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Dossier

Electronic Intelligence in Vehicles
Intelligence électronique dans les véhicules

Design and Optimization of Future Hybrid and Electric Propulsion Systems: An Advanced Tool Integrated in a Complete Workflow to Study Electric Devices

F. Le Berr, A. Abdelli, D.-M. Postariu and R. Benlamine

IFP Energies nouvelles, 1-4 avenue de Bois-Préau, 92852 Rueil-Malmaison Cedex - France
e-mail: fabrice.le-berr@ifpen.fr - abdenour.abdelli@ifpen.fr

Résumé — Développement et optimisation des futurs systèmes de propulsion hybride et électrique : un outil avancé et intégré dans une chaîne complète dédiée à l'étude des composants électriques — Le recours à l'électrification pour réduire les émissions de gaz à effet de serre dans le domaine du transport est désormais reconnu comme une solution pertinente et d'avenir, très étudiée par l'ensemble des acteurs du domaine. Dans cet objectif, un outil d'aide au dimensionnement et à la caractérisation de machines électriques a été développé à IFP Energies nouvelles. Cet outil, appelé EMTool, est basé sur les équations physiques du domaine et est intégré à un ensemble d'outils de simulation dédiés à l'étude des groupes motopropulseurs électrifiés, comme les outils de modélisation par éléments finis ou les outils de simulation système. Il permet d'étudier plusieurs types de topologies de machines électriques : machines synchrones à aimants permanents à flux radial ou axial, machines asynchrones, etc. Ce papier présente les grands principes de dimensionnement et les principales équations intégrées à l'EMTool, les méthodes pour évaluer les performances des machines dimensionnées ainsi que les validations effectuées sur une machine existante. Enfin, le positionnement de l'EMTool dans la chaîne d'outils et des exemples d'applications sont exposés, notamment en couplant l'outil à des algorithmes d'optimisation avancés ou à la modélisation par éléments finis.

Abstract — Design and Optimization of Future Hybrid and Electric Propulsion Systems: An Advanced Tool Integrated in a Complete Workflow to Study Electric Devices — *Electrification to reduce greenhouse effect gases in transport sector is now well-known as a relevant and future solution studied intensively by the whole actors of the domain. To reach this objective, a tool for design and characterization of electric machines has been developed at IFP Energies nouvelles. This tool, called EMTool, is based on physical equations and is integrated to a complete workflow of simulation tools, as Finite Element Models or System Simulation. This tool offers the possibility to study several types of electric machine topologies: permanent magnet synchronous machine with radial or axial flux, induction machines, etc. This paper presents the main principles of design and the main equations integrated in the EMTool, the methods to evaluate electric machine performances and the validations performed on existing machine. Finally, the position of the EMTool in the simulation tool workflow and application examples are presented, notably by coupling the EMTool with advanced optimization algorithms or finite element models.*

ABBREVIATIONS

CFPM	Concentrating Flux Permanent Magnet
EM	Electric Motor
EV	Electric Vehicle
FEM	Finite Element Model
GHG	Greenhouse Gases
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
IM	Induction Machine
IPM	Internal Permanent Magnet
MTPA	Maximum Torque Per Ampere
PM	Permanent Magnet
PMBL	Permanent Magnet Brushless
PMBLDC	DC Permanent Magnet Brushless
PMSM	Permanent Magnet Synchronous Motor

INTRODUCTION

Fighting against the planet global warming, by limiting or even reducing the emissions of greenhouse effect gases (GHG) and notably the CO_2 emissions, will certainly be one of the major challenges of the next decades. The transport sector is recognized as one of those major responsible of these GHG. This sector has been in a considerable expansion during the last fifty years, notably due to the increase of human activity and mobility demand. In this context, it seems to be difficult to reduce CO_2 emissions, except by improving energy efficiency of transport systems. For instance, this objective motivates all the developments on the well known Internal Combustion Engine (ICE) which is now becoming a remarkable innovative and efficient system. Nevertheless, to go further and to keep on improving global efficiency of the global powertrain, it is time to consider a breakthrough: the transport electrification.

By introducing new perspectives and notably a new source of energy, electrification seems to be an interesting alternative way to continue the progress on the powertrain efficiency. Nevertheless, electrification introduces new challenges to face to: new degrees of freedom to optimize and thus an increase in powertrain complexity, a new type of energy to manage with new problems of efficiency, new challenges in terms of reliability, security and cost as evidence. In a context where industrial world is affected by successive economic and financial crises, engineers have to find cost effective solutions to keep on progress on system efficiency improvement and one of these solutions consists in developing and extending numerical simulation in order to manage system complexity while limiting development cost and duration.

The objective of this paper is to present a tool dedicated to the study of electrification notably for the transport sector.

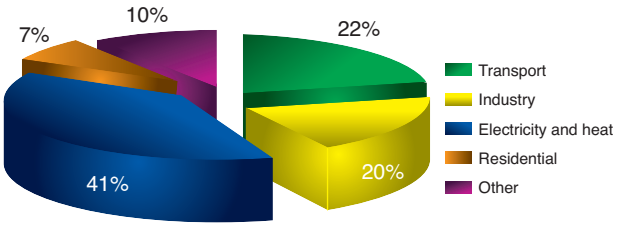


Figure 1

World CO_2 emissions by sector in 2008.

After a first explanation of the motivations to develop such a design and modeling tool to help engineers to face to the new challenges of transport electrification, this paper presents the global methodology used in this tool dedicated to the pre-sizing and characterization of the electric machines. A validation case is presented by comparison with experimental results obtained on an Electric Motor of the automotive sector. At the end of the paper, some concrete application examples are presented to illustrate the interesting potential of the tool to support the specification, the optimization and the management of the complex electrified powertrain envisaged in the transport sector.

1 CONTEXT

1.1 The Complex Issue of Transport Electrification

It is now an acknowledge fact that human activity and notably transport sector is one of those major responsible of the increase of the global warming. Indeed, the transport sector is the second-largest sector in terms of CO_2 emissions, just after the sector of generation of electricity and heat. The transport sector represented 22% of global CO_2 emissions in 2008 in the world *(Fig. 1)*, [1]. In France for instance, the transport sector represents more than 34% of the whole CO_2 emitted by the country [2]. Taken into account this context and to tackle the difficult challenge of global warming, the whole transport sector is now focused one important objective: reducing CO_2 emissions by improving energy efficiency.

The different transport sectors have decided to take measures and incentives to limit or reduce the CO_2 emissions. In the automotive industry, the European Community in association with the car manufacturers has set the objective to limit the CO_2 emissions at 130 g/km in 2012 and 95 g/km in 2020 for light-duty vehicles with high penalties (in the order of billions Euros) for those who would not reach their targets. In the aeronautic sector, the Advisory Council for Aeronautics Research (ACARE) wishes a reduction of about 50% for the CO_2 emissions of air transport before 2020 [3]. Even if it is

TABLE 1

General comparison of different types of Electric Motors for traction powertrain purposes

	DC motor	Asynchronous (induction) motor	Synchronous wound rotor machine	Synchronous permanent magnet machine	Synchronous permanent magnet machine	Switched reluctance machine
Field orientation	Radial	Radial	Radial	Radial	Axial	Radial
Torque	+	-	-	++	++	+
Efficiency	-	-	+/-	++	++	+
Max speed	-	+/-	-	+/-	+/-	+
Cooling	-	-	+/-	+	-	+
Field weakening	+	+	+	+/-	+/-	+/-
Reliability	-	+	-	+	+	+
Economic potential	+	++	-	-	+/-	+

considered as the most efficient transport sector as far as emissions in gCO_2/km/ton are concerned, the maritime transport sector is also concerned by these incentives and a reduction of about 40% between 1990 and 2050 is recommended [4]. In this context, engineers are facing to a veritable technological bottleneck because future improvements of existing powertrains will probably be not sufficient to reach these ambitious targets. Indeed, classical propulsion powertrains are now becoming very complex but also very efficient system. For instance, the Internal Combustion Engines (ICE) designed for automotive applications are combining turbochargers, high pressure direct injection system able to perform multi-pulses injections, devices able to change the valve lifts, etc. To keep on improving the efficiency of such optimized systems, technological breakthroughs are indispensable and electrification seems to be one of the most relevant and realistic approaches to face to these difficult challenges, envisaged in automotive [5-7], aeronautic [8, 9] and maritime transport sectors [10].

Even if electric devices are systems well known and widespread in the industry and rail transport, the constraints and the requirements on these kinds of systems embedded in powertrains are very different compared to a classical industrial application. Generally, transport propulsion systems are operating during relative short duration, with a lot of transient phases and on a wide range of operating conditions. These considerations impose to review the requirements on the electric devices to envisage an extension to the road transport sector. Nevertheless and before dealing with the design of electric devices and notably Electric Motors, what kind of Electric Motors are the most suited to tackle transport electrification?

1.2 Electric Motor Review for Transport

Electric machine includes two types of elements, namely electric and machinery elements. They play a key role in the development of electrical energy in modern civilization. Nowadays electric machines can be found everywhere. In a modern industrialized country, electric machines consume nearly about 65% of the generated electrical energy and cover industry, domestic appliance, aerospace, military, automobiles, renewable energy developments, etc. [32-39].

Among the different types of Electric Motor drives, different types are considered as viable for powertrain electrification, namely the DC motor, the asynchronous motor (induction motor), the synchronous motor with wound rotor, the switched reluctance motor and the Permanent Magnet Brushless (PMBL) motor drives. The different characteristics, advantages and drawbacks of the different electric machines are listed in Table 1.

Considering Table 1, the selection of electrical machine topologies for traction machines has been narrowed into interior and Concentrating Flux Permanent Magnet synchronous motors with radial flux but also synchronous permanent magnet axial flux machine. Permanent magnet machines are getting more widespread in traction applications [48] due to their superior power density, compactness and current availability of power electronics needed for effective control. Despite recent increase in price of permanent magnet materials, they are still cost effective. Axial flux permanent magnet machines in particular benefit from short axial length, which might be a considerable advantage to embed the machine into vehicle powertrain [47]. Moreover, rotors of axial flux machines may replace engine's flywheel and sits in engine's existing flywheel housing [49]. Induction Machines (IM) are also selected because they are recognized as a matured technology being widely accepted in traction applications [50]. 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 are not considered in this study. Same observation can be done on the synchronous wound rotor machine. This machine is not selected for the moment

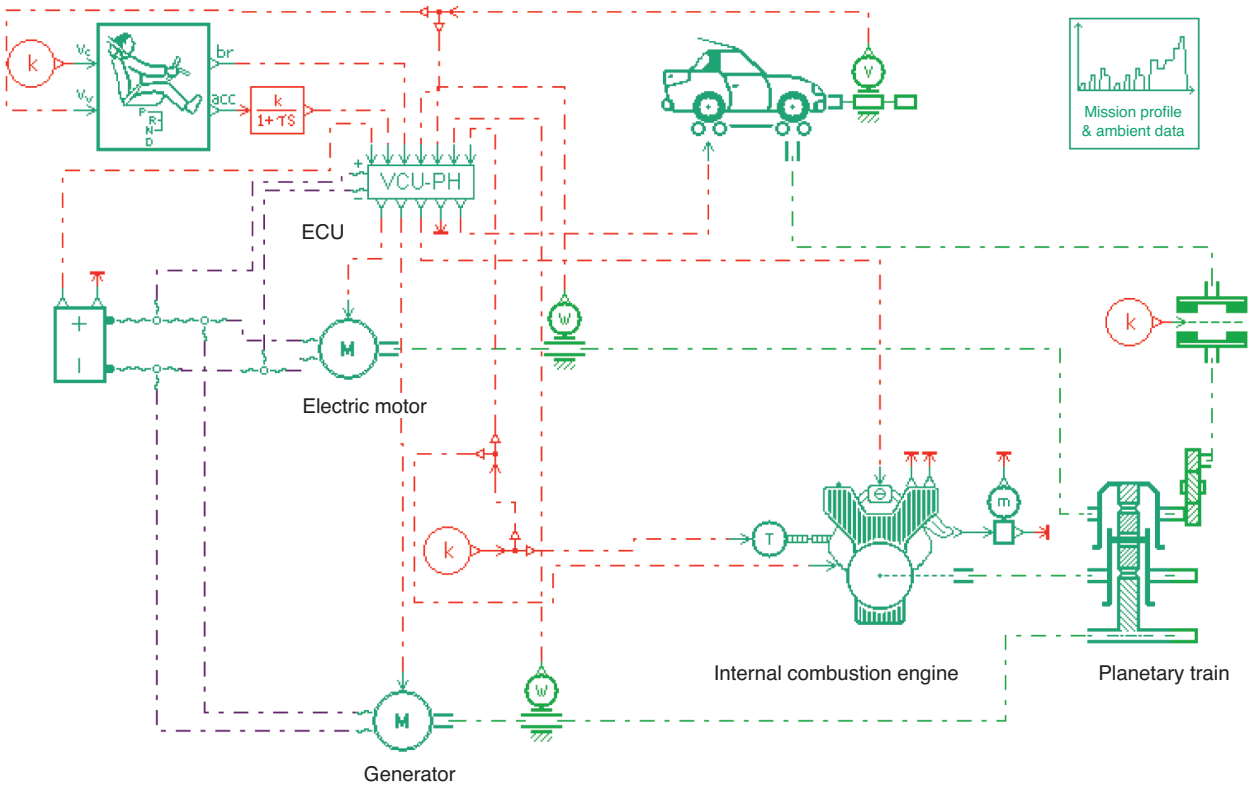


Figure 2

Example of a complete HEV simulator (powersplit architecture) developed on the LMS.IMAGINE.Lab AMESim® environment.

because of rotor copper losses difficult to evacuate but it would be a relevant machine in the future because it uses no Permanent Magnet and is thus cost attractive for future applications.

1.3 Modelling and Simulation Contribution for Electrification

In spite of its undeniable potential, electrification has also one major drawback: the increasing complexity of the propulsion system. With electrification, the latter has to manage several energy sources (from fuel and electrical energy storage systems) and several types of propulsion devices (ICE, Electric Motors) to benefit from these new degrees of freedom in the most optimal way. In this context and taken into account that the duration and the cost of the development of the propulsion system have always to be reduced, numerical simulation can offer an interesting potential to support the design, the evaluation and the management of such complex systems [11-13]. In the case of propulsion system electrification and particularly for the study of electric devices, a lot of tools are nowadays available to address different objectives.

To study one specific component, multi-dimension or finite element simulations are considered as the most accurate tools because they take into account the detailed geometry of the component and use an accurate modelling of the different phenomena occurring in the component. For Electric Motor (EM), Finite Element Models (FEM) [14] are considered as the reference tool to understand EM, develop and validate more simplified models [15, 16]. Nevertheless, FEM are also complex and CPU expensive models. They cannot be embedded in complete simulators representative of the complete system, to study component interactions.

To study complex interactions within the complete system, zero dimension (0D) simulation is acknowledged as a helpful and even essential tool. In the automotive world, many studies on the new Hybrid Electrical Vehicle (HEV) or the Electric Vehicle (EV) concepts have been the opportunity to create complete vehicle simulators, notably to understand the system and the component interactions [17, 18], to help to specify the characteristics of the different components [11] and to develop and validate control strategies [12, 13]. An example of such a HEV simulator, design on the LMS IMAGINE.Lab AMESim® platform [19], is presented in Figure 2. These kinds of simulators are also developed in the aeronautic sector [20].

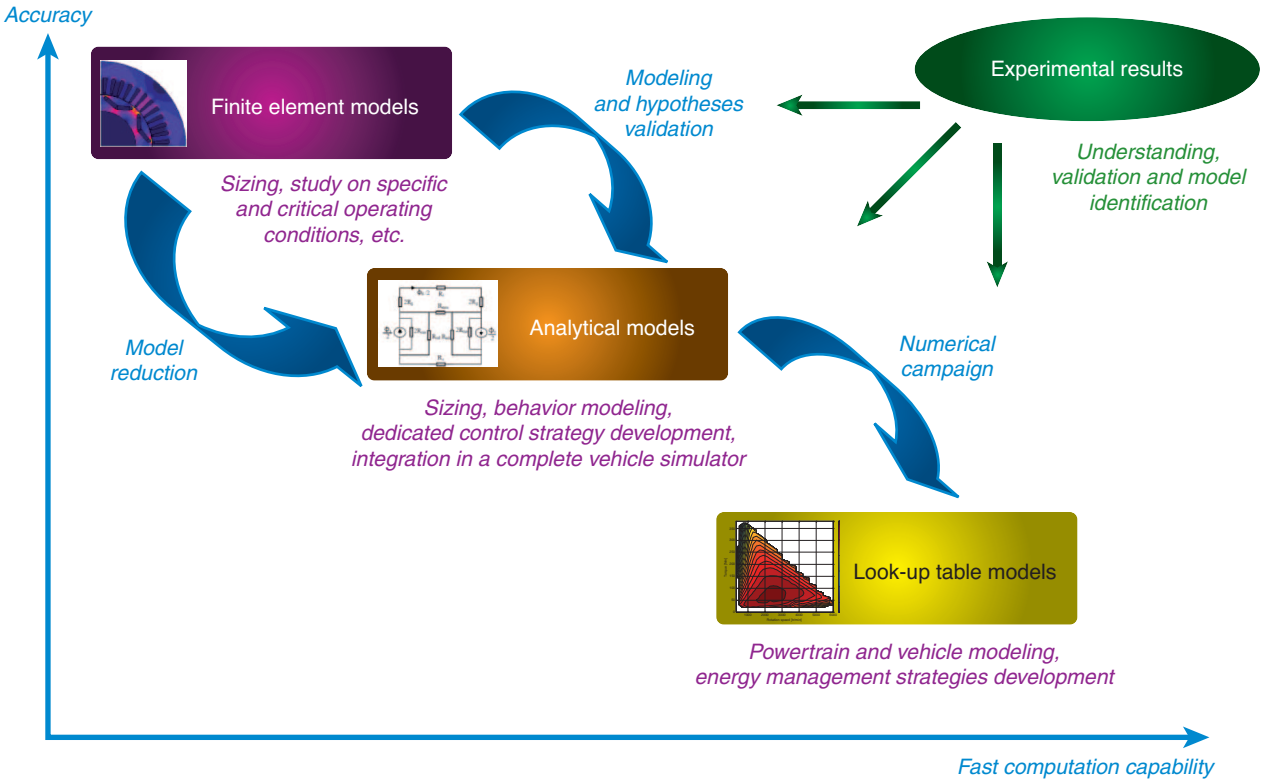


Figure 3

Model classification for Electric Motor models.

To be widely used during the different phases of the design of a new concept, system simulation has to reconcile model representativeness and reduced CPU time. Most of the time, these two objectives are not compatible and methodology coupling FEM and analytical models for system simulation are used [15] to take benefit of the advantages of the different tools. In fact, tools can be organised on a diagram illustrating the permanent compromise between accuracy and computation duration [21, 16]. For electrification and more specifically for Electric Motors, this kind of diagram is illustrated in Figure 3.

2 A TOOL FOR PRE-SIZING AND CHARACTERIZATION OF ELECTRIC MOTORS: THE EMTOOL

2.1 The Motivations

Electric machine models used in system simulation are generally composed of the two types of models presented in Figure 3: the look-up tables or the analytical models. Look-up table's models are relevant to estimate with simple simulations the energy consumption of transport systems [5] or to develop strategies for energy management [12] notably on powertrain architecture coupling at least two power generation devices. Analytical models are more dedicated to estimate in a more physical approach the behaviour of the electric machine, by taken into account all the phenomena occurring inside the electric machine: electro-magnetic phenomena, iron and copper losses, thermal aspects, non-linear behaviours such as saturation phenomena [15]. Based on more physical modelling approaches, these types of models are relevant to estimate more accurately the system energy consumption or to develop more specific control strategies related to the electric machine with some constraints from its environment. They are also more adapted to analyse the behaviour of the electric machine on non-reference or critical operating conditions.

To be relevant, look-up and analytical models always need input data, for instance losses map for look-up table models and electromagnetic parameters for analytical model. In an early stage of the development of a new concept (where the simulation is the only tool available to evaluate the concept), these data are generally not available. A tool able to design an electric machine to evaluate its losses map or their electromagnetic parameters is thus relevant. This is the main objective of the tool developed at IFP Energies nouvelles (IFPEN). This tool, called "EMTool", is presented in the following parts of the paper.

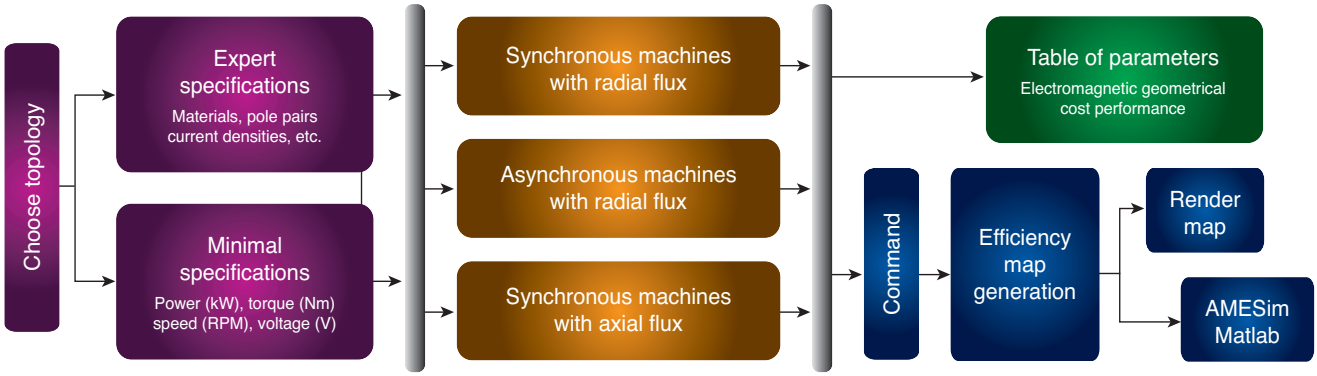


Figure 4

Overview of EMTool.

Some analytical software's dedicated to the design of electrical machines are available on the market. The well-known software's are Ansoft Corporation RMxprt and SPEED. These tools are generally dedicated to specialist of electric machine design. The EMTool was in a first time developed for non-specialist engineers, with few specific skills in the design and modeling of electrical machines, needing data to model the behavior of the electrical machine in complex hybrid powertrain simulators. This tool is also evaluative and new topologies can be easily added if needed. For a Research and Development center as IFP Energies nouvelles, such an in-house tool is very important to study new innovative and complex electrified powertrains.

2.2 EMTool Requirements and Overview

The main objective of the EMTool is to provide the means to design and to model an electric machine in order to be used in system simulation at an early stage of the development of a new concept, while data on the Electric Motor are often not available. In order to extend the use of this tool, EMTool has to be usable by engineers who are not specialists in electric devices, even if the tool integrates physical models and correlations. These two points are the main requirements taken into account in the EMTool. Among the topologies listed in Table 1, the EMTool integrates for the moment the main types of Electric Motors adapted for transportation: a cheap to produce and well known topology (AM), a robust, widespread and very efficient motor (PMSM) with radial and axial flux rotor topologies.

To widespread the use of such a tool, it has to be able to design a virtual motor using a limited number of motor specifications, which are listed in Table 2 and consist in: maximum torque, maximum power, maximum speed and DC-bus voltage. The expert data necessary for the process of design and modeling are pre-defined in function of the topology chosen for the motor and also in function of the 4 main characteristics defined for the minimal specifications.

TABLE 2

Example of minimal specs

	Torque	Power	Max. speed	Battery voltage
Motor specs	300 Nm	63 kW	5 000 RPM	650 V

EMTool is based on an analytical approach to design in order to reduce the CPU time at its maximum. This software tool has been imagined to provide an easy and technically comprehensive help to an engineer working on projects dedicated to the design of electric and hybrid powertrain. The tool outputs are of three types: motor geometrical parameter, motor electromagnetic parameters and motor efficiency map. In order to be used in system simulation software, they can be saved in formats such as Matlab, AMESim or Excel. An overview of the EMTool complete process for sizing, characterization and output creation is presented in Figure 4.

2.3 Electric Motor Design Procedure and Performance Analysis

2.3.1 Design Procedure

The design procedure taken into account in the EMTool is presented in the following paragraph. This procedure has been described for an electric machine topology widely encountered in Hybrid and Electric Vehicles: the radial flux Permanent Magnet Synchronous Motor with magnets buried below the rotor surface *(Fig. 5)*. Vehicles, such as the Hybrid Toyota Prius, the Toyota Camry and the Chevrolet Volt or

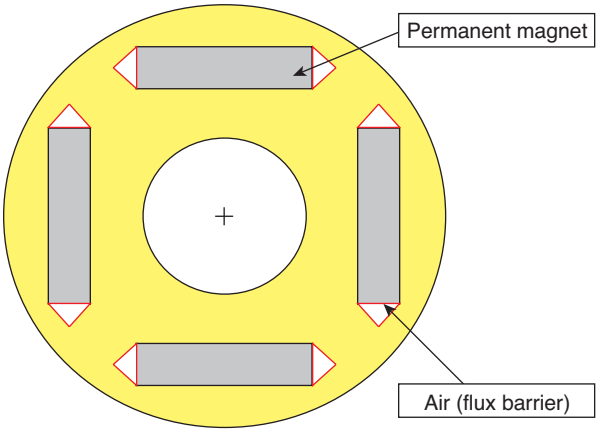


Figure 5

Rotor geometry.

boats, such as the EPIC 23E speedboat are powered by this class of motor. The sizing procedure of the other topologies implemented in EMTool are similar for other types of radial flux electric motors [22-25, 43], while axial flux motors' design procedure follows a different philosophy [26-29]. The main steps are described bellow [30, 31].

The pre-sizing part consists in computing the base speed of the motor, which is determined thanks to the power and the torque specified in the minimal specifications. The shape of the motor is determined by a classical D2L sizing methodology. The product D2L is determined from analytical expression of the torque. Using the ratio of the length of the machine to the air-gap diameter (χ) which is estimated by an empirical formula based on pole pairs number, the inner rotor diameter and length of electric machine can be estimated thanks to the following equations:

$$D_g^2 L = \frac{2 \cdot T_n}{\pi} \cdot \frac{1}{\hat{Al}.\hat{B}_g}$$
$$\chi = \frac{\pi}{4 \cdot p} \cdot p^{0.5} \quad (1)$$
$$D_g = \left(\frac{D_g^2 L}{\chi} \right)^{0.33}$$

where T_n (Nm) represents the nominal torque, Al (A/m) the peak linear current density, B_g (T) the peak airgap induction, p the pole pairs and D_g (m) the air-gap diameter.

Minimum rotor volume is determined from a torque constraint, while the actual rotor diameter is computed based on a constraint on the maximum rotor diameter: respecting a maximum tangential speed on the frontier of the rotor to avoid the tearing of the rotor surface. This constraint is particularly important for surface mounted permanent magnet motors where the magnet's fixations are subjected to rather high values of centrifuges force:

$$D_{r\max} = 2. \left(\frac{\sigma_{mec}}{\left(\frac{3+\upsilon}{8} \right) \cdot \rho_{fe} \cdot \Omega_{\max}^{\ 2}} \right)^{0.5} \quad (2)$$

where σ_{mec}, υ, ρ_{fe}, $\Omega_{\max}$ are maximal mechanical stress of the rotor material, Poisson's ratio, material density and motor's maximum speed.

The mechanical air gap g is calculated from the empirical relation:

$$g = 0.001 + 0.003\sqrt{D_g.L/2} \quad (3)$$

The Inner stator diameter sizing is based on the rotor diameter and imposed mechanical constraints. The stator yoke thickness is obtained as follows:

$$h_y = \frac{B_{mg} \cdot \tau_p}{2 \cdot k_f \cdot B_s} \quad (4)$$

where $B_{mg} = B_g \cdot \alpha_i$ represents the average air gap induction, τ_p the pole pitch, k_f the axial iron percentage and B_s the stator yoke induction.

The slot surface is determined using the following equation:

$$S_s = \frac{4.T_n \cdot \tau_s}{\pi \cdot D_g^{\ 2} \cdot L \cdot B_g \cdot J_c \cdot K_r} \quad (5)$$

where τ_s is the slot pitch, K_r the slot fill factor and J_c the surface current density.

Thus a tooth's width w_t is computed in function of the tooth induction B_d using the flux conservation law:

$$w_t = \frac{B_g \cdot \tau_s}{k_f \cdot B_d} \quad (6)$$

The number of slots is chosen as high as possible while respecting a mechanical constraint imposed on tooth's length/width ratio. Magnet sizing is based on the specified torque and the air gap diameter and gives the magnetic flux. Using magnet's field H_c and induction B_r, the tool computes the appropriate magnet size that creates the necessary flux. The dependence between the length and height of the magnets is defined by the following equation:

$$l_m = \left(\frac{h_m}{p} \right) \frac{B_d \cdot 2p \cdot Ep_b + B_g \cdot D_{re}}{h_m \cdot B_r - g \cdot \mu_r \cdot B_g} \quad (7)$$

where l_m and h_m are respectively the length and the height of the magnet, g the air gap and Ep_b the width of the flux barrier.

The last part of the sizing procedure is dedicated to the characterization of the machine and notably the computation of the electromagnetic parameters: d-q frame inductances,

resistances, currents, etc. The *d*- and *q*-axis inductances can be expressed as [42]:

$$L_d = 3\cdot\mu_0\cdot D_r\cdot\frac{L}{g}.\frac{1}{\pi}.\left(\frac{k_b\cdot N_{bs}}{p}\right)^2. \left(1-\left(8\cdot D_r\cdot\frac{l_m}{2\pi p\cdot g\cdot h_m}+\pi^2\cdot l_m\cdot D_r\right)\right).N_{cs}^2+L_f \quad (8)$$

$$L_q = 3\cdot\mu_0\cdot D_r\cdot\frac{L}{g}.\frac{1}{\pi}.\left(\frac{k_b\cdot N_{bs}}{p}\right)^2.N_{cs}^2+L_f \quad (9)$$

where L_f is the per-phase leakage inductance.

The maximum value of permanent magnet flux linkage is obtained with:

$$\Psi_m = \frac{4D_rL}{\pi}\left(\frac{k_bN_{bs}}{p}\right)B_g\sin(\alpha).N_{cs} \quad (10)$$

The current phase is calculated by:

$$I_s = \frac{J_sK_rS_s}{N_{cs}} \quad (11)$$

To compute all the parameters of the electric machine, the number of conductors in one slot N_{cs} has to be determined. It should be designed in order to fulfil the operating conditions at the base point. The electric machine must be able to provide the base torque $T_m = T_b$ under the supply voltage $V_m = V_b$ at the electrical pulsation $\omega = \omega_b$. By considering the electrical diagram of the machine operating at the base point (T_b, ω_b) and the electromagnetic parameters calculated to one conductor per slot, the number of conductors in one slot can be determined.

After computing all the electromagnetic parameters relevant to the performance analysis, the tool makes a first estimation of the cost of the materials used to build the motor, based on the volume and the masses of the different parts and the prices of the different materials. This evaluation may be interesting to differentiate two technologies as far as cost is concerned.

2.3.2 Performance Analysis

To achieve performance analysis of the designed electric machine, three steps have been developed. The first step is to represent the electromagnetic behaviour in the *d*/*q* axis reference frame. The second step is to develop a control strategy allowing to establish the relevant strategy at each operating point. And the last step is to evaluate the different losses occurring in the machine. These different aspects are illustrated in the following sections.

Equations for Electric Model

A conventional steady state *d*–*q* electrical hypothesis in a synchronously rotating reference frame is used to model the behaviour of the radial and axial permanent magnet synchronous machines. The steady-state equations describing a rotor flux-oriented induction machine in the synchronous frame given by [44] have been also used.

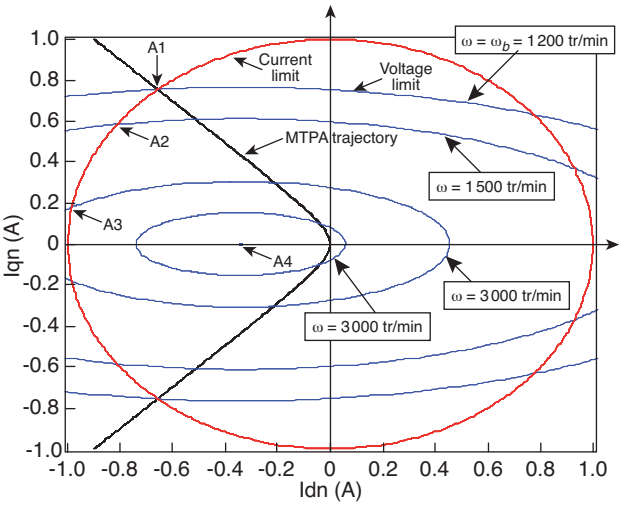


Figure 6

Control trajectories in i_d-i_q plane.

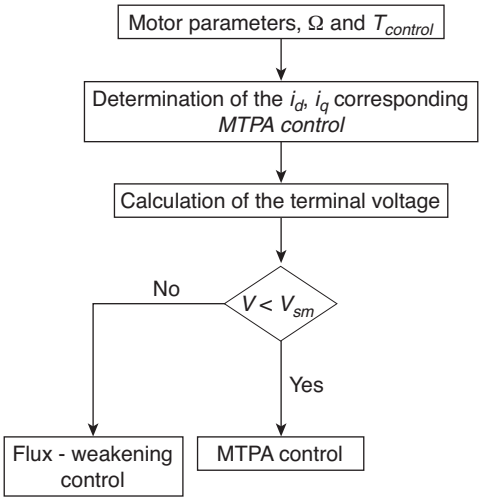


Figure 7

Flow chart of control mode transition.

Control Strategy

In order to satisfy current and voltage limits in the synchronous machines, the stator current vector must stay inside the current limit circle and voltage limit ellipse for all operating conditions as shown in Figure 6. Therefore, the control trajectories under the vector control are set by these limits. For any operating point, in the case where the stator current vector lies inside the current limit circle and voltage limit ellipse, the Maximum Torque Per Ampere (MTPA) control algorithm is applied to the machine. However, when the terminal voltage reaches its limit value, the flux-weakening control is selected in order to satisfy both current and voltage limits. The transition between the MTPA and flux-weakening control is determined by the flow chart given in Figure 7.

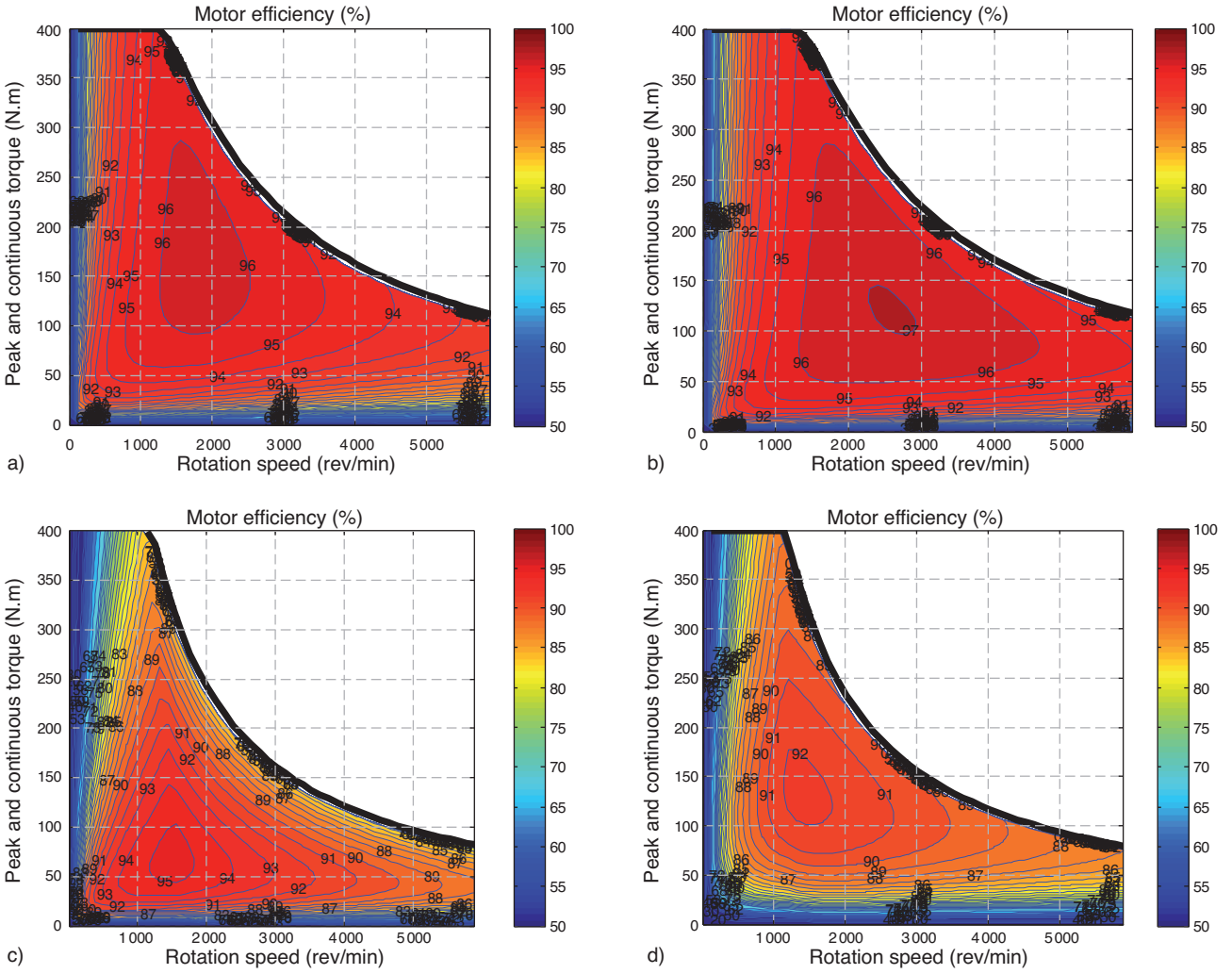


Figure 8

Efficiency maps: a) interior permanent magnet type, b) flux-concentrating type, c) axial flux type, d) induction machine.

In order to estimate machine efficiency values for the various operating regions of the induction machine, the Rotor-Flux-Oriented (RFO) control has been considered [45]. The rotor flux reference is equal to the rated rotor flux below base speed. For the field weakening operation, a commonly used method is to vary the rotor flux reference in proportion to 1/ω. Usually, the *d*-axis reference current i_d^{sref} is decreased in order to reduce the rotor flux. And the *q*-axis reference current i_q^{sref} is increased according to the decrease of the *d*-axis reference current to use the current rating fully.

Loss Modelling

Generally, three types of losses are generally taken into account in an electric machine model: iron losses, copper losses and mechanical losses. For each topology, these main losses have been taken into account. In the radial permanent magnet synchronous machines, the iron losses have been calculated according to [46]. For the axial permanent magnet synchronous machines, depending of the type of topology, iron losses have been calculated according to [47]. In the induction machine, iron losses have been calculated by the formulas given by [43]. According to the selected topology, copper losses in the stator and rotor are calculated by the classical formula RI^2. Mechanical losses are also taken into account with classical formula (depending of rotor speed).

Efficiency Maps

Figure 8 shows efficiency maps generated by the EMTool for electrical machines under investigation, using the electric and loss models described in the previous sections. These models have been associated with the control strategy presented previously. Electric machines have been sized to meet the

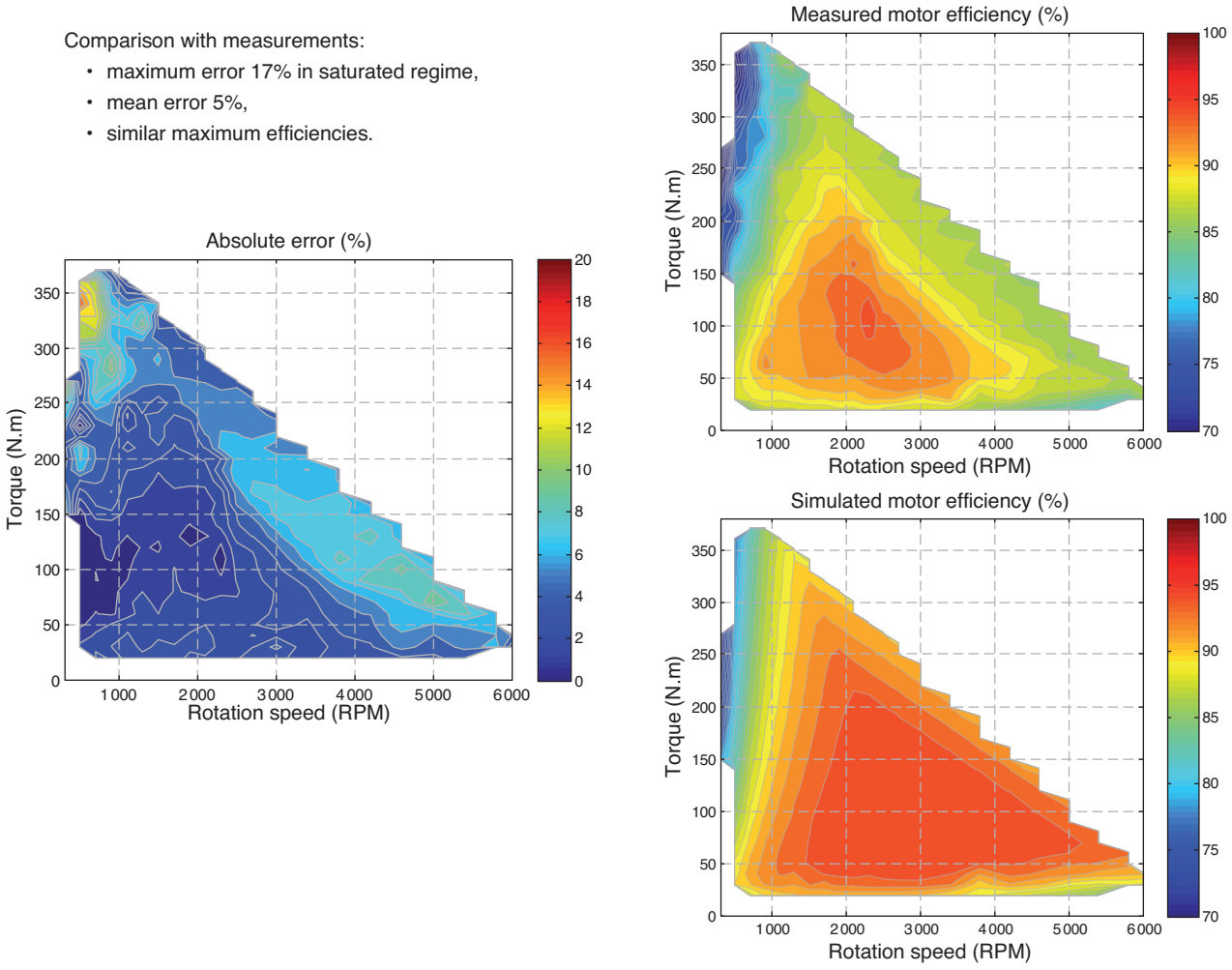


Figure 9

Comparison between simulated and measured efficiency map of the Prius II Electric Motor.

specifications of the Prius II. The minimum specification is as follows: maximum power is 50 kW at the base speed of 1 200 rev/min. The battery voltage is 500 V.

2.4 EMTool Outputs and Validation

The process ends by the generation of the efficiency map using a command similar to the performance analysis. It computes losses for every pair of torque and speed between zero and nominal values. The map can be saved in formats compatible with AMESim libraries (IFP-Drive library) or Matlab's models. The tool also generates a result file which contains the data of the sized motor: the topology and type of command, the geometrical parameters from the outer size to the size of the slots, the evaluated performances (torque and power), the electromagnetic parameters (direct and inverse inductance) and the bill of materials.

A comparison of the performances of the motor designed by EMTool to measurements performed on the Prius II Electric Motor shows the relevance of the process *(Fig. 9)*. Efficiency maps have a mean difference of 5% and a maximum of 17% in highly saturated regimes (saturation phenomena are not taken into account in EMTool for the moment). The maximum efficiencies of the two maps are similar.

EMTool has also been validated thanks to FEM. An example of validation procedure is given in Section 3.3.

3 EMTOOL APPLICATION

3.1 EMTool Position in the Workflow Dedicated to Study Electric Machines

As explained in Section 1.3, system simulation and Finite Element Models are two complementary tools to study

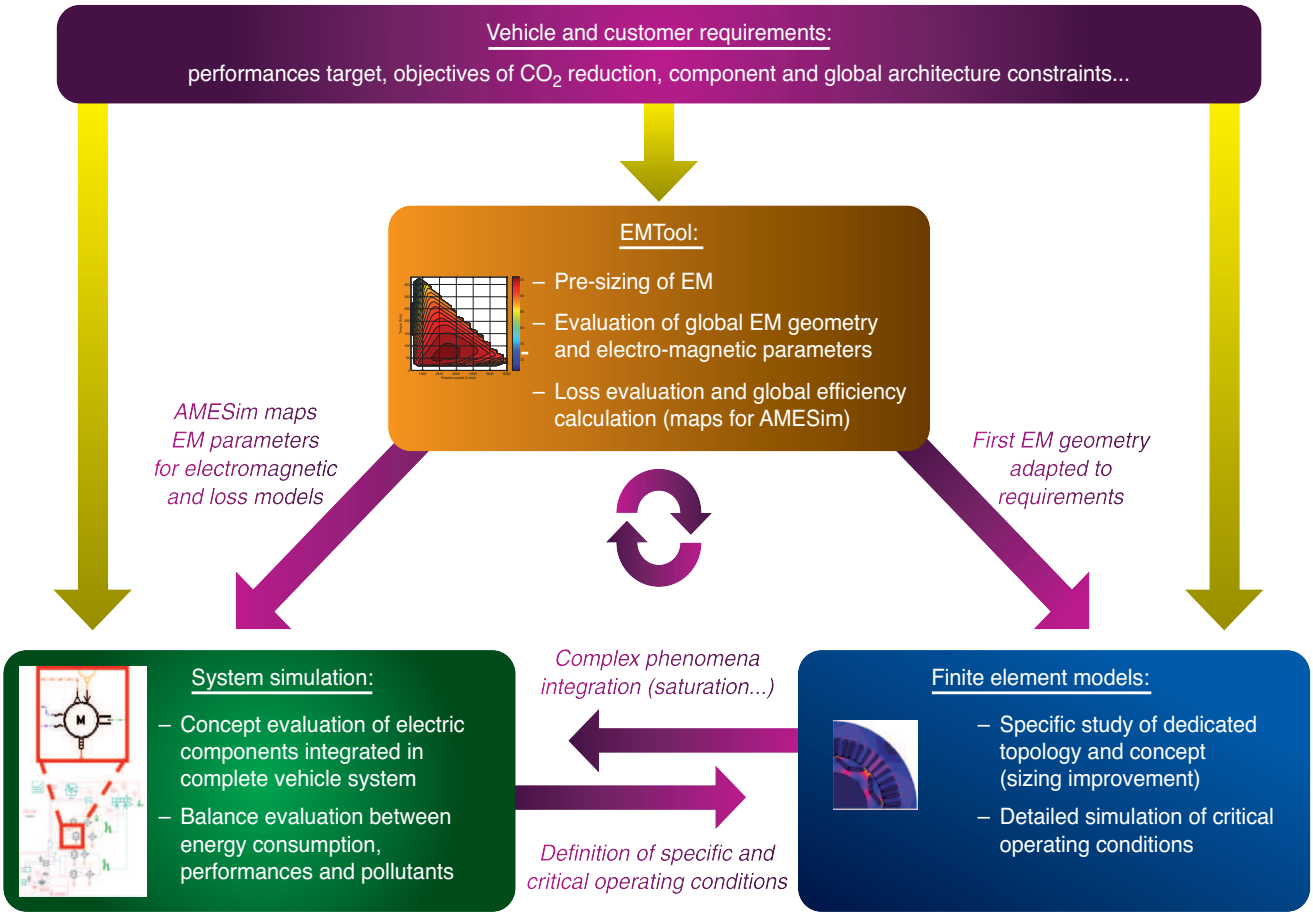


Figure 10

Complete tool workflow dedicated to Electric Motor study.

transport electrification. EMTool becomes completely integrated into this complete tool chain devoted to the specification, the design and the optimization of electric devices in order to reach vehicle and customer requirements (performances, CO_2 reduction, etc.). A scheme of the complete workflow dedicated to the study of electric devices is presented in Figure 10. As explained before, EMTool is able to help the parameterization of models used in complete system simulator. With its ability to generate very quickly virtual motor characteristics and notably efficiency maps, this tool can also be coupled with optimization algorithm to help to the design and specification of electric devices embedded in complete vehicle system. An example of such a procedure is presented in Section 3.2. EMTool can also be used in a first step to generate a motor geometry before analysing and optimizing it in details on FEM software suites. An example of such a procedure is presented in Section 3.3.

3.2 EMTool Coupling with Optimization Algorithm to Help Vehicle System Design

3.2.1 Context: The Design of an Electric Vehicle

The design of a vehicle system and notably the specification of its powertrain is a complex procedure. In fact, the step-by-step design of the different powertrain components is generally difficult, due to the fact that some component characteristics have opposed impact on a target parameter, like the energy consumption for instance. In the case of the design of an Electric Vehicle, the Electric Motor has to face to a double objective: to be efficient and compact as far as mass and volume are concerned. Generally these two criteria do not evolve in the same direction and the objective of the design is to find the good compromise for the vehicle system.

To solve this global problem for the vehicle system, EMTool can be coupled to global optimization algorithms. In

this application, the optimization of the Electric Vehicle is carried out using a multi objective genetic algorithm. In this optimization problem, EMTool is used to design and to model the selected Electric Motor using the design variables optimization. Vehicle performance constraints are imposed on the design problem to ensure that the performance requirements of the vehicle are met. These constraints are defined from Table 3 to Table 6.

TABLE 3

Vehicle performances for take-off

Parameter	
Loaded mass	400 kg
Slope	25%
Vehicle speed	10 km/h

TABLE 4

Vehicle performances for maximum speed

Parameter	
Loaded mass	75 kg
Maximum speed at 0% slope	140 km/h
Maximum speed at 5% slope	110 km/h

TABLE 5

Vehicle performances for acceleration

Parameter	
0-50 kph	3 s
0-100 kph	9 s
1 000 m with zero initial speed	33 s

TABLE 6

Vehicle range

Parameter	
Loaded mass	75 kg
Total range	60 km
Driving cycle	NEDC

3.2.2 Design Variables, Constraints and Objectives

The design variables considered for the Electric Vehicle optimization and their associated bounds are shown in Table 7. Seven variables are continuous (*i.e.* k_{si}, B_y, J_s, A, T_b, Ω_b and N_{gear}) and four are discrete (*i.e.* p, N_{spp}, N_{scel} and N_{pcel}). Two conflicting objectives have to be minimising thanks to these variables: the motor losses and the total embedded mass of the Electric Vehicle.

When varying the design variables in their corresponding range, six constraints have to be fulfilled to ensure the system feasibility. The first two constraints (g_1 and g_2) concern the number N_{cs} of copper windings per slot. This number has to be higher than one and bounded by the slot section in relation to the winding section. The third constraint (g_3) checks that maximum transition torque of the Electric Motor meet the maximum torque required by the powertrain. In this study, in order to take into account the thermal effect, we suppose that the Electric Motor can develop a maximum torque equal to 2 times its nominal torque. The fourth constraint (g_4) concerns the maximal power of Electric Motor that has to meet the maximal power required by the vehicle. We suppose also that the Electric Motor is able to develop 1.5 times of its nominal power. An additional constraint (g_5) checks that the battery is able to offer the maximal power required by the powertrain. Finally, the last constraint (g_6) ensures that the battery meet the required vehicle range.

TABLE 7

Design variable bounds

Design variable	Type	Bounds
Electric Motor design variable		
Diameter/length ration	Continuous	$k_{si} \in [0.1, 10]$
Induction in the stator yoke (Tesla)	Continuous	$B_y \in [1.2, 1.9]$
Current density (A.mm^{-2})	Continuous	$J_s \in [1, 60]$
Linear current density (A.mm^{-1})	Continuous	$A \in [1, 30]$
Number of pole pairs	Discrete	$p \in [1, 30]$
Number of slots per pole per phase	Discrete	$N_{spp} \in [1, 6]$
Base torque (N.m)	Continuous	$T_b \in [1, 1\,000]$
Base speed (rad.s^{-1})	Continuous	$\Omega_b \in [1, 500]$
Differential gear design variable		
Gear ratio	Continuous	$N_{gear} \in [1, 20]$
Battery design variable		
Number of series cells	Discrete	$N_{scel} \in [1, 300]$
Number of parallel cells	Discrete	$N_{pcel} \in [1, 5]$

3.2.3 The Optimization Process

The non-dominated sorting genetic algorithm (NSGA-II) is applied for the optimization of the Electric Vehicle [40]. The NSGA-II is coupled with EMTool, a battery sizing model and a vehicle model. For each candidate solution investigated by the multi objective genetic algorithm, objectives and constraints are evaluated considering the standard automotive cycle (NEDC) and the vehicle performance constraints. Five independent runs are performed to take into account the stochastic nature of the NSGA-II. The population size and the number of non-dominated individuals in the archive are

set to 100. The number of generations is set also to 100. Mutation and recombination operators are similar to those presented in [41]. They are used with a crossover probability of 1, a mutation rate on design variables of $1/m$ (m is the total number of design variables in the problem) and a mutation probability of 5% for the X-gene parameter used in the self-adaptive recombination scheme.

In first, the selected variables are used to design the traction drive components of the EV which consists of gear transmission, Electric Motor, power electronics and battery storage. The designed components are then used to evaluate the Electric Motor losses, the total mass of the vehicle and the vehicle constraints. Note that in this study, the Electric Motor is represented by its minimum torque, maximum torque and loss maps (coming from EMTool). The power electronics is represented by an efficiency coefficient and the battery is considered ideal with charge and discharge efficiency.

3.2.4 Final Results

The best trade-off solutions determined from the five independent runs are displayed in Figure 11. The global Pareto-optimal front is obtained by merging all the fronts associated with these runs. Moreover, the values of the optimization variables corresponding to one particular solution of the front are detailed in Table 8. This particular solution has been chosen after the analysis of the vehicle consumption of the solutions presented on the Pareto front. As we can see in Figure 12, the solutions of the Pareto front present an optimal solution in term of vehicle consumption.

3.3 Using EMTool as Input to FEM Analysis

As showed in Figure 10, EMTool can be also be used as a first pre-sizing step of an Electric Motor before performing a detail analysis on FEM. Indeed, the geometry outputs provided by EMTool can be considered as the starting elements for a finite element simulation. To illustrate this application, the set of "minimal specifications" in Table 2 is used with EMTool to generate a 3 pole asynchronous motor geometry which is then analyze in the Flux2D finite element simulation software. An example of the outputs supplied by EMtool relevant to a finite element simulation is given in Table 9 (the hypothesis for the stator slot shape taken into account in EMTool is represented in *Fig. 13*). The electromagnetic regions and the mesh for the asynchronous motor used in Flux2D are presented in Figure 14 and Figure 15. Finally, finite element simulations can be run on the nominal operating condition used in EMTool to size the electric machine (torque of 300 N.m at base speed). Figure 16 shows the electric field lines and an evaluation of the output torque of the machine versus the slip. The maximum torque predicted by the EMTool is about 5% accurate if compared to torque evaluated by FEM.

TABLE 8

Details of a particular solution

Diameter/length ration	0.3
Induction in the stator yoke (Tesla)	1
Current density (A.mm^{-2})	60
Linear current density (A.mm^{-1})	12.45
Number of pole pairs	4
Number of slots per pole per phase	1
Base torque (N.m)	99
Base speed (tr.mn^{-1})	4 800
Gear ratio	7
Number of series cells	76
Number of parallel cells	3

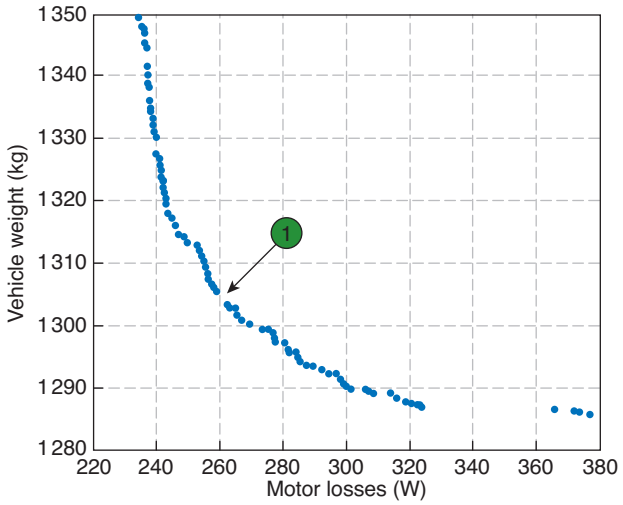


Figure 11

Pareto front of the best trade-off solutions.

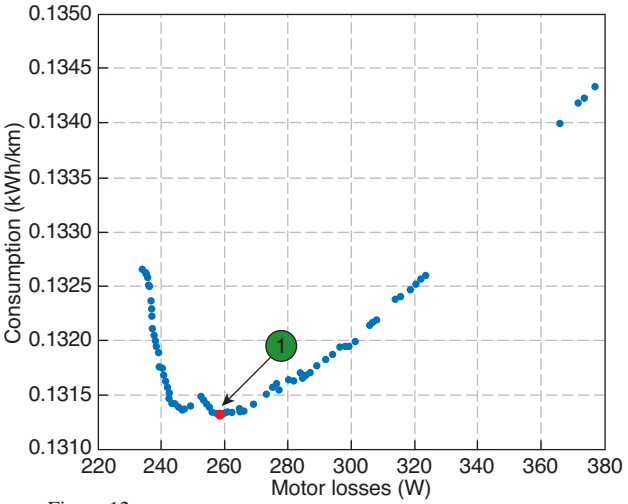


Figure 12

Vehicle energy consumption of the best trade-off solutions.

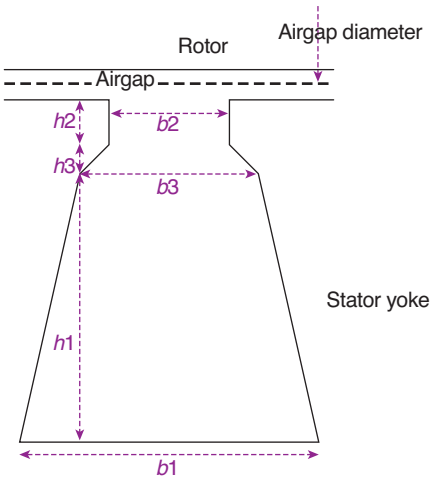


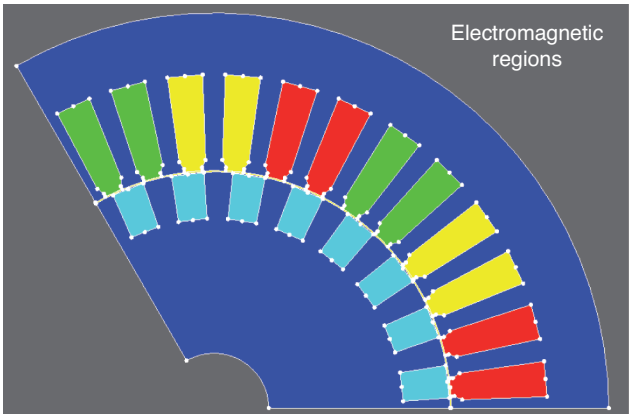
Figure 13

Hypothesis for stator slot shape in EMTool.

As a conclusion, the motor generated by EMTool can thus be seen as a "first step" motor upon which improvements can be brought using the FEM software. EMTool has been designed with simplicity in mind and to be able to provide an electric machine in a short amount of time when the user doesn't have detailed information on what specificities the motor needs to have. Finally, EMTool can be used as a pre-sizing tool before using a more advanced design methodology based on finite element software.

CONCLUSION AND PERSPECTIVES

To keep on improving efficiency of future powertrains and reduced CO_2 pathway of transport sector, electrification is considered as a key issue to reach these ambitious objectives. In this context of increasing complexity of the powertrain, it is



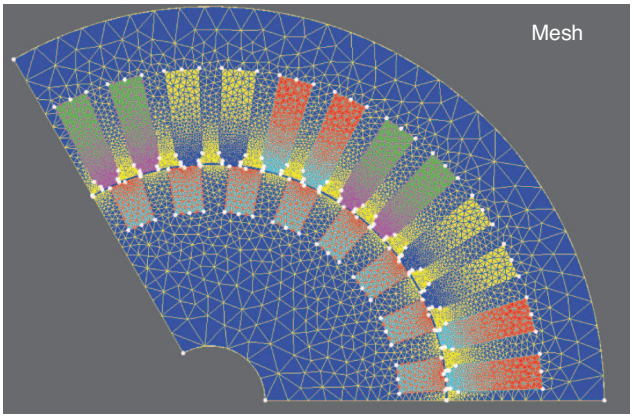


Figure 14

Representation of an asynchronous motor in Flux2D.

TABLE 9

Geometry data generated by EMTool

Topology	Asynchronous machine	
Type of command	Vector command	
Minimal specifications		
Power	63	kW
Torque	300	Nm
Max. speed	5 000	RPM
Battery voltage	650	V
Size		
Outer diameter	34.6	cm
Axial length	15.7	cm
Total mass	83.3	kg
Rotor inertia	0.226	kg.m^2

Stator geometry		
Number of pole pairs	3	-
Number of slots/pole/phase	2	-
Outer diameter	36	-
Airgap diameter	20.8	cm
Airgap width	1.38	mm
Stator yoke	26.89	mm
Teeth height	41.8	mm
Teeth width	10.4	mm
Slot height h1	41.8	mm
Slot height h2	2.5	mm
Slot height h3	4.7	mm
Slot width b1	7.8	mm
Slot width b2	3.9	mm
Slot width b3	5.8	mm

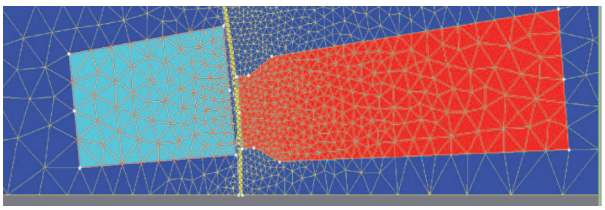


Figure 15

Zoom on the mesh created for the slots and airgap in Flux2D.

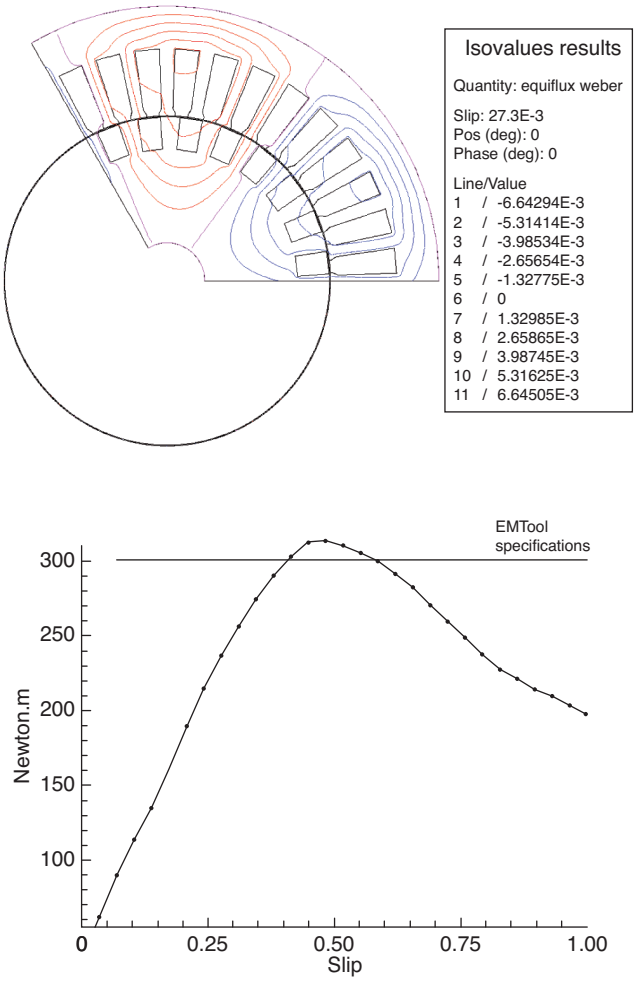


Figure 16

Electric field repartition and representation of the torque function of the slip computed in FEM.

now recognized that simulation tools are indispensable to design, optimize and manage the global system. For a few years, IFPEN invests a lot of efforts on powertrain simulation, notably by developing system simulation solutions, generally build and validated thanks to multi-dimension model.

For electric devices, this typical scheme associating system modelling and Finite Element Model has been set up. To complete this tool workflow, a tool dedicated to the pre-sizing and the characterization of electric machines has been designed and linked to the different existing tools. This tool has several objectives and notably the ability to help the parameterization of simulation model of Electric Motor, to participate to the complete powertrain sizing in a global approach and to define a first geometry of electric machine based on simple requirements.

This tool is flexible and will be improved in the next steps. Some new electric machine topologies will be introduced to cover a large scale of electric devices used in transport sectors. A specific work will also be done to deal with specific operating conditions faced in electric machines used in transport sector, notably improvements on thermal and saturation behaviours. Thermal modelling is very important and a future key step in the development of the EMTool, particularly if high current density (such as 60 A/mm^2) is chosen as bounds for the electromagnetic modelling.

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