Integration of an Induction Machine Synthesis in a Multiphysic Simulation Tool for Automotive Applications

J. Legranger, G. Friedrich, R. Trigui, F. Badin

Abstract— As a part of the powertrain system of vehicle, variable speed induction machines are subject to constrained conditions : high power density, wide speed range, temperature, saturation, low cost. Conventional design methods based on constant speed induction machines must evolve into systemic techniques to take into account all these specifications. This paper presents a simplified multiphysic design program called "synthesis" dedicated to be integrated in a systemic hybrid vehicles simulation tool, VEHLIB, to study the influence of the flux weakening range on induction machine's size. The design synthesis program demonstrates that for an integrated structure, above 2.5 times the base speed, the flux weakening range affects the machine's length. Simulation analyses are compared with experimental data to substantiate the method.

***Index Terms*— Induction machine, synthesis, constant power speed range.**

I. INTRODUCTION

THE powertrain system of hybrid vehicles is a complex and constrained architecture, that leads to adopt a global systemic strategy both in term of simulation (with flexible libraries of models like ADVISOR developed by NREL or VEHLIB developed by LTE [1]) and design of its components.

Different structures may be used for the electric machines that belong to the powertrain system : induction machine, wound rotor synchronous machine, reluctant and permanent magnet machine. Permanent magnets machines allow high performances (efficiency and specific power) but they require special control and design for high flux weakening range [2]. Lack of control of the power converter associated with a high machine speed result indeed in high terminal voltages which can cause severe damage to the whole vehicle. Similarly, wound rotor synchronous machines also own a high specific power but the rotor supply, generally gliding contacts, increase the cost, the length of the machine and worsen the fiability [3]. Finally, induction machines do not need such a rotor supply but involve more rotor losses than permanent magnet machines. Thus, each structure of machine is a compromise between performance and cost and requires a specific and systemic design strategy**.**

The proposed paper focuses on a squirrel cage induction machine (IM) design synthesis procedure that is integrated in the VEHLIB software package and particularly on the influence of the constant power speed range on the length of the machine. First, traditional sizing equations are discussed to highlight the particularities of wide speed range induction machines. Besides, the analytical design synthesis method developed for induction machine operating as a steady state motor is presented. Then, this program is applied to an induction machine for hybrid vehicles, which requires a high power size ratio, to study the influence of the constant power speed range and discuss the integration in VEHLIB. Finally, the synthesis program is validated with experimental results.

II. GENERAL SIZING EQUATIONS

The sizing equations have originally been created to determine the main dimensions of constant speed induction machines thanks to the evaluation of a power density or a torque density. Some authors [4] also used them to compare the capability of different machine topologies such as doubly salient permanent magnet machines and induction machines. Three main sizing equations are commonly mentioned in the literature : the D_{is}^2L equation, the tangential stress criterion and the D_{os}^3L equation. Other formulas such as $D_{es}^{2,5}L$ and $D_{is}^{2,5}L$ [5] are not discussed here as they are far less used and result in a combination of the three main equations. [6]

A. D_{is}^2L Equation

The D_{is}^2L equation is a well known standard formula based on Faraday's law and the assumption that the machine produces a sinusoidal electromotive force [7]. It relates the output power P_o and the synchronous speed N_s to the stator

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J. Legranger is with the Laboratoire d'Electromécanique de Compiègne, Université de Technologie de Compiègne, BP 20529, 60250 Compiègne Cedex, France (phone : 33.03.44.23.45.13; fax : 33.03.44.23.79.37; e-mail: jerome.legranger@utc.fr).

G. Friedrich is with the Laboratoire d'Electromécanique de Compiègne, Université de Technologie de Compiègne, BP 20529, 60250 Compiègne Cedex, France (e-mail: guy.friedrich@utc.fr).

R. Trigui is with Laboratoire transport et Environnement (LTE), Institut National de Recherche sur les Transports et leur Sécurité (INRETS), 25 avenue François Miterrand, Case 24, 69675 Bron Cedex, France, (e-mail: rochdi.trigui@inrets.fr).

F. Badin is with Laboratoire transport et Environnement (LTE), Institut National de Recherche sur les Transports et leur Sécurité (INRETS), 25 avenue François Miterrand, Case 24, 69675 Bron Cedex, France, (e-mail: françois.badin@inrets.fr).

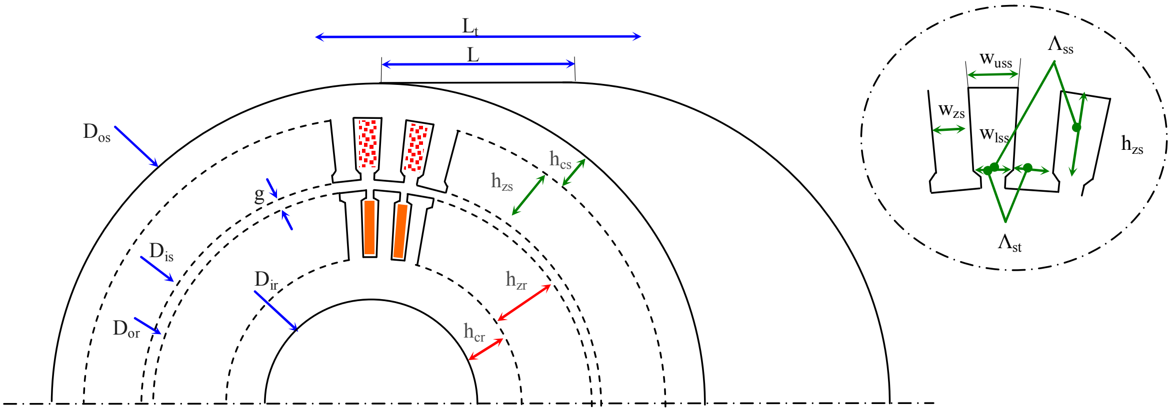

Fig. 1 : Induction machine geometric variables

inner diameter D_{is} (airgap diameter) and the active length L as follows :

$$\frac{P_o}{N_s} = C_0 \ \eta \ \cos\varphi \ D_{is}^2 \ L \tag{1}$$

The output coefficient C_0 (Esson's output "constant" [8]), the efficiency η along with the power factor cosφ are variables generally estimated according to experimental data [4] [6]. C_0 depends indeed on the fundamental airgap flux density B_g and the surface current density in stator inner circle A_{is} of the IM:

$$C_0 = f\left(B_g, A_{is}\right) \tag{2}$$

Consequently, the equation first accumulates three imprecisions due to the determination of three machine parameters (C_0, η, cosφ). It's all the more so as C_0 has continuously changed over the last decade as magnetic material quality and cooling systems improved [8]. Furthermore, the influence of the inverter and particularly the harmonic content of the flux and the current are not taken into account [10]. Finally, the equation requires the careful choice of an "aspect ratio" [6], to determine the effective core length and the stator inner diameter, and not directly the total length or the stator outer diameter which are true design specifications.

A. Tangential force criterion

Conversely, the tangential force criterion consists in evaluating a single parameter : the tangential stress coefficient σ_{tan} through the determination of the tangential force at the rotor surface for a specific torque T_0, using Laplace's law along with the first harmonic hypothesis [9].

$$T_o = \frac{\pi}{2} \ \sigma_{tan} \ D_{is}^2 \ L \tag{3}$$

σ_{tan} is a function of the average induction under a pole $<B_{gp}>$ and the stator line current density K_{is}.

$$\sigma_{tan} = f\left(< B_{gp} >, \ K_{is}\right) \tag{4}$$

Nonetheless, the determination of a suitable σ_{tan} is very difficult as the coefficient varies from 0.2 to 5 N/cm^2 for standard induction machines [8] and even from 0.2 to 20 N/cm^2 for special applications with a high pole number [9]. Moreover, neither the influence of the inverter nor the total volume of the machine are evaluated.

In fact, this method is generally devoted to compare the performance of different structures as it is suitable for both linear and rotating machines or to design completely new structures. [8]

B. D_{os}^3L equation

The D_{os}^3L equation, where D_{os} is the outer stator diameter, improves the D_{is}^2L equation by introducing the geometry of the stator and the current density in the conductor J_s. The output coefficient C_0 (D_{is}^2L) is then replaced by a third order function f of the ratio of the stator inner D_{is} to the stator outer diameter D_{os} to maximize :

$$\frac{P_o}{N_s} = f\left(\frac{D_{is}}{D_{os}}\right) D_{os}^3 \ L \tag{5}$$

This function emphasizes the flux and densities existing in the machine and consists in an appropriate choice of the proportion of stator copper to stator steel [5].

Regarding the inverter influence, the function includes the ratio of the inverter's voltage harmonics and fundamental components. [10]

Although this equation estimates the stator outer diameter and takes into account the inverter's harmonics, the speed range is not encompassed. In fact, the D_{os}^3L along with the other sizing equations cannot predict the machine performances and by extension the torque/speed characteristics [5] as electrical parameters, like the leakage inductances stay unknown. They are only a good design start and must be completed at least with electrical, mechanical and thermal models, before evaluating the real performances of the machine.

In summary, the evaluation of the constant power speed range on the size of the IM is related to the development of a whole design program and can not be limited to the utilization of standard sizing equations.

III. DESIGN SYNTHESIS

The design program proposed aims at determining the influence of the flux weakening area on the total length of the induction machine. It is an analytical "synthesis", that is to say that it focuses on finding a "feasible" machine instead of a totally optimized one [11]. The program adopts therefore an iterative procedure divided into four steps (Fig. 3) :

- specifications
- a research algorithm
- a sizing process combining a magnetic model with "rules of art" to calculate the main dimensions of the stator and the rotor.
- a performance evaluation method based on electric and thermal models

A. Specifications

The specifications deal with geometric, torque-speed, supply, thermal and economical constraints. The geometric requirements traditionally include a maximal external diameter D_{os} and a rotor internal diameter D_{ir}. (Fig. 1). The steady state torque-speed characteristics focus on two points :

- the base point characterized with a speed Ω_b, an output power P_b or an output torque C_b, and possibly a minimum efficiency η
- the flux weakening constant power point with a maximum speed Ω_{lim}

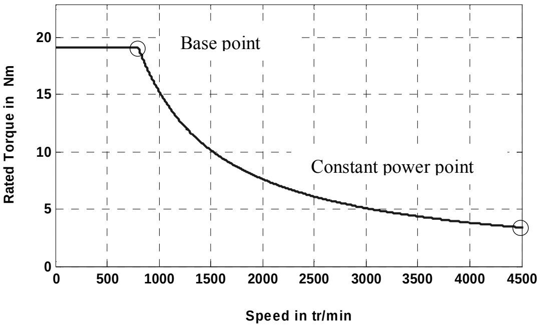

Fig. 2 : Torque-speed characteristics

The supply specifications give information on the battery nominal voltage V_{bat}, the inverter switching frequency and the MOSFET or IGBT ratings.

Although the thermal constraints are strongly linked to the implantation of the induction machine in the vehicle, an average motor external temperature T_e is specified.

Finally, the economical constraints appear with a choice of the quality of the iron silicon sheet, as the sheet's performances (magnetization curve, losses) are related to its price.

B. Research algorithm

The synthesis of a variable speed induction machine is a non linear, multiphysic and multivariable problem [12]. This complexity leads to adopt a coherent solution research methodology. Assuming that we only need to find a "feasible" machine, a simple solution consists in repeat statements with fixed step.

Then, the main difficulty relies on the appropriate selection of the synthesis research variables (SRV), which require to be independent and limited to shorten the calculation time. Four variables have been chosen : the total length Lt, the stator internal diameter D_{is}, the stator current density J_s and ratio r_{bher} of the height her to the width w_{er} of rotor slot. (Fig. 1).

This choices result in fact from a compromise between the integration with the sizing process and the performances evaluation. The total length is indeed compulsory since it has to be minimized. Then, the selection of the airgap diameter D_{is} is due to that on the one hand it replaces the classical sizing equation, such are D_{is}^2L, and on the other hand it enables to calculate directly the pole pitch which is widely exploited in standard design formula [7].

The two remaining research variables concern the definition of the stator and the rotor inner geometry. For the stator, assuming that the magnetic material is specified by the customer, the slot opening dimensions are fixed according to conventional values [11] and the stator slots are trapezoidal, only the slot height h_{es}, the slot number per pole and phase q_s, the slot lower width w_{lss} and the stator current density J_s are relevant SRV. Nonetheless, these variables are dependant as they are linked with the slot geometry. Finally, the current density J_s is preferred as it implies thermal considerations.

For the rotor, a similar reasoning leads to select the ratio r_{bher} as it is related to the value of the leakage inductance and so the speed range. In fact, a high breakdown torque is required to widen the speed range and for fixed supply conditions along with a constant pole number, the only solution is to reduce the stator leakage inductance and mostly the rotor leakage inductance.

C. Sizing processs

The sizing process relies on a magnetic model along with the application of classical design "rules of art" to calculate the dimensions of the machine.

The "rules of art" consist first in selecting an appropriate shape to the slots and a stator winding type. Typically, double layer chorded windings and trapezoidal slot are selected [8]. Then, technical limitations are implemented, such as a minimal tooth width of 3 mm due to the sheet stamping process, to avoid unrealistic design. Finally, some variables as the airgap flux density B_g and the saturation coefficient k_s (which depends on the magnetomotive force (mmf)) are estimated and the parameters of the stator and the rotor are determined with standard design formula [8] [7].

The results are injected in an analytical magnetic model. The quality of the magnetic sheet is given by the specifications and is implemented with Marrocco's formula [13]. Moreover, assuming that the slotting effect is taken into account with Carter coefficient and that we adopt the first harmonic hypothesis, the calculation of all the fundamental of the mmf and flux density is then carried out through a classical lumped parameter network [6]. An iteration process (trial and error process) corrects the former estimations of B_g, and k_s.

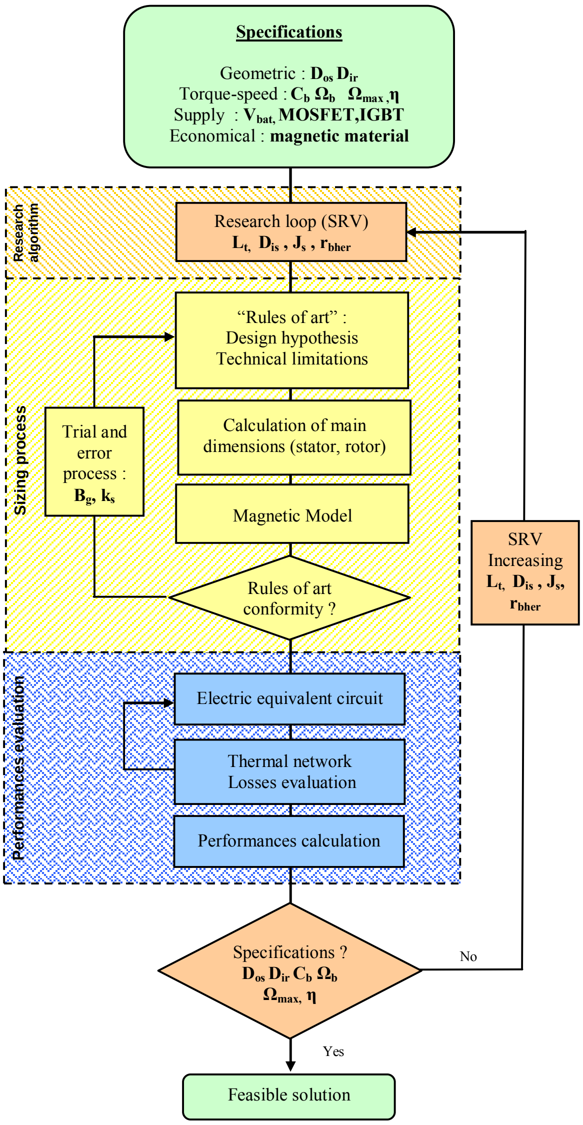

Fig. 3 : Flow chart of the synthesis

D. *Performances evaluation*

The electric model is a classical or "natural" T circuit as developed in [14] (Fig. 4). The maximum value of the coils' voltage V_s encompasses the voltage collapse of the power switch and the coupling of the machine. Then, the calculation of the leakage inductance L_{ls} L_{lr} includes the slot, the differential, and end ring inductance along with the influence of the skin effect. The magnetizing inductance L_m is also figured out through classical formula [8].

Conversely, for the determination of the resistances R_s and $R_{r'}$, the dependence of copper and aluminum resistivity on the temperature T is taken into account with an iteration process based on a thermal model and losses evaluation.

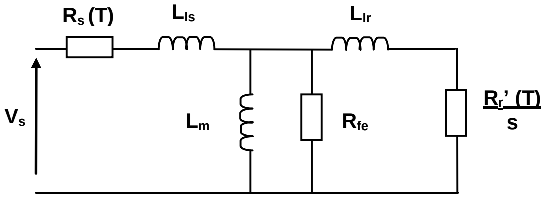

Fig. 4 : Natural T circuit with temperature dependence

The thermal model aims at finding a machine representative temperature and not to obtain a full picture of the thermal state. The model is so a one node network with a global thermal resistance for the rotor and the stator of the machine.

The losses implemented in the thermal model consist of the copper losses due to Joule effect in the windings and the iron losses. The calculation of the iron losses relies on the losses separation between hysteresis and eddy current losses as well as the hypothesis of a sinusoidal waveform for the flux density, as developed in [15].

Finally, the mechanical losses are evaluated though empirical formula of [7].

The performances such as the base point characteristics (Ω_b, C_b, η) and maximum constant power limit speed range characteristics (Ω_{max}) along with the size (D_{os}, D_{ir}) are determined and compared with the specifications of the specifications book.

IV. APPLICATION

A. *Influence of the flux weakening range on the length of the induction machine*

The program described above is applied to a typical specifications book of an integrated motor similar to [16] in order to study the influence of the flux weakening range on the length of the induction machine. In fact, the induction machine of 1600 W permanent power and 3200 W peak power (micro hybrid application) is located between the internal combustion engine (ICE) and the transmission (Fig. 5).

The specifications include consequently an important external temperature (100°C). Then, the maximum stator outer diameter D_{os} is 255 mm and the minimal rotor inner diameter D_{ir} is 135 mm. Finally, the induction motors are designed for several flux weakening speed ranges with a battery supply voltage of 36V.

Maximum stator router diameter	D_{os}	255 mm
Minimum rotor inner diameter	D_{ir}	135 mm
Base speed	Ω_b	800 rpm
Base output power	P_b	1600 W
External temperature	T_{ext}	100°C
Battery supply voltage	V_{batt}	36 V

Table 1 : Integrated motor specifications

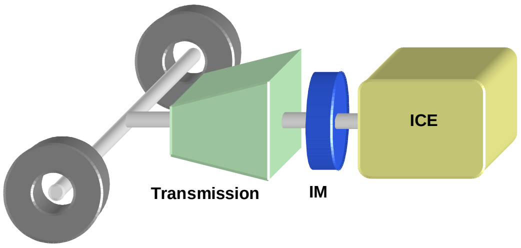

Fig. 5 : Integrated induction machine

Finally, we limit the variations of the efficiency next to 83% as well as we fix the pole number to 10.

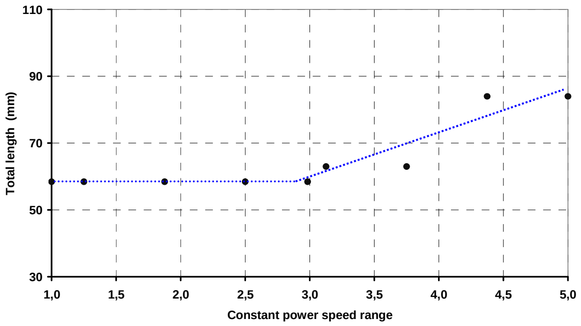

Fig. 6 : Total length of the induction machine to the constant power speed range

The above graphic is divided into two distinct areas. In the first area, the size of the machine remains constant up to 2.5 times the base speed. It corresponds to low range speed applications also called sensodrive applications by [8]. The base characteristics are nearly sufficient to design the induction machine and so the standard sizing equations are still accurate.

Conversely, in the second area, related to wide speed range applications and by extension to automotive applications, the size raises drastically. In fact, for a speed range of 4, you multiply the total length by 1.3. Thus, both base and maximum flux weakening points prevail. It's all the more important as the global modifications of the powertrain of conventional vehicles to adopt such a high flux weakening range motor is rated to several billions euros by length centimeters of the electrical machine. Even if some length can be taken up in the bellhousing, which is usually wasted space, this solution is too expensive for a base power of 1600W. In the early stage of a systemic approach, the dependence of the machine size with the flux weakening ratio so conditions the localization of the induction machine in the vehicle.

B. Link with a systemic hybrid vehicles simulation tool : VEHLIB

VEHLIB is a simulation tool created to analyze and quantify the impact of new architectures of vehicle powertrains on their performances, particularly in terms of fuel consumption and pollutant emission. As a result, VEHLIB adopts a systemic approach where electrical machines are generally modeled with efficiency maps and global consumption is determined according to standard driving cycles along with optimized energy management laws [1]. By allowing a fast systemic design of an induction machine and an easy efficiency mapping of IM, the synthesis program is a suitable complement to VEHLIB. For instance, assuming that the IM can also be used in generator mode, a more cost efficient solution than the former integrated (Fig. 5) concept consists in a separated structure replacing the conventional alternator with the IM and keeping the belt transmission system. (Fig. 7)

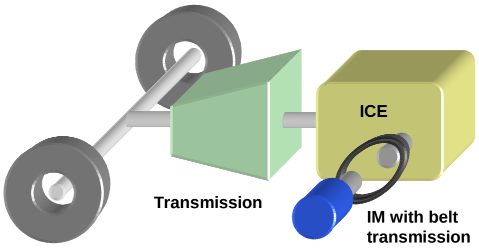

Fig. 7 : Separated structure with transmission belt

If we only consider the motor specifications book, we modify the torque-speed requirements to adopt a belt ratio of 1:3 along with a constant power ratio of 4 (Table 2). Besides, we fix the diameters so that they correspond to a typical alternator. The other specifications are the same as the integrated structure.

Maximum stator router diameter	D_{os}	140 mm
Minimum rotor inner diameter	D_{ir}	35 mm
Base speed	Ω_b	2400 rpm
Constant power maximum speed	Ω_{lim}	9600 rpm
Base output power	P_b	1600 W
External temperature	T_{ext}	100°C
Battery supply voltage	V_{batt}	36 V

Table 2 : Separated motor specifications

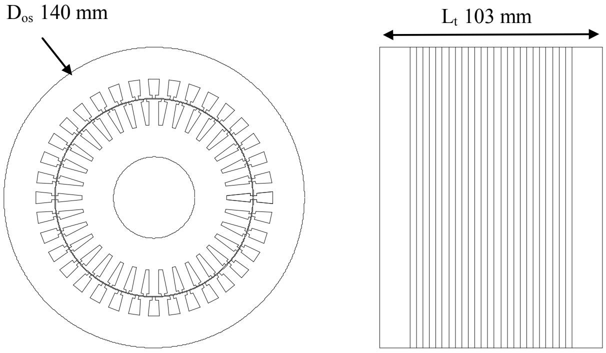

Fig. 8: Separated structure with transmission b

Finally, the design synthesis solution (Fig. 8) is linked with VEHLIB as an efficiency map. The simulation of a typical micro hybrid vehicle according to a standard driving cycle demonstrates that although the separated structure is lighter than the integrated solution with 10.5 kg (transmission include) against 11.6 kg, the average energy consumption of the integrated structure is 5 % smaller because of the belt transmission system efficiency.

V. COMPARISON WITH EXPERIMENTAL DATA

The practical test consists in comparing a design made with the presented synthesis program with an existing and optimized machine dedicated to an automobile application. The specification of this induction motor are the same as in the table 1, expected that the constant power speed limit is 3000 rpm and we have fixed the total length to 70 mm. To complete these data, aluminum was selected for the rotor bar and the stator windings use copper.

		Synthesis	Existing
Pole numbers	p	10	10
Stator conductors per slot	n_s	6	6
Stator slot number	N_s	60	60
Rotor slot number	N_r	52	52
Stator slot aspect ratio	Λ_{ss}	2.56	2.61
Rotor slot aspect ratio	Λ_{rs}	3.51	2.98
Stator teeth / slot lower width ratio	Λ_{st}	0.92	0.97
Rotor teeth / slot lower width ratio	Λ_{rt}	0.98	0.91
Efficiency (base speed)	η	83 %	80 %
Estimated winding temperature	T_{bob}	117 °C	< 130°C

Table 3 : Synthesis main results compared to an existing IM

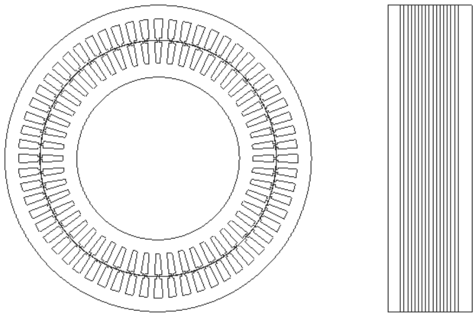

Fig. 9: Synthesis Motor cross section

The key results developed in Table 2, show only slight differences between the two designs. The pole number is the same. It is a compromise between the low base speed as well as a base supply frequency and the size of the IM. The stator conductor number per slot, which is necessarily an even number due to the two layers windings, is a direct consequence of the low battery voltage and somewhat the quality of magnetic material.

Besides, the stator Λ_{rs} and rotor Λ_{ss} slot aspect ratio, which are the ratios of the height to the mean width of the slot, are relatively low to reduce the total leakage inductance and ensure the speed range of 3.75. To this point, the synthesis program is less optimized. The stator Λ_{st} and rotor Λ_{rt} teeth / slot ratio are both next to 1 which correspond to a normal proportion of copper to steel.

Finally, the temperature rise of 117°C does not require any additional cooling system neither special insulation material.

VI. CONCLUSION

We proposed a synthesis of induction machine dedicated to be included in a software package VEHLIB which consists in a "global simulation" to determine performances of various structures of hybrid vehicles. The synthesis demonstrates that the general sizing equation such as the D^2L, are suitable for low speed range up to 2.5 the base speed, where the base characteristics prevail in the determination of the machine dimensions.

Conversely, high speed induction machine requires at least a synthesis as both the flux weakening range and the base characteristics affect the total length of the induction machine. A comparison with an existing machine shows a sufficient accuracy of the synthesis method for the considered application.The developed technique and software may be also used for the determination of an initial solution for the optimization of a high flux weakening induction machine for automotive applications.

REFERENCES

[1] B. Jeanneret, R. Trigui, F. Badin, F. Harel, "New hybrid concept simulation tools, evaluation to the Toyota Prius car", The 16th international electric system symposium, Bejing China, Oct. 1999

[2] L. Chédot , G. Friedrich, "Comparison of direct and adaptative optimal controls for interior permanent magnet synchronous integrated starter generator", IEEE International Electrical Machine and Drive Conference (IEMDC 03), Madison, Wisconsin, United States , Jun. 2003

[3] G. Friedrich, L. Chédot , J.M. Biedinger "Comparison of two optimal machine designs for integrated starter-generator applications", ICEM 02, Bruges, Belgium, 2002

[4] S. Huang, J. Luo, F. Leonardi, T. A. Lipo, "A general approach to sizing and power density equations for comparison of electrical machines", IEEE Trans. on Industry applications, vol. 34, pp. 413-420, Jan. /Feb. 1998

[5] V. B. Honsinger, "Sizing equations for electrical machinery", IEEE Trans. on Energy Conversion, vol. EC-2, pp. 117-121, Mar. 1987

[6] T. A. Lipo , "Introduction to AC machine design", University of Wisconsin, 1996

[7] M. Liwschitz, "Calcul des machines électriques", Tomes 1 and 2, SPES Lausanne, 1967 (in French)

[8] Boldea S. Y. Nasar, "The induction machine handbook", CRC Press, 2004

[9] B. Multon, "Problème de la motorisation d'un véhicule hybride", 3EI, n° 4, pp. 53-64, Dec. 1995 (in French)

[10] Z. M. Zhao, S. Meng, C. C. Chan, E.W.C. Lo "A novel induction machine design suitable for Inverter-Driven Variable speed systems", IEEE Trans. on Energy Conversion, vol. 14, pp. 413-420, Dec. 2000

[11] M. Nurdin, M. Poloujadoff, A. Faure, "Synthesis of squirrel cage induction motors : a key to optimization ", IEEE Trans. on Energy Conversion, vol. 6, n°2, pp. 327-335, Jun. 1991

[12] J. M. Biedinger, J.-P. Vilain, "Dimensionnement des actionneurs électriques alimentés à fréquence variable sous faible tension", The European Physical Journal Applied Phyics, n°3, pp. 101-118, Apr. 1998

[13] A. Marrocco, F. Hecht, "A finite element simulation of an alternator connected to an non linear external circuit", IEEE Trans. on Magnetics, vol. 26, n° 2, pp. 964-967, Mar. 1990

[14] P. L. Alger, "The nature of polyphase induction machines ", John Wiley & Sons New York / Chapman & Hall London, 1951

[15] G. Bertotti., "General properties of Power Losses in Soft Ferromagnetic Materials", IEEE Trans. on Magnetics, vol. 24, n° 1, pp. 621-630, Jan.1988.

[16] G. Friedrich, L. Chédot, J. M. Biedinger, P. Macret, "Integrated starter generator : need of an optimal design and control approach. Application to a permanent magnet machine", IEEE IEMDEC San Antonio Texas, 2005