POLITECNICO DI TORINO
Repository ISTITUZIONALE

Doubly Excitated Synchronous Machines for Traction Applications

Original
Doubly Excitated Synchronous Machines for Traction Applications / Graffeo, F.; Stiscia, O.; Vaschetto, S.; Cavagnino, A.; Tenconi, A.. - ELETTRONICO. - 2021:(2021), pp. 1-8. (Intervento presentato al convegno 30th IEEE International Symposium on Industrial Electronics, ISIE 2021 tenutosi a Kyoto, Japan nel 20-23 June 2021) [10.1109/ISIE45552.2021.9576244].

Availability:
This version is available at: 11583/2957071 since: 2022-03-10T12:28:18Z

Publisher:
Institute of Electrical and Electronics Engineers Inc.

Published
DOI:10.1109/ISIE45552.2021.9576244

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright
IEEE postprint/Author's Accepted Manuscript

©2021 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collecting works, for resale or lists, or reuse of any copyrighted component of this work in other works.

(Article begins on next page)

17 April 2024

Doubly Excitated Synchronous Machines for Traction Applications

Federica Graffeo
Student Member, IEEE
Politecnico di Torino
Dipartimento Energia
Torino, Italy
federica.graffeo@polito.it

Ornella Stiscia
Student Member, IEEE
Politecnico di Torino
Dipartimento Energia
Torino, Italy
ornella.stiscia@polito.it

Silvio Vaschetto
Senior Member, IEEE
Politecnico di Torino
Dipartimento Energia
Torino, Italy
silvio.vaschetto@polito.it

Andrea Cavagnino
Fellow, IEEE
Politecnico di Torino
Dipartimento Energia
Torino, Italy
andrea.cavagnino@polito.it

Alberto Tenconi
Senior Member, IEEE
Politecnico di Torino
Dipartimento Energia
Torino, Italy
alberto.tenconi@polito.it

***Abstract*— Electrical motor is the crucial component in the drivetrain of hybrid and electric vehicles. Over the last decades, most traction drive systems have been mainly equipped with induction machines, wound field synchronous machines, and permanent magnet machines. Among these three alternatives, permanent magnet is currently the most used topology for traction applications. This paper discusses alternative machine solutions reported in literature that combines advantages of both permanent magnet machines and wound field synchronous machines. These machine topologies, usually referred in literature as doubly excited synchronous machines, are classified on the basis of three criteria: excitation paths, excitation sources location, field direction. The paper reports feature and drawbacks for the considered machine structures and compares both performance and constructive complexity in the light of their perspective use in traction applications.**

Keywords—traction motor, doubly excited, synchronous machine, permanent magnet machines, flux controllability, hybrid excitation

I. INTRODUCTION

Hybrid vehicles (HV) and electric vehicles (EV) represent the future of transportation due to their high fuel economy, ultralow emissions, and similar driving performance with respect to internal combustion engine. Electric machines of HEV and EV must present high efficiency, high rated torque, wide speed range, wide constant power speed range, high specific power and torque density, good flux weakening capability, and good fault tolerant characteristics [1] – [5].

Among the different types of electrical machines, the induction machine (IM) features simplicity, low cost, ruggedness, good dynamic response, high peak torque [4] – [6]. However, the ever increasing requirements in terms efficiency, specific power and power density justifies the current trend of moving from the IM toward the permanent magnet synchronous machines (PMSMs) for most of the traction applications [4], [5], [7]. There are various topologies of PMSMs and the main classification is based on the position of the PMs: surface permanent magnet (SPM) and interior permanent magnet (IPM). The two machines show different constant power speed range and flux weakening capability. In PMSMs, the torque is the sum of two different contributions: the torque due to the flux linkage created by the magnets and the reluctance torque due to the saliency of the machine. This torque contribution is absent in the SPM machine, because of its isotropic structure. Moreover, the limited flux weakening capability of SPM machines has favoured the application of IPM machines in automotive applications [6].

Recently there has been an increasing interest in equipping electric vehicles with the wound field synchronous machines (WFSMs) [8] – [11]. In WFSMs, the excitation on the rotor side is obtained thorough a *dc* current. This machine topology features a wide constant power speed range thanks to the possibility of regulating the excitation field by varying the current on the rotor winding. However, the *dc* current on the rotor increases the total amount of Joule losses. Furthermore, a method to supply the rotor must be included. The historical system to feed the rotor consists of slip rings, which cause concerns about reliability and maintenance when it comes to traction applications. Therefore, different solutions have been studied and adopted, such us rotary transformers, capacitive power transfer and harmonic power transfer. This implies higher machine complexity, costs and weights. However, the absence of permanent magnets and the good flux weaking capability have made this electric motor appealing for electric traction applications.

Unlike the aforementioned classical machines, where the characteristics required from the electric traction application are quite difficult to find them all, doubly excited synchronous machines (DESMs) seem to be able to satisfy these specifications thanks to their hybrid excitation field topology [12]. The main characteristic of DESMs is the presence of two excitation flux sources: PMs and field coil excitation. The advantage is to combine the flux weakening capability of the WFSMs and high efficiency and torque density of PMSMs. The double excitation allows to reduce the total amount of PMs and so the final cost of the machine. The presence of the excitation winding (EW) introduces an additional degree of freedom with respect to PMSMs, resulting in a better flux weakening capability. Indeed, at full load or at the flux-weakening operation, the excitation winding is supplied either to generate the additional necessary torque or to decrease the magnetic field in order to increase the speed. Another advantage of DESMs is the reduction of the overvoltage during the uncontrolled generator operation at high speed. For all these reasons, DESMs can be considered competitive candidates in electric traction application [13].

In this paper, the general classification of doubly excited synchronous machines adopted by most authors is reported. Some representative machine topologies from literature are described, highlighting their advantages and drawbacks. Finally, a qualitative comparison of all the considered machines is presented in the light of their potential use in traction applications.

978-1-7281-9023-5/21/$31.00 ©2021 IEEE

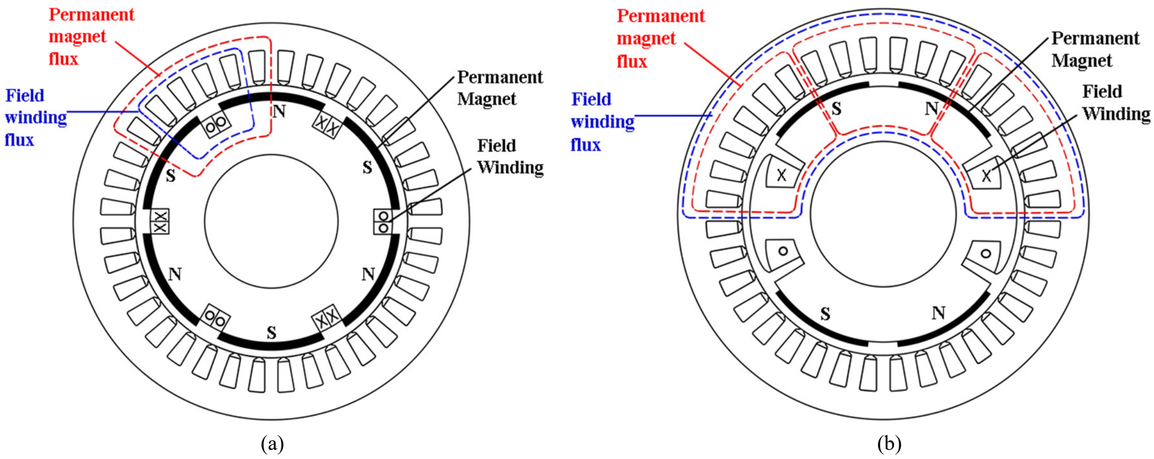


Fig. 1 Examples of series (a) and parallel (b) excitation configurations on the rotor side.

II. Classification Criteria

At present, there is a wide variety of topologies of DESMs both in study and prototype levels. Indeed, the position of the two excitation sources, as well as their magnetic combination represent additional degrees of freedom in the machine design. For this reason, all the different topologies are generally classified following three criteria [12]-[15]:

- sources location;
- excitation paths;
- field direction.

A. Sources Location

According to the literature, the PMs and the excitation winding can be located either on the rotor side, or in the stator side, or in a combination of the two. Each choice presents some advantages and disadvantages. In locating both sources in the rotor, the magnetic flux density in the air gap features a better waveform. However, this implies that there must be an appropriate method to bring current on the rotor side. The possible supply methods are the same discussed for the WFSMs. If brushes and slip rings are used to feed the excitation winding, concerns about reliability and maintenance represent the main drawback. Any other alternative method inevitably leads to a more complex resulting system and it generally increases weights and costs. Moreover, the presence of Joule losses on the rotor side makes the extrapolation of the heat more difficult. These issues can be solved by locating the excitation winding on the stator side. This implies a heat generation closer to the ambient and a static and simple supply method of the excitation winding. The drawback of this solution consists of a more significant saturation phenomenon of the stator iron. Indeed, under the same machine volume, the total stator iron is reduced to host the excitation winding. Similarly, under the same machine saturation conditions, bigger volumes are needed, resulting in lower torque densities. This effect is even more pronounced if both sources are located in the stator, even though this considerably simplify the rotor structure that becomes a passive rotor, similarly to that of the synchronous reluctance motors. For the advantages and drawbacks above discussed, it seems not advantageous to place the PMs on the stator side and the *dc* excitation winding on the rotor side.

Indeed, in the best author's knowledge, this solution has not been proposed in literature.

B. Excitation paths

This classification criterion follows the analogy with electrical circuits, depending on the combination of flux paths created by the PMs and the excitation winding. Based on this concept, two groups can be identified: series excitation and parallel excitation. For the first group, the magneto-motive force (m.m.f.) created by the excitation winding is in series with the m.m.f. created by the PMs. This implies that the excitation winding flux passes through the PMs, as it can be seen from Fig. 1(a). On the contrary, in machines belonging to the parallel excitation group, the m.m.f. created by the excitation winding and that created by the PMs are in parallel. In this case, the flux lines have independent paths and those of the excitation winding do not cross the PMs, as shown in Fig. 1(b).

Since the permeability of PMs is close to that of the air, the reluctance of the paths of the field lines is higher in the series excitation group than in the parallel excitation group. Indeed, in the latter, the only significant reluctance is encountered in the air gap. Moreover, in the series excitation group, during flux weakening operations, the current in the excitation winding generates a magnetic flux that is opposite to that of the PMs and passes through the PMs. Consequently, this group presents the risk of the PMs demagnetization. For these reasons, the parallel excitation group is, generally, preferred over its counterpart. Several configurations of both groups can be adopted, depending on the source location and the direction of the flux. While the concept of series excitation machines is rather straightforward, the operating principle of the parallel excitation machines may vary significantly from case to case. For this reason, an analysis of two parallel excitation machines, that work in two distinct ways, is presented in Appendix A.

C. Field direction

The last classification criterion is based on the machine structure: 2D or 3D. The difference depends on the field direction. The 2D machine presents a radial flux direction, and therefore it is easy for manufacturing, more robust, and reliable. The investigation of 3D structures requires a more complex level of analysis. Nevertheless, many contributions of this kind of DESMs are reported in literature and patent database. This structure allows a wide variety of topologies to be realized and most of them are of the parallel excitation type.

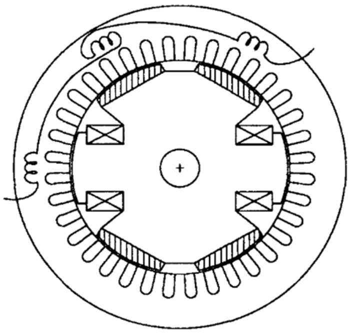


Fig. 2 PMs and excitation winding both on the rotor side in parallel configuration proposed in [16].

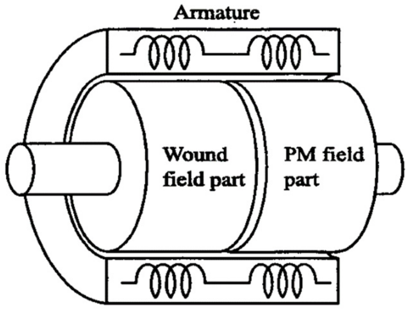


Fig. 4 Machine with both excitation sources on the rotor side in parallel configuration [19].

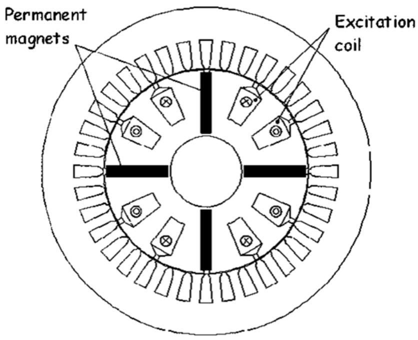


Fig. 3 PMs and excitation winding both on the rotor side in parallel configuration [12], [17].

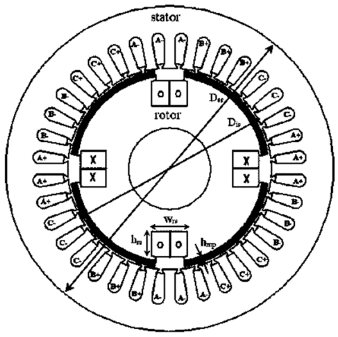


Fig. 5 PMs and excitation winding both on the rotor side in series configuration [20].

III. DOUBLE EXCITATION SYNCHRONOUS MACHINES

The presented classification criteria are necessary to categorize the large number of machine structures that can be realized when the double excitation is adopted. In this section, the most common and representative machine topologies reported in literature are presented and briefly analyzed. The classification criterion adopted to present the different types of machines is based on the source location.

A. PMs and excitation winding on the rotor side

Fig. 2 shows the machine proposed in [16]. It is excited by surface PMs and excitation winding, both placed in the rotor side. The flux created by the excitation winding does not pass through the PMs and thus the machine belongs to the parallel excitation group. The flux direction is radial, hence the machine is a 2D topology. The machine has 6 poles, in which 4 of the rotor poles are PM poles and the other two are excitation winding poles. This enables to change the number of poles from 6 to 2, by varying the excitation current. This structure features high torque density, good flux weakening capability and low demagnetization risk. The main drawback is the presence of slip rings and brushes, as well as torque ripple and acoustic noise during flux weakening operations.

Fig. 3 shows a machine where internal PMs and excitation winding are both placed in the rotor side [12], [17]. The radial flux created by the excitation winding does not pass through the PMs and thus the machine belongs to the 2D parallel excitation group. Thanks to the parallel configuration, this machine does not suffer from demagnetization risk. Again, the main drawback is represented by the slip rings and brush requirement. A solution to overcome this issue has been studied by FEM analysis in [18], in which two additional windings are placed one in the rotor and the other in the stator, to create the harmonic power transfer.

Fig. 4 shows the machine proposed in [19]. The rotor is divided in two parts in the axial direction: one hosts the PMs and the other hosts the *dc* coil. The flux created by the excitation winding and that created by the PMs are radial and independent, thus the machine is categorized as parallel excitation. Between the two rotor parts some space is necessary to avoid PM leakage and to place the end winding of the excitation coil; this inevitably affects the machine torque density. In detail, the machine in [19] is a 0.75 kVA, 2 poles machine with a rated voltage of 200 V. In this machine the field regulation is achieved by varying the excitation current as follows: the air gap flux is increased when the flux of the wound field parts is in the same direction as the PM; the air gap flux is PM flux only, when the field current is zero. Numerical analyses performed by means of FEM simulations have been validated through tests on a prototype.

In Fig. 5 it is shown a machine that is excited by surface PMs and excitation winding, both placed on the rotor side [20]. The flux created by the excitation winding passes through the PMs and thus the machine belongs to the series excitation group. The machine is a 2D topology. It is a 2 poles machine, with a rated power of 5.5 kW, a rated speed of 1500 rpm, a rated voltage of 380 V, and a typical IM stator. By means of the proposed DESM, a speed increase of 2.8 has been achieved within the safety demagnetization limits of the PMs, while for the SPM synchronous motor with conventional distributed windings it is typically less than two. Moreover, compared to the traditional SPM machines, the proposed DESM topology features a reduced equivalent air gap and a lower stator current during flux weakening operations. In summary, the motor cost would be increased, but the speed range is much larger with a good efficiency.

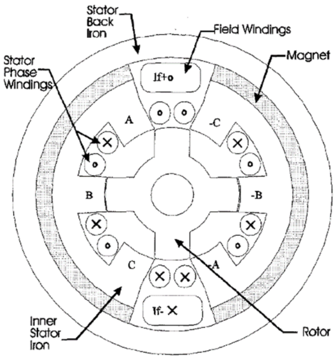


Fig. 6 Doubly salient machine with PMs and field winding excitation both on the stator side in series configuration [23].

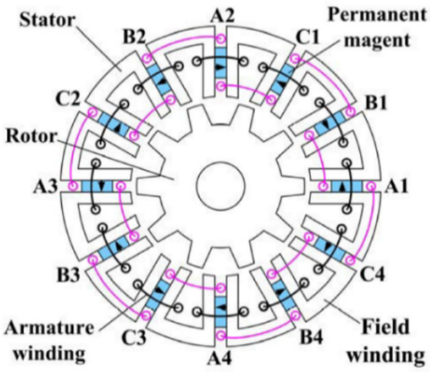


Fig. 7 Flux-switching machine with PMs and excitation winding on the stator side in parallel configuration [27].

The adopted method to bring the current on the rotor side is the ring brushes system that represents the main drawback of this machine. On the other hand, the authors claim a reduction on the total losses (up to 10%) in a wide speed operation range while keeping good efficiency values, thanks to the decrease of the flux density in all the active parts of the machine. An older and similar structure can be found in [21] with a higher number of poles and a speed range of 1 to 2.2 [22], under conditions of flux weakening.

B. PMs and excitation winding on the stator side

Among all the DESMs, the machines with PMs and excitation winding both placed on the stator side are the most common ones because of the achieved robustness of the rotor structure, making it suitable for high-speed applications.

The doubly salient machine shown in Fig. 6 is one of the first examples of DESM with PMs and excitation winding both placed on the stator side [23]. The PMs and the excitation winding flux lines are in series and in radial direction. Hence the machine is a 2D topology. Because of the large reluctance introduced by the PMs in the stator structure, high *dc* currents are needed to reach a good flux weakening capability, which implies a reduction on the machine efficiency. To overcome this issue, magnetic bridges can be introduced to reduce the required *dc* current [24]-[26].

Fig. 7 shows a flux-switching permanent magnet machine, where a set of field windings are added reducing the permanent magnet length, in order to enhance the machine flux regulation capability [27]. The resulting machine is excited by PMs and excitation winding, both placed in the stator side. Hence, the machine belongs to the parallel excitation group and it is a 2D topology. The reference paper reports analyses based on FEM simulations.

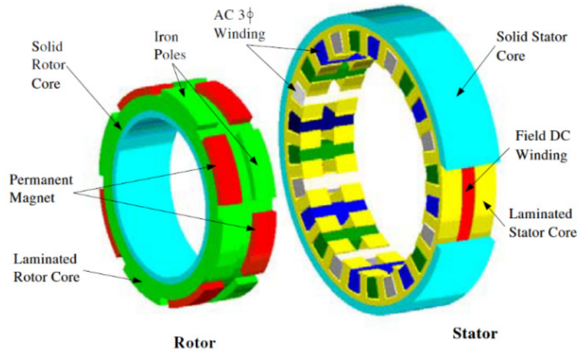


Fig. 8 Parallel excitation configuration with PMs on the rotor side and *dc* field winding on the stator side [35].

In [28] the same machine has been analyzed by varying the position of the PMs. The PMs can be located in the top or middle or bottom of the stator slots. They are referred as PM-Top, PM-Middle and PM-Bottom, respectively. Results show that the weakest flux-regulation capability is exhibited in the PM-Middle topology. In [29], a similar machine structure is proposed with the aim of comparing two core stator laminations: E-core and C-core. Based on both 2-D and 3-D FEA methods validated by measurements on prototypes, two six-phase DESMs employing E-core and C-core stator laminations have been designed and compared. The conducted studies show that the E-core machine presents a larger torque and better magnet utilization compared to the C-core alternative. On the other side, both the flux weakening and flux strengthening characteristics have been found to be much better in the C-core machine. Similar structures and comparisons can be found in [30]-[34].

C. PMs on the rotor side and and excitation winding on the stator side

This configuration has a good potential to realize a high torque density thanks to the presence of the magnets on the rotor side. However, hosting the excitation winding in the stator generally requires an additional space that increases the machine volumes and lower the torque density. Slip rings and brushes are not necessary since the excitation winding is static [35], [36]. A typical machine belonging to this group is shown in Fig. 8. This machine was originally investigated by Spooner in [37] and then patented by Mizuno [38]. Its operation features a 3D flux distribution, and it is usually referred as consequent pole PM machine. The rotor consists of two sections. Each section alternates a radially magnetized PM pole and a laminated iron pole. A classical three-phase winding is hosted in the stator slots, while in the middle of the stator a toroidal excitation winding is placed to achieve flux regulation.

The flux created by the excitation winding is independent of the flux created by the PMs, hence this machine belongs to the parallel group. In detail, the radial flux created by the PMs circulates from one PM to the next one, through the air gap, teeth, the stator and the rotor yoke. On the other hand, the axial flux produced by the field winding passes from one iron pole to the next one across the air gap, teeth, the stator and the rotor yoke. Because of this particular 3D configuration, a wide constant power speed range can be obtained without demagnetization risk for the PMs. Nevertheless, the power density is affected by the necessity of a larger stator volume to host the excitation winding.

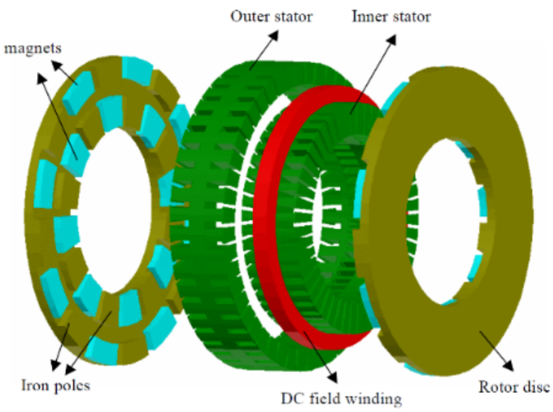


Fig. 9 Machine with PMs on the rotor side and toroidal *dc* field winding on the stator side in parallel configuration [39].

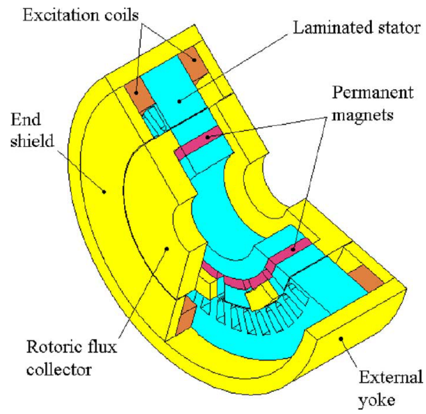


Fig. 11 Parallel excitation configuration with PMs on the rotor side and excitation coils between the stator and the end plates [44].

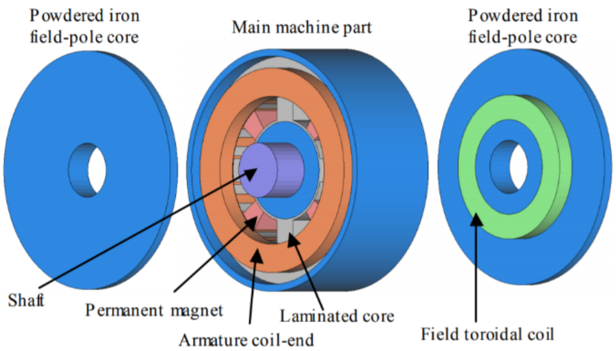


Fig. 10 Machine with PMs on the rotor side and excitation winding on the stator side in parallel configuration [42].

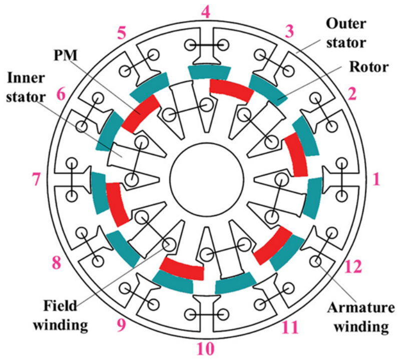


Fig. 12 Partitioned stator machine in series configuration [45].

Fig. 9 shows the machine proposed in [39] – [41], which is a 3D topology with PMs on the rotor side and toroidal *dc* field winding on the stator side in parallel configuration. In detail, the rotor consists of alternate PMs poles and iron poles excited by the *dc* field winding. The toroidal *dc* field winding is placed between the inner and outer stator so that the excitation current effectively controls the air gap flux. The proposed prototype suffers from topological complexity and inter-pole flux leakage [14].

In [42], two types of 3D doubly excited machines using powdered iron core are proposed. One of these structures is shown in Fig. 10, where both powdered iron field-pole core, placed at each end of the machines, host a toroidal excitation winding that generates flux in axial direction. The rotor alternates a PM pole and a laminated core pole. The conducted FEM analyses qualitatively validated by a downsized machine prototype shows that this structure exhibits high torque density, thanks to the possibility of strengthening the magnetic field by means of the excitation winding. The second machine structure proposed in [42], and analyzed also in [43], has a rotor with a permanent magnet which is sandwiched by N- and S-pole rotor endcap and magnetized in the axial direction. The FEM analyses reveal that a good flux weakening capability is achieved. However, the machine structure is unquestionably complicated.

Fig. 11 shows the machine proposed in [44], in which a toroidal excitation winding is placed in the space between the stator and the end plates, while PMs are located on the rotor. The proposed machine belongs to the parallel excitation group and it is a 3D topology.

The stator is composed of a laminated core, while the external yoke and the end-shields are made of solid iron. This provides a low reluctance path for the excitation windings and thus an excellent flux control can be achieved.

D. PMs and excitation winding on partitioned stator

Fig. 12 shows the partitioned stator machine proposed in [45], in which the armature winding is located in the outer stator while the inner stator accommodates the excitation winding and the PMs. The PMs poles and the excitation winding poles alternate; thus, the machine belongs to the series excitation group. This structure allows to overcome the problem arising from placing the excitation winding on the stator, i.e. low values of torque density, and benefits from the same advantages, i.e. a static supply of the excitation winding. The realized prototype exhibits a wide flux regulation range, good torque density. Nevertheless, despite the 2D nature, the main drawback of this machine consist of its relatively complicated structure.

A similar machine structure is presented in [46], but in a parallel excitation version. In particular, two excitation winding poles alternate with two PMs. The machine has excellent flux regulation capability due to the parallel magnetic paths, as well as high torque output thanks to the better space utilization ensured by the partitioned stator. Nevertheless, the authors report that the back electromotive force harmonics are considerable since the excitation poles are not perfectly balanced.

TABLE. I TRADE-OFF AMONG STRUCTURES WITH BOTH EXCITATION SOURCES LOCATED ON THE SAME MACHINE SIDE.

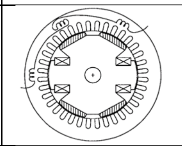
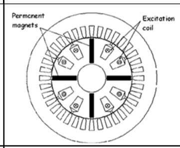
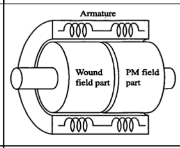
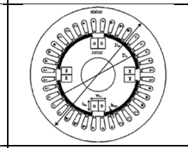
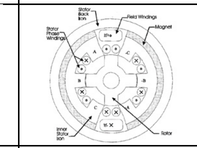
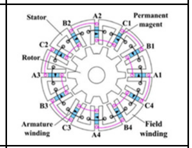
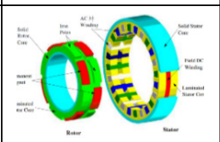
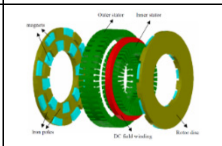
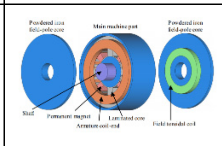
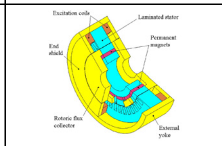
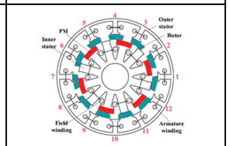
Sources location	PMs and EW both on the rotor side				PMs and EW both on the stator side	
Excitation paths	Parallel	Parallel	Parallel	Series	Series	Parallel
Machine						
Torque density	Green	Green	Red	Green	Yellow	Yellow
Topological Complexity	Green	Green	Yellow	Green	Yellow	Red
Current on the rotor	Y	Y	Y	Y	N	N
Flux weakening	Green	Green	Yellow	Yellow	Yellow	Green
PM demagnetization	Green	Green	Green	Red	Red	Green
Level of investigation	FEM	-	Prototype	Prototype	Prototype	FEM

TABLE. II TRADE-OFF AMONG STRUCTURES WITH EXCITATION SOURCES LOCATED ON DIFFERENT MACHINE SIDES.

Sources location	PMs on the rotor side and EW on the stator side				Partitioned stator
Excitation paths	Parallel	Parallel	Parallel	Parallel	Series
Machine					
Torque density	Yellow	Yellow	Yellow	Red	Yellow
Topological Complexity	Yellow	Yellow	Yellow	Yellow	Red
Current on the rotor	N	N	N	N	N
Flux weakening	Yellow	Yellow	Yellow	Yellow	Green
PM demagnetization	Green	Green	Green	Green	Red
Level of investigation	FEM	FEM	Scaled size prototype	FEM	Prototype

IV. MACHINES TRADE-OFF

In order to compare the considered machines in the light of their potential use in traction applications, Table I and Table II present a comparison of their main characteristics, according to the pros and cons reported literature. It has to be remarked that the proposed comparison is qualitative since the literature lacks of detailed quantitative information about the performances of these machines, especially in terms of torque density.

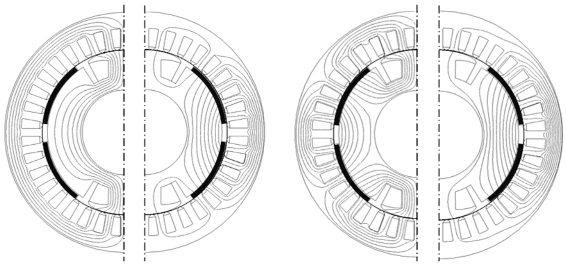
In general, the parallel excitation configuration exhibits better performances with respect to the series configuration. Indeed, the latter suffers from the demagnetization risk and it generally shows worse flux weakening capability because of larger magnetic reluctances of the flux paths.

Overall, the machines with both sources on the rotor side benefit from simple mechanical structures, but they require a method to bring the current on the rotating excitation winding. On the contrary, the machines that host either the excitation winding or both sources on the stator side eliminate slip rings, brushes or other methods to bring current on the rotor side. In particular, the machines with both sources on the stator side are the most common ones because of the achieved robustness of the rotor structure, making it suitable for high-speed applications. However, they inevitably exhibit relatively low torque densities and topological complexity.

A solution to obtain high values of torque density by keeping a static supply of the excitation winding is offered by the partitioned stator machine. However, its topological complexity is a major concern.

V. CONCLUSIONS

With reference to the classification criteria of excitation paths, excitation sources location, and field direction, this paper discussed different doubly excited synchronous machine topologies reported in the literature. In detail, the main characteristics and drawbacks for each considered solution have been reported and discussed. Features in terms of torque density, flux weakening capability and magnets demagnetization risk, as well as topological complexity and brush requirements have been considered. Finally, a qualitative trade-off among the different machines has been presented in order to highlight the advantages and drawbacks of each doubly excited synchronous machine topology in the light of their potential use in traction applications. In the authors' opinion, this analysis reveals that the doubly excited synchronous machines allow enhancing specific performance, such as the flux weakening, compared to conventional asynchronous, synchronous PMs and wound field machines, but typically at the expense of higher topological complexity.



(a) (b)

Fig. 13 Parallel excitation machine readapted from [16] with (a) only one excitation source (left – only EW, right – only PMs, and (b) with both excitation sources (left – positive current; right – negative current).

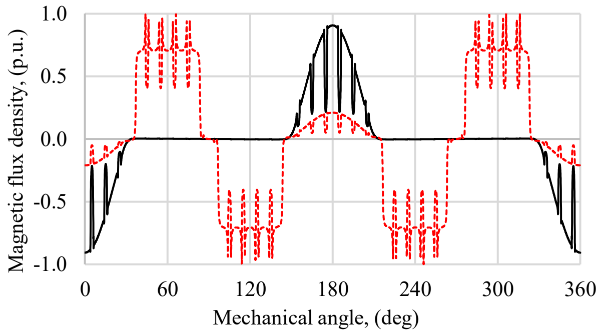


Fig. 14 Air gap magnetic flux density generated by PMs only (dotted red) and EW only (black) of the machine readapted from [16].

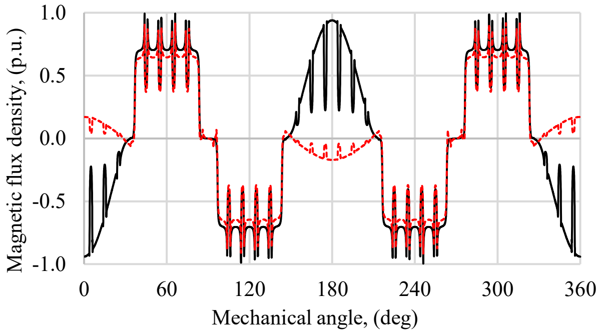


Fig. 15 Air gap magnetic flux density with a positive (black) or negative (dotted red) excitation current of the machine readapted from [16].

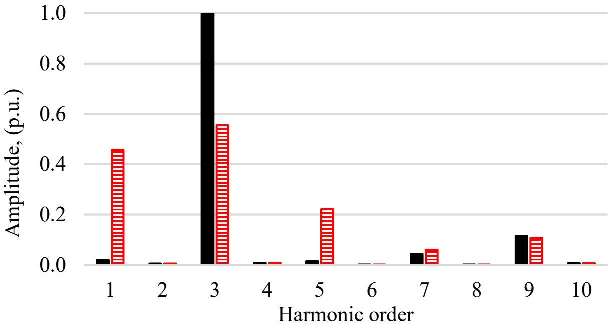
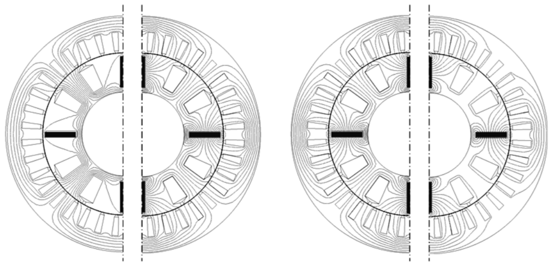


Fig. 16 Harmonic spectrum of the air gap magnetic flux density with a positive (black) or negative (red) excitation current of the machine readapted from [16].



(a) (b)

Fig. 17 Parallel excitation machine readapted from [17] with (a) only one excitation source (left – only EW, right – only PMs, and (b) with both excitation sources (left – positive current; right – negative current).

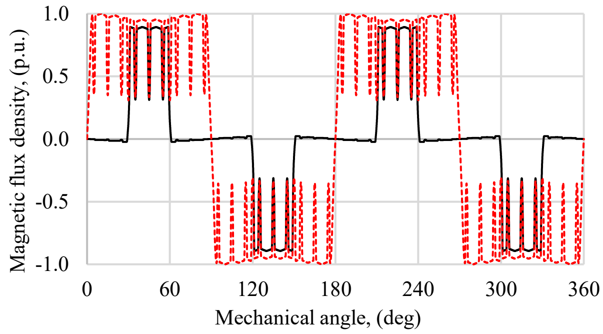


Fig. 18 Air gap magnetic flux density generated by PMs only (dotted red) and EW only (black) of the machine readapted from [17].

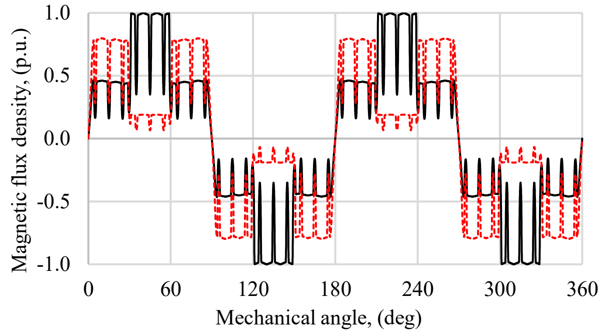


Fig. 19 Air gap magnetic flux density with a positive (black) or negative (dotted red) excitation current of the machine readapted from [17].

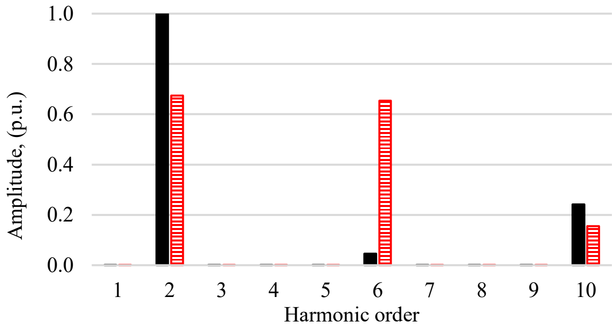


Fig. 20 Harmonic spectrum of the air gap magnetic flux density with a positive (black) or negative (red) excitation current of the machine readapted from [17].

Appendix A

Figures 13 – 20 show the conducted FEM analyses for two different parallel excitation machines readapted from [16] and [17]. To understand the contribution of each source separately, Fig. 13(a) and Fig. 17(a) show the magnetic field lines when only one source (EW or PMs) excites the machine. Fig. 13(b) and Fig. 17(b) depict the magnetic field lines for a positive or negative excitation current.

Looking at Fig. 14 and Fig. 18, it is clear the different role played by the excitation current in the two machines: while in Fig.14 one pole is almost entirely magnetized by the excitation current, in Fig.18 the excitation current operates together with the PMs in magnetizing the poles. Fig. 15 and Fig. 19 show the total air gap flux density waveforms for a positive and a negative excitation current, while Fig. 16 and Fig. 20 report their spectra.

REFERENCES

[1] Z.Q. Zhu, D. Howe, "Electrical Machines and Drives for Electric, Hybrid, and Fuel Cell Vehicles," *Proc. of the IEEE*, vol. 95, no. 4, pp. 746-765, April 2007.

[2] K. T. Chau, C. C. Chan, C. Liu, "Overview of Permanent-Magnet Brushless Drives for Electric and Hybrid Electric Vehicles," in *IEEE Transactions on Industrial Electronics*, vol. 55, no. 6, June 2008.

[3] C.C. Chan, "The state of the art of electric and hybrid vehicles," in *Proc. of the IEEE*, vol. 90, no. 2, 2002.

[4] J. de Santiago, H. Bernhoff, B. Ekergard. S. Eriksson, S. Ferhatovic, R. Waters, M. Leijon, "Electrical Motor Drivelines in Commercial All-Electric Vehicles: A Review," *IEEE Trans. Vehicular Technology*, vol. 61, no. 2, pp. 475-484, Feb. 2012.

[5] Y.A. Alamoudi, A. Ferrah, R. Panduranga, A. Althobaiti, F. Mulolani, "State-of-the Art Electrical Machines for Modern Electric Vehicles," *2019 Advances in Science and Engineering Technology Int. Conf. (ASET)*, Dubai, United Arab Emirates, 2019.

[6] M. Zeraouila, M. E. H. Benbouzid, D. Diallo, "Electric motor drive selection issues for HEV propulsion systems: a comparative study," *2005 IEEE Vehicle Power and Propulsion Conf.*, 2005.

[7] Z. Wang, T.W. Ching, S. Huang, H. Wang, T. Xu, "Challenges Faced by Electric Vehicle Motors and Their Solutions," *IEEE Access*, vol. 9, pp. 5228-5249, 2021.

[8] D.G. Dorrell, "Are wound-rotor synchronous motors suitable for use in high efficiency torque-dense automotive drives?," IEEE-IECON 2012, Montreal, QC, Canada, 2012, pp. 4880-4885.

[9] A. Frias, P. Pellerey, A.K. Lebouc, C. Chillet, V. Lanfranchi, G. Friedrich, L. Albert, L. Humbert, "Rotor and stator shape optimization of a synchronous machine to reduce iron losses and acoustic noise," IEEE Vehicle Power and Prop. Conf., Seoul, Korea, 2012, pp. 98-103.

[10] C. Stancu, T. Ward, K. M. Rahman, R. Dawsey, P. Savagian, "Separately Excited Synchronous Motor With Rotary Transformer for Hybrid Vehicle Application," *IEEE Trans. Ind. Appl.*, vol. 54, no. 1, pp. 223-232, Jan. – Feb. 2018

[11] A. Di Gioia, I.P. Brown, Y. Nie, R. Knippel, D.C. Ludois, J. Dai, S. Hagen, C. Alteheld, "Design and Demonstration of a Wound Field Synchronous Machine for Electric Vehicle Traction With Brushless Capacitive Field Excitation," *IEEE Trans. Ind. Appl.*, vol. 54, no. 2, pp. 1390-1403, March-April 2018.

[12] Y. Amara, L. Vido, M. Gabsi, E. Hoang, A. H. Ben Ahmed, M. Lecrivain, "Hybrid Excitation Synchronous Machines: Energy-Efficient Solution for Vehicles Propulsion," in *IEEE Transactions on Vehicular Technology*, vol. 58, no. 5, pp. 2137-2149, Jun 2009.

[13] Q. Wang, S. Niu, "Overview of flux-controllable machines: Electrically excited machines, hybrid excited machines and memory machines," *Renewable and Sustainable Energy Reviews,* 2017.

[14] H. Yang, Z.Q. Zhu, H. Lin, W. Chu, "Flux adjustable permanent magnet machines: A technology status review," *Chinese Journal of Electrical Engineering*, vol. 2, no. 2, pp. 14-30, Dec. 2016.

[15] S. Hlioui, Y. Amara, E. Hoang, M. Lecrivain, M. Gabsi, "Overview of hybrid excitation synchronous machines technology," Int. Conf. Electrical Engineering and Software Applications, 2013, pp. 1-10.

[16] Xiaogang Luo and T. A. Lipo, "A synchronous/permanent magnet hybrid AC machine," in *IEEE Trans. Energy Conv.*, vol. 15, no. 2, pp. 203-210, June 2000.

[17] A.D. Akemakou, S.K. Phounsombat, "Electrical machine with double excitation, especially a motor vehicle alternator," Nov. 14, 2000, US Patent 6,147,429.

[18] X. Yonghong, W. Shanming, M. Mingyuan, H. Liangliang, Q. Ami, H. Shaogang, "Basic principles of hybrid excitation PM synchronous generator utilizing harmonic for excitation," 2010 Int. Conf. on Electrical Machines and Systems, Incheon, Korea, 2010, pp. 1010-1013.

[19] N. Naoe and T. Fukami, "Trial production of a hybrid excitation type synchronous machine," IEEE-IEMDC, Cambridge, MA, USA, 2001.

[20] D. Fodorean, A. Djerdir, I. Viorel, A. Miraoui, "A Double Excited Synchronous Machine for Direct Drive Application—Design and Prototype Tests," *IEEE Trans. Energy Conv.*, vol. 22, no. 3, 2007.

[21] G. Henneberger, J.R. Hadji-Minaglou, R.C. Ciorba, "Design and test of permanent magnet synchronous motor with auxiliary excitation winding for electric vehicle application," European Power Electronics Chapter Symposium, Lausanne, October, 1994, pp. 645 – 649.

[22] Y. Amara, L. Vido, M. Gabsi, E. Hoang, M. Lecrivain, F. Chabot, "Hybrid Excitation Synchronous Machines: Energy Efficient Solution for Vehicle Propulsion," 2006 IEEE Vehicle Power and Propulsion Conference, Windsor, UK, 2006, pp. 1-6.

[23] F. Leonardi, T. Matsuo, Y. Li, T.A. Lipo, P. McCleer, "Design considerations and test results for a doubly salient PM motor with flux control," Conf. Rec. IEEE-IAS, San Diego, CA, USA, 1996.

[24] X. Zhu, M. Cheng, W. Hua, J. Zhang, W. Zhao, "Design and Analysis of a New Hybrid Excited Doubly Salient Machine Capable of Field Control," Conf. Rec. IEEE-IAS, Tampa, FL, USA, 2006, pp. 2382-2389.

[25] X. Zhu, M. Cheng, W. Zhao, C. Liu, K.T. Chau, "A Transient Cosimulation Approach to Performance Analysis of Hybrid Excited Doubly Salient Machine Considering Indirect Field-Circuit Coupling," *IEEE Trans. Magnetics*, vol. 43, no. 6, pp. 2558-2560, June 2007.

[26] K.T. Chau, J.Z. Jiang, Y. Wang, "A novel stator doubly fed doubly salient permanent magnet brushless machine," *IEEE Trans. Magnetics*, vol. 39, no. 5, pp. 3001-3003, Sept. 2003.

[27] G. Zhang, W. Hua, M. Cheng, J. Liao, K. Wang and J. Zhang, "Investigation of an Improved Hybrid-Excitation Flux-Switching Brushless Machine for HEV/EV Applications," in *IEEE Trans. Ind. Appl*, vol. 51, no. 5, pp. 3791-3799, Sept.-Oct. 2015.

[28] W. Hua, G. Zhang, M. Cheng, "Flux-Regulation Theories and Principles of Hybrid-Excited Flux-Switching Machines," *IEEE Trans. Ind. Electron.*, vol. 62, no. 9, pp. 5359-5369, Sept. 2015.

[29] G. Zhang, W. Hua, M. Cheng, J. Liao, "Design and Comparison of Two Six-Phase Hybrid-Excited Flux-Switching Machines for EV/HEV Applications," *IEEE Trans. Ind. Electron.*, vol. 63, no. 1, Jan. 2016.

[30] J.T. Chen, Z.Q. Zhu, S. Iwasaki, R. P. Deodhar, "A Novel Hybrid-Excited Switched-Flux Brushless AC Machine for EV/HEV Applications," *IEEE Trans. Vehicular Technol.*, vol. 60, no. 4, 2011.

[31] E. Hoang, M. Lecrivain, M. Gabsi, "3-D thermal model of an hybrid excitation flux switching synchronous machine using a 2-D FE method software," *SPEEDAM 2010*, Pisa, Italy, 2010, pp. 101-104.

[32] R.L. Owen, Z.Q. Zhu, G.W. Jewell, "Hybrid-Excited Flux-Switching Permanent-Magnet Machines With Iron Flux Bridges," *IEEE Trans. Magnetics*, vol. 46, no. 6, pp. 1726-1729, June 2010.

[33] E. Sulaiman, T. Kosaka, N. Matsui, "A novel hybrid excitation flux switching synchronous machine for a high-speed hybrid electric vehicle applications," *Int. Conf. on Electrical Machines and Systems*, Beijing, China, 2011, pp. 1-6.

[34] Y. Wang and Z. Deng, "Hybrid Excitation Topologies and Control Strategies of Stator Permanent Magnet Machines for DC Power System," *IEEE Trans. Ind. Electron.*, vol. 59, no. 12, pp. 4601-4616, Dec. 2012.

[35] J. A. Tapia, F. Leonardi and T. A. Lipo, "A design procedure for a PM machine with extended field weakening capability," IEEE-IAS, Pittsburgh, PA, USA, 2002, pp. 1928-1935.

[36] J.A. Tapia, F. Leonardi, T.A. Lipo, "Consequent-pole permanent-magnet machine with extended field-weakening capability," *IEEE Trans. Ind. Appl.*, vol. 39, no. 6, pp. 1704-1709, Nov. – Dec. 2003

[37] E. Spooner, S.A.W. Khatab, N.G. Nicolaou, "Hybrid excitation of AC and DC machines," IEEE-IEMDC, London, UK, 1989, pp. 48-52.

[38] T. Mizuno, "Hybrid excitation type permanent magnet machine," 1997, US Patent 5,682,073.

[39] M. Aydin, S. Huang, T.A. Lipo, "A new axial flux surface mounted permanent magnet machine capable of field control," IEEE-IAS Pittsburgh, PA, USA, 2002, pp. 1250-1257.

[40] M. Aydin, S. Huang, T.A. Lipo, "Design, Analysis, and Control of a Hybrid Field-Controlled Axial-Flux Permanent-Magnet Motor," *IEEE Trans. Ind. Electron.*, vol. 57, no. 1, pp. 78-87, Jan. 2010

[41] M. Aydin, S. Huang, T.A. Lipo, "Performance evaluation of an axial flux consequent pole PM motor using finite element analysis," IEEE-IEMDC, Madison, WI, USA, 2003, pp. 1682-1687.

[42] T. Kosaka, N. Matsui, "Hybrid excitation machines with powdered iron core for electrical traction drive applications," 2008 Int. Conf. on Electrical Machines and Systems, Wuhan, China, 2008, pp. 2974-2979.

[43] T. Kosaka, M.Sridharbabu, M. Yamamoto, N. Matsui, "Design studies on hybrid excitation motor for main spindle drive in machine tools," *IEEE Trans. Ind. Electron.*, vol. 57, no. 11, pp. 3807-3813, Nov. 2010

[44] B. Nedjar, S. Hlioui, Y. Amara, L. Vido, M. Gabsi, M. Lecrivain, "A New Parallel Double Excitation Synchronous Machine," *IEEE Trans. Magnetics*, vol. 47, no. 9, pp. 2252-2260, Sept. 2011.

[45] H. Hua, Z.Q. Zhu, H. Zhan, "Novel Consequent-Pole Hybrid Excited Machine With Separated Excitation Stator," IEEE Trans. Ind. Electron., vol. 63, no. 8, pp. 4718-4728, Aug. 2016.

[46] H. Hua, Z.Q. Zhu, "Novel Parallel Hybrid Excited Machines With Separate Stators," *IEEE Trans. Energy Conversion,* vol. 31, no. 3, pp. 1212-1220, Sept. 2016.