Overview of Hybrid Excitation Synchronous Machines Technology

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***Abstract*— This paper describes the state of the art of hybrid excitation synchronous machines. Different hybrid excited synchronous structures from scientific and technical literature are described and analysed. Advantages and drawbacks of the different structures are discussed. Different method of classification of these structures will also be discussed. The contribution of the hybrid excitation principle for motoring and generating mode is detailed and the different models for the design of these structures are presented.**

***Index Terms*— Hybrid excitation, permanent magnet machines, electric machines design, flux weakening region, high speed application, embedded applications**

I. INTRODUCTION

Hybrid excitation machines are those which use two excitation flux sources: permanent magnets (PM) as well as field coil excitation source. The goal behind the association of both sources is to combine advantages of both PM machines and wound field synchronous machines [1]. The good performances of hybrid excitation machines, such as improved flux weakening capability and efficiency, is stimulating increased interest for their study. In generating mode, hybrid excitation machines connected to a passive rectifier constitute an interesting alternative to permanent magnet alternators associated to an active power converter [2], [3]. In motoring mode, hybrid excitation principle allows an easier high-speed operation while the use of permanent magnets helps increase the energy efficiency [1]. Hybrid excitation principle can also be used to reduce PM volumes and save material cost. Some comprehensive reviews on hybrid excited topologies can be found in [1], [2], [4–9]. An alternative and updated review will be provided in this paper.

II. STATE OF THE ART

Before presenting the literature review of the recently investigated hybrid excited topologies, it should be noticed that different terms are used to qualify this kind of machines in scientific and technical literature:

1) Hybrid excitation synchronous machines;
2) Double excitation synchronous machines;
3) Dual excitation synchronous machines;
4) Combined excitation synchronous machines;
5) Permanent magnet synchronous machines with auxiliary exciting windings.

Criteria used for classification of hybrid excitation machines are first discussed and an updated review of recently developed hybrid excitation machines will be provided in this section.

A. Classification criteria

The double excitation principle allows a wide variety of structures to be realized. Many criteria can then be chosen for the classification of double excitation machines. Classical criteria used for classification of other types of electric machines can be used; such as 2D and 3D structures, radial field and axial field structures. However, regarding the particular structure of double excitation machines, the presence of two excitation flux sources, two criteria seem more specific for classification of these machines [6]:

1) by analogy with electric circuits, the first criterion concerns the way the two excitation flux sources are combined: series and parallel double excitation machines [1];
2) the second criterion concerns the localization of the excitation flux sources in the machine: both sources in the stator, both sources in the rotor and mixed localization. By mixed localization it is meant that one source (excitation coils or permanent magnets) is located in the rotor or the stator and the other source in the stator or the rotor respectively. Having excitation coils in the stator is favored to avoid sliding contacts [6].

B. Review of Recent Literature

A non exhaustive review of literature, dedicated to hybrid excitation machines, is presented in this section. In this section, the structures studied in scientific and technical literature are presented according to the nature of magnetic field trajectories within these machines, i.e. 2D and 3D structures. The choice of this classification is motivated by the fact that 2D structures are more simple to study, design, and manufacture than the 3D structures, and therefore more attractive for industrial applications. Advantages and drawbacks of both configurations (2D and 3D structures) will be discussed.

C. 2D Hybrid Excitation Synchronous Machines

One of the structures which attracted considerable research efforts, in the last years, is the hybrid excited flux switching structure. Different hybrid excited flux switching topologies have been investigated [10–14]. The 2D nature of magnetic flux in flux-switching machines and the presence of all magnetic field sources [permanent magnets and windings (armature and excitation coils)] in the stator, which implies a completely passive rotor, makes it a very good candidate in many different applications. Fig. 1 presents a hybrid excited flux switching structure which has been investigated in [11] and [14]. This structure is also investigated in [13] and compared to two other hybrid excited flux switching structures with iron flux bridges. Authors concluded that this structure (Fig. 1) has the most efficient open circuit flux control capability as compared to the two other structures presented in [13]. More recently, a new hybrid excited flux switching structure has been investigated in [12]. This structure has been developed to eliminate some disadvantages present in structures with iron flux bridges that suffer from the presence of the flux path of dc excitation (iron flux bridges) which significantly reduces the main flux excited by magnets and even short circuits the magnet flux. While all structures, studied in [11–14], can be classified as parallel hybrid excitation machines, the hybrid excited flux switching structure investigated in [15] can be classified as series hybrid excitation machines. This structure of hybrid excited flux switching machines suffer from the fact that the dc excitation field is in series with the field excited by magnets, which limits the flux-adjusting capability due to low permeability of magnets.

Other 2D hybrid excited structures where both magnetic excitation field sources are located in the stator as for flux switching machines do exist [16–18]. The EMF is induced in armature windings as a consequence of the modulation of armature flux linkage, which is unidirectional in the armature coils, due to the variation of air-gap magnetic permeance when the salient rotor is turning. Different structures based on this principal have been investigated in [16–18]. The fact that armature flux linkage is unidirectional implies a lower power density for these machines as compared to flux switching structures for same design conditions. While structures studied in [16] and [17] can be classified as series hybrid excitation machines, the structure studied in [18] can be classified as parallel hybrid excitation machine.

In all structures studied in [11–18], all magnetic field sources are located in the stator, thus avoiding sliding contacts. Indeed, the presence of sliding contacts implies some drawbacks, as brush sparking and slip ring maintenance problem. Nevertheless, hybrid excited structures with slip rings do exist [3], [6], [19–22]; problems linked to the presence of sliding contacts being less restrictive for relatively low power applications in which these structures may be used.

Fig. 2 shows a series hybrid excitation synchronous machine where both excitation flux sources are located in the rotor [19].

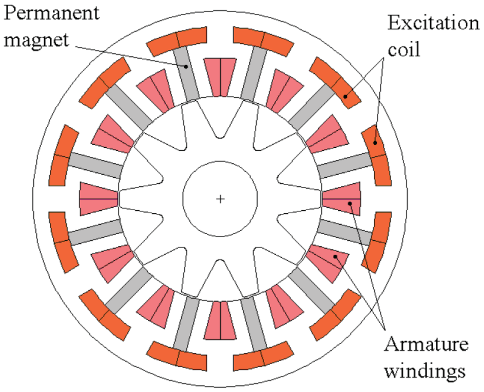


Fig. 1 Hybrid excited flux switching structure with iron flux bridges [11], [23]

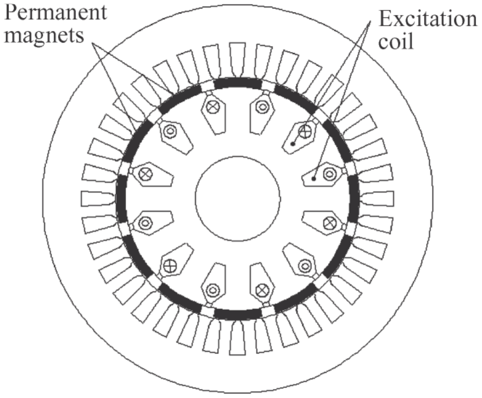


Fig. 2 Series hybrid excited structure [19].

The machine shown in Fig. 2 has been investigated in [19]. A modified series hybrid excited synchronous structure has been studied in [6]. As the structure investigated in [15], these structures suffer from the fact that the dc excitation field is in series with the field excited by magnets, which limits the flux-adjusting capability due to low permeability of magnets. However, the series hybrid excited structure studied in [6] should have a more efficient flux control capability as compared to the one studied in [19].

In [20–22], parallel hybrid excited synchronous structures, where both excitation flux sources are located in the rotor, have been investigated. The harmonic of open circuit magnetic field responsible of torque production is in fact modulated using the dc excitation.

Each structure has some advantages and drawbacks as compared to other structures. Flux switching structures, even with a simple excitation (permanent magnets or excitation windings), are subject to magnetic saturation more than other structures. Indeed, the presence of all magnetic field sources in the stator, within a limited radial excursion, limits the available space for iron cores. Hybrid excited structures where an unidirectional flux linkage is modulated by a variable reluctance rotor should have a lower power density as compared to other 2D hybrid excited structures for same design constraints. Furthermore, the fact that the different magnetic field sources are distributed over a larger radial excursion should make them heavier compared to flux switching machines, in particular for interior radial flux structures. 2D structures where excitation flux sources are located in the rotor help solve the problem of magnetic saturation of stator core as compared to flux switching structures, and should have a higher power density as compared to hybrid excited structures where an unidirectional flux linkage is modulated by a variable reluctance rotor. However, the presence of slip rings constitutes the major drawback of these structures.

D. 3D Hybrid Excitation Synchronous Machines

Even if 3D structures are relatively more difficult to analyze and manufacture than 2D ones, research on hybrid excitation machines having 3D structures still relatively important [24–39]. Compared to 2D structures, the choice of a 3D structure allows a wide variety of machines to be realized. Most of 3D hybrid excited structures are based on parallel hybrid excitation. Nevertheless, a 3D hybrid series excited synchronous machine has been reported in [26] (Fig. 3). Fig. 4 shows a 3D parallel hybrid excited structure which has been investigated in [5]. In most of the 3D structures, the excitation coils are static, thus avoiding sliding contacts. However, providing a low reluctance path for static wound field excitation flux implies the need of additional ferromagnetic pieces which make 3D structures heavier than 2D counterparts.

Given the diversity of 3D hybrid excited machines studied in scientific and technical literature [24–38], a classification according to the second criterion (localization of the excitation flux sources) is provided:

1) both sources in the rotor: [24] and [25];
2) both sources in the stator: [26] (Fig. 3);
3) mixed localization (static excitation coils and permanent magnets in the rotor): [27–38].

The structures studied in [24] and [25] consist in two rotors, a permanent magnet rotor and a wound field rotor, arranged in the machines axial direction (perpendicular to motion plane) under same stator. The armature windings span the two rotors.

Fig. 3 shows a 3D series hybrid excited structure which has been reported in [5]. This machine is the sole 3D series hybrid excitation structure reported in technical literature.

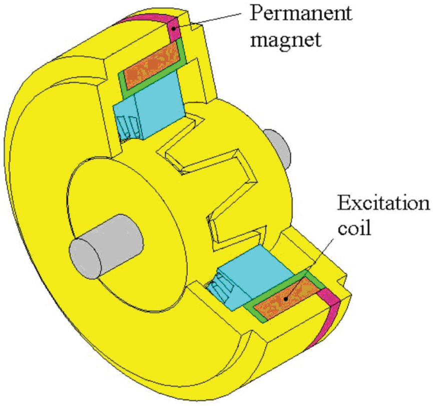


Fig. 3 Series hybrid excited 3D structure [26]

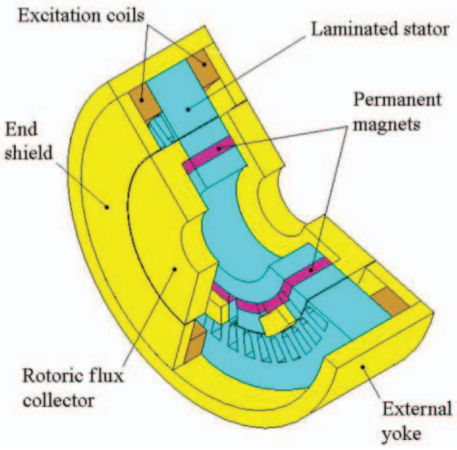


Fig. 4 Parallel hybrid excited 3D structure [5]

For all the rest of 3D hybrid excitation structures, the excitation coils are static and permanent magnets located in the rotor.

Even if all structures discussed earlier are rotating machines, it should be noticed that hybrid excitation principal has also been applied to the case of linear motion structures [39–41]. It should be noticed that many hybrid excitation structures have been also reported in many patent applications [21], [23], [24], [26], [28], [29], [38], [42–54]. While first applications where from European countries, Japan and USA, there is a notably increase of patent applications from China [46–54].

III. CONTRIBUTION OF HYBRID EXCITATION PRINCIPAL

The goal behind the association of both sources (permanent magnets and excitation windings) is to combine advantages of PM machines and wound field synchronous machines. Improved flux weakening capability is one of the characteristics of hybrid excitation synchronous machines; another one is the hybridization ratio α, which is an additional degree of freedom from a design point of view and is defined as

$$\alpha = \frac{\Phi_{pm}}{\Phi_{e\,max}} \tag{1}$$

where, Φ_{pm} is the PM flux linkage, and $\Phi_{e\,max}$ is the maximum value of armature flux linkage.

The advantages brought by hybrid excitation principle are discussed for motoring and generating modes in following subsections.

A. Motoring Mode

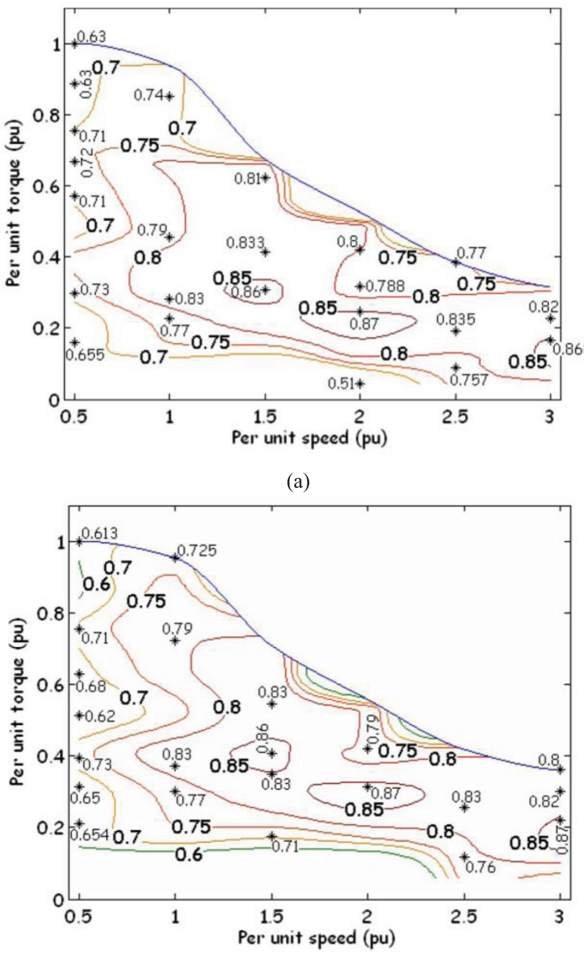
The advantages of hybrid excitation principle are assessed in what follows for electric and hybrid traction applications [1], [14]. Even if hybrid excitation machines are used in other applications [37], the assets offered by hybrid excitation principle are fully exploited in electric traction [1].

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 α.

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. Furthermore, maximum efficiency is equal to that of PM machines, 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.

In automotive application, traction motors operate over the entire torque/speed range. Efficiency maps constitute then a convenient way to assess motor design [55–58]. 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. By adjusting the value of α, in hybrid excited machines, it is possible to shift a high efficiency area into the desired (torque, speed) region.

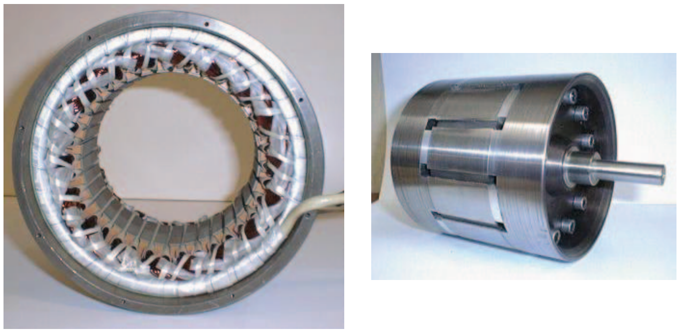
Fig. 5 (a) and (b) shows, respectively, efficiency maps for two values of hybridization ratio, i.e., $\alpha \approx 0.72$ and $\alpha = 1$. Both maps are drawn from experimental data. The machine used in this experimental study is shown in Fig. 6. More details concerning this experimental study can be found in [1]. Fig. 7 illustrates the flux control capability of this machine.



(a)

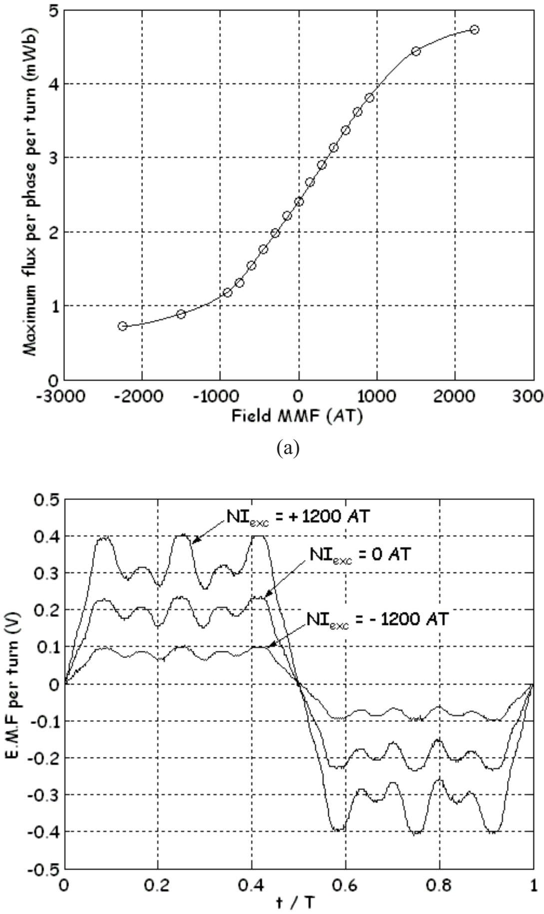
(b)

Fig. 5. Measured efficiency maps in the torque/speed plane. (a) $\alpha \approx 0.72$. (b) $\alpha = 1$



(a) (b)

Fig. 6. Hybrid excitation synchronous machine prototype. (a) Stator. (b) Rotor



(a)

(b)

Fig. 7. Measured flux control capability. (a) Flux variation. (b) EMF variation (170 r/min).

As it has been highlighted in this section, the hybrid excitation machines allows combining advantages of PM machines and those of wound field 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.

B. Generating Mode

The use of hybrid excited synchronous generators for various applications has been reported in scientific literature [3], [59–61]. In [60], authors compared different hybrid excited generators for an islanded application. In [61], authors investigated a hybrid excited machine for wind generation systems. In [3], authors investigate the use of a hybrid excitation machine as an automotive alternator.

In generating mode the hybrid excitation structures can be advantageously exploited in applications requiring variable speed constant voltage operations, e.g., automotive alternators applications (Fig. 8). Indeed, there is a growing demand for efficient electric power generation in automobiles [62]. One of the potential solutions to meet these requirements is the use of permanent magnet alternators [62]. However, the use of permanent magnet alternators implies the need of a controllable power converter, which will impact negatively the cost of the generation system. In hybrid excited alternators, the use of auxiliary windings to control the armature flux linkage allows the use of simple diode rectifier, thus avoiding the use of a costly controllable power converter.

As for the motoring mode hybrid excitation alternators allow combining the advantages of the PM and wound field machines.

IV. COMPARISON OF SERIES AND PARALLEL HYBRID EXCITATION MACHINES

As Said previously in section II, hybrid excitation synchronous machines can be classified by analogy to electric circuit to Series Hybrid Excitation Machines (SHEM) and Parallels Hybrid Excitation Machines (PHEM). The main difference between these two categories is that, for the SHEM, the flux created by the excitation windings passes through the permanent magnets unlike the PHEM case. This means that for the SHEM case, the risk of demagnetization of the permanent magnets is existent and during the design process of these machines a special care have to be taken in order to avoid this disagreement.

Apart from this, depending of the studied case, both SHEM and PHEM can have good flux control capabilities. In order to compare this flux control capability, in [63] authors have developed and analytical model, based on the formal resolution of the Maxwell equations, to design and study a SHEM (Fig. 2). This machine has been optimally designed so as to obtain the better flux control capability. Then, the obtained structure has been compared to a PHEM (Fig. 6).

Fig. 9 shows the total open flux evolution versus DC excitation current MMF for these two machines.

The obtained performances are summarized in Table 1. We can notice that the parallel hybrid excitation machine has better flux control than the series hybrid excitation machine. In fact, for the PHEM, the flux created by the excitation coils does not pass through the permanent magnet (unlike the SHEM case). Consequently, the path is less reluctant and the excitation windings are more efficient and the risk of PM demagnetization does not exist.

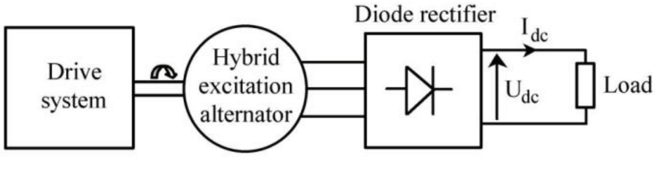


Fig. 8. Automotive electrical power generation system.

	Flux Weakening	Flux Enhancement	Flux (MMF=0 A)
SHEM	-30%	+17%	87mWb/m
PHEM	-70%	+95%	65mWb/m

Table 1. SHEM and PHEM Flux control capability comparison

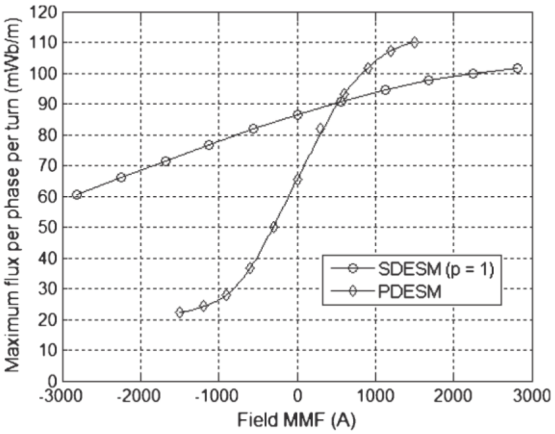


Fig. 9. Comparison of the open flux control capability for a parallel and a series hybrid excitation machines

However, it is important to mention that the PM demagnetization risk in this SHEM, due to excitation windings, is completely cancelled if this DC coils are only used for flux enhancing. Nevertheless, for vehicle propulsion applications, the electric traction machine is supposed to operate at relatively high speed. Designing the double excitation machine for only flux enhancing mode means that the high-speed operation will condition the PM excitation circuit design. In this case, the improvement of efficiency in the most used operating points, which are mostly located around the base speed under light load in the torque/speed plane (or power/speed plane), may not be possible.

Otherwise, considering the total flux obtained by permanent magnets, i.e when the DC excitation MMF is equal to zero, we can see in Fig. 9, that the SHEM produces more flux than the PHEM. This is mainly due to the difference between the used permanent magnets in these machines. In fact, while for the SHEM NdFeB magnets are used, ferrite magnets were employed for the PHEM. However, it should be noticed that ferrite magnets can be easily replaced by NdFeB magnets. The use of NdFeB magnets helps increase the excitation flux due to permanent magnets, which can reach the same level compared with SHEM.

Finally, even if the PHEM seems to have a better flux control capability than the SHEM, a drawback related to the construction of the studied PHEM should be pointed out. Indeed, since the flux created by excitation coils should pass through the rotor laminated part in the axial direction (the permeability is low in this direction), the open circuit flux control capability of such a design should decrease as the volume/length ratio of the structure decreases. Nevertheless, massive magnetic material can be used in rotor construction instead of laminations to overcome this problem [64].

V. DESIGN OF HYBRID EXCITATION MACHINES

Hybrid excitation machines, regardless of their structures, are mainly dedicated to variable speed/torque applications. In fact, for single operating point applications, classical permanent magnets machines are fare more interesting since they have high power and torque densities, are easier to manufacture, and do not require the additional power converter for the DC coils needed in the case of the hybrid excitation machines. However, for variable speed applications, especially when the speed range is very wide, the hybrid excited structures become more adapted than simple excited PM machines. For this type of applications, e.g., HEV or EV, the existence of the DC excitation coils (for hybrid excitation machines) provides an additional degree of freedom that can be used to increase the efficiency in the most used regions of the torque/speed plane as explained in section III-A.

In this section, a design approach of hybrid excited structures is discussed. First, modeling methods used in the design of hybrid excited structures are presented. Then, the design optimization of a flux switching hybrid excited machine is presented to illustrate the adopted approach.

A. Modeling for the design

Different models for the design of hybrid excitation machines are developed and can be classified into two categories:

- Analytical models:
    - equivalent magnetic circuits;
    - formal solution of Maxwell equations.
- Numerical models:
    - Finite elements analysis.

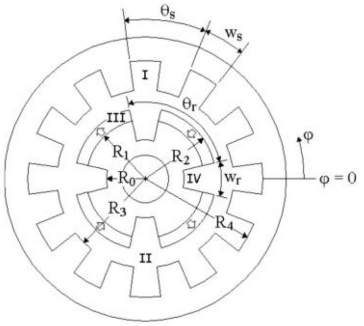
1) Analytical models

Different analytical models, based on the formal solution of Maxwell equations, have been developed [63], [65–67]. In [66], authors presents an analytical model of a series hybrid machine (Fig. 2). Fig. 10. shows the idealized geometry in which the formal solution of Maxwell equations in low permeability regions is developed. General expression of the magnetic vector potential solution is given in Fig. 10.

The main advantage of this formalism is its reduced execution time and its ability to handle wide geometric parameters variations (genericity). In fact, in an optimization process, for example, it is interesting to test all the possible values of the different geometric parameters (such as the stator's tooth width, the PM height and width, … etc.) in order to optimize the design of the studied machine.

However, it is important to mention that this kind of model considers that the iron have an infinite permeability in order to be able to solve the problem. Thus, the magnetic saturation phenomenon is not taken into account.

For different embedded applications, the attributed volume for the electrical machine is generally too small to be able to design an optimal machine without reaching high induction values that exceed those of the used material B-H linear region. In order to take into account the saturation phenomena, designers develop models based on the equivalent magnetic circuit method (MEC).



$$A_z = a_0 + A_{\mathrm{ps}}(r,\varphi) + \sum_{n=1}^{+\infty}\Big[\left(a_{1n}r^{m_n} + a_{2n}r^{-m_n}\right)\cos(m_n\varphi) + \left(a_{3n}r^{m_n} + a_{4n}r^{-m_n}\right)\sin(m_n\varphi)\Big]$$

Fig. 10. Analytical model (Maxwell equations formal resolution)

This type of modeling (MEC) has been already largely applied to permanent magnet machines. It has been recently applied to different hybrid excitation machines, 2D [61], [68] or 3D structure [69–71]. In [71], authors have developed and equivalent magnetic circuit of the machine presented in Fig. 6, in order to study its flux control capability. Fig. 11. shows the 3D equivalent magnetic circuit in d-axis position. As said previously, the main advantage of these models is their capability to take into account the saturation phenomena. They gives good agreement with measurement, however, due to complex topology of studied machine, the setting of the equivalent model is quite difficult and the different flux paths in the machine must be well known in order to have the right estimation of the different reluctances. So generally, finite element analysis (FEA) are used to help for the establishment of the reluctances network.

2) Numerical models

These models are the most used to study and design hybrid excitation synchronous machines. In fact, thanks to the quite facility to establish these models and the good agreements they give compared to measurements, the finite elements analysis are the most used method for the study of classical electrical machines and non classical ones, such as the hybrid excitation machines.

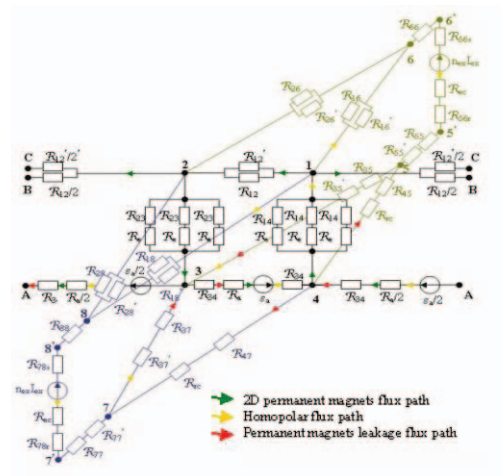


Fig. 11. 3D equivalent magnetic circuit of a hybrid excitation synchronous machine

Fig. 12. shows a 3D finite element model of the hybrid excitation synchronous machine presented previously in Fig. 4. However, the main drawback of this method is the time of computation. In fact, FEA analyses, especially the 3D ones, are too time consuming. In an optimization process it is not possible to use this kind of model especially when the optimization parameters vary in a very large domain. In this case, finite elements analysis and especially the 3D ones are used for the validation process of obtained optimal machines.

B. Application to electric and hybrid traction

As previously presented in section III, hybrid excitation machines are well suited for the hybrid and electric vehicle application. In fact, in the case of these applications, the electrical machine has to fulfill different constraints like: high efficiency, high torque density, high torque and wide speed range. Different topologies of Hybrid excitation synchronous machines were studied for these applications [1], [14], [15], [72], and it was shown that, thanks to the double excitation principle, these special machines are good candidates for such applications. The hybrid excitation flux switching machine (HESFM) is one of these structures that has been optimally designed, using 2D finite elements analysis, for the hybrid vehicle application [14].

The obtained geometry is given in Fig. 13. In order to appreciate the control capability of these hybrid excitation machine, Fig. 14 shows the evolution of the torque average value versus armature current density for different DC excitation current densities.

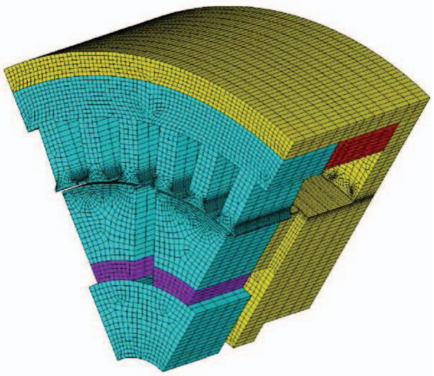


Fig. 12. 3D Finite elements model of a parallel hybrid excitation synchronous machine

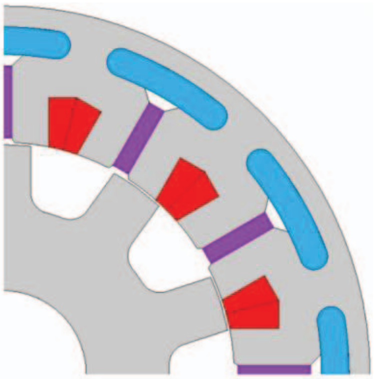


Fig. 13. Design of the HEFSM for a Hybrid Vehicle application

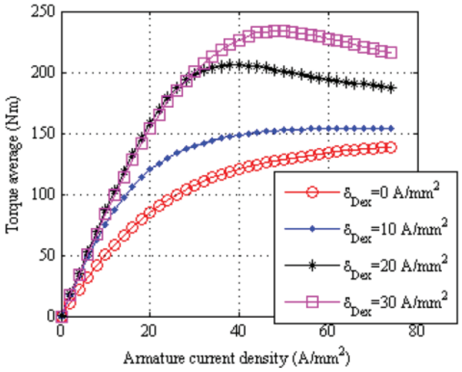


Fig. 14. Torque versus armature current for different excitation currents.

It can be observed that when the excitation current density varies from 0 to 20 A/mm², the torque's average value is doubled for an armature current density equal to 20A/mm².

The analysis of optimized machine performance shows that must used operating (torque, speed) points, located in partial load, low speed region, are reached without the need of the auxiliary DC excitation coils, thus obtaining higher efficiency. By supplying the DC excitation coils and reinforcing the linkage flux, it will be possible to reach higher torque operating point.

In [73], the authors analyzed the optimized machine performance considering the New European Driving Cycle (NEDC) shown on Fig. 15. This cycle represents the typical usage of a car in Europe.

For each operating point of this driving cycle, the optimal control parameters of this machine were determined in order to fulfill different constraints.

For each operating point:

- The torque average value must be reached;
- The DC excitation and the d-axis current densities must be determined in order to fulfill the DC maximum voltage constraint;
- The q-axis, d-axis and DC excitations current densities must be chosen in order to minimize the total power losses, i.e. copper losses and iron losses.

Copper losses are computed by classical formula taking into account: current densities, windings sections, filling factors and windings lengths.

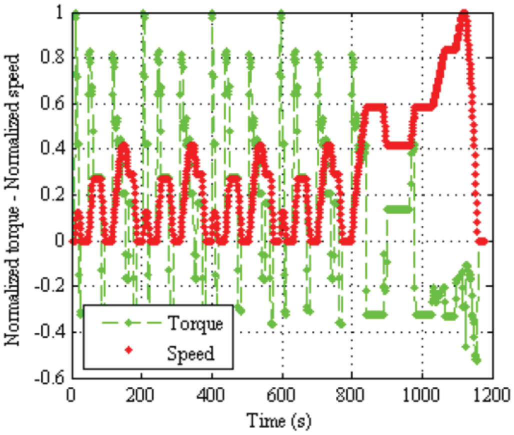


Fig. 15. NEDC Driving cycle

Iron losses are computed by considering the formula given below (1) [74]. The iron losses are calculated in each element of the 2D mesh of the finite element model of the machine.

$$L_{iron\ i,\vec{r}\,or\,\vec{\theta}}\,(W/m^3) = L_h + L_{ec} \tag{1}$$

where, $L_h = \left(k_{h1}\,\Delta B_{ppi,\vec{r}\,or\,\vec{\theta}} + k_{h2}\,\Delta B^2{}_{ppi,\vec{r}\,or\,\vec{\theta}}\right) f$, and

$$L_{ec} = \frac{1}{T}\int_0^T \alpha_p \left(\frac{dB_{i,\vec{r}\,or\,\vec{\theta}}}{dt}\right)^2 dt,$$

and,

k_{h1}, k_{h2} and α_p: constant corresponding to used iron steel;
ΔB : peak to peak value of the flux density;
$B_{\vec{r}}$: radial component of the flux density;
$B_{\vec{\theta}}$: ortho-radial component of the flux density.

Core loss density distribution in the machine is given in Fig. 16 and total power losses for the NE driving cycle are given in Fig. 17. Peak power losses are corresponding to high torque and high speed values.

Fig. 18 shows the DC excitation coils current density for each operating point of the NEDC driving cycle. These coils are supplied in order to reach the higher torque operating points and to minimize to total losses for most used (torque, speed) operating points [73].

The average power losses over the driving cycle are computed and are given below:

- Average losses = 1915 W
- Copper losses = 955 W (q-axis = 450 W; d-axis = 65 W ; Exc. = 440 W)
- Iron losses = 962 W

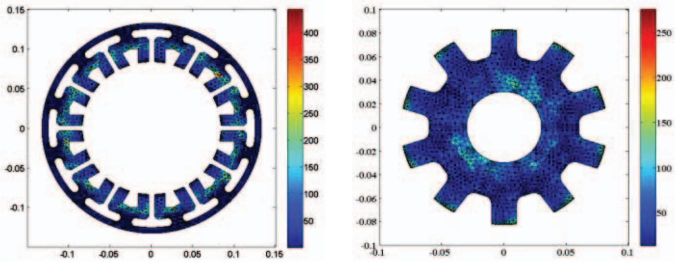


Fig. 16. Iron power losses density (in W/kg) distribution in the rotor and the stator of the HEFSSM for N=4000 rpm, an armature current density equal to 30A/mm² and an excitation current density equal to 30A/mm²

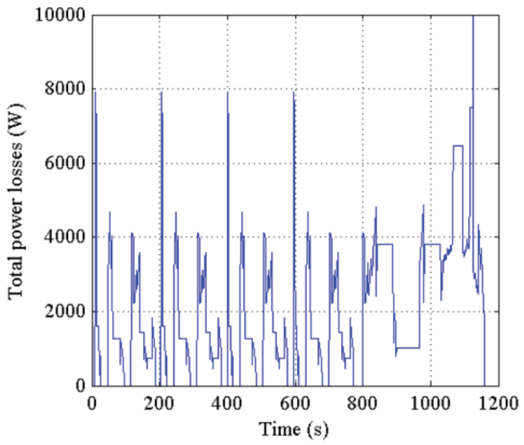


Fig. 17. Total power losses of the HEFSM on the NEDC driving cycle

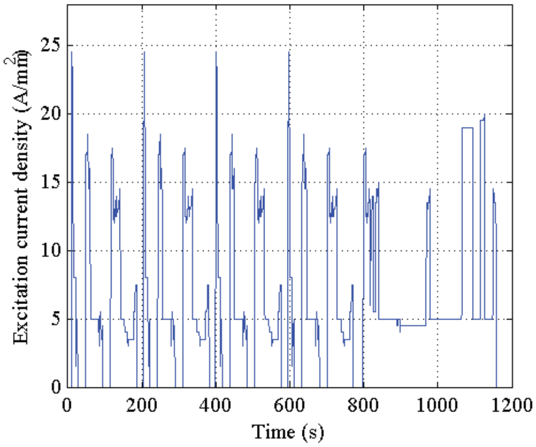


Fig. 18. DC excitation current density of the HEFSM on the NEDC driving cycle

VI. CONCLUSION

In this paper, an overview of hybrid excitation machines technology has been presented. An update state of the art of the different existing structures has been reported and a classification of these structures has been given by considering their 2D or 3D structure. The advantages and drawbacks of these different machines topologies were qualitatively discussed. The interest of the hybrid excitation machines was, then, presented for both motoring and generating modes. It was shown that these kind of electrical machines are suitable for variable speed applications and especially for hybrid electrical vehicles and electrical vehicles applications. The different models used for the design of these structures were presented. Advantages and limitations of each model were discussed. Finally, an example of a hybrid excitation switching flux machine optimal design and performance analysis was presented. This paper highlighted the contribution of hybrid excitation principle for variable speed applications. The additional degree of freedom, inherent to the constitution of hybrid excitation structures, makes them good candidates for many applications.

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