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DESIGN OF AN OPTIMIZATION METHOD TO ENHANCE THE EFFICIENCY OF DRIVING MOTOR IN HYBRID ELECTRIC VEHICLES

Qi Wang, Yinsheng Luo, Shaobang Xing and Taihong Chen

School of Electrical and Information Engineering
Jiangsu University of Technology
No. 1801, Zhongwu Road, Zhonglou District, Changzhou 213001, P. R. China
wangqitz@163.com

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Abstract. *In order to enhance the driving motor efficiency in hybrid electric vehicles (HEV), a nonlinear programming optimization algorithm was implemented for the control of a permanent magnet synchronous machines (PMSM) to find the optimum current vector references which minimize the total copper and core losses in the entire operating region of the motor, including the field weakening mode. The maximum voltage and current constraints of the drive system are also included in the optimization. The driving motor in HEV had been secondarily developed under MATLAB/ADVISOR, so did the optimization method. The simulation results indicate that the power losses after optimization of driving motor are reduced greatly with the energy efficiency being enhanced. At the same time, the working points of driving motor in high efficiency area are increased.*
Keywords: Hybrid electric vehicles, Driving motor, Efficiency, Optimization method

1. **Introduction.** Permanent magnet synchronous machines (PMSM) are widely used in hybrid electric vehicles (HEV) applications. There are different algorithms that can be used to current controllers of PMSM. A good current vector reference should, for instance, provide the maximum possible torque for a given magnitude of current or minimize the losses in the machine. These objectives can be achieved by using an appropriate control method. There are different approaches to minimize the losses. In [1] a fuzzy logic controller is used whereas in [2] a neural network algorithm is proposed while the maximum torque per ampere (MTPA) control has remained a popular choice in many applications. However, the question is that if the last approach gives the lowest losses when core losses are considered. There have been different suggestions to compensate for this deficiency. In [3] a model based PMSM including the core loss is used to derive an analytical equation for calculation of the current vectors. In [4] the same model of PMSM is used and a weighting factor is proposed to get the current vectors which produce even lower losses. However, a fully optimized model based current vector control and quantification of how much energy could be gained by using an energy optimized control instead of the MTPA strategy for various drive cycles, is missing.

In order to overcome the above problems, the purpose of this paper is to use a nonlinear programming optimization and an ordinary MTPA control to find and compare the efficiency and losses in the HEV for some selected driving cycles. Furthermore, a target is to derive and demonstrate a more advanced circuit model where the core loss resistance as a function of speed is implemented. In Section 2, the model of PMSM was introduced in detail, and in Section 3 loss minimization of current vector control was given. In Section 4, the nonlinear programming method was used to minimize the losses of PMSM. Before concluding, we simulated the whole optimization system in Section 5. Section 6 concludes the paper.

2. **Model of the PMSM.** Since the optimization is intended to acquire the current vector trajectories, it is sufficient to know about the steady state operation of the machine. As a result, the steady state equivalent circuits of the PMSM in d-q system considering core losses without transient components are illustrated in Figure 1.

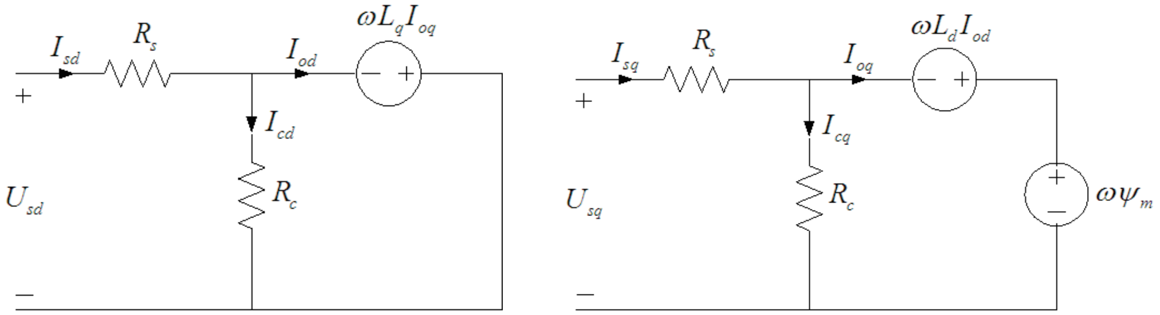

FIGURE 1. Equivalent d-q circuits of PMSM in the steady state considering core losses

The equations corresponding to the equivalent circuits are written as

$$U_{sd} = R_s I_{sd} - \omega L_q I_{oq} \tag{1}$$

$$U_{sq} = R_s I_{sq} + \omega L_d I_{od} + \omega\psi_m \tag{2}$$

$$I_{od} = I_{sd} - I_{cd} = I_{sd} - \frac{\omega L_q I_{oq}}{R_c} \tag{3}$$

$$I_{oq} = I_{sq} - I_{cq} = I_{sq} - \frac{\omega L_d I_{od} + \omega\psi_m}{R_c} \tag{4}$$

where I_{sd} and I_{sq}: d- and q-axis components of armature current; I_{cd} and I_{cq}: d- and q-axis components of core loss current; U_{sd} and U_{sq}: d, q components of terminal voltage; ψ_m: $\sqrt{3/2}\ \psi_f$, ψ_f: maximum flux linkage of permanent magnet; R_s: armature winding resistance; R_c: core loss resistance; L_d and L_q: inductance along d- and q-axis; w: motor electrical angular velocity.

By using (1) to (4) and some simplification the input voltages can be expressed as

$$U_{sd} = \left(R_s + \frac{\omega^2 L_d L_q}{R_c}\right) I_{sd} - \omega L_q I_{sq} + \frac{\omega^2 L_q \psi_m}{R_c} \tag{5}$$

$$U_{sq} = \left(R_s + \frac{\omega^2 L_d L_q}{R_c}\right) I_{sq} + \omega L_d I_{sd} + \omega\psi_m \tag{6}$$

Finally the electromagnetic torque can be expressed as

$$T_e = \frac{3}{2} p \big(\psi_m I_{oq} + (L_d - L_q)\, I_{od} I_{oq}\big) \tag{7}$$

where p is the pole-pairs of PMSM.

2.1. **Losses in PMSM.** A PMSM machine contains electrical and mechanical losses. However, the mechanical losses are not controllable by current vector control; in addition, they are relatively low. The electrical losses can be said to consist of copper and core losses. The copper losses (P_{cu}) are proportional to the currents squared and can be calculated by

$$P_{cu} = \frac{3}{2} R_s \left(I_{sd}^2 + I_{sq}^2\right) \tag{8}$$

Core losses can be divided into hysteresis, eddy current and excessive current. It is generally very difficult to find an accurate analytical model for core losses but they can be roughly expressed as proposed in [5] by

$$P_{Fe} = k_{eddy} f^2 B^2 + k_{hyst} f B^2 + k_{ex} f^{1.5} B^{1.5} \tag{9}$$

The entire no-load losses are assumed to be dominantly due to the core losses and represented by a parallel resistance called R_c which can be found in the equivalent circuits in Figure 1. R_c can be calculated by

$$R_c = \frac{3}{2}\frac{(w\psi_m)^2}{P_{Fe}} \tag{10}$$

2.2. **Practical constraints of the system.** An inverted fed PMSM has some constraints due to limitations of the inverter that should be respected by the controllers. These limitations are mainly the maximum current and voltage of the machine.

$$U_{\max} \geq \sqrt{U_{sd}^2 + U_{sq}^2} \tag{11}$$

$$I_{\max} \geq \sqrt{I_{sd}^2 + I_{sq}^2} \tag{12}$$

These constraints are incorporated in the optimization method.

3. Loss Minimization of Current Vector Control.

An aim of a current vector control method is typically to minimize the electrical losses in the machine. This vector is often derived without considering the effect of the core losses. However, in a practical solution, it is important that the method fulfills the constraints and includes both core and copper losses. A general MTPA control method without the core losses and without the voltage and the current constraints can be obtained by the following steps. First, the *d*-*q* currents and torque can be expressed as a function of current angle by

$$I_{sq} = I_a \cos(\phi) \tag{13}$$

$$I_{sd} = I_a \sin(\phi) \tag{14}$$

where I_a is the current magnitude vector and ϕ is the angle between I_{sd} and I_{sq}. Consequently the torque equation can be rewritten as

$$T_e = \frac{3}{2}p\left[\psi_m I_a \cos(\phi) + (L_d - L_q) I_a I_a \cos(\phi)\sin(\phi)\right] \tag{15}$$

The torque can be maximized with regards to the current angle by

$$\frac{dT_e}{d\phi} = 0 \tag{16}$$

Finally the current vector angle as a function of current magnitude is obtained as

$$\sin(\phi) = -\frac{\psi_m}{4(L_d - L_q) I_a} \pm \sqrt{\frac{\psi_m^2}{16(L_d - L_q)^2 I_a^2} + \frac{1}{2}} \tag{17}$$

4. Nonlinear Programming.

A problem needs to be solved by nonlinear programming when the function which is supposed to be optimized is at least quadratic or "more nonlinear" and the constraints to these functions are not linear [6]. The main purpose of this optimization is to minimize the target function $f(x)$,
$\min f(x)$
with the following constraints.

$A \cdot X = B$ Linear equality
$C \cdot X \leq D$ Linear non-equality
$E(X) = 0$ Nonlinear equality
$F(X) \leq 0$ Nonlinear non-equality

The target function $f(x)$ consists of the copper losses and core losses which can be introduced as

$$f(x) = P_{core} + P_{copper} = R_s\left(I_{sd}^2 + I_{sq}^2\right) + R_c\left((I_{sd} - I_{od})^2 + (I_{sq} - I_{oq})^2\right) \tag{18}$$

The state matrix X is chosen to be

$$X = [I_{od} \quad I_{oq} \quad I_{sd} \quad I_{sq} \quad U_{sd} \quad U_{sq}]^T$$

The relations between the states can be represented by the linear equations in matrix A and B or nonlinear equations in matrix E. Thus, the equivalent circuit equations will be rewritten for all four loops in the d and q equivalent circuits which were shown in Figure 1.

$$-R_cI_{od} - R_cI_{sd} - wL_qI_{oq} = 0 \tag{19}$$

$$-R_cI_{oq} - R_cI_{sq} - wL_dI_{od} = 0 \tag{20}$$

$$R_cI_{od} - (R_s + R_c)\,I_{sd} - U_{sd} = 0 \tag{21}$$

$$R_cI_{oq} - (R_s + R_c)\,I_{sq} - U_{sq} = 0 \tag{22}$$

All the above equations are linear and hence they can be included in the A and B matrixes shown below.

$$A = \begin{bmatrix} -R_c & wL_q & R_c & 0 & 0 & 0 \\ -wL_d & -R_c & 0 & -R_c & 0 & 0 \\ R_c & 0 & -(R_c + R_s) & 0 & 1 & 0 \\ 0 & -R_c & 0 & -(R_c + R_s) & 0 & 1 \end{bmatrix}$$

$$B = [0 \quad w\psi_m \quad 0 \quad 0]$$

Equality equations are vital in order to decrease the degree of freedom for the optimization. They can also shorten the optimization time. Every constraint involving a state should be represented in the linear or nonlinear non-equalities matrixes (C, D, F), and there is no linear non-equality in the optimization, which means the matrixes (C, D) are null matrix. The constraints presented below are in motoring mode.

$$E(X) = \left[T_{ref} - \frac{3}{2}p\left(\psi_m I_{oq} + (L_d - L_q)I_{od}I_{oq}\right)\right]$$

$$F(X) = \begin{bmatrix} -U_{\max} + \sqrt{U_{sd}^2 + U_{sq}^2} \\ -I_{\max} + \sqrt{I_{sd}^2 + I_{sq}^2} \\ -\sqrt{I_{sd}^2 + I_{sq}^2} \\ I_{sd} \\ I_{sq} \end{bmatrix}$$

5. **Simulation Results.** In order to verify the optimization model and method which we proposed in this paper, the simulation research has been carried out under the environment of MATLAB/ADVISOR which is an advanced vehicle simulator developed by American Natural Renewable Energy Library. The basic parameters of HEV and PMSM are in Table 1, and we choose the Urban Dynamometer Driving Schedule (UDDS) shown in Figure 2 as the driving cycle which is usually selected as the testing condition.

The simulation results are shown in Figure 3. Figure 3(a) and Figure 3(b) are the power losses and efficiency of driving motor respectively, and Figure 3(c) is the efficiency working points' distributions of PMSM. From Figure 3, we can find that the power losses after optimization have been reduced, and the losses of every operating point of PMSM are decreased. The efficiencies of PMSM after optimization have been enhanced obviously,

TABLE 1. The parameters of HEV and PMSM

Vehicle Quality	1191 kg
Frontal Area	2 m^2
Coefficient of Aerodynamic Drag	0.335
Radius of Rolling	0.28 m
Maximum Power of Motor	58 kW
Voltage of Battery Pack	336 V
Initial Value of Battery SOC	0.9
R_s	0.0079 Ω
L_{sd}, L_{sq}	0.23 mH, 0.50 mH
Ψ_m	0.104
P	2

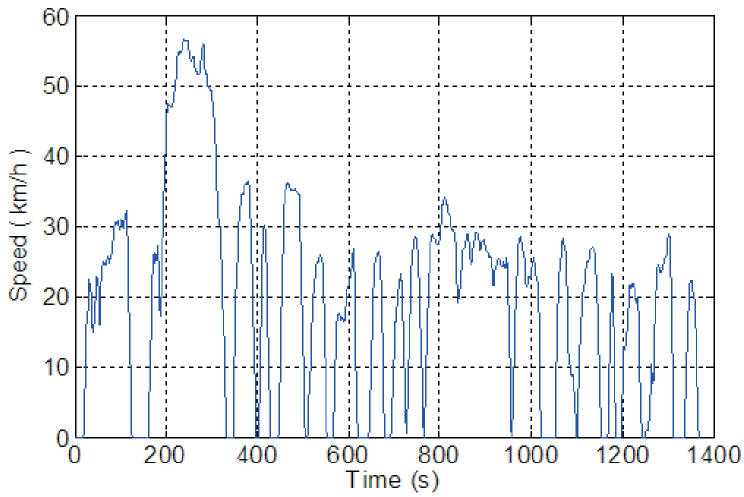

FIGURE 2. The UDDS driving cycle

the points in high efficiency area are more intensive, and the effect of optimization is significant.

6. **Conclusions.** In this paper, we designed an optimization method to enhance the efficiency of driving motor in HEV on the basis of establishing the mathematical model of PMSM, and secondarily developed the PMSM system and optimization method under MATLAB/ADVISOR simulation environment. And from the simulation results, we can get the following conclusions: the mathematical model of PMSM is effective, and it can accurately reflect the complex relationship between internal parameters. After optimization, the losses of PMSM are reduced obviously, and the efficiency is enhanced. Next, we will focus on the experiment of efficiency enhancing of PMSM by using the method we proposed in this paper and put in application as soon as possible.

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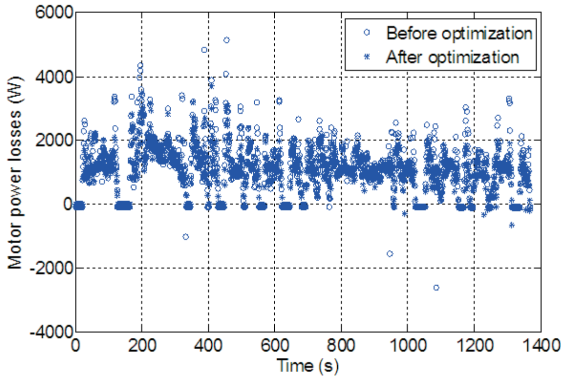
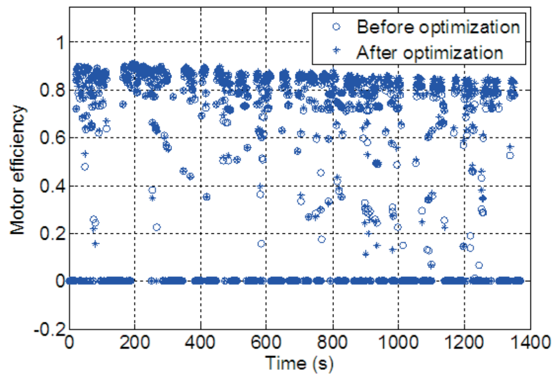
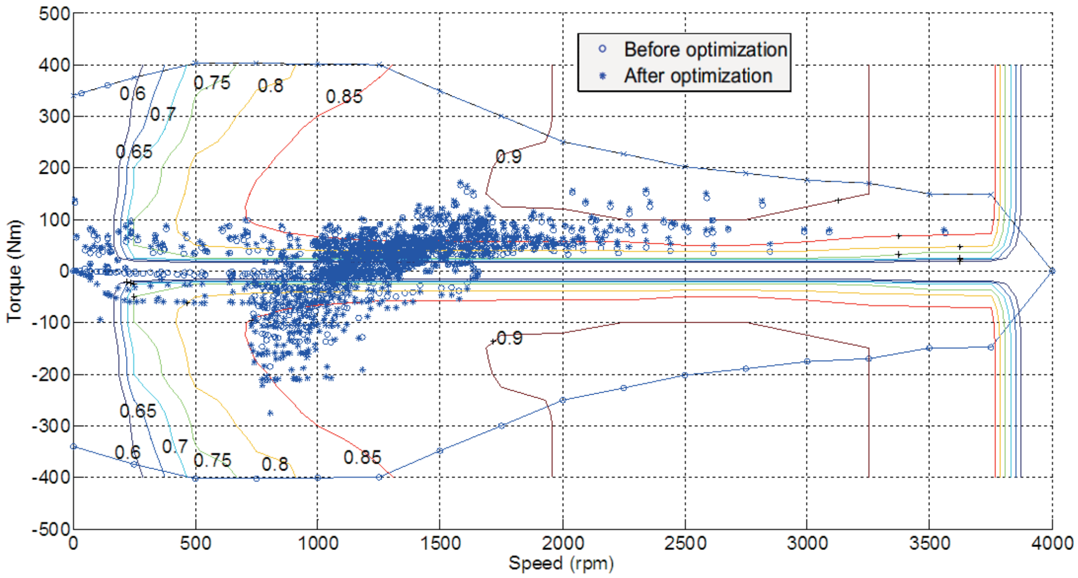


(a) The power losses of PMSM



(b) The efficiency of PMSM



(c) The efficiency working points' distributions of PMSM

FIGURE 3. The simulation results of PMSM

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