Hybrid Excitation Synchronous Machines: Energy-Efficient Solution for Vehicles Propulsion

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Abstract—In this paper, the suitability of a class of electric machines for vehicle traction applications is discussed. These machines, which are known as hybrid excitation synchronous machines, combine permanent-magnet (PM) excitation with wound field excitation. The goal behind the principle of hybrid excitation is to combine the advantages of PM excited machines and wound field synchronous machines. It is shown that these machines have good flux weakening capability compared with PM machines, and that they constitute an energy-efficient solution for vehicle propulsion.

Index Terms—Electric propulsion, energy efficiency, hybrid excitation synchronous machines, permanent-magnet (PM) machines.

I. INTRODUCTION

AUTONOMY is a key issue in the development of electric vehicles. The major problem of electric traction is the electric energy source, which is often a battery. Batteries suffer from limited energy storage capacity to mass ratio, which limits the autonomy of electric vehicles and pushes industrialists to find other solutions such as fuel-cell electric vehicles or hybrid electric vehicles. Energy management is the key problem of electric vehicles. Therefore, the efficiency of each component of the traction chain should be optimized. In [1], Biais and Langry show that improving the efficiency of traction motors in the most frequently used operating zones by a few points can significantly increase vehicle range.

The aim of this paper is to present a new class of electric machines and discuss their suitability for vehicle traction applications. Their main advantage is the additional degree of freedom that they offer from a design point of view and that can be used to optimize the energy consumption of the electric propulsion system.

Hybrid excitation synchronous machines combine permanent-magnet (PM) excitation with wound field excitation. The goal behind using two excitation field sources is to combine advantages of PM excited machines and wound field synchronous machines. Wound field excitation is used to control excitation flux in the airgap, which improves flux weakening capability. Hybrid excitation allows, by controlling excitation flux, the design of machines with a relatively low armature magnetic reaction and, at the same time, the extension of the speed operation range. Furthermore, it improves efficiency in the most frequently used operating zones of the traction motor.

Machines with a relatively low armature magnetic reaction have better power factor, which implies a lower power rating for the power converters connected to them. Again, from the design point of view, hybrid excitation offers an additional degree of freedom and improves energy efficiency of the traction motor. The degree of freedom is the hybridization ratio \( \alpha \) of hybrid excitation machines. It is the ratio of the PM excitation flux \( \Phi_a \) to the maximum value of the total excitation flux \( \Phi_{e \text{ max}} \).

II. HYBRID EXCITATION SYNCHRONOUS MACHINES

Several hybrid excitation synchronous machines have been reported in the scientific and technical literature [2]–[11]. They can be divided into the following two groups, depending on how excitation flux sources are combined:

1) series hybrid excitation;
2) parallel hybrid excitation.

A. Series Hybrid Excitation Synchronous Machines

For the first group (series hybrid excitation), PMs and excitation coils are in series (see Fig. 1). In these machines, the flux created by excitation coils passes through PMs. Due to the magnetic properties of PMs, some drawbacks can be identified. Since the permeability of PMs is close to that of air, the reluctance of the excitation coil’s magnetic circuit is relatively high. Furthermore, the risk of demagnetization should be considered.

Fig. 1 shows two machines that belong to this first group [2]–[4]. Fig. 1(a) shows a structure for which both excitation flux sources are in the rotor, which implies the presence of...
sliding contacts [2], [3]. Fig. 1(b) shows a structure in which PMs and excitation coils are placed in the stator, avoiding sliding contacts. The rotor of this structure [see Fig. 1(b)] is as simple as that of switched reluctance machines [4].

B. Parallel Hybrid Excitation Synchronous Machines

For parallel hybrid excitation synchronous machines, the excitation flux created by PMs and excitation coils have different trajectories. The flux created by excitation coils does not pass through PMs. Compared to the first group, parallel hybrid excitation allows a wide variety of structures to be realized. Figs. 2 and 3 show different structures based on the principle of parallel hybrid excitation. They illustrate the diversity of structures based on this principle. Fig. 2(a) and (b) presents structures for which both sources are placed in the rotor [5], [6]. Fig. 3(a) presents a structure where PMs and excitation coils are located in the stator [7]. For the structure shown in Fig. 3(b), the excitation coil is placed in the stator, and the PMs are placed in the rotor [8].

All figures shown until now are of radial flux machines. Hybrid excitation principle is not limited to radial flux machines; Figs. 4 and 5 show two examples of axial flux parallel hybrid excitation machines [9], [10].

Combining two excitation flux sources has some advantages and drawbacks. For series hybrid excitation synchronous machines, since PM permeability is close to that of air, the magnetic reluctance of the excitation coil’s magnetic circuit is high. Therefore, parallel hybrid excitation machines have more flux weakening capability than series machines, and they allow a wide variety of structures to be realized. Each structure has its advantages and drawbacks. The machine shown in Fig. 3(b), for example, needs an external yoke to channel wound field, which makes the machine heavier.

III. HYBRID EXCITATION SYNCHRONOUS MACHINE MODEL

The widely used first harmonic model for PM machines based on a synchronous d–q reference frame, including iron loss [13], [14], is adapted to include the hybrid excitation aspect. Fig. 6(a) and (b) shows equivalent circuits for armature, and Fig. 6(c) shows an equivalent circuit for wound field excitation. This model is used to study the effect of some important parameters ($L_d$, $L_q$, $\Phi_{exc}$, $\alpha$, ...) on the performance of hybrid excitation machines and draws some conclusions about the optimal design for a given set of specifications.
Fig. 3. Parallel hybrid excitation synchronous machines with excitation coils located in the stator.

Fig. 4. Axial flux parallel hybrid excitation machine (first example).

From Fig. 5, steady-state equations are expressed as

\[
\begin{bmatrix}
  v_d \\
v_0d
\end{bmatrix} = R_a \cdot \begin{bmatrix}
i_{0d} \\
i_{0q}
\end{bmatrix} + \left(1 + \frac{R_a}{R_f}\right) \cdot \begin{bmatrix}
v_0d \\
v_0q
\end{bmatrix} \quad (1)
\]

\[
\begin{bmatrix}
v_0d \\
v_0q
\end{bmatrix} = \begin{bmatrix}
  0 & -\omega L_d \\
  \omega L_d & 0
\end{bmatrix} \cdot \begin{bmatrix}
i_{0d} \\
i_{0q}
\end{bmatrix} + \begin{bmatrix}
  0 \\
  0
\end{bmatrix} \quad (2)
\]

\[
V_e = R_e \cdot I_e \quad (3)
\]

where

\[
i_{0d} = i_d - i_{fd} \quad i_{0q} = i_q - i_{fq} \quad (4)
\]

\[
i_{fd} = -\omega L_q \cdot i_{0q} \quad i_{fq} = \frac{\omega \cdot (\Phi_{exc} + L_d \cdot i_{0d})}{R_f} \quad (5)
\]
The total excitation flux varies with the excitation current; it can be expressed, in most cases, as

$$\Phi_{\text{exc}} = \Phi_a + k_e \cdot I_e = k_f \cdot \Phi_{e,\text{max}}$$  \hspace{1cm} (6)$$

where
- $\Phi_{e,\text{max}}$ is the maximum value of the total excitation flux;
- $k_e$ is the hybridization ratio, which is an additional degree of freedom from a design point of view and is defined as
  $$\alpha = \frac{\Phi_a}{\Phi_{e,\text{max}}}.$$  \hspace{1cm} (7)

### A. Per-Unit System

The per-unit system model allows a better understanding of the effect of parameters on machine performance. It is also a powerful tool for electric machine drives classification [15], [16]. Base values of electromotive force (EMF) and current are chosen as the rated values for the motor at rated speed (base speed). In a per unit expression, the armature current and terminal voltage are given by

$$I_n = \frac{\sqrt{v_d^2 + v_q^2}}{I_m}$$

$$V_n = \frac{\sqrt{v_d^2 + v_q^2}}{\Phi_{e,\text{max}} \cdot p \cdot \Omega_b}$$

where
- $I_m$ is the maximum armature current (in $d$–$q$ referential);
- $p$ is the number of pole pairs;
- $\Omega_b$ is the base speed (rated speed).

Note the use of the subscript $n$ to indicate per unit value.

Per-unit expressions of output power, copper loss, and iron loss are given by

$$P_n = \frac{P}{V_m \cdot I_m}$$

$$P_{\text{Cu,n}} = \frac{P_{\text{Cu}}}{V_m \cdot I_m}$$

$$P_{\text{Fe,n}} = \frac{P_{\text{Fe}}}{V_m \cdot I_m}$$

where $V_m$ is the maximum armature terminal voltage (in $d$–$q$ referential). Total copper loss includes armature copper loss and excitation coil copper loss.

Per-unit values of the different resistances and synchronous inductances in the $d$ and $q$ axes are also defined as follows:

$$R_{\text{en}} = \frac{R_a \cdot I_m}{\Phi_{e,\text{max}} \cdot p \cdot \Omega_b}$$

$$R_{\text{fn}} = \frac{R_f \cdot I_m}{\Phi_{e,\text{max}} \cdot p \cdot \Omega_b}$$

$$R_{\text{em}} = \frac{R_e \cdot I_m}{V_{em}}$$

$$L_{dn} = \frac{L_d \cdot I_m}{\Phi_{e,\text{max}}}$$

$$L_{qn} = \rho \cdot L_{dn}$$

where
- $I_{em}$ is the maximum excitation current;
- $V_{em}$ is the maximum excitation coil terminal voltage;
- $\rho$ is the saliency ratio ($L_q/L_d$).

### B. Efficiency Maps

In automotive application, traction motors operate over the entire torque/speed range. Efficiency maps constitute then a convenient way to assess motor design [17]–[20]. Traction motors should be able to operate at any torque/speed combination within the motor’s operating envelope. In particular, traction motors should have the maximum efficiency at the most frequently used operating point, which is located, in most cases, in partial load areas.

Prior to the description of the algorithm that allows calculation of efficiency maps, per unit values of speed and torque have to be defined. The normalized torque value, as defined by (13), at base speed gives an idea about power factor at this speed. We have

$$\Omega_n = \frac{\Omega}{\Omega_b}, \quad T_n = \frac{T}{\Omega_b}.$$  \hspace{1cm} (13)$$

Fig. 7 shows the algorithm used to calculate the efficiency maps. As defined by (13), normalized torque can vary between 0 and 1 as a maximum value. Per-unit value of speed varies between 0 and $\Omega_{n,\text{max}} > 1$.

The algorithm allows, for each combination of $(\Omega_n, T_n)$, selecting $(k_f, I_n, \psi)$ combination, which maximizes efficiency. $\psi$ is the phase difference between armature current and EMF. For each $(\Omega_n, T_n)$ combination, three imbricated loops allow establishing a table that contains all $(k_f, I_n, \psi)$ combinations, which answer the (speed, torque) demand while respecting the current and voltage limits. Then, the chosen $(k_f, I_n, \psi)$ combination is the one maximizing efficiency. For $(\Omega_n, T_n)$ combinations for which no $(k_f, I_n, \psi)$ combination respecting voltage limit is found, the efficiency is set to 0.

Efficiency maps are displayed by drawing isolines of efficiency. Mechanical losses are neglected in efficiency calculation. Fig. 8 shows efficiency maps in the torque/speed plane for a PM motor [see Fig. 8(a)] and a wound field synchronous motor [see Fig. 8(b)]. Efficiency maps drawn in these figures do not include static converter efficiency.
Both machines share the same per unit parameters, except for the fact that the wound field machine has additional parameters, as for hybrid excitation machines, which are excitation coil resistance $R_e$, excitation coil–armature winding mutual inductance $k_e$, and excitation current $I_e$. The per unit value of excitation coil resistance has been defined in (11); the per-unit expressions of mutual inductance $k_e$ and excitation current are given by

$$ I_{en} = \frac{I_e}{I_{em}} \quad k_{en} = \frac{k_e \cdot I_{em}}{\Phi_{e,\text{max}}}. $$

(14)

The power rating ratio $\beta$ of converters connected, respectively, to armature windings and excitation coils needs to be defined for wound field and hybrid excitation machines, and it is given by

$$ \beta = \frac{V_m \cdot I_m}{V_{em} \cdot I_{em}}. $$

(15)

According to (6) and (14), the excitation coefficient $k_f$ and per-unit excitation current are linked by

$$ k_f = \alpha + k_{en} \cdot I_{en}. $$

(16)

For PM machines, the excitation coefficient is constant and is equal to unity [$\alpha = 1$ and $k_{en} = 0$ in (16)], whereas for wound field machines, it depends on the excitation current [$\alpha = 0$ and $k_{en} = 1$ in (16)].

The shared parameters of the PM machine and wound field machine are given as follows: $L_{dn} = 0.5$; $\rho = 1$; $R_{an} = 0.1$; and $R_{fn} = 20$. For the wound field machine, additional parameters are given as follows: $k_{en} = 1$; $R_{en} = 1$; and $\beta = 27$.

These parameters have been derived from a 3-kW prototype of hybrid excitation machine designed to evaluate hybrid excitation technology (see Fig. 9). This prototype has been designed using simple magnetic circuits model; it has not been fully optimized.

Under base speed, both machines have the same maximum performance. Since the per-unit value $L_{dn}$ is equal to 0.5 < 1, the maximum operating speed for the PM machine is limited by the constant excitation flux, whereas it is theoretically infinite for the wound field machine. The controllable excitation flux of the wound field machine greatly simplifies flux weakening control.

PM machine efficiency is better for relatively low speed (around base speed) and high power because the excitation provided by PMs is current free and lossless compared with
that of the wound field synchronous machine [21]. At high speed, due to relatively high current needed for flux weakening control, PM machine efficiency is lower than that of wound field synchronous machine.

The wound field machine has a wider operating area; its maximum efficiency is lower compared with that of the PM machine because of additional excitation copper loss. However, high speed efficiency is higher due to more efficient flux weakening control.

As said before, the goal behind using two excitation field sources is to combine the advantages of PM excited machines and wound field synchronous machines. Section IV will discuss the advantages of hybrid excitation synchronous machines.

IV. ADVANTAGES OF HYBRID EXCITATION SYNCHRONOUS MACHINES

The hybrid excitation principle gives an additional degree of freedom in the control and design of synchronous machines. Electromagnetic loss in hybrid excitation machines depends on two groups of parameters (17): One group corresponds to control parameters, and the other one corresponds to design parameters. We have

$$P_{Cu} + P_{Fe} = f(I, \psi, k_f, \alpha, L_{d}, \rho, \beta).$$

From the control point of view, hybrid excitation machines are similar to wound field machines. From the design point of view, hybrid excitation machines have an additional degree of freedom, which is the hybridization ratio \(\alpha\).

Fig. 10(a) shows an efficiency map for a hybrid excitation machine sharing the same parameters as the previous wound field machine, with \(\alpha = 1\). Setting \(\alpha = 1\) means that excitation coils are only used to weaken the total excitation flux. Fig. 10(b) shows a corresponding excitation coefficient map.

Compared with a PM machine, the hybrid excitation one has an extended operating area as for a wound field machine. The maximum operating speed can be theoretically infinite as long as excitation coils can decrease the total excitation flux such as \(k_f \leq L_{d}\). Furthermore, maximum efficiency is equal to that of the previous PM machine, and it is higher than that of the wound field motor. Thus, the hybrid excitation machine allows combining the advantages of the PM and wound field machines.

Fig. 11 shows an algorithm used to optimize the hybridization ratio. Compared to the algorithm shown in Fig. 7, this one includes design and control parameters. It allows definition of the value of the hybridization ratio \(\alpha\), which maximizes efficiency for the desired speed–torque point \((\Omega_n, T_n)\).

This algorithm allows choosing, for \(\alpha\) varying between 0 and 1, combinations of the excitation coefficient \(k_f\), normalized armature current \(I_n\), and phase shift \(\psi\), which maximizes efficiency \(\eta\) while respecting the voltage limit. The optimal value of hybridization ratio \(\alpha_{opt}\) is the one that maximizes efficiency [see Fig. 13(a)].

By adjusting the value of \(\alpha\), it is possible to shift a high-efficiency area into the desired (torque, speed) area. As an example, Fig. 12(a) shows an efficiency map for a hybrid excitation machine that have the same parameters as the one before but with a different hybridization ratio \(\alpha \neq \alpha_{opt} = 0.72\).
The hybridization ratio $\alpha$ has been chosen, for this machine, to shift the high-efficiency area around point $(\Omega_{n0} = 1.5, T_{n0} = 0.36)$. This point can be, for example, the most frequently used operating point for vehicle traction. By adapting a hybridization ratio value, it is then possible to improve energy efficiency of traction machines in electric or hybrid vehicle applications. Fig. 12(b) shows a corresponding excitation coefficient map.

In [1], Biais and Langry show that improving the efficiency of traction motor in the most frequently used operating zones by a few points can significantly increase vehicle range. They have compared two designs that have the same maximum performances but different efficiency maps. One design has better efficiency for the most frequently used operating point. They announce an increase in vehicle range in almost all cycles [1]. Up to 6% economy of energy consumption, in an extra urban cycle, has been reached.

Fig. 13(a) and (b) shows, respectively, variations of efficiency $\eta$ and excitation coefficient $k_f$ with hybridization ratio for a previous case $(\Omega_{n0} = 1.5, T_{n0} = 0.36)$. The optimal value of the excitation coefficient $k_{f_{\text{opt}}} \alpha_{\text{opt}}$ is equal to $\alpha_{\text{opt}}$ ($k_{f_{\text{opt}}} \alpha_{\text{opt}}$), which means that the copper loss of wound field excitation circuit is null (the excitation current $I_e$ is null). Torque $T_{n0}$ is only produced by PMs. These figures illustrate how this algorithm helps in choosing the optimal value of the hybridization ratio.

For the case studied here, the optimal hybridization ratio $\alpha_{\text{opt}}$ is equal to 0.72. From a design point of view, this means that wound field excitation should be able to enhance or weaken the excitation flux. The efficiency map shown in Fig. 12 is calculated assuming that wound field excitation is able to enhance or completely cancel the PM excitation flux such that the excitation coefficient $k_f$ varies between 0 and 1. Power converter feeding wound field excitation circuit should be bidirectional in this case. A cheaper solution can be obtained by using a unidirectional converter. Fig. 14(a) shows an efficiency map in the torque/speed plane, for a previous machine ($\alpha = 0.72$), when wound field excitation is only used to enhance the total excitation flux. Fig. 14(b) shows a corresponding excitation coefficient map in the torque/speed plane.

Fig. 14(a) shows that even if a unidirectional converter is feeding wound field excitation circuit, it is still possible to shift the maximum efficiency area to the most frequently used operating point, at least for this case. However, a reduction in power capability for high speeds can be noticed. This reduction in power capability has to be weighed against the reduction of cost related to the use of unidirectional converters.
V. EXPERIMENTAL VALIDATION

An experimental study based on the double excitation prototype shown in Fig. 9 is described in this section. The operating principle and flux control capability of this prototype are first presented. Efficiency characteristics are studied in the second part. These characteristics are studied for two values of hybridization ratio, namely, $\alpha \approx 0.72$ and $\alpha = 1$.

A. Operating Principle and Flux Control Capability

Fig. 15 shows a cut view of the studied machine. It combines PM excitation with wound field excitation. This machine belongs to parallel hybrid excitation structures. Excitation coils are located in the stator, on top of armature end windings, thereby avoiding sliding contacts. Azimuthally magnetized ferrite PMs are located in the rotor. The flux focusing principle is used to obtain reasonable values of air gap flux density. This machine has 12 magnetic poles ($p = 6$).

The stator is composed of a laminated core, solid iron yoke and end-shields, conventional ac three-phase windings, and two excitation annular coils. Solid iron components (external yoke and end-shields) provide a low reluctance path for the wound
field excitation flux. The rotor is, among other things, composed of two solid iron collectors and 12 ferrite PMs. Fig. 16 shows a lamination sheet used to build the prototype’s rotor. Fig. 9(b) shows a photograph of the assembled rotor.

Fig. 17(a) shows the principal flux trajectory of the PM excitation flux. This flux circulates from one pole to another, as for classical PM machines. These flux lines participate to power conversion contrary to these shown in Fig. 17(b). Flux lines shown in Fig. 17(b) are designated as nonactive because they do not pass through armature windings and, therefore, do not participate in power conversion. A design procedure should increase the reluctance path for these lines.

Fig. 18 shows homopolar paths of fluxes created by PMs. Each magnet creates a flux that has a homopolar path creating a north pole while another flux creates a south pole.

Fig. 19 shows wound field excitation flux trajectories. The machine has two annular excitation coils. Each coil acts on one kind of magnetic poles. The flux created by an excitation coil passes one time through active part’s airgap (homopolar path). Depending on the dc excitation current direction, excitation coils can either be used to enhance or decrease (weaken) excitation flux passing through armature windings.
Table I gives the machine’s main data. This prototype has been designed using simple magnetic circuits model; it has not been fully optimized. The principle of operation of this structure has been investigated using 3-D finite element analysis. This study is being used to help establish an analytical model based on a reluctance network—a model that is more convenient to use in the process of design optimization.

Fig. 20(a) shows a variation in the maximum air gap flux versus field MMF. It can be seen that a wide range of air gap control can be achieved. The field MMF is given for one excitation coil. The airgap flux changes with a variation of +95% when air gap flux is enhanced and −70% when it is weakened, with respect to the no-field excitation flux. Fig. 20(b) shows the EMF for different field ampere-turns measured for a machine speed of 170 r/min.

B. Efficiency Maps

Fig. 21 shows a schematic of the experimental test bench used to establish the efficiency maps over the entire torque/speed plane. The calculated efficiency includes the power inverter and the double excitation machine. Output power is calculated from measurements of speed and output torque. Input power includes power inverter input power and wound field excitation circuit input power.

Fig. 22(a) and (b) summarizes, respectively, measurements procedure, how the higher efficiency point is selected, and how efficiency maps are derived. For each speed (varying from 1000 to 6000 r/min by a step of 1000 r/min), an armature current reference is imposed to the power inverter. Four values of armature current reference $I_{\text{ref}}$ are imposed for each speed, i.e., 2.5, 5, 7, and 10 A. Five values of excitation current $I_{\text{exc}}$ are then imposed for each (speed, armature current reference) couple, i.e., $-4, -2, 0, 2, \text{and} 4 \text{A}$. For each (armature current reference, excitation current) combination, the armature current/EMF phase angle $\psi$ is varied to maximize the output power $\{(I_{\text{armature}}, I_{\text{exc}}, \psi)\}$ combination, which maximizes power (or torque). The efficiency is then measured for this point. One hundred twenty measurements points (6 speed values $\times$ 4 armature current reference values $\times$ 5 excitation current values) covering the entire torque/speed plane are then obtained. The second step, which is summarized by Fig. 22(b), leading to efficiency map drawings, starts by dividing the torque/speed plane into 72 areas (6 speed values $\times$ 12 torque values). An algorithm that allows the selection of a higher efficiency point in each area is applied, and finally, fitting curves are used to draw efficiency maps in the torque/speed plane.
Fig. 22. Measured efficiency maps in the torque/speed plane. (a) Measurement procedure. (b) Efficiency maps calculation.

Fig. 23(a) and (b) shows, respectively, efficiency maps for two values of hybridization ratio, i.e., $\alpha \approx 0.72$ and $\alpha = 1$. Both maps are drawn from experimental data collected during the experimental procedure described in Fig. 22(a). For $\alpha \approx 0.72$, all measured points are used (120 measurements points), while for $\alpha = 1$, only 72 measurements points (6 speed values $\times$ 4 armature current reference values $\times$ 3 excitation current values) are utilized. For $\alpha = 1$, only excitation current values smaller or equal to 0 A are taken into account (i.e., $-4$, $-2$, and 0 A). Efficiency values of some measured points (asterisk) are also reported in these figures.

Fig. 24(a) and (b) shows, respectively, efficiency maps, for the two values of hybridization ratio, in which excitation current values of some measured points (asterisk) are also reported. The speed in Figs. 23 and 24 is normalized with respect to the reference value of 2000 r/min for both hybridization ratios. Torque, for $\alpha \approx 0.72$ and $\alpha = 1$, is normalized with respect to reference values 11.4 and 8.6 N·m, respectively. Maximum output power is then different for each hybridization ratio; it is higher for $\alpha \approx 0.72$. The use of per unit values makes it possible to bring this experimental study closer to the previous theoretical study. It can be noticed that the excitation current values for these points is mostly distributed around the null value. It can also be noticed that the highest efficiency zones are shifted to greater values of normalized torque when the hybridization ratio is equal to 1 ($\alpha = 1$) compared with $\alpha \approx 0.72$. For a speed of 3000 r/min (1.5 pu), the highest efficiency point is shifted from a normalized torque value of 0.3–0.4 pu when the hybridization ratio is, respectively, equal to 0.72 and 1. These results are in good agreement with theoretical ones.

VI. CONCLUSION

The study presented in this paper has shown the advantages of hybrid excitation machines. Hybrid excitation offers an additional degree of freedom that allows improving the energy efficiency of the traction motor in electric or hybrid vehicle applications. Moreover, the hybrid excitation principle allows a wide variety of structures to be realized. Thus, magnetic structures may be adapted to constraints of the application.
and the aimed performances. Advantages and drawbacks of different hybrid excitation synchronous machines have been discussed.

A general model that can be used for all synchronous machines has also been defined. This model includes copper loss and iron loss. It has been used to calculate efficiency in all torque/speed planes and to define efficiency maps of different machines. Efficiency maps have been used to theoretically discuss the advantages of hybrid excitation machines compared with other synchronous machines for vehicle traction applications. An experimental study allowed highlighting and confirming the advantage brought by the additional degree of freedom (hybridization ratio) offered by hybrid excitation synchronous machines.

REFERENCES

Yacine Amara (S’00–M’03) was born in Algiers, Algeria, in 1975. He received the Ingénieur d’Etat degree from the Ecole Nationale Polytechnique, Algiers, in 1997 and the Ph.D. degree in electrical and electronic engineering from the University of Paris South XI, Paris, France, in 2001. From 1998 to 2001, he worked toward the Ph.D. degree with the Laboratoire d’Electricité Signaux et Robotique (LESiR), Ecole Normale Supérieure de Cachan, Cachan, France. From 2003 to 2004, he was a Research Associate with the Department of Electronic and Electrical Engineering, University of Sheffield, Sheffield, U.K. From 2004 to 2007, he was a Lecturer with the Department of Electrical Engineering, Technical University of Belfort-Montbéliard, Belfort, France. Since 2008, he has been with the Groupe de Recherche en Electrotechnique et Automatique du Havre (GREAH), University of Le Havre, Le Havre, France, where he is currently a Lecturer. His research interests include the modeling, design, modeling, and control of rotating and linear permanent-magnet machines for automotive applications.

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