

Designing High Power Density In-Wheel PMSM for Sustainable Hybrid Electric Vehicles

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Abstract – The permanent magnet (PM) motors have recently become very popular in the hybrid electric vehicles (HEVs) manufacturing industry. Especially, the PM synchronous motor presents attractive characteristics when an outer rotor configuration is combined with non-overlapping concentrated windings. Consequently, more attention has to be paid to this promising technology. Moreover, many studies focus entirely on the motor design itself without examining the sustainability features of their outcomes. In this study, an effective methodology is proposed for the development of high power density direct-drive in-wheel PMSMs that are going to be used in light HEV applications. The achievement of motor's high performance is guaranteed by incorporating an optimization algorithm. Simultaneously, the analytical model of the HEV subsystems was included for the motor's operation assessment and the estimation of the overall powertrain performance. Apart from the improved technical characteristics, the obtained results reveal overall HEV/motor sustainable operation in terms of efficiency as well as economic behavior and thus qualifying the proposed methodology.

Index Terms—Dynamic modeling, electrical motor design, hybrid electric vehicles, high power density, in-wheel permanent magnet motor, optimization, sustainability.

I. INTRODUCTION

GLOBAL warming, air pollution, forthcoming fuel depletion and other recent environmental concerns motivated many countries to seek for effective and economically feasible solutions aiming to replace the conventional internal combustion (IC) engine vehicles [1]. Additionally, several new regulations regarding the fuel economy and the emissions have been published in the last few years [2]. In this direction, the alternatives of fuel cell vehicles, electric vehicles and hybrid electric vehicles were investigated. The hybrid electric vehicles (HEVs) are considered by manufacturers, governments and consumers as the most attractive alternative in terms of requirements [3], [4]. The high fuel economy, the high resale price, the low emissions, the low operating cost and noise are only some of their main advantages. At the same time, they require an engine with a much smaller size and they are characterized by longer operating life and longer driving range [5].

In this context, the sustainability of the electric motors participating in these systems can be acceptable enough. The world HEVs market presents a rapid growth and the commercially available hybrid powertrains have been incorporated in various vehicle types. In the case of in-wheel traction systems a complete drive-train is placed inside the

wheel's hub as depicted in Fig. 1. In this limited space, the braking components and the motor-drive electronics have also to be accommodated [6]. According to the technical reports of vehicles manufacturers and plenty road tests the in-wheel motors exhibit important advantages in several areas [7]. For instance, the traction and stability control are significantly enhanced, as the in-wheel motors are capable of delivering precisely controlled braking or motoring torque on a millisecond timescale. Thus, the stopping distances are reduced. This increases both HEVs' drivability and safety and ultimately impacts its overall performance [8]. For the conventional vehicles the aforementioned functions respond slowly and they are limited to applying retarding force. Furthermore, motors of this type allow "torque vectoring" i.e. the application of different torque to different wheel. This can markedly improve handling and the specific hardware ability comes essentially free as only the incorporation of the right software is required. The result can be a vehicle that corners as if on rails; one that can feel both nimble in city traffic and stable at high speeds.

Moreover, the electric motor's type and its structure have to be carefully selected. High efficiency over a wide range of speed and increased power density are the major requirements for traction motors. The aforementioned features can easily be met when permanent magnet synchronous motors (PMSMs) are used. PMSMs with one or multi-layer magnets embedded in the rotor's core are the dominant topology for commercial light duty HEVs [9]. For hybrid passenger cars, the motors' output power usually varies from 30 to 70 kW, while for sport utility vehicles (SUVs) it exceeds 120 kW. Recently, it has been proven that surface mounted permanent magnet synchronous motors (SPMSMs) are also promising candidates for HEV applications especially when non-overlapping concentrated windings are used instead of distributed ones [10]. They present high efficiency, higher overload capability, low cogging torque, acceptable flux-weakening capability and much easier manufacturing procedure [11].

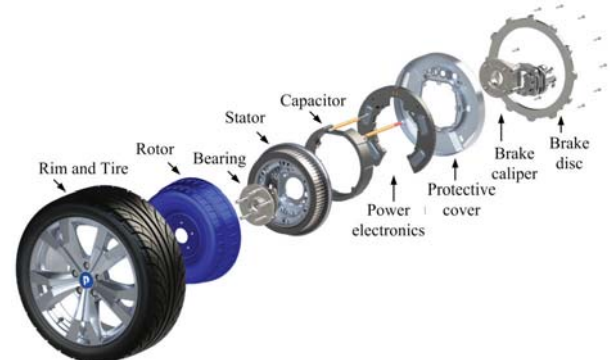


Fig. 1. Exploded view of a modern integrated in-wheel PM motor system.

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However, the overall HEV performance depends strongly on the operational characteristics of its components. The internal combustion engine, the electrical motors, the auxiliary generator, the batteries and the drive-control system collaborate and interact to each other determining the traction system's effectiveness [12]. Plenty techniques have already been proposed and applied in order to find out the optimal design and increase the vehicle's energy management [13]. This task is characterized by increased complexity as there are numerous variables to be estimated and requirements to be fulfilled. For this reason, a multi-objective optimization process combined with a decision made approach is usually implemented [14].

Based on the above, this paper aims to discuss a suitable in-wheel SPMSM design with high-power density for a light HEV application aiming to the overall system sustainability. Additionally, another scope of this work is to demonstrate that even if a less efficient motor (in terms of design) is going to be used in a HEV, it might cause substantial fuel saving during the vehicle's operation compared to those of a more efficient motor. In this case, the total system will be more energy efficient. For this purpose, the proposed methodology which includes the design, optimization and modeling of the examined here motor is thoroughly described in Section II. An analytical HEV's model has been developed by using Simulink. At each step of this approach the motor's specifications are incorporated in this model. The analysis of the entire system's dynamic behavior follows while simultaneously a better performance estimation of each single subsystem is allowable. Several parameters of great interest, such as the fuel consumption during different driving cycles are calculated in a far more accurate way. For demonstration purposes here, the adopted methodology is applied to the scenario of a hybrid passenger car with series-parallel configuration, which has two in-wheel SPMSMs with an output power of 15.3 kW. The obtained results are presented in Section III and relevant discussion is made in Section IV, whereas Section V concludes this work.

II. DIRECT DRIVE IN-WHEEL MOTORS

By delivering power directly to the wheel (Fig. 2a), a technological leap forward has been essentially created. Direct drive needs no gears and it is combined with leading brake systems permitting the development of efficient friction brakes that can be used at any type of vehicle. This kind of traction provides the following essential advantages: a) enhanced handling, b) less charging requirements, c) greater range, d) improved torque response and e) faster acceleration. Also, the motor presents simplified assembly. Thus, it can be said that for manufacturers the specific technology delivers design freedom and production efficiency, while they are able to develop HEVs that reflect their costumers' lives and needs. Since fewer components are required, the production process cost becomes lower and a more efficient supply chain can be easily achieved. As cities increasingly control vehicle access, it provides dramatic emission reductions and acts as a passport to the clean cities of the future.

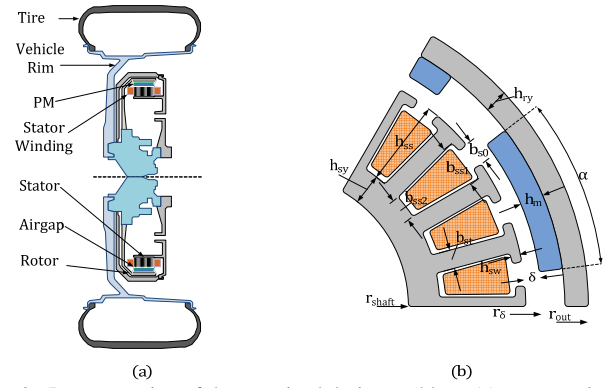


Fig. 2. Representation of the examined design problem: (a) cross section of an in-wheel motor assembly and (b) detailed view of the used here SPMSM geometrical parameters (variables given in text).

A. Requirements

The complexity of the direct-drive SPMSMs for such an application is quite increased. Plenty geometrical characteristics (illustrated in Fig. 2b) will be calculated and numerous constraints have to be satisfied. Among the most important ones are the motor's dimensions, the stator winding's maximum current density and the maximum dc-link voltage. Furthermore, through the proper design the motor's electromotive force has to be close to sinusoidal aiming to conclude to a low current harmonic content and low torque ripple. The aforementioned feature is crucial in order to guarantee to the vehicle's passengers safety and a high comfort class rating. For a non-saturable operation and low cogging torque the magnets' span and the stator teeth dimensions have to be selected carefully. Additionally, the motor's thermal behavior estimation under different load conditions is of great importance. Poor temperature alleviation usually occurs due to the motor's position and its short axial length. The implementation of an efficient cooling system is necessary in order to reduce the magnets' demagnetization risk and ensure high driving performance even under overload operation [15].

Another important issue is the motor's losses minimization at different driving cycles. It is clear enough that the design parameters which have been optimized for one driving cycle are not necessarily optimal when the vehicle's use is modified [16]. The incorporation of various representative driving cycles and the approximation of HEV's performance at twelve characteristic points are required as mentioned in [8]. Cruising, acceleration and regenerative phases have to be included among the above points for a better estimation of vehicle's profile.

However, technically speaking, there are some other (and stricter) requirements for such an application. Due to space limitations, the reader can refer to [17] for clarification.

B. Proposed Methodology Framework

Electrical machines design should be addressed as an inverse problem, i.e.: From the characteristics values given by the schedule of conditions (for instance a motor's torque), specify the topology, the geometrical parameters, the thermal behavior and the operational features [18]. The designer usually tries to find out an optimal design for which the

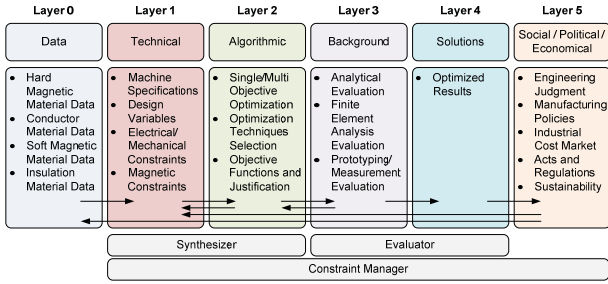


Fig. 3. Electrical machine design knowledge base system architecture previously developed by the authors [20].

optimization of a certain criterion (e.g. magnets mass minimization) occurs. This criterion varies along with the major set requirements. In some cases, the adoption of a multi-criteria optimization approach is preferable. The perspective of combining both optimization algorithms and analytical models in the electrical machines design has been discussed thoroughly in the recent literature (e.g. [19]). Nevertheless, a designer generally deals with a large number of sub-problems for which there are more than one solution. An “ideal” design results to a PMSM topology whose performance coincides with the requirements of high efficiency, high power density, low temperature rise and cost. At the same time, it has to present increased reliability and durability. However, a compromise often is needed between the “ideal” design and a solution which complies with the material availability, manufacturing conditions, country regulations, competitive market, etc.

For SPMSM optimized design, the authors have developed recently [20] a knowledge base system architecture (KBSA). This system consists of several knowledge sources (KSs) organized into many layers (also called levels), as it can be seen from Fig. 3. A brief description of this architecture follows. The “Data” level specifies the appropriate domain-independent level according to the information given about the properties of: a) the magnetic materials (i.e. iron steel and magnets), b) the conductors (e.g. conductivities and commercially available wire diameters, etc.) and c) the insulation materials (e.g. dielectric strength, sheet width, thermal properties, etc.). This level “controls” many tasks, such as the activation of other KSs in the next levels. The electric motor’s characteristics, the problem design variables and a large amount of constraints are incorporated in the forthcoming level, which is referred as “Technical”.

The KSs of this level can be “fired” also from the information provided in the data level, as the majority of the constraints are strongly related with the properties of the used materials. Next, mixed coding of optimization methods (i.e. GA) along with the appropriate engineering expert *if-then* rules are involved in the KSs of the “Algorithmic” level. At this step, the designer has to pay a lot of attention to the selection and formulation of the appropriate objective function. The evaluation of the conceptual design is evolved through a mixed-coded layer, which is named as “Background” level. Moreover, finite element analysis (FEA) is employed as a geometric reasoner KS. When this KS is fully fed, it has to complete among other the following tasks: a) the interpretation of engineering sketches and

drawings, b) the development of geometric models and justification of them and c) the performance of interference checking among the various design objects. The last level of the proposed KBSA structure is the “Economical” one. This level incorporates all the required KSs taking into account manufacturing, economical and market information.

This design framework is successfully used here for obtaining a suitable SPMSM candidate for our HEV sustainability economical assessment. It has been also applied in [17] and the derived results will be used here for comparison. It should be mentioned, that due to the actual scope of this paper described in the introduction, the strictly technical and mathematical background of the aforementioned motor is not presented here.

III. CASE STUDY AND RESULTS

The problem of the design and optimization of two SPMSMs that are accommodated inside the driving wheels of a light HEV is demonstrated in this Section. The considered here HEV has a series-parallel configuration. The specific architecture permits the IC engine and the electric motors to deliver power to the wheels independently or in conjunction with one another. When low vehicle speed is required, the system seems to operate more as series vehicle. On the other hand, at high speed operation, the engine takes over. The engine has to be able to deliver a torque of 115 Nm, while its speed is equal to 4200 rpm. Its output power is equal to 57 kW and its maximum speed is 5000 rpm. Regarding the in-wheel motors’ specifications the nominal output power of each one is equal to 15.3 kW providing a torque of 170 Nm at 850 rpm. A salient pole synchronous permanent magnet generator, which is going to be driven by the engine, is also included. The generator either delivers electric power to the in-wheel motors or charges the batteries when it is necessary. The battery pack has nominal voltage of 201.6 V and its capacity is equal to 6.5 Ah. A boost converter has been used for the increment of battery pack voltage leading finally to a 400 V dc-link voltage. The motors are fed by a three-phase inverter and they are individually controlled by applying vector control method. A planetary gear has also been implemented aiming to split power among the differential, the engine and the generator. The overall HEV’s performance is estimated with the help of a HEV model, which is available in Matlab/Simulink. The specific model (depicted in Fig. 4) allows the analysis of vehicle’s dynamic behavior incorporating both its aerodynamical and frictional phenomena. It must be noted here that the model was re-constructed in order to coincide with the specifications of the examined here problem. The HEV’s specifications and the characteristics of its main components are summarized in Table I.

Concerning the in-wheel motor structure, the most suitable candidates will be chosen along with the fulfilment of the set criteria. Some requirements are related to the motor’s physical dimensions, as important constraints are imposed by this application. For example, as the motor is placed under the wheel’s rim its outer rotor diameter is fixed and equal to 432 mm. At the same time, its axial length can’t

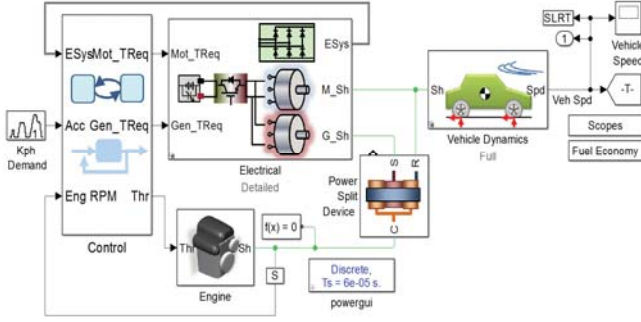


Fig. 4. General view of the incorporated HEV's model.

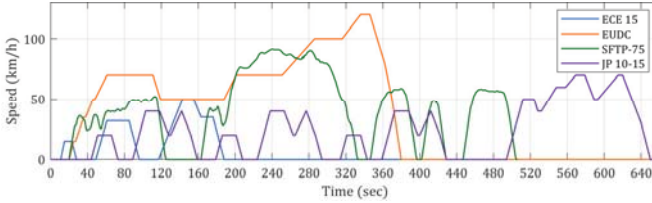


Fig. 5. The driving cycles considered here during the proposed optimization process.

be larger than 30 mm. Furthermore, the motor's mass has to be as low as possible aiming to the unsprung mass reduction and the elimination of vibrations. In-wheel motors, which have been already implemented in commercially available HEVS exhibit power density higher than 1 kW/kg. One of the main scopes of this study is to investigate if the power density can be further increased. Except from the aforementioned quantity, the high efficiency is also of great importance. The motor has to be present efficiency higher than 90% for a wide speed range in order to benefit the vehicle's energy consumption. Consequently, the applied objective function was carefully selected proceeding to a compromise between motor's mass and losses minimization. The considered SPMSMs requirements are given in Table II.

The number of motor's design variables that have to be determined through the optimization procedure is larger than 15. Apart from the geometrical characteristics that are depicted in Fig. 2b, variables such as the pole number ($2p$), the number of slots per pole per phase (q) and the number of conductors per slot (n_c) are also involved. The upper and lower bound of these quantities are mentioned in Table III. Moreover, reader can refer to [6] and [21] for more information about the analytical equations that have been used to approximate the motor's electromechanical and magnetic behavior. For the sake of space, the aforementioned equations are not given here. High quality silicon steel has been used for the stator and rotor core. NdFeB-35 has been selected for the permanent magnets due to its high energy product and the increased reliability, which makes it suitable for such a demanding application [22].

The optimization results derived from the application of the proposed design methodology are presented in Table IV, where the specifications of a final topology ("Motor A") are given. Let us also denote "Motor B" another similar design, which has been obtained previously for the same problem [17]. The validation of SPMSMs electromagnetic performance was conducted through 2D finite element analysis. The motors' operational features at rated condition

TABLE I
HEV'S MAIN SUBSYSTEMS CHARACTERISTICS

Component	Specification	Value
Vehicle	Mass (kg)	1200
	Frontal area (m ²)	2.16
	Tire radius (m)	0.50
	Total wheel inertia (kgm ²)	0.10
	Aerodynamic drag coefficient	0.26
	Transmission inertia (kgm ²)	0.50
	Transmission friction coefficient	0.001
	Engine to wheel gear ratio	1.30
Internal combustion engine	Nominal power (kW)	57
	Maximum speed (rpm)	5000
	Torque (Nm) @ 4200 rpm	115
In-wheel SPMSMs (x2)	Nominal power (kW)	15.3
	Nominal speed (rpm)	850
	Nominal torque (Nm)	170

TABLE II
IN-WHEEL SPMSMS DESIGN SPECIFICATIONS

Variable	Symbol	Value
Motor efficiency	η	$\geq 90\%$
Magnets' mass	M_m	≤ 1 kg
Motor total mass	M_{tot}	≤ 15 kg
Axial active length	L	30 mm
Rotor outer radius	r_{out}	216 mm
Max. dc-link voltage	V_{dc}	400 V
Inverter's module ratio	m_a	0.7

TABLE III
OPTIMIZATION PROBLEM CONSTRAINTS (SYMBOLS ACCORDING TO FIG. 2b).

Variable	Symbol	Value
Slot width at the base	b_{s2}	$(0.15 h_{ss} - 0.5 h_{ss})$ mm
Slot width at the opening	b_{s0}	≥ 2.0 mm
Stator tooth width	b_{st}	≥ 2.5 mm
Magnet height	h_m	≤ 10 mm
Stator yoke length	h_{sy}	$\geq (h_{ss}/3)$ mm
Rotor yoke length	h_{ry}	≥ 9.0 mm
Air gap length	δ	$(1 - 3)$ mm
Stator yoke flux density	B_{sy}	≤ 1.8 T
Stator teeth flux density	B_{st}	≤ 1.8 T
Rotor yoke flux density	B_{ry}	≤ 1.8 T
Airgap flux density	B_{δ}	≤ 1.0 T

are summarized in Table V. The overall HEV's system assessment, the estimation of its subsystems collaboration and the calculation of important parameters, such as the fuel consumption, were done while applying different driving cycles. Specifically, the European Driving Cycle (ECE 15), the Extra Urban Driving Cycle (EUDC), the Supplemental Federal Test Procedure (SFTP-75) and the Japanese 10-15 Mode Driving Cycle (JP 10-15) were incorporated. The HEV's speed profile during each one of the aforementioned driving cycles is presented in Fig. 5. The specific driving cycles involve: a) short distance trips with a low vehicle's speed (see ECE 15), b) aggressive and high speed driving mode (see EUDC), c) typical routes for light duty vehicles (see SFTP-75) and d) modes with driving both in urban cycles and high speed road. Especially, the JP 10-15 is commonly used for emission certification and fuel economy testing. In the examined here case, the upper limit for the acceptable fuel consumption has been set equal to 5.0 litres/100 km. Each topology that did not meet the above requirement had been excluded. The followed optimization process was terminated when this target has been achieved

TABLE IV
DESIGN VARIABLES OF THE DERIVED TOPOLOGIES
(SYMBOLS ACCORDING TO FIG. 2B. ALL DIMENSIONS IN MM).

Variable	Symbol	Motor A	Motor B ^[17]
Stator inner radius	r_{shaft}	159	162.47
Airgap radius	r_{δ}	199	200.84
Airgap length	δ	2	2.50
Poles number	$2p$	28	48
Slots number	Q_s	30	54
Slot width at the opening	b_{s0}	18.50	12.05
Slot width at the top	b_{ss1}	18.61	15
Slot width at the base	b_{ss2}	18.62	12.46
Stator tooth width	b_{st}	22.42	7.96
Slot total height	h_{ss}	25	25.92
Stator yoke length	h_{sy}	13	9.95
Rotor yoke length	h_{ry}	14.5	11.66
Magnet height	h_m	2.5	3.50
Pole arc to pole pitch ratio	α	0.79	0.60
Slot fill factor	s_f	0.6	0.60
Conductor per slot	n_c	34	16
Wires per conductor	n_w	1	1
Wire diameter	d_w	2.906	3.665
Number of layers	n_l	2	2
Winding factor	k_w	0.951	0.945

TABLE V
PERFORMANCE COMPARISON OF THE DERIVED TOPOLOGIES
(RATED CONDITION).

Quantity	Symbol	Motor A	Motor B ^[17]
Motor efficiency (%)	η	94.41	94.97
Phase current (A)	I_{ph}	62.49	92.41
Current density (A/mm ²)	J_c	9.42	8.76
Copper losses(W)	P_{cu}	839.81	722.06
Core losses (W)	P_{core}	66.93	87.75
Nominal frequency (Hz)	f	198.3	340
Cogging torque (mNm)	T_{cog}	41.07	31.05
Torque ripple (%)	T_{rip}	2.1	3.3
Torque angle (deg)	T_{ang}	44.79	26.62
Magnets' mass (gr)	M_m	713.16	593.45
Motor total mass (kg)	M_{tot}	14.82	12.49
Power density (kW/kg)	P_d	1.03	1.22

TABLE VI
HEV FUEL CONSUMPTION COMPARISON USING THE DESIGNED IN-WHEEL
SPMSMs FOR DIFFERENT DRIVING CYCLES.

Driving Cycle	Fuel Consumption	Motor A	Motor B ^[17]	Fuel savings
ECE 15	litres/100km	3.83	4.76	-19.54%
	km/litre	26.11	21.00	-24.33%
	Total fuel (litres)	0.0381	0.0473	-19.45%
EUDC	litres/100km	2.68	3.42	-21.64%
	km/litre	37.31	29.24	-27.60%
	Total fuel (litres)	0.2064	0.2634	-21.64%
SFTP-75	litres/100km	2.04	2.58	-20.93%
	km/litre	49.02	38.76	-26.47%
	Total fuel (litres)	0.1176	0.1488	-20.97%
JP 10-15	litres/100km	3.39	3.94	-13.96%
	km/litre	29.49	25.41	-16.06%
	Total fuel (litres)	0.1180	0.1371	-13.93%

for all the examined driving cycles. The corresponding results are given in Table VI. As it can be seen from the data provided in Table IV-VI the proposed approach results to both optimal and feasible design solutions which also satisfy the considered here constraints and requirements. Moreover, from Table VI it is noted that “Motor A” can achieve 14%-21.5% fuel economy compared to “Motor B” although having a slightly lower efficiency. The key quantity for this is the much less nominal phase current (~62.5 A).

IV. DISCUSSION

From the overall assessment in this study, the following further information is given below along with relevant conclusions:

a) The proposed design methodology results to feasible and reliable solutions confirming its effectiveness. With the incorporation of the optimization process and the application of several objective functions a large number of SPMSM structures have been obtained over a wide range of poles number. These topologies were evaluated by taking into account many aspects (i.e. technical, economical, etc.) and the optimal designs are presented here. Also, many electromagnetic quantities (not shown here) have been estimated. Among them, the phase back electromotive force, the torque and their corresponding harmonic content, the flux density distribution were included.

b) All the set constraints and requirements have been satisfied. The stator winding's current density is close to the maximum acceptable value for this quantity. The above combined with the motor's short axial length and the fact that the motor is embedded inside the wheel make the incorporation of a cooling system necessary. However, this is out of scope of this study.

c) The obtained motors exhibit high performance. Their efficiency at rated operation can be considered as high (94%-95%). This characteristic is more essential for this application when it is combined with low input current demands. In terms of current requirements “Motor A” has been found to be a more preferable choice.

d) The implementation of HEV's analytical model and the incorporation of its subsystems contributed to this direction. The calculation of parameters of great importance, such as the fuel consumption, allowed a better approximation of the optimal designs. This is verified by the fact that “Motor A” with the less efficiency concluded to lower fuel consumption during the considered here driving cycles. In terms of HEV sustainability, this would not be so clear (and is demonstrated here) if only the motor's efficiency characteristics were taking into account.

e) The power density of the two final topologies was calculated to be equal to 1.03 kW/kg and 1.22 kW/kg correspondingly. Thus, the target of achieving a value higher than 1 kW/kg for this quantity was also met. Despite the low active mass of the motor non saturable operation has been achieved and the final designs are not imposed to extensive mechanical stresses.

V. CONCLUSIONS

This paper deals with an effective design methodology for SPMSM for in-wheel direct-drive traction application. A previously developed KBSA was applied successfully and combined with a suitable design and optimization procedure. The development of high power density in-wheel motors has been achieved. Furthermore, the corresponding beneficial assessment of the overall HEV's system performance is also derived and discussed. This approach permits the interaction of motor's operational characteristics with the vehicle's subsystems by using an analytical and dynamic HEV model.

Through a case study, the effectiveness of the proposed overall process was evaluated. It was found that the motor efficiency is not explicitly the sole factor for HEV sustainability in terms of fuel economy. Based on the overall results, the introduced methodology seems very promising and could be of great aid to designers in order to conclude to the optimal HEV/motor configuration.

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