Improved Control System of PM Machine with Extended Field Control Capability for EV Drive

Piotr Paplicki and Rafał Piotuch

West Pomeranian University of Technology, Szczecin, Poland
Department of Power Engineering and Electrical Drives
{paplicki,rpiotuch}@zut.edu.pl

Abstract. The paper presents novel concept of prototyping, analysis and optimization of an Electric Controlled Permanent Magnet Excited Synchronous Machine (ECPMSM) drive with a field weakening capability for electric vehicle (EV). Operation modes, features, characteristics, FEA and analytical results, improved control system of the machine, and schematic diagram of EV central drive system with ECPMSM machine were also presented.

Keywords: electric vehicles, PM machines, hybrid excitation, field weakening, control system, prototyping, optimization.

1 Introduction

Environmental as well as economic issues provide an impetus to develop clean, efficient, low-emission hybrid (HEV) and zero-emission electric vehicles (EV). Nowadays, the development of EV propulsion systems equipped with electric motor, transmission device and wheels, has been caused by rapid growth in power electronics, digital signal processors, control algorithms, and advances in material technologies [1].

Major requirements for EV motor as one of the most important element of EV drive system, can be summarized as follows: high power density, high torque at low speeds, very wide speed range including constant-torque and constant-power regions and high efficiency over wide speed and torque ranges. Moreover, important characteristics of electrical machines include flexible drive control, fault tolerant, and low acoustic noise. Additionally, motor drive must be capable of handling voltage fluctuations from the source and comply with the other requirements as: ruggedness, high torque-to-inertia ratio; peak torque capability of about 300 % of continuous torque rating, low electromagnetic interference and low cost.

The majority of EVs developed so far are based on DC machines, permanent magnet (PM) machines and induction machines (IM). In order to minimize their size and weight they are designed for high-speed operation for a given power rating. At present, IM machines are widely accepted and most commonly used for EV propulsion system because they are highly reliable and free from maintenance but they have relatively low power density [2, 3]. Therefore, the PM machines with excellent performance become more popular and suitable for EV drives among other machine types.

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There are many studies regarding PM brushless machines usage for EV drive including PM hybrid excited motors, where the air-gap magnetic field is developed by the combination of PM and additional winding [1, 2, 4–6].

There are many ways to achieve excellent efficiency of the energy conversion in the lower speed range of the PM machines [7]. One of these is oversizing PMs that they excite an increased no-load flux density and required torque values are achieved by smaller stator currents values. This advantage is inherently connected with challenges in the high speed regions, where due to the limited battery voltage values a force creating current cannot be driven into the machine windings [8].

In order to obtain required wide speed range, an optimal PM machine design for EV should offer a field weakening capability of at least 1:4. A common technique for the field weakening is based on a shift in the stator currents in such a way, that a part of current-caused field counteracts (weakens) the PM-excitation field. This requires an unfavorable oversizing of the machine and current converter [3, 4]. The technique is also commonly used in PM machines with embedded magnets [8].

This paper focuses on an Electric Controlled Permanent Magnet Excited Synchronous Machine (ECPMSM) as hybrid topology which has already been analyzed in details by the authors [2, 9–12] and others in [1, 5, 13] with Field Oriented Control (FOC) for EV applications.

2 Operation Modes of the ECPMSM Machine

The electric motor for EV drive is designed to operate at high speeds to minimize the size of the machine. Hence, gearbox is used to match high speed of the electric motor with lower speed of the wheels. Moreover, motors with extended constant power region and wide-operating speed range minimize the gearbox size, eliminate multiple gear ratios and clutch in EVs. This way, a single gear transmission in the range of 10 to 15:1 is sufficient to provide required driveshaft torque value.

Conventional electric motors have three major segments in its torque-speed characteristic: constant torque region (1), constant power region (2), and natural mode region (3) shown in Fig. 1a.

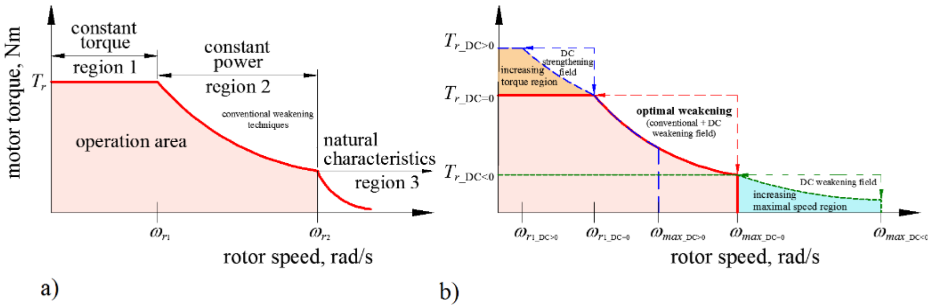

Fig. 1. Electric motor torque-speed curve: conventional motor (a), ECPMSM machine (b)

The motor delivers rated torque T_r up to the base speed ω_{r1} or up to the rated speed ω_{r2} of the motor when it reaches its power supply voltage limits. The motor operates in a constant power mode above the rated speed, where torque falls steadily at a rate that is inversely proportional to speed. Electric motors can operate at speeds higher than rated speed using field weakening techniques. There is a third natural mode region for high motor speeds, where the torque falls rapidly, being inversely proportional to the square of the speed. The natural characteristic region is an important part of the overall torque-speed curve of certain motors used in EVs. Moreover, extended constant power range capability is also extremely important to eliminate the use of multiple gear ratios and to reduce the power supply volt-ampere rating.

Hence, in order to extend the operating range of the motor and control its torque-speed characteristic the hybrid PM machines with field weakening and strengthening capability are used.

Fig. 1b shows extended torque $T_{r\_DC>0}$ and speed region of ECPMSM machine which can be operated in the field-weakening mode, similar to the DC motor, to extend the constant power range and achieve higher speeds $\omega_{max\_DC<0}$.

In order to realize field excitation control to increase or decrease the magnetization level of the ECPMSM machine an auxiliary direct current (DC) control coil is mounted in the stator of the machine. Fig. 2 (left) shows unique machine with a 12-pole double inner rotor topology and two sheeted stator cores. The machine offers broader speed range and higher overall efficiency but more complex construction and lower power density.

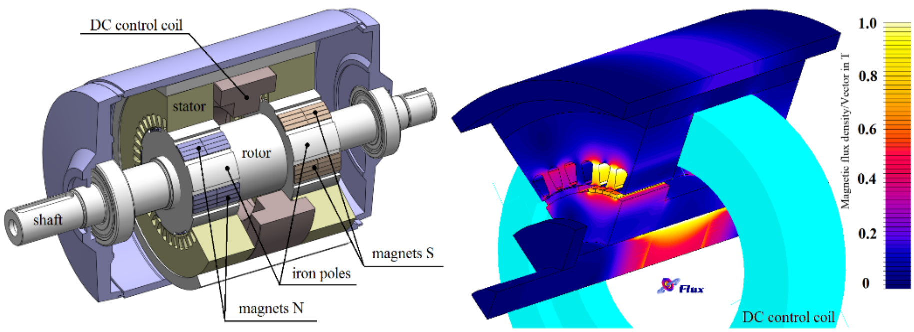

Fig. 2. The **ECPMSM** cross section with DC control coil (left); 3-D FE analysis model (right)

The ECPMSM machine design takes into account not only mechanical aspects of the machine but mainly electromagnetic considerations. The size of the motor depends on the maximum torque required on the machine shaft. During this study the maximum torque up to 100 Nm and rated speed of the motor equal to 5000 rpm have been assumed. Equation torque (1) for the ECPMSM machine shows that if a d-axis stator current i_d is constant ($i_d = 0$), generated torque is proportional to the q-axis current i_q and magnetic flux linkage Φ_d which is not constant compared to conventional PM machines. Torque and magnetic fluxes of the ECPMSM machine can be described by the following equations:

$$T = \frac{3}{2} p\left(\Phi_d i_q - \Phi_q i_d\right) \tag{1}$$

$$\Phi_d = \left(\Phi_{PM} + \Phi_{IP}\right)/2 \tag{2}$$

$$\Phi_q = L_{q,q} I_q \tag{3}$$

$$\Phi_{PM} = \Phi_{PM,PM} + \Phi_{PM,I} \tag{4}$$

$$\Phi_{IP} = \Phi_{IP,PM} + \Phi_{IP,I} \tag{5}$$

$$\Phi_{PM,I} = L_{PM,d} I_d + L_{PM,q} I_q + M_{PM,DC} I_{DC} \tag{6}$$

$$\Phi_{IP,I} = L_{IP,d} I_d + L_{IP,q} I_q + M_{IP,DC} I_{DC} \tag{7}$$

where: T – torque, p – number of pole pairs, $i_{d,q}$ – d, q-axis currents, Φ_z – z linked magnetic flux, $\Phi_{x,I}$ – x linked magnetic flux caused by current, $L_{X,Y}$ – X flux Y-current inductance, $M_{x,\mathrm{DC}}$ – x flux DC current inductance, and: z = d, q, PM or IP; $x = IP$ or PM; $X = IP$, PM, d or q; $Y = d$, q or DC.

Due to the complex electromagnetic behavior of the machine, calculation of the flux linkage characteristics is very difficult. Therefore, the linkage flux versus stator currents characteristic should be obtained by simulation or test results. In this study, the machine design have been supported by finite element analysis (FEA) and various computer-aided design tools as Flux-3D, GOT-It optimization tool, and MATLAB, making the design process highly efficient.

Calculation of the magnetic field distribution within the ECPMSM machine has been performed using the 3D-calculation code via FLUX-3D (Finite Element Electromagnetism module), and it has been shown in Fig. 2 (right).

Fig. 3 shows torque versus excitation field current I_{DC} characteristics (left) and linked flux waveform versus rotor position for different I_{DC} current values (right).

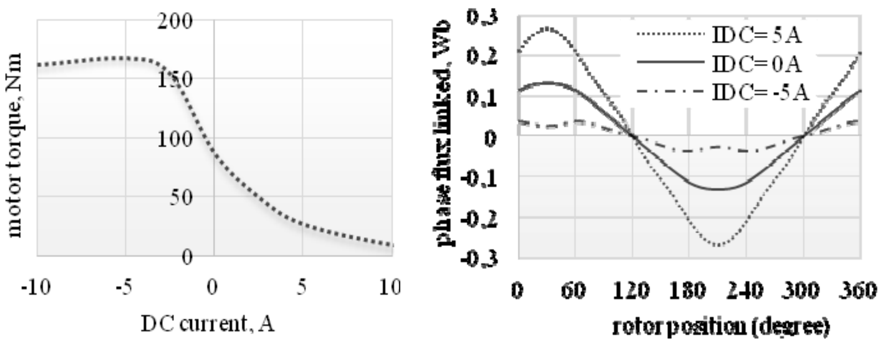

Fig. 3. 3-D FEA results of the ECPMSM machine torque versus excitation field current I_{DC} (left); FEA results of linked flux waveform versus rotor position for different excitation field current I_{DC} (right)

The equations and FEA results have been utilized to develop a prototyping and optimization system for EV drive design with ECPMSM machine. Figure 4 shows a Finite Element Modeling (FE-modeling), solving and post processing FEA block coupled with analytical block to calculate set of efficiency maps (Fig. 5), and maximum efficiency paths (Fig. 6) of the machine and EV performance evaluator. This designing procedure allows to determine optimal I_{DC} values for different torque T set and angular speed ω values to efficiently control the ECPMSM machine according to selected drive mode.

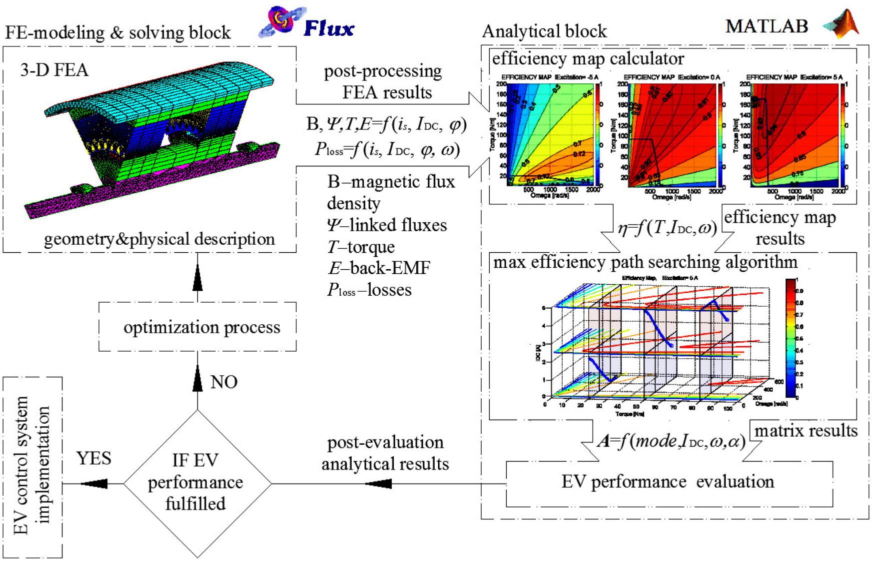

Fig. 4. Prototyping and optimizing EV drive design with **ECPMSM** machine

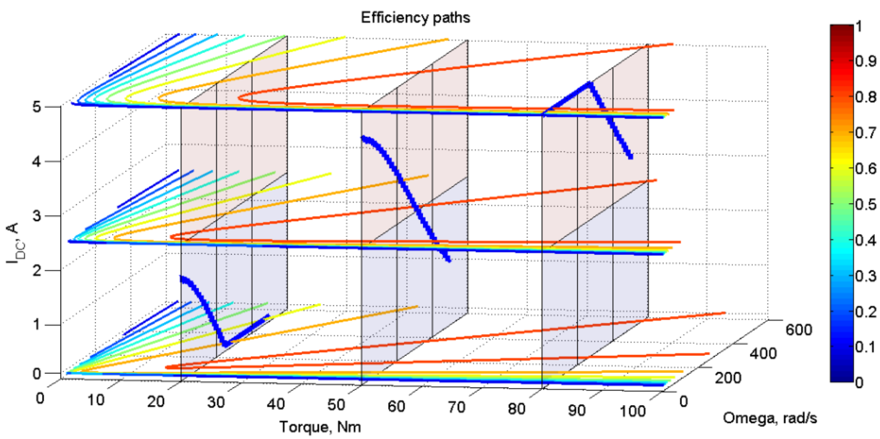

Fig. 5. Optimal maximal efficiency paths (blue lines) for three different sets torque values

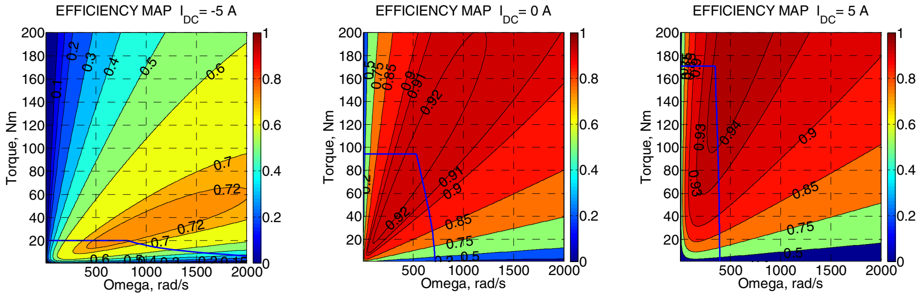

Fig. 6. Selected efficiency maps used in control algorithm regarding torque envelope

3 Vector-Controlled ECPMSM Drive

ECPMSM drive is a modern and powerful technology among various brushless motor drives. In order to achieve improved dynamic and static performance of ECPMSM drive for EV propulsion, vector control is preferred. Considering sensorless control methods problems, high precision position information of the rotor machine is also needed.

Fig. 7 shows the concept of vector control of the ECPMSM machine for EV drive. Proposed control scheme is able to control motor torque and field component current in such a way that total losses are minimized at any loading conditions.

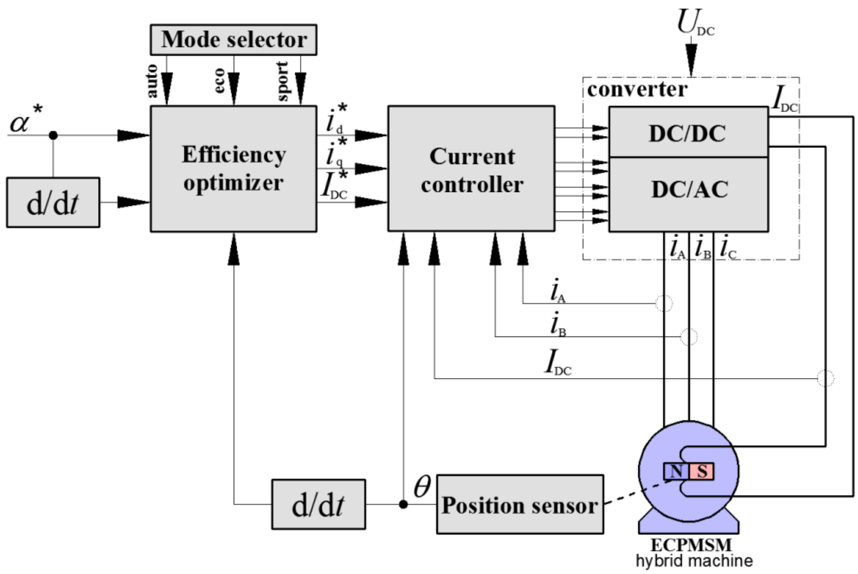

Fig. 7. Vector control of the ECPMSM machine for EV drive system

Although, FOC may offer wide speed range up to 4 times of base speed, but efficiency at high-speed range drops significantly. In order to increase the speed range and improve the efficiency of the ECPMSM machine, i_d and i_q and I_{DC} currents can be controlled in the proper manner to improve torque-speed curve and maximize drive efficiency.

4 EV Drive Components with ECPMSM Machine

The essential components of the concept of EV drive system with the ECPMSM machine are also controller, power source, and transmission. The idea of the EV drive system are shown in Fig. 8.

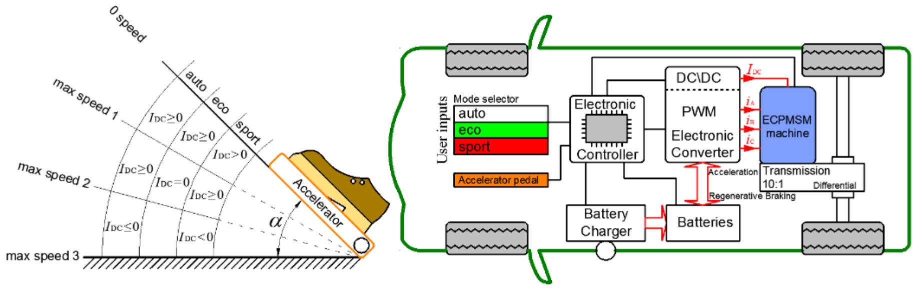

Fig. 8. The idea of the EV central drive system with ECPMSM machine with extended field control capability

It should be noted that the control algorithm considers the accelerator position α and its dynamics. The control drive system should be user-friendly to provide required EV performance, therefore authors proposed three drive modes – auto, eco and sport. Eco mode allows long-distance performance because control systems selects $I_{DC} \geq 0$ value to provide maximum efficiency and field-weakening method is never used. Sport mode is preferred to provide maximum torque without speed limitations – this mode uses field-weakening I_{DC} <0 control method to extend EV speed. The Auto mode automatically switches between previous two, according to accelerator position handling dynamics.

5 Summary

The paper presents the concept for the application of ECPMSM machine in EV drive system regarding extended control algorithm aspects. It is possible to follow a maximum efficiency paths for selected torque values in different drive modes. Total EV may be evaluated considering only proper simulation models applied in FLUX and MATLAB computing tools. The proposed control algorithm for unique PMSM with hybrid excitation provides high efficiency thanks to reduced losses and extended high-speed features, thanks to field weakening. Such solution gives possible highest EV range and also increases acceleration capabilities for low speeds regions and, at the same time, increases highway-cycle characteristics.

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