A Hybrid MIP-CBO Approach for Loss Minimization of the PMSM-fed Electric Vehicle Drive System

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ABSTRACT

This paper presents an efficient operation method suitable for Permanent Magnet Synchronous Motors (PMSMs). The proposed algorithm provides control of copper and iron losses across the range of operations. The machine operating concept was initially reviewed to establish the control method, and a model was created for control purposes. The efficient operation boundary of the machine was then established based on PMSM voltage and current constraints. A rapid search for the optimal operating point was made possible by a hybrid COOT optimization with Mixed Integer Programming. This expands the high-efficiency area of the motor drive in an electric vehicle, leading to longer Km between charges.

Keywords-loss minimization; Permanent Magnet Synchronous Motor (PMSM); mixed integer programming; COOT bird optimization

I. INTRODUCTION

Currently, HEVs are a popular and efficient solution for personal and urban public transport due to the fuel-energy crisis and environmental concerns. The provision of efficient and power-intensive electric motors is critical for the development and rapid implementation of HEVs. In general, induction motors have the potential advantages of low cost and a wide speed range but are less efficient than Permanent Magnet Synchronous Motors (PMSM) despite the use of the loss minimization algorithm [1]. In [1-14], a wide range of mathematical and soft computing methods were addressed. In [1], a mathematical loss minimization algorithm was developed to minimize the power loss of PMSM and balance the EV energy. In [2], a variable voltage control strategy was proposed to optimize motor electrical loss and improve motor, inverter, and the entire drive system efficiency. Moreover, the current harmonic of the motor stator winding was also reduced. In [3], a one-dimensional analytical model was presented to analyze the distribution of motor energy of the driving cycle and to reduce the loss and cost of the PMSM. In [4], fuzzy logic with a PI controller was applied to improve efficiency, maintenance cost, and power diversity, and reduce machine tracking error. In [5], a look-up table-based field-oriented with sliding mode control was proposed for an EV drive system. ANNs have been applied to reduce the loss of PMSMs. In [6], an equivalent conversion method was applied to minimize the loss for interior PMSM, studying both copper and iron losses and improving PMSM efficiency. The same machine was analyzed in [7]. In [8], harmonic analysis was applied to a Model Predictive Torque Control (MPTC) to maximize the efficiency and loss of FM motors and compare the results with an old model and other optimization methods. In [9], the PI-PSO technique was applied to improve the efficiency and robustness of an EV drive, and the results were compared with four different algorithms. In [10], copper loss reduction for PMSM was presented to determine machine torque and loss.

This study proposes a novel COOT bird technique integrated with Mixed Integer Programming (MIP) to minimize power loss and improve the efficiency of PMSM-based electric drive systems. The proposed algorithm was designed to minimize both copper and iron losses and improve the efficiency of the PMSM-subjected machine components. The proposed hybrid approach properly tuned the PMSM variables to improve performance. A comparative study was conducted for a PMSM with and without the proposed optimization method.

II. THE PROPOSED METHOD

An inverter-fed PMSM is a common topology in EVs. The input to this system is the acceleration and torque command. Figure 1 shows that the optimization algorithm searches for the optimal values of *Id* and *Iq* to produce a minimal loss. This study applied hybrid MIP and the Coot Bird Optimization (CBO) algorithm to minimize the loss of PMSM interconnected with an EV drive system.

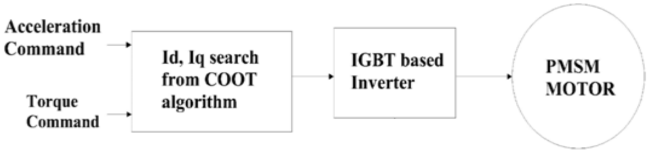

Fig. 1. Loss minimization by COOT optimization.

A. *Mixed Integer Linear Programming (MILP)*

In general, Mixed Integer Linear Programming (MILP) can be mathematically represented as follows: Let's assume X and Y two column variables, the components of which are x_i, i=1 to p, and y_j, j=1 to q, respectively. The two rectangular matrices A and B are of the order (m, p) and (m, q), respectively. Then the problem can be mathematically defined as:

$$\min F = A_0^T X + B_0^T Y \tag{1}$$

subjected to equality and inequality constraints

$$AX + BY = D \tag{2}$$

$$\alpha_i \leq y_j \leq \beta_j \tag{3}$$

$$y_j \text{ integer}, j = 1 \text{ to } q$$

$$0 \leq x_i, i=1 \text{ to } p \tag{4}$$

where x_i are the continuous variables, and y_j are integer variables. The objective function F should satisfy (2) and (3), and an optimal integer solution can be obtained by minimizing F.

B. *Coot Bird Optimization (CBO) Algorithm*

CBO is a new and efficient metaheuristic algorithm, inspired by the natural behavior of different movements of coot birds on the water surface [20]. Coot birds have two different modes of movement on the water surface: irregular and regular. Each coot bird moves in the direction of a group of leaders to reach a food supply. The characteristics of coot birds on the water surface are [20]:

- Random movement.
- Chain movement.
- Adjusting the position based on the group leaders.
- Leader movement.

The population of the coot is randomly generated and mathematically represented using:

$$\text{CootPos}(i) = \text{rand}(1, d).* (ub - lb) + lb \tag{5}$$

where CootPos(i) is the coot position, d is the number of variables or problem dimensions, lb is the lower bound of the search space [lb_1, lb_2, …, lb_d], and ub is the upper bound of the search space [ub_1, ub_2, …, ub_d].

C. *Random Movement*

The random movements of the coot birds at position Q are determined using:

$$Q = \text{rand}(1, d).* (ub - lb) + lb \tag{6}$$

To keep away from a local optimum solution, the position of the coot is updated using:

$$\text{CootPos}(i) = \text{CootPos}(i) + A \times R2 \times \left(Q - \text{CootPos}(i)\right) \tag{7}$$

where $R2$ is a random number in the interval [0, 1], and A is determined using:

$$A = 1 - L \times \left(\frac{1}{iter}\right) \tag{8}$$

where L is the current iteration, and $iter$ is the maximum iteration number.

D. *Chain Movement*

The chain movement can be given by the average position of two coot birds as:

$$\text{CootPos}(i) = 0.5 \times \left(\text{CootPos}(i-1) + \text{CootPos}(i)\right) \tag{9}$$

where CootPos(i-1) is the position of the second coot.

E. *Adjusting Position Based on Group Leaders*

The coot bird updates its position according to the position of the leader in the group. The leader is selected using:

$$K = 1 + (\text{iMOD}\ NL) \tag{10}$$

The next position of the coot based on the selected leader is premeditated using:

$$\text{CootPos}(i) = \text{LeaderPos}(k) + 2 \times R1 \times \cos(2R\pi) \times \left(\text{LeaderPos}(k) - \text{CootPos}(i)\right) \tag{11}$$

F. *Leader Movement*

The leader must jump from the existing local optimal position to the global optimal position using:

$$\text{LeaderPos}(i) = \begin{cases} B \times R3 \times \cos(2R\pi \times \left(\text{gBest} - \text{LeaderPos}(i)\right) \\ \qquad +\text{gBest},\ R4 < 0.5 \\ B \times R3 \times \cos(2R\pi \times \left(\text{gBest} - \text{LeaderPos}(i)\right) \\ \qquad -\text{gBest},\ R4 \geq 0.55 \end{cases} \tag{12}$$

where gBest is the best position ever found, R3 and R4 are random numbers in the interval [0, 1], R is a random number in the interval [-1, 1], and B is calculated using:

$$B = 2 - L \times \left(\frac{1}{Iter}\right) \tag{13}$$

III. PROPOSED PMSM MODEL AND PROBLEM FORMULATION FOR LOSS MINIMIZATION

This section describes the proposed PMSM vector control model for the loss minimization problem, which forms the background for the Simulink models used in MATLAB. Various control techniques can be used, such as Field-Oriented Control (FOC) or Direct Torque Control (DTC), to accurately regulate the motor's speed and torque. Figure 2 shows the complete simulation model for the FOC.

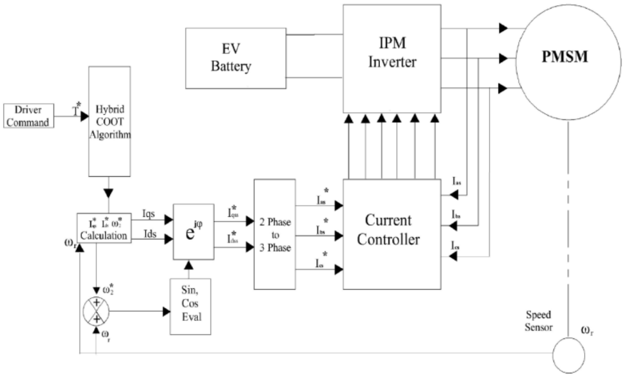

Fig. 2. Vector control model for PMSM electric drive.

Copper, iron, stray, and mechanical losses, including windage loss, are included in PMSM losses. This modeling fails to discuss windage loss because it is not directly related to motor current or flux level.

A. Objective Function

The primary objective is to minimize the power loss of the PMSM:

$$\text{Minimize } P_t(i_d, i_q) \tag{14}$$

B. Copper Loss

The copper loss occurs in the stator and rotor windings due to the resistance of the copper r_s, given by:

$$P_{cu} = \frac{3}{2} r_s (i_d^2 + i_d^2) \tag{15}$$

C. Iron Loss

The iron loss is mathematically defined as:

$$P_{fe} = c_{fe} \omega^{\gamma} (\lambda_d^2 + \lambda_q^2) \tag{16}$$

where $\gamma = 1.5 \sim 1.6$ and C_{fe} is the iron coefficient.

D. Stray Loss

The computation of stray losses is laborious and cannot be relied upon to provide accurate results. In reality, stray losses are assessed as:

$$P_{str} = c_{str} \omega^2 (i_d^2 + i_q^2) \tag{17}$$

E. Constraints of PMSM

Subject to:

$$T_e = T_0 \tag{18}$$

The voltage constraints used are as follows:

$$V_d^2 + V_Q^2 = \omega^2 \big(L_{dd}(1 - \alpha, i_q) i_d\big) - \big(L_{dq} + \alpha_m\big)^2 \tag{19}$$

The current constraint is:

$$i_d^2 + i_q^2 < I_{max}^2 \tag{20}$$

$$\propto_m = L_{dd} i_f \tag{21}$$

and again:

$$V_d^2 + V_q^2 = \frac{V_{DC}}{\sqrt{3}} \tag{22}$$

IV. IMPLEMENTATION OF THE PROPOSED MIP-CBO FOR LOSS MINIMIZATION

The fundamental goal of a vector controller is to convert the PMSM's three-phase stator currents and voltages from a stationary reference frame, commonly referred to as the ABC or 0 reference frame, to a revolving reference frame, commonly referred to as the *dq* or rotor reference frame, which is aligned with the rotor flux. The control system architecture is made simpler by this transformation, which decouples the motor control variables. As shown in Figure 3, there are several sets (i_d, i_q) that can be used to generate a certain amount of torque T_0 and speed. The present set (i_d, i_q) was taken into account to minimize loss at a given torque value t_0.

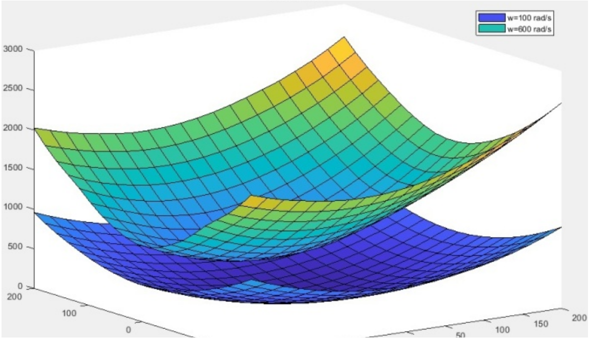

Fig. 3. Variation of machine loss with I_d and I_q.

The hybrid COOT optimization used is to find the current reference $\left(i_d^*, i_q^*\right)$ which can produce minimal loss. In addition, the voltage and current limits (fed as inequality constraints) need to be met. The simulation study involved the following steps:

- Step 1: Use a separate *m*-file to initialize the set of controller gains. This was loaded into the MATLAB workspace as a startup file. In Simulink, speed was set at a constant speed w_r.
- Step 2: Use the constant torque mode for the inverter controller, and set the torque command as T_0.
- Step 3: Use the hybrid COOT optimization to evaluate the objective function.
- Step 4: For the initial range, a feasible solution is obtained using MIP. For this increase, the *d*-axis current command is $I_d^c + \Delta I_d$.
- Step 5: The objective function is further refined using the COOT optimization in (14).

V. RESULTS AND DISCUSSION

The proposed MIP-CBO approach was effectively applied to minimize the various losses and improve the efficiency of a PMSM drive system. For PMSM, note that a maximum current is imposed before the iron core of the motor becomes magnetically saturated. The motor is said to be running in a "constant torque" region when the current exceeds this threshold because the torque can no longer be raised. The motor must work above its base speed in applications where higher speeds are necessary. The "flux-weakening" control approach is used to attain faster speeds. The torque starts to decrease in this manner, but the current increases past the constant torque area. The motor's back-EMF (electromotive force) voltage rises with speed, making up for the loss of torque and allowing the motor to run at higher speeds.

A. *Performance of PMSM with Optimal Controller Gains*

The optimal controller gains, shown in Table I, were fed into a simulation model and Figures 4-7 show the performance results. A simulation model was used in MATLAB/Simulink to evaluate the relation between I_d, I_q, power loss, and torque. During the simulation study, the initial SOC of the battery was assumed to be 90%, and a step of 0.001 was used.

TABLE I. CONTROLLER BLOCK GAINS

Conventional controller values		Hybrid COOT controller values	
DC To DC Conv. Kp	0.1	DC To DC Conv.Kp	.234
DC To DC Conv. Ki	10	DC To DC Conv.Ki	7
ICE.Kp	0.02	ICE.Kp	0.14
ICE.Ki	0.01	ICE.Ki	0.1
Controller.Veh_Spd. Kp	0.02	Controller.Veh_Spd.Kp	0.2
Controller.Veh_Spd.Ki	0.04	Controller.Veh_Spd.Ki	0.84

To increase the torque output of the motor, the current flowing through the motor windings should be increased. In contrast, reducing the current will decrease the torque. The torque-current characteristics of a PMSM show how current changes due to torque demand. A PMSM may generate more torque at low speeds using the same amount of current, while the torque output tends to decrease as the speed increases. The experiments were carried out under different load torque conditions. Figures 4 and 5 show the variation of motor current for torque changes, while Figure 6 shows the power variation of the machine under different load torques.

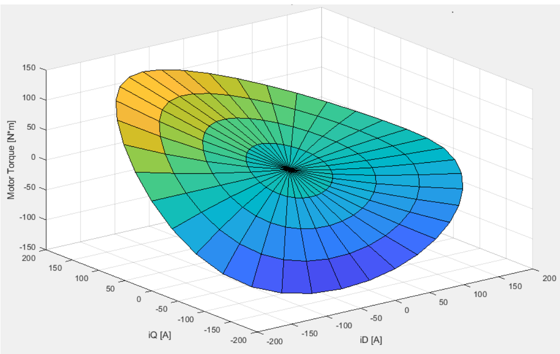

Fig. 4. Variation of torque with I_d and I_q.

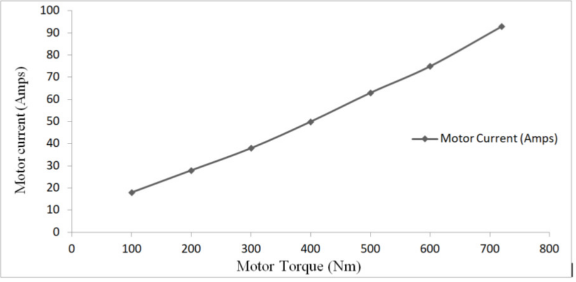

Fig. 5. Torque and current variation of PMSM.

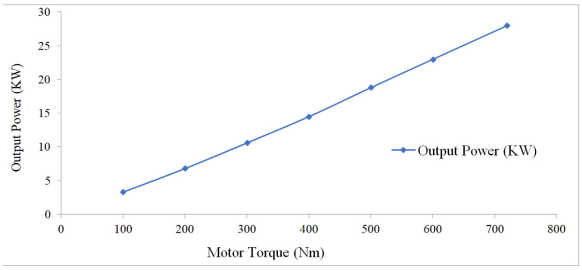

Fig. 6. Torque and output power variation of PMSM.

TABLE II. COMPARISON OF SIMULATION RESULTS AT RATED SPEED WITH VARIABLE TORQUE

Test Case	Torque Demand (N/m^2)	Efficiency (%)			Power loss (%)		
		Classical method [15]	MTPA Control [15]	MIP-CB0 (Proposed)	Classical method	MTPA Control	MIP-CB0 (Proposed)
1	725	92.05	92.13	96.34	7.95	7.87	3.66
2	600	92.08	92.18	96.23	7.92	7.82	3.77
3	500	91.87	91.97	96.42	8.13	8.03	3.58
4	400	91.28	91.42	92.08	8.72	8.58	7.92
5	300	89.95	90.13	93.22	10.05	9.87	6.78
6	200	86.89	87.17	90.59	13.11	12.83	9.41
7	100	77.9	78.42	83.02	22.1	21.58	16.98

TABLE III. COMPARISON OF SIMULATION RESULTS AT RATED TORQUE WITH VARIABLE SPEED

Test Case	Speed of PMSM (rpm)	Efficiency (%)			Power loss (%)		
		Classical method [15]	MTPA Control [15]	MIP-CB0 (Proposed)	Classical method	MTPA Control	MIP-CB0 (Proposed)
1	360	92.05	92.13	93.34	7.95	7.87	6.66
2	300	91.92	91.98	92.23	8.08	8.02	7.77
3	250	91.55	91.59	92.42	8.45	8.41	7.58
4	200	90.76	90.78	91.08	9.24	9.22	8.92
5	150	89.15	89.15	90.22	10.85	10.85	9.78
6	100	85.65	85.64	87.59	14.35	14.36	12.41
7	50	75.93	75.90	79.02	24.07	24.1	20.98

The COOT optimization with MIP was tested in different torque conditions, and the efficiency is presented in Table II. Obliviously, efficiency was improved in all seven load conditions. Additionally, the torque reference tracking ability of the controller was tested, as shown in Figure 7. Here, it can be seen that the machine's actual torque can track the reference torque. When load is applied, the speed drops from 3000 rpm to 2998 rpm, showing the speed regulation of the proposed method.

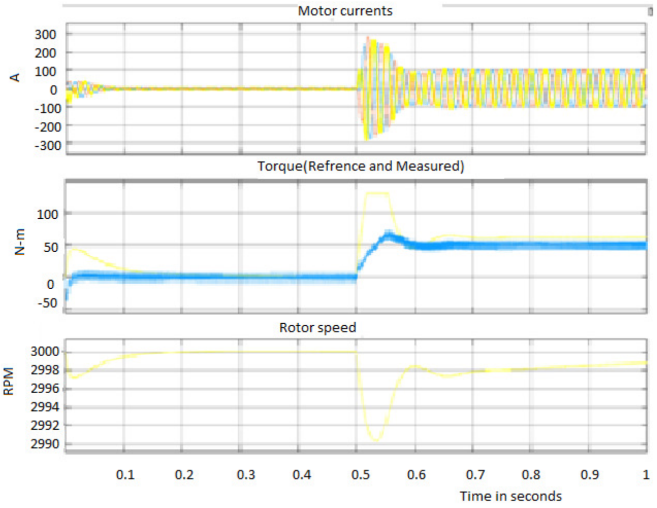

Fig. 7. Performance of the proposed drive under load change.

VI. CONCLUSION

This study presented a straightforward way to determine the best *d*- and *q*-axis current references to obtain the best efficiency. The value of the *DQ* component for a given torque and speed also satisfies voltage and current limitations. For a certain PMSM model, the COOT algorithm was used and tested under various driving cycles. With this strategy, an efficiency of up to 96 % was observed during the simulations. Torque reference tracking was studied in MATLAB/Simulink, where the controller was able to reach a steady state in 2 s. Peak overshoots in currents during loading were only twice the rated load current. The speed drop of the machine under load changes was very small, i.e. 2 rpm. Future work will attempt to implement this strategy into a real vehicle. Furthermore, the proposed method can be extended to a four-wheel drive mechanism. The proposed method improves the efficiency of the machine by altering only two parameters, the *Id* and *Iq* references. The COOT algorithm works in coordination with the FOC control algorithm as an add-on module. However, since most modern drives use FOC in their control module, a simple subroutine can be inserted to modify their performance.

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