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Design of Hybrid Excited Synchronous Machine for Electrical Vehicles

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The paper deals with the optimal design of a new synchronous motor particularly suitable for electric vehicles. The unique advantage of this motor is its possibility to realize field weakening at high speeds, which is the most important demand for such drives. The main design goal is to identify the dimensions of certain crucial regions of the machine in order to avoid saturation of the iron and to minimize the mass to volume ratio, while simultaneously maximizing the torque. The originality of the contribution is manifold: formulating the design problem in multi-objective terms, solving it by means of evolutionary computing, solving the associated direct problem based on a 3D-FEA field model, considering a reduced set of design variables by means of response surface method, referring to a real-life problem.

***Index Terms*—electric machines, design optimization, genetic algorithms, permanent magnet machines, Pareto optimization**

I. Introduction

HIGH-SPEED permanent-magnet motors with a brushless direct-current control scheme have found wide applications in the past few decades, because of their advantages such as high efficiency, high power density, and high drive performance [1]. For automotive applications, other than the obvious goal of efficiency, the reduction of weight at a constant power and torque has also become a strategic target for the design of these machines [2]. Additionally an optimal drive for electro-mobiles should offer extended high speed capabilities, demanded in a highway cycle – it can be achieved thanks to proper machine geometry design and sophisticated field weakening control strategies [3]-[6].

This paper is focused on the performance of a modified ECPMSM (Electric Controlled Permanent Magnet Excited Synchronous Machine) structure with two-layer windings, where the field weakening can be achieved by an additional stator fixed DC-coil [7], [8]. To control the magnetic field in the range from zero up to maximal values (and, consequently, wide speed variations), this coil has to be fed by a typical DC-chopper. Similar machines, possessing a conventional three phase stator, have also been analyzed in [9]. A patent close to this was published by Mizuno in 1997 [10]. The goal of this paper is to develop a cost-effective method for the optimal design of a machine which enables field weakening in a wide range of velocities subject to a prescribed torque. In the last decade, various methods for optimization of electromagnetic applications have been developed. Stochastic optimization has proven to be effective in finding the global solution without get stuck in local minima. However, in view of the practical implementation of these methods to industrial application, attention to the runtime has to be paid [11]. In this paper, a contribution towards this goal is also presented (Sections II and III).

The paper presents a unique concept of the hybrid excited machine having field weakening capabilities. The original structure of the machine has been optimized (Section III) and the prototype of the machine has been built at the laboratory scale. Finally, the experimental set-up has been shown together with some measurement results (Section IV).

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II. Direct problem

Figs. 1 and 2 show the fundamental structure of the proposed machine in detail. In order to perform the analysis of the magnetic field, a finite-element model of the device was developed taking the *B-H* non-linearity into account. The determination of all features of the ECPMS motor (torque, inductances, high-speed and field-weakening properties) is possible by using the 3D-calculation model. By means of this model, the ECPMS motor has been originally optimized according to the essential practical requirements. The following parameters were defined as main design parameters: the air-gap flux, the electromotive force, the cogging torque, the stator resistance/phase and inductance (self and mutual). The strategic target for the machine design was the maximization of the torque and the best high speed performance (field weakening).

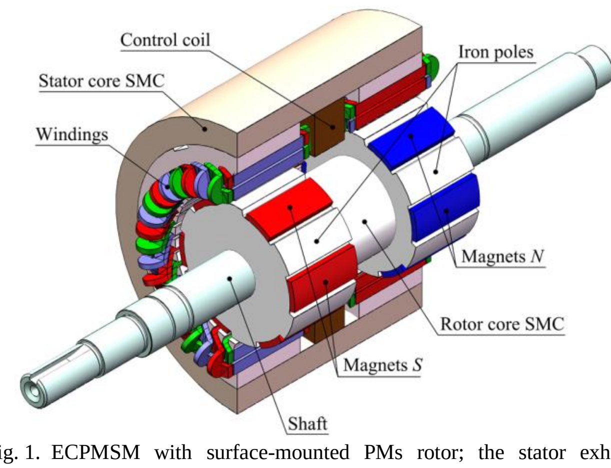

Fig. 1. ECPMSM with surface-mounted PMs rotor; the stator exhibits a three-phase two-layer windings with DC excitation auxiliary coil.

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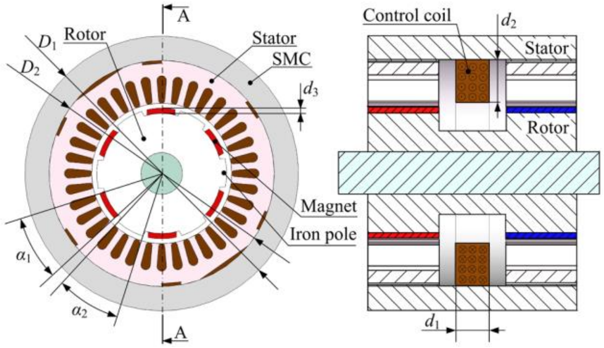

Fig. 2. Cross section of ECPMSM (left); longitudinal section: control coil (right).

III. Design problem

It is of great interest to improve motor geometry by design optimization, thus to reduce production costs and improve performance of motors [1]. The fundamentals of the field optimization have originally been described in [11], [12], [13] and [14] e.g. The initial 2D optimization of the machine has been partially done in [8]. The main geometrical dimensions of the machine under study were defined by the application requirements and the design problem consisting of identifying some crucial dimensions of the machine, so that the mass is minimized and the torque is maximized. For a vector of selected geometrical design variables **x**, the following objective functions have been defined:

$$f_1(\mathbf{x}) = \int_{\Omega} \rho(\mathbf{x}) d\Omega \tag{1}$$

to be minimized with respect to **x**, and

$$f_2(\mathbf{x}) = T(\mathbf{x}) \tag{2}$$

to be maximized with respect to **x**, with $\rho(\mathbf{x})$ − mass density and $T(\mathbf{x})$ − average torque on load, respectively.

In previous optimizations of ECPMS motor ([8], [16], [17]), NSGA-II algorithm was applied for solving the multi-objective problem of minimizing the mass of the motor while maximizing the average torque on load; three design variables, *i.e.* thickness and angular width of the magnet and radius of the rotor, were considered. The optimization was based on 2D-FEA calculations; only a posteriori, in the post-processing step, the optimization results were assessed by means of 3D-FEA simulations. The impact of the control coil on the optimal design was taken into account only in the post-processing phase.

The minimization of the cogging torque in the ECPMS motor using the topological gradient and a modified multi-level set method with total variation regularization has been performed in [18] and [19], respectively. The topology optimization of rotor poles in the ECPMSM using level set method and continuum design sensitivity analysis has been presented in [20] (foundations of these methods can be found *e.g.* in [21], [22] and [23]). In this way it was possible to determine all geometrical dimensions of the machine and fulfill all fundamental optimization targets.

The goal of designing a machine which enables field weakening in a wide range of speed subject to a prescribed torque has been achieved by means of two subsequent optimizations.

Initially, the structure and all dimensions of the stator are set depending on application requirements. Accordingly to the problem formulation, a vector of design variables **x** has been defined: $\mathbf{x}=(D_1, \alpha_1, \alpha_2, d_1, d_2, d_3, d_4)$, where:

1. outer stator diameter D_1,
2. angular width α_1 of the magnet,
3. angular width α_2 of the iron pole,
4. dimensions of the control coil d_1, d_2,
5. height of the magnet d_3,
6. thickness of the outer stator yoke $d_4=(D_1–D_2)/2$.

All these variables have to be determined in order to fulfil such constrains as non-saturation of the magnetic core, maximum current density in the machine, power losses, etc.

When considering above multi-criteria optimization problem, the Pareto optima theory states the existence of a set of non-dominated solutions – Pareto optimal front, which points out the degree of conflict between objective functions [15]. In order to solve the problem numerically, different optimization tools coupled with the FLUX-3D FEM code have been developed and applied. The target was to automatically drive numerical models and search for optimal configurations in design studies. These tools can solve the aforementioned problem with different constraints of equality and inequality; both single-objective and multi-objective optimization scenarios are possible. Finally, for the optimization of the machine, two different optimization algorithms have been developed and adopted: Genetic Algorithm (GA) and Sequential Surrogate Optimizer (SSO).

Fig. 3 shows the initial model of ECPMSM which has been subjected a process optimization. Additionally, the regions most important for the determination of the magnetic field within the machine used for the optimization have been shown. These regions are: the SMC (soft magnetic composite material) face region situated in the central part of the stator and two regions in the middle of the air-gap under the magnet and the iron pole. The SMC material was used to enable the proper flux distribution control [24].

The purpose of the 1st study is to find the optimal thickness $d_4=(D_1–D_2)/2$ of the outer stator yoke made from SMC without exceeding a magnetic field of B_{sat}=1.2 T.

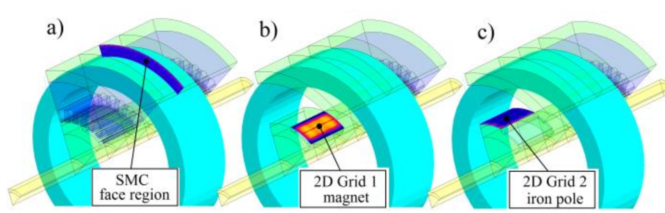

Fig. 3. Regions of magnetic field calculations used for optimization.

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Furthermore it has been assumed that the current density in the control coil can not exceed J_{cmax}=5A/mm^2 and the torque should have at least its nominal value $T(\mathbf{x})_{nom}$. These requirements define the main constraints for the optimization:

$$B \le B_{sat}, \quad J_c \le J_{cmax}, \quad T(\mathbf{x}) \ge T(\mathbf{x})_{nom}, \tag{3}$$

and the following objective function which should be minimized:

$$f_3(\mathbf{x}) = \int_{\substack{SMC \\ region}} Abs(B - B_{sat})dS, \tag{4}$$

where B is the induction in the SMC face region (Fig. 3a).

In the above defined case, when the explicit objective function behavior is not known, it is recommended to rely on approximation functions or response surfaces methods first. In order to determine the relative impact of design variables on the objective function $f_3(\mathbf{x})$, the screening analyzer tool was used [25]. This is accomplished by building approximated response surface, which allows the user to determine the most influential parameters and to reduce the number of possible variables. The results of such sensitivity analysis are shown in Fig. 4 – the influence of each parameter is represented by the amplitude of the expected effect. Due to this, the most influential parameter is d_4 – the influence of other parameters as α_1, α_2, d_1, d_2, d_3 is insignificant and should not be taken into account. The goal of the study is to optimize the quantity d_4, yielding a given magnetic flux, while respecting the size and physical constraints (saturation, maximum current density).

In order to make the optimization work, magnetic field analysis has been coupled with an appropriate optimization algorithm. In this respect, when dealing with objective functions and/or constraint functions which are known only numerically (see Eq. (3) and Eq. (4) which are finite-element dependent), standard assumptions like e.g. convexity and smoothness cannot be applied by any means. In this respect, according to a long-lasting experience, evolutionary computing has proven to be successful in identifying the global minimum – at the single-objective level – or the global Pareto front – at the multi-objective level – independently of the starting solution. This was the main rationale behind the choice of the optimization method. Finally the GA and the SSO have been used to compare effectiveness and costs of these optimization methods.

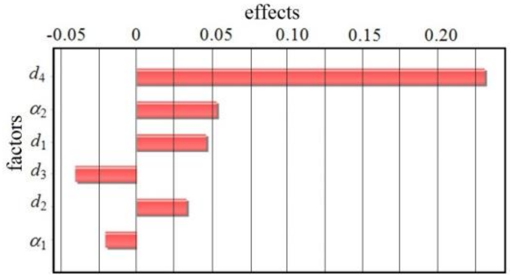

Fig. 4. Influence of the analyzed geometrical factors on f_3.

Each iteration of GA corresponds to one generation composed of a population of candidate solutions. The method permits to avoid the trap of the local optimum. Therefore, the algorithm is costly in terms of evaluations and is based on successive random evaluations. The SSO utilizes the surrogate building and evaluation methods, as well as automatic sequential iteration, in order to reach convergence between surrogates and functions. The purpose of an SSO is to find the local optimum of a constrained problem. The results of both optimizations are shown in table 1 (the other design parameters were fixed: α_1=0.8, α_2=0.8, J_c=5A/mm^2, d_1=30mm, d_2=30mm, d_3=3mm).

TABLE I
OPTIMIZATION RESULTS

Algorithm	Genetic Algorithm	Sequential Surrogate Optimizer
Max generation	20	-
Population size	50	-
Max iteration number	-	6
Tolerance	-	1E-6
d_4	4.36 mm	4.37 mm
f_3	2.20E-3	3.27E-4
B_{max}	1.202 T	1.19967 T
Calculation time	5h:5 min	1h:15 min

As it is shown above, both optimization algorithms give very accurate similar results; however, they don't have the same calculation costs. Table 2 shows the development of the optimization quantities using SSO in following iterations.

TABLE II
CHANGES OF D_4 AND B_{MAX} IN SUBSEQUENT ITERATIONS

Number of iteration	d_4 [mm]	B_{max} [T]
1	2.00	1.5700
2	4.42	1.1871
3	4.38	1.1972
4	4.37	1.1997

The purpose of the 2nd study is to find the optimal dimensions of the control coil d_1, d_2 (Fig. 2) under the assumption that a minimum ratio between the magnetic flux of magnets and iron poles, in the case of weakening magnetic field (with opposite direction of current control coil), is equal to the defined value ε. This value should be chosen in order to avoid the saturation of iron parts and to ensure the proper ratio between magnetic fluxes for both directions of the auxiliary currents.

According to previously obtained results [26], it can be concluded that in the proposed ECPMS machine, a field-weakening ratio over 2:1 (or even higher) can be actually obtained if the ratio of flux Φ_1 passing through the magnet to flux Φ_2 passing through the iron pole ε is equal to 0.5 (calculated while the magnetic field is weakened). This know-how has been adopted here as the design criterion. This leads to the machine with very good field weakening and optimal control properties. The flux over the PM in the case of strengthening of the magnetic field should be much greater than the total flux over the iron part. Parameters obtained from the FEM model used for the evaluation are:

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Φ_1 – magnetic flux calculated on the 2D Grid 1 for the permanent magnet (according to Fig. 3b),

Φ_2 – magnetic flux calculated on the 2D Grid 2 for the iron pole (according to Fig. 3c).

This leads to the formulation of the next objective function, which should be minimized:

$$f_4(\mathbf{x}) = Abs(2\Phi_1 - \Phi_2). \tag{5}$$

As far as the optimization algorithm is concerned, GA has been used with a maximum number of 20 iterations and a population size of 50. Additionally, a uniform crossover with probability equal to 0.6, and non-uniform mutation with probability equal to 0.32 were implemented for the seed of the pseudo-random generator. Each iteration lasts approximately 1.5 hours on a platform based on Intel Core i7 980X processor. All these considerations made it possible to determine optimal dimensions of the ECPMSM − see Table 3 (initial values of d1 and d2 were equal to 20 mm).

TABLE III
EVALUATION RESULTS

d_1	d_2	d_3	B_{max}	f_3	f_4
28.40 mm	27.25 mm	3.00 mm	0.88 T	0.42 T	2.47e^{-7} Wb

For the optimized geometry the fluxes over the PM and over the iron pole have following values: $\Phi_1 = 2.17\text{e}^{-4}$ Wb and $\Phi_2 = 4.31\text{e}^{-4}$ Wb, minimizing the objective function f_4 almost perfectly.

The magnetic field distributions within the ECPMS motor for different currents in the DC-coil have been shown in Fig. 5. In this figure all regions with the highest saturation can be easily observed.

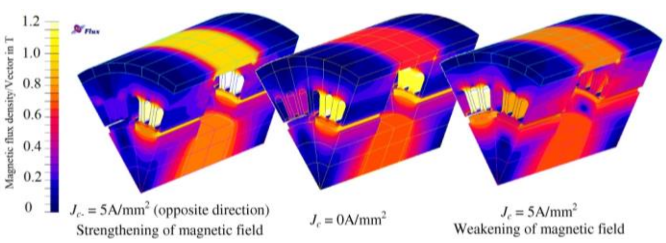

Fig. 5. Magnetic field distribution within Flux3D post optimization model of ECPMSM in the case of strengthening (left) and weakening (right) of the magnetic field.

Fig. 6 shows the magnetic flux density (magnitude) in the air-gap under the magnet and the iron pole in the middle of the air-gap in a single part of the machine for different current densities J_c of the stator control coil.

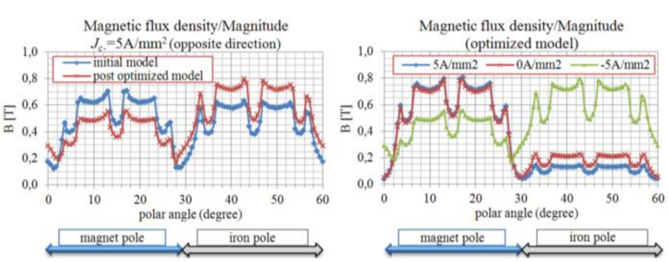

Fig. 6. Magnetic flux density in the air-gap under magnet and iron pole at the different current density J_c of the control coil.

Moreover Fig. 7 shows the magnetic flux density (magnitude) across the total air-gap over magnets and iron poles and its change along the axis direction of the initial (top of the figure) and post optimized model of ECPMSM (bottom of the figure). For each case the magnetic flux Φ_1 and Φ_2 was calculated and shown. It can be observed that, in the post optimized model, the ratio of Φ_1 to Φ_2 is nearly equal to 0.5. This condition makes it possible to vary the induced voltage in the machine in required range [2], [6], [7].

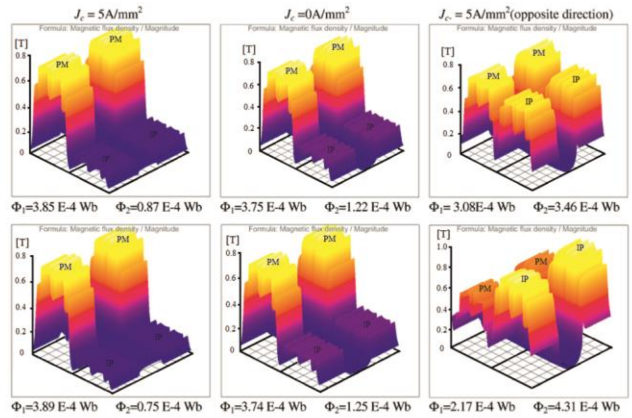

Fig. 7. Magnetic flux density (magnitude) in the air-gap under magnets and iron poles: initial model (top), post optimized model (down).

Fig. 8 shows the initial (left) and post optimized mapped meshed model (right) of ECPMSM with the fixed control coil. The most significant change in comparison to the initial model is the bigger size of the DC-coil and lower thickness of the back-iron.

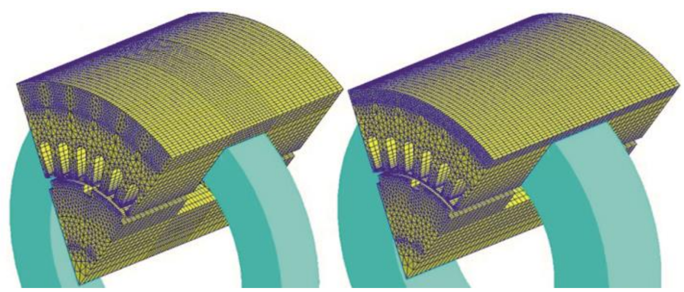

Fig. 8. Initial (left) and post-optimization meshed model (right).

IV. Test Results

The experimental results of both the capability of the flux control and the dynamic performance of the ECPMSM (partially given in Fig. 9), have been done using the experimental setup shown in Fig. 10. This setup consists of the ECPMS machine, load/drive induction machine CM-5-7 (ABB) controlled by ACS 800 (ABB), the torque meter and the power supply system.

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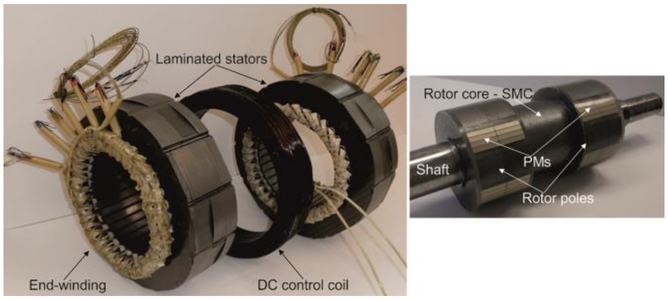

Fig. 9. Stator and rotor parts of the ECPMS machine.

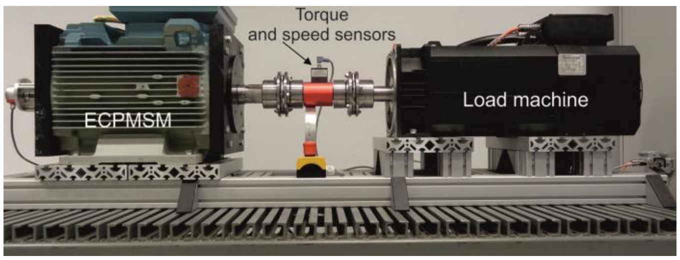

Fig. 10. Experimental setup.

In order to supply and control of the machine specific three-phase voltage inverter and DC/DC converter (for auxiliary coil power supply) have been used. Field Oriented Control algorithm has been applied with linear PI controllers, acting independently on the *d*- and *q*-axis current components. Power Analyzer Norma 5000 (Fluke), digital oscilloscope, torque and position meters have been used to determine both no-load and load characteristics i.e.: torque curves, efficiency maps and voltage waveforms etc. Whole drive system and measurement devices were controlled by a central computer.

First, the characteristic of the starting torque depending on the DC control coil current value in range from I_{DC} = -5 A to I_{DC} = 5 A have been measured (presented in Fig. 11). Obtained results show that the values of the torque depend on the DC control coil current and they are strongly increased during strengthening of the magnetic field.

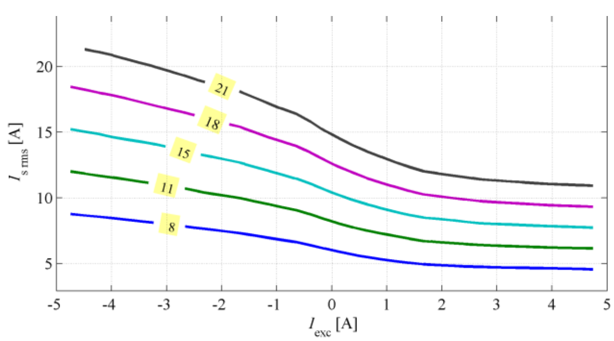

Fig. 11. Starting torque vs. current in stator windings (I_{srms}) and in the DC control coil.

In the next stage of the research back-EMF waveforms, values and harmonics have been measured. Fig. 12 shows Back-EMF waveforms for three different values of the DC control coil current I_{DC} = 2; 0; -2A, at 1000 rpm velocity, and it also shows a real weakening and strengthening possibility of the machine.

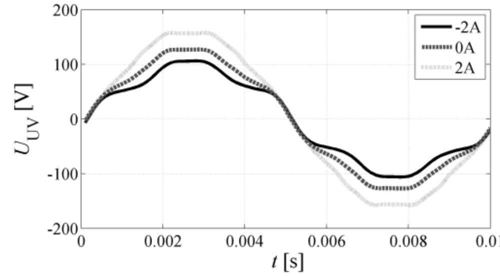

Fig. 12. Back-EMF phase-to-phase waveforms at 1000 rpm for the selected values of the DC control coil current.

In order to perform the operation analysis of the ECPMS machine, required values of I_d, I_q, and I_{DC} were calculated offline and stored in the look-up table control (*LUT*) ([27]-[30]). For a selected range of operating points (a combination of torque and speed), these three values of current were identified *a posteriori* by means of a searching algorithm in order to minimize the total losses of the machine. The block diagram of power and control systems, with implemented *LUT* method in the hybrid ECPMS machine, is shown in Fig. 13.

The coil current values obtained by the searching algorithm are shown in Fig. 14. In the high speed region, I_{DC} value was reduced (flux weakening operation). In contrast, increasing this current allowed to obtain higher torque and reduction of stator current in the low speed region. On the other hand, it should be noted that thermal losses generated in the DC control coil may be an important component of overall losses in the ECPMS machine.

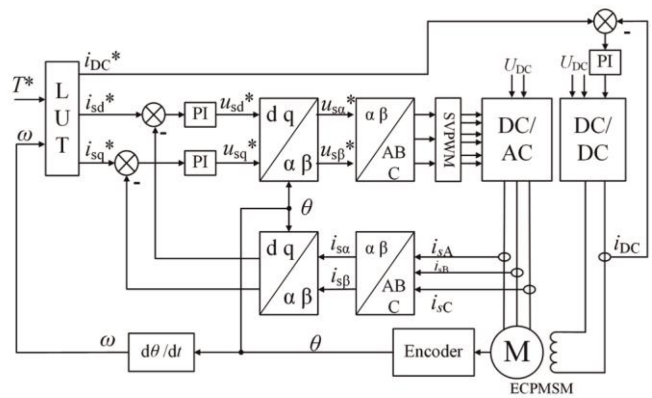

Fig. 13. Diagram of power system with *LUT* control method for hybrid ECPMS machine.

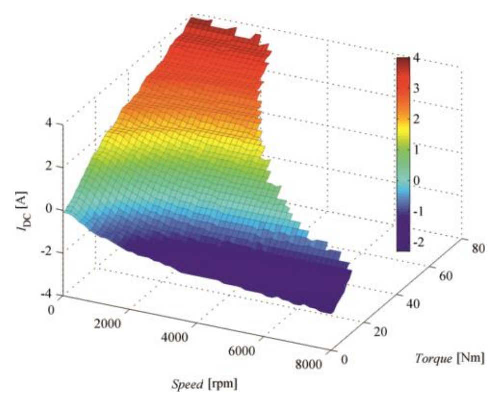

Fig. 14. I_{DC} current values *vs* motor speed and torque after *off-line* calculation.

V. Conclusion

In this paper the shape optimization of an ECPMS machine has been performed. For this optimization the Genetic Algorithm and the Sequential Surrogate Optimizer have been used. Finally, all crucial dimensions of the machine have been determined in order to enable the field weakening in a wide range of velocities subject to a prescribed torque. Additionally all design objectives and associated constraints typical for electric vehicles have been fulfilled. Considering that the analysis solution is based on a 3D finite element model and comparing the runtime of both optimization algorithms, the implemented procedure of optimal design is compliant with the industrial process. In particular, the wide investigation of feasible solutions highlighted the most sensitive design variables in the search for an optimal solution. Measurements done on the built set-up show that the main optimization target (proper weakening of the magnetic field at high velocities) has been gained and the proposed control system offers an effective flux control method allowing to extend the maximal speed of the machine over 2 times (with respect to no excitation control strategy) at constant-power range.

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