current can be calculated from (19), and used to optimize the inverter angle. From (17) and (18):

$$\varphi_{op} = \tan^{-1}[(\omega_s L i_{oq} / (R_s i_{oq} + \omega_s \lambda))] \quad (20)$$

To prove the effect of the inverter angle of advance on the drive efficiency, the efficiency and electric torque for $\varphi = 0$, and for $\varphi = \varphi_{op}$ are plotted versus speed in Fig.(9). Results show that a much higher torque and a higher efficiency is obtained when φ is varied with speed to follow the values of φ_{op}

5.2 Comparison Between Maximum Efficiency Operation Schemes

A comparison is done between the values of efficiency obtained by flux weakening technique, and that obtained by varying the inverter angle of advance in SPMSM. Figure (11) shows the electric torque and efficiency with loss minimization scheme ($Te1$ and $eff1$), and electric torque and efficiency for optimum inverter angle operation ($Te2$ and $eff2$). It is concluded that while the efficiencies are nearly equal, the electric torque is slightly higher for the case of optimum inverter angle operation. Therefore, since the two investigated techniques for maximum efficiency operation gave same results, setting the d-axis current component to zero while varying the optimum angle of advance might be more economic to implement, and more safe from the point of view of magnet demagnetization. Flux weakening is better used for high speed operation of PMSM drives.

5.3 Neural Network Implementation

For fast and robust application of optimum inverter angle at all operating speed range, an off line trained neural network NNA is designed, and is applicable for both SPMSM and IPMSM drives. The inputs to the NNA are the drive speed, and the load torque (which determines the q-axis component of the stator current). The output of the network is the optimal value of the inverter angle of advance φ_{dop} . The input/output pattern used to train NNA is obtained from the simulation results given in the previous section. A 3-layer NN with two input neurons, 2- hidden layer neurons, and one output neuron gave the required error goal after few epochs.

In order to verify the fast response of the established NNA maximum efficiency controller, a step change of 0.2 N.m.in load torque is applied to the SPMSM, and NNA output (optimum inverter angle), as well as the calculated inverter angle are plotted in Fig.(12). Results proves the fast response of the designed NNA.

6.Conclusion

In this paper, efficiency of two types of permanent magnet synchronous machine drives, namely; surface type permanent magnet synchronous machine (SPMSM) and interior type permanent magnet synchronous machine (IPMSM), are investigated is maximized by minimizing copper and iron losses. Loss minimization is implemented using flux weakening. A neural network controller (NNC) is designed for each drive, to achieve loss minimization at different speed and load values. Data for training the NNC are obtained through off-line simulations of SPMSM and IPMSM at different operating conditions. The accuracy and fast response of each of the NNC is proved by applying sudden changes in speed and load and tracking the NNC output.

Also the PMSM drives' efficiency is derived when setting the d-axis current component to zero, while varying the angle of advance " φ " of the PWM inverter supplying the PMSM drive. A neural network NNA is also designed, and trained to vary φ following the derived control law. The accuracy and fast response of NNA controller is also proved.

Comparison is done between the drive efficiency obtained with flux weakening, and the drive efficiency obtained with the conventional " $i_d=0$ control". Results proved that the two methods lead to equal efficiencies. This result are in favor of the " $i_d=0$ control", since less control circuits are needed for its implementation. Also it prevents magnet demagnetization that may occur due to any maloperation of the control system.

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Appendix

(i) IPMSM parameters:

900watt, 1700rpm,

$L_d=0.027$ H.

$L_q=0.067$ H.

$R_s=4.3$ ohm

$V_{dc}=250$ V.

$P=4$ poles.

$\lambda=0.232$ web.

(ii) SPMSM parameters

400 watt, 1700 rpm,

$R_s=3$ ohm

$L_s=0.0121$ H.

$\lambda=0.083$ web

$P=4$ poles

$V_{dc}=100$ V

Fig.(1) Equivalent Circuit for PMSM in the d and q axes

Fig.(2) Power Loss Versus Stator Voltage at Variable Speed and Constant Load

Fig.(7) NNS Output and i_{dop} versus Speed

Fig.(8) NNS Output at Step Change in Load Torque

Fig.(9) NNS Output at Step Change in Speed

Fig. (10) Te_1 and eff_1 Te_2 and eff_2 ϕ_{opt} Operation

Fig. (11) Te_1 and eff_1 with Loss Minimization Technique, and Te_2 and eff_2 for Optimal Inverter Angle Operation

Fig.(12) Performance of NNA at Step Change in Load Torque