

ELECTRIC MOTOR-GENERATOR FOR A HYBRID ELECTRIC VEHICLE

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Several topologies of electrical machines can be used to meet requirements for application in a hybrid electric vehicle. This paper describes process of an electric motor-generator selection, considering electromagnetic, thermal and basic control design. The requested electrical machine must develop 45 kW in continuous operation at 1300 rpm with field weakening capability up to 2500 rpm. Both radial and axial flux topologies are considered as potential candidates. A family of axial flux machines is represented by a permanent magnet, single stator and two rotor plates topology. An induction machine was included into the selection process, alongside an embedded and inset permanent magnet synchronous machine, all of the radial type machines.

Keywords: *electrical machines, hybrid electric vehicles, electromagnetic, thermal and control design*

1. Introduction

Electrical machine is one of the critical components of a Hybrid Electric Vehicle (HEV). The design aim for such application is to maximize efficiency over wide torque/speed range, achieve adequate inertia of rotating parts to avoid compromising driveability of the vehicle and come up with compact package.

The initial selection of electrical machines' topologies has been narrowed into synchronous PM Inset (IPM) and Embedded (EPM) radial flux machines alongside with synchronous PM axial flux machine (APM). Permanent magnet machines are getting more widespread in traction applications [1] due to their superior power density, compactness and current availability of power electronics needed for effective control. Despite recent drop in price of permanent magnet materials, they still need to be cost effective. Axial flux permanent magnet machines in particular benefit from short axial length, which might be considerable advantage by means of placing the machine into vehicle's powertrain [2]. Moreover, rotors of an axial flux machine may replace engine's flywheel and sits in engine's existing flywheel housing [3]. An Induction machine (IM) is recognized as a matured technology being widely accepted in traction application [4] and therefore, was also selected. A cross-sectional view for considered machine's topologies depicts the following Figure 1.

DC machines have been excluded from the selection list for well known issues associated to mechanical commutation. Switched reluctance machines have also been considered as a candidate for HEV application. However, they are still less widespread and hence were not considered in this study.

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The requested electrical machine is supposed to operate in two-quadrant mode. A drive cycle of the motor-generator may be characterized as intermittent, consisting of positive and negative load torque with idling operation in between. The motor generator must develop 45kW of rated power at base speed of 1300 rpm with ability to run over constant power speed range up to 2500 rpm. Factor of 1.4 characterizes the overload capability of the machine.

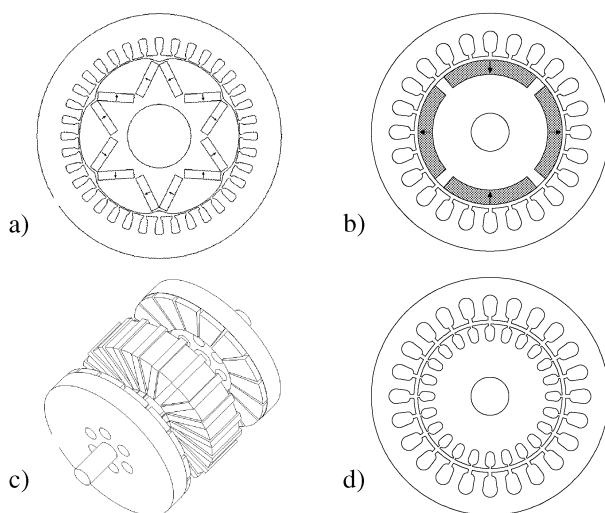


Fig.1: Cross-sectional views of a) EPM, b) IPM, c) APM, d) IM

The motor-generator is supplied by a three-phase voltage-source inverter. However, the DC bus voltage is fluctuating due to the inverter being directly connected to the battery pack. Electromagnetic design considers the minimum DC-bus voltage as a worst case scenario. This ensures that, particularly, PM machines have sufficiently high voltage for their operation, especially in field-weakening mode, when d-axis current is imposed on the machine in order to suppress Back-EMF. The other design constraint is characterized by the maximum collector-to-emitor voltage of IGBT transistors. In a case of lost control of a PM machine at relatively high speed, an excessive Back-EMF may appear on winding terminals causing breakdown of transistors.

The following chapters summarize electromagnetic, thermal and control design stages leading eventually to a comparison of considered machines' topologies. The actual design process in this paper covers only for Embedded PM machine topology. However, an in-house design capability has been developed to tackle the design of the remaining considered topology.

2. Electromagnetic design

The initial electromagnetic design is based on analytical calculations of a magnetic circuit, parameters of machine's equivalent circuit and its losses. However, some of the machine topologies can be inherently nonlinear. A typical example could be the bridges holding PMs in the rotor of Embedded PM machine. Then Finite Element Analysis (FEA) plays important role in the optimization process and more precise in the determination of losses and the parameters of the equivalent circuit.

There are major commonalities in the electromagnetic design of synchronous PM machines with slight alterations for a particular topology.

2.1. Synchronous PM machines

The design procedure will be demonstrated on a case of Embedded- PM machine. An equivalent reluctance circuit has been used as a common design tool for all magnetic circuits of PM machines.

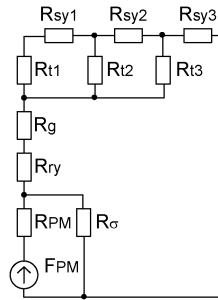


Fig.2: Equivalent reluctance circuit of EPM for no-load conditions

PM machines employ high energy density magnets, in particular NdFeB, in order to achieve high flux density in the airgap. A flux focusing technique, created by placing two magnets in V-shape for Embedded-PM machine allows the achievement of airgap flux density up to 1 T. Its pole shoe has quasi-sinusoidal shape in order to decrease the level of high harmonics in the airgap flux density waveform. Figure 3 clearly shows difference on flux density waveforms of Embedded and Inset PM machines.

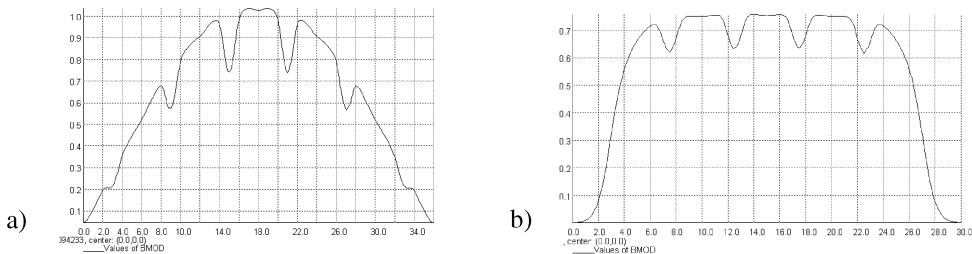


Fig.3: No load airgap flux density waveforms for a) an Emebddd and b) Inset PM machines

FEA tools are widely used in validating of machine parameters and optimizing its size and performance. Particular attention has been paid to the estimation of magnet flux linkage, inductances in d - and q -axis and torque production. As machines have been designed with target flux density in teeth up to 1.8 T at no load-condition, a non-linear solution with a specified current range has been adopted in order to capture potential nonlinearities in the magnetic circuit. A common feature shared by all selected PM machine topologies is the use of saliency, meaning difference in d - and q -axis inductances. This is beneficial feature in field weakening operation, particularly for traction drives [5]. The machine then produces reluctance torque alongside magnet torque. FEA iterations have verified the proportion between magnet and reluctance torque.

2.2. Induction machines

The induction machine was designed based on design procedures and equations obtained from [6], [7]. The main design inputs used, in order to size up the machine are the choice of electric and magnetic loadings, together with a suitable choice of length-to-pole-pitch ratio. The electromagnetic design was carried out in parallel with the thermal design, in order to select appropriate materials and current densities for the stator winding, rotor bars and rotor end-rings. Because of the high operating temperature conditions, a copper-cage rotor has been selected. A drop-shaped bar was considered, to achieve a compromise between mechanical integrity and thermal issues.

The number of rotor slots in the Induction Machine was chosen in relation to the number of stator slots, to avoid undesirable effects such as torque ripple and noise [6].

In the initial design stage, the leakage inductances were computed using analytical formulae, however given the importance of the equivalent circuit parameters in estimating the machine efficiency at different operating conditions, a variable-parameter equivalent circuit was developed for the designed machine as in [8]. In this equivalent circuit leakage inductance and rotor resistance are modeled as a function of slip, while the magnetizing inductance is modeled as a function of flux-linkage.

3. Thermal design

Electrical machines in HEV are faced with the challenge of maximizing their power density in order to fit into available space within the vehicle's chassis. According to [9], water cooling provides the highest cooling performance. Water jackets have been designed and assessed to provide adequate cooling to all the machines. Totally enclosed design ensures protection of sensitive components, such as PM and stator winding, against harsh environment.

A Computational Fluid Dynamic simulation provided heat transfer coefficient at specified flow rate and its inlet temperature. This has been taken as a reference value for thermal calculations of designed machines. Analytical thermal calculations are based on equivalent transient thermal circuits, which alter with machine topology.

3.1. Synchronous PM machines

Losses in synchronous PM machines are allocated mainly on stator side, particularly copper and iron losses. However, rotor participates by eddy current losses and stray iron losses.

The 2D equivalent thermal circuit assumes that all heat is dissipated by conduction out of the machine through the cooling jacket, and neglects the heat dissipated in endbrackets and the shaft.

The transient equivalent circuit allows the designer to investigate dependency of on-time and duty cycle on overload factor $k = P/P_{\text{nom}}$ as shows Figure 5.

3.2. Induction machine

An 8-node, two-dimensional thermal circuit has been developed to model the thermal behavior of the induction machine in this application. The thermal circuit is shown in

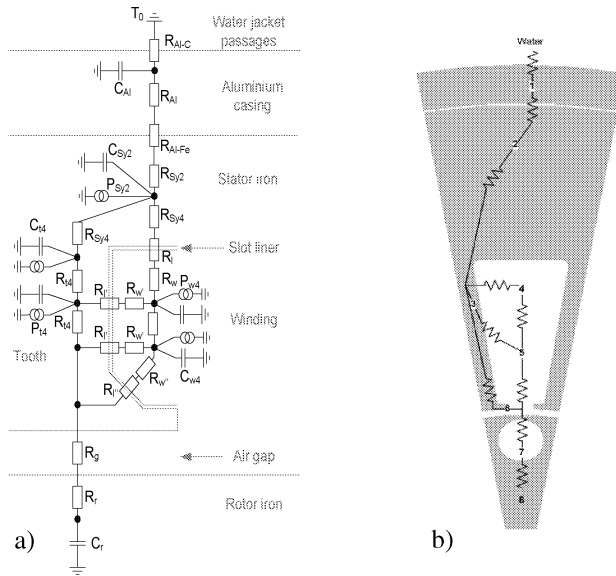


Fig.4: Equivalent thermal circuit for a) radial PM machines and b) for induction machine

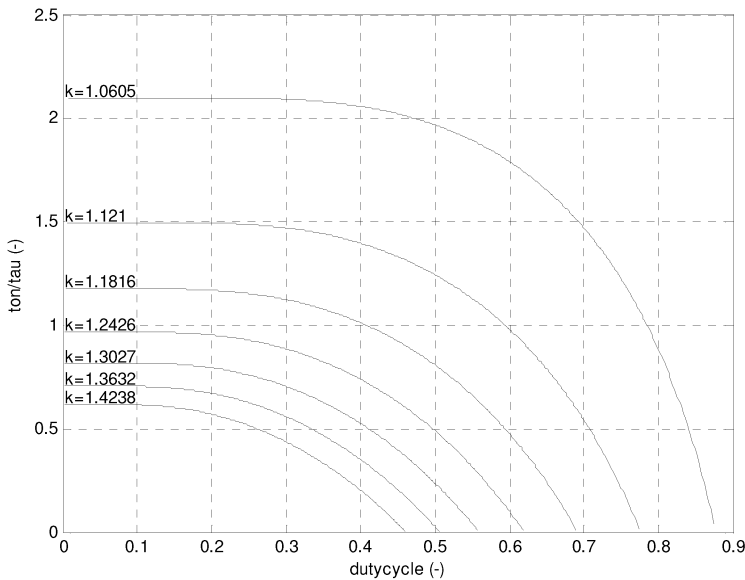


Fig.5: Dependency of on-time (scaled according to thermal time constant τ) and duty cycle on overload factor k ; the thermal design provides the necessary inputs for updating electromagnetic calculations and determining the temperature of winding and permanent magnets

Figure 4b. The heat in this network is assumed to flow radially upwards, from the rotor, which is the hottest part, to the water jacket. The main issue with using an induction machine for this application, when compared to the other machines, is that in the aforesaid machine there is a fundamental loss in the rotor copper, which is required for operation. Removing this heat can be difficult, given the relatively low-values of air-gap heat trans-

fer coefficients. Several strategies were then investigated to reduce the rotor temperature, namely that of shifting the current from the rotor to the stator.

4. Control design

Selection of appropriate control strategies is nowadays strongly linked with the electrical machine design, particularly for machines operating in variable-speed drives. Control strategy closes the design loop starting by electromagnetic design, followed by thermal calculations and enclosed by selection of power electronics devices taking into account the DC bus voltage, maximum current and required switching frequency. Control strategy must not only guarantee the operation of electrical drive in required torque-speed range with sufficient response to the reference signals, but also optimize efficiency of entire drive, particularly in HEV application where the overall efficiency may impact the fuel consumption of the vehicle.

4.1. Synchronous PM machines

There are many control strategies associated with synchronous PM machines. However, the most common strategies are $I_d=0$, Maximum Torque-per-Ampere, Maximum Efficiency and Forced output Power for field-weakening operation [10]. $I_d=0$ control strategy takes in account magnet torque only, represented by the first term (1) of Equation (1).

$$T_{em} = \frac{3}{2} pp \underbrace{(\Phi_{PM} i_q)}_1 + (L_d - L_q) i_d i_q . \quad (1)$$

Therefore, $I_d=0$ control strategy does not maximize neither torque production, nor efficiency. Nevertheless, $I_d=0$ control strategy seems to be beneficial for initial estimation of torque production during the design of PM machine.

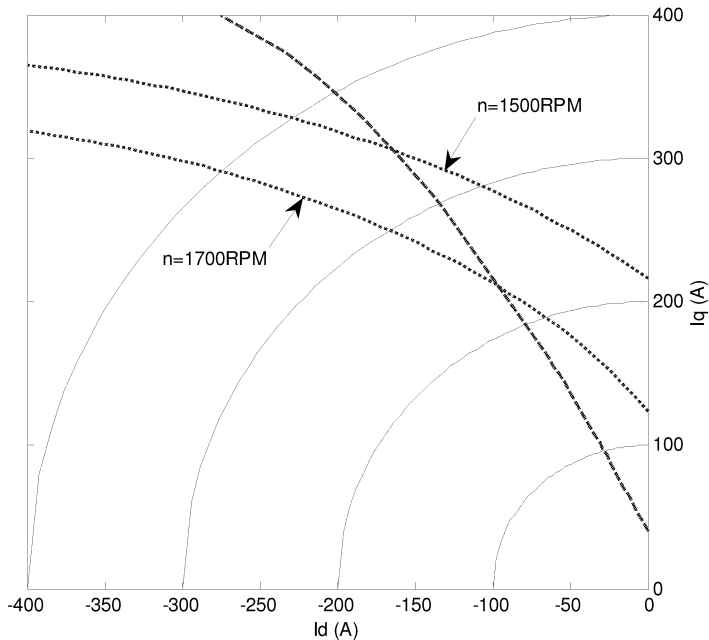


Fig.6: Trajectory of optimal d - and q -axis current combinations (dashed curve) restricted by speed-dependent voltage ellipses

MTPA control strategy aims to find optimal combination of d - and q -axis currents according to Equation (1) such that overall torque production for a given current locus is maximized and as a result the copper losses are minimized. Figure 6 shows the trajectory of optimal d - and q -axis current combinations for Embedded-PM machine.

MTPA control strategy is limited by maximum available voltage. As the machine speed increases above the base speed, the availability of MTPA is limited by voltage locus ellipses, depicted in Figure 6. The controller must switch, in this case, into field weakening mode so that negative d -axis current opposes Back-EMF and the requested voltage does not exceed maximum supply voltage.

Speed, when the controller switches into field weakening, is not fixed for a given load due to the floating DC-bus voltage. Hence, calculations of performance and efficiency considered transition into field weakening at base speed that means at the minimum DC bus voltage.

4.2. Induction machines

In order to estimate machine efficiency values for the various operating regions of the machine, constant volts/Hz operation has been considered. Below base speed, a reduction in voltage is accompanied by a proportional reduction of frequency, so that the air-gap flux is maintained constant. The pull-out torque remains constant, except in the low-frequency region, since the air-gap flux here is reduced by the voltage drop across the stator resistance. To mitigate this effect, a ‘boost’ voltage is applied in this region.

Under volts/Hz control, the machine operates at low slip, which means that the rotor resistance is at a low value, thus giving high values of efficiency. Above base speed, machine operates in a constant power region, where the air-gap flux reduces, but stator current is held constant by increasing slip.

5. Efficiency maps

Fuel savings and reduction of emissions, are the main parameters which need to be accomplished in HEV. Both combustion engine and electrical machine must operate for that reason in zones of torque-vs-speed characteristics with maximum efficiency. A way of representing electrical machines performance in HEV simulation can be achieved by means of a look-up table, which may be graphically interpreted as an efficiency map [11]. Figure 7 shows efficiency maps generated by the electrical machines under investigation using control strategies described in sections 4.1 and 4.2. The constraining factors are maximum winding temperature and minimum DC bus voltage. Efficiency maps were reduced into 1st quadrant showing motoring mode only. However, 2D efficiency map does not have ability to consider variation of input parameters having impact on efficiency of electrical machine. Namely, variation of temperature influences winding resistance and flux due to PMs. The other variable affecting efficiency is floating DC-bus voltage, especially in field weakening mode, when DC-bus voltage influences d -axis current.

Efficiency maps show that the optimal operating point for PM machines lies in field weakening mode, reaching efficiency up to 95% unlike the IM, achieving efficiency from 92% up to 93% in wider operational zone.

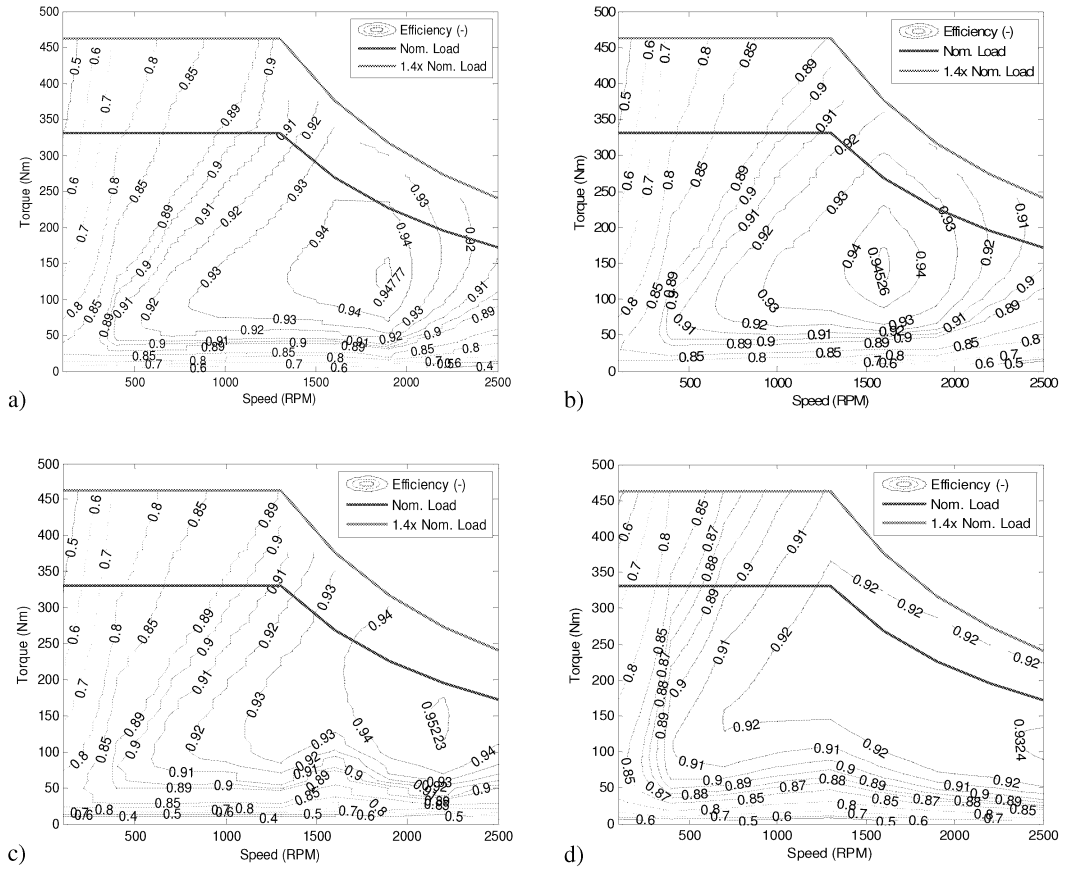


Fig.7: Efficiency maps: a) EPM, b) IPM, c) AFM, d) IM

6. Comparison of machines under study

This section highlights the outcomes of some critical parameters which may impact machine selection for HEV application. These are summarized in Table 1.

Dimensions and mass presented in the table below, consider only active components of machines. Table 1 shows that Embedded PM machine is the most competitive topology in all selected criteria. However, the axial flux machine might be convenient choice due to a shorter axial length and possibility of better integration with the engine.

	IPM	EPM	APM	IM
Outer diameter (m)	0.29	0.267	0.48	0.375
Axial length (m)	0.294	0.28	0.15	0.309
Power density (kW/m^3)	2317	2870	1657	1318
Mass (kg)	101.4	81.3	123.9	193
Inertia (kg.m^2)	0.302	0.147	2.126	0.597
Peak Efficiency (%)	94.5	94.8	95.2	93.2

Tab.1: Summary of parameters for designed machines

7. Conclusion

This paper describes design process of four electrical machine topologies in HEV application with particular interest in electromagnetic, thermal and control design. Constraints associated with application in HEV are specified and considered in design requirements. Efficiency maps are the main outcome needed for performance simulations of entire HEV powertrain. However, efficiency maps do not consider variation of machines' parameter due to its two-dimensionality. The Embedded PM machine offers the most compact design and efficiency comparable with the other PM machines. The axial flux machine becomes a strong candidate for HEV topologies with particular interest in axial length. However, its relatively high inertia may play an important role in driveability of the vehicle.

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