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Performance Investigation of Various Flux-Switching Machines for Hybrid Electric Vehicles: A Review

Arvind Kumar[1], Ajay Srivastava[2]

Research Scholar, Department of Electrical Engineering, G. B. Pant University of Agriculture & Technology, Pantnagar, Uttarakhand, India[1]

Professor, Department of Electrical Engineering, G. B. Pant University of Agriculture & Technology, Pantnagar, Uttarakhand, India[2]

ABSTRACT: A demand for vehicles using electrical propulsion drives is getting higher and higher from the stand points of preventing global warming and saving fossil fuel recently. Hybrid electric vehicles (HEV) using combination of internal combustion engine and one or more electric motors, are considered as the most promising clean vehicles. In recent years, flux-switching machines (FSM) have emerged as an attractive machine type over conventional electric motors with an advantage of all excitation sources located in the stator allowing a simple robust rotor. Other advantages are simple robust rotor, superior control capability, smooth flux and torque pulsation, as well as producing much higher torque density and efficiency, which suit for HEV. This paper overviews various flux permanent magnet machines and their design and performance features, with particular emphasis on machine topologies and literature survey on the different configurations of flux switching machines.

KEYWORDS: Hybrid electric vehicles (HEV), flux-switching motors (FSM)

I. INTRODUCTION

The demand for electrical propulsion drives vehicles is getting higher to replace fossil fuel vehicles because people nowadays have getting more concern of the environmental issues surrounding the world. Electric vehicles (EVs) compared to the internal combustion engine vehicles (ICEV), contribute significantly to the energy saving and environmental protection. This matter encouraged people to look at EV's as a possible alternative mode of transportation. Currently, HEVs and EVs are making a comeback in mainstream transportation. Many automotive companies have started to design a new type of vehicle called Hybrid Electric Vehicles (HEV) in which an electric motor is incorporated to the vehicles along with the usage of internal combustion engine (ICE). The first HEV was developed as early as 1899. The oil crisis in the 1970s maintained the interest and founding in the research of EVs. Social and economic factors are also making EVs attractive. Toyota Prius has been the first economic success of an HEV. The stator of electric motors has not changed much since Jonas Wenstrom invented the slotted armature in 1880.The incentives that have led to the development of innovative types of electrical machines in the past half-century have mainly been driven by economical and environmental imperatives. While recognizing the influence of these pressures and requirements, it is also acknowledged that the notable developments shown in the appearance of innovative electrical machines during this period are due to the corresponding rapid developments in power semiconductor and integrated circuit devices, micro computing technology including facilities for numerical analysis, and discoveries of new electromagnetic materials.

In electric propulsion systems, the most popular electric machine used for traction drive is DC commutating machines due to their torque-speed characteristics suit for traction requirements and no need for complex controller. However, drawbacks of DC machines are high maintenance, low efficiency, low reliability and huge in size. Important constraints that have to be fulfilled by the electrical machine when it is designed for hybrid electrical vehicle (HEV) or full electrical vehicle (EV) applications are high efficiency, high power factor, high Torque/Volume ratio, high torque and speed operating points. IN almost every branch of industry, the primary aim is to

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find energy efficient solutions for applications at a minimum cost. In order to satisfy these different constraints special electrical machines like the hybrid excitation machines seem to be an interesting solution.

In recent years, flux-switching motors (FSMs) have emerged as an attractive machine type over conventional electric motors with an advantage of all excitation sources located in the stator allowing a simple robust rotor. Other advantages are simple robust rotor, superior control capability, smooth flux and torque pulsation, as well as producing much higher torque density and efficiency, which suit for HEV. Hybrid-excited machines utilize the advantages of both PM machines and wound field synchronous machines. Hybrid-excited machines are those which utilize primary excitation by permanent magnets (PMs) as well as a secondary field coil excitation source. As such hybrid excitation PM machines have the potential to improve the flux weakening and flux-enhancing performance and efficiency. However, the differences between the hybrid excitation topologies have great influence on the utilization ration of excitation current, torque density, efficiency, and reliability of the hybrid excitation flux switching machines. Currently, the current increase in rare-earth PM prices, combined with risks of shortages, pose great issues of cost and supply delays. In another structure of HEFSM machine with iron flux bridges is introduced. By adding an iron bridge at outer radius of the machine, the field coil excitation can be effectively increased at the cost of slightly reduced torque density.

CLASSIFICATION OF ELECTRIC MOTORS

There are four main types of electric machines that potentially can be applied as traction drive in EV such as DC machines, induction machines (IMs), permanent magnet synchronous machines (PMSMs), and switched reluctance machines (SRMs).

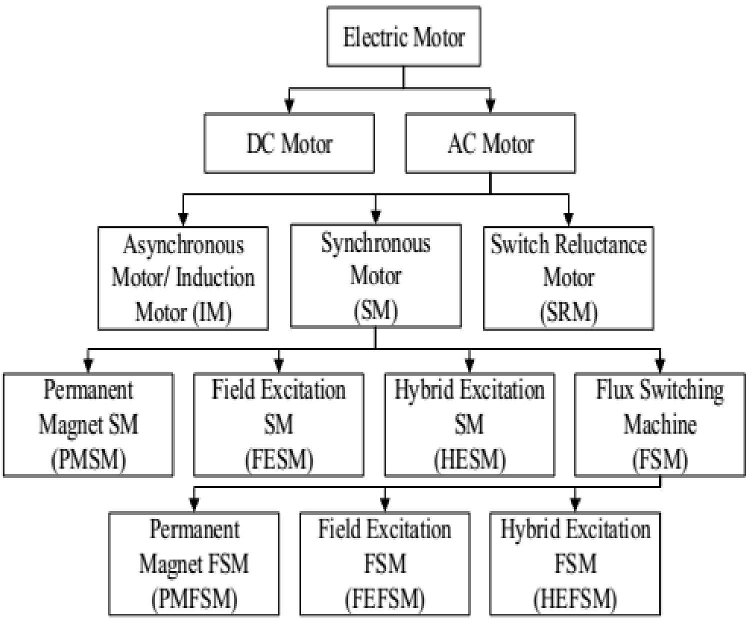

Fig. 1: Classification of Electric Motors

CLASSIFICATION OF FLUX SWITCHING MACHINES (FSM)

The flux switching machines (FSMs) concept was first invented in the middle of 1950's (Rauch & Johnson 1955). The term "flux switching" is introduced by shifting of polarity of the flux linkage by following the motion of a salient pole rotor.

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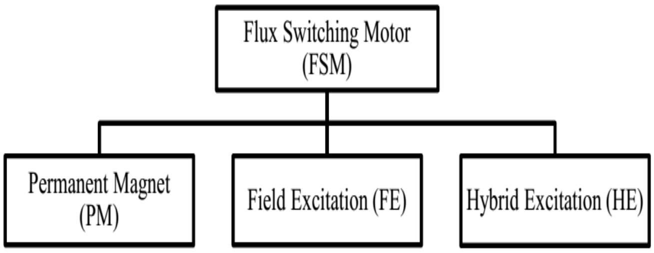

Fig 2: *Classification of FSMs*

A flux-switching machine comprises a non-wound rotor devoid of permanent magnets and a stator comprising phase windings and excitation windings or permanent magnets. The AC voltage at the terminals of the phase windings is produced by the switching of the flux following the rotation of the rotor. With the significant achievements and improvements of permanent magnet materials and power electronics devices, the brushless machines excited by PM associated with FEC are developing dramatically. Generally, the FSMs can be categorized into three groups that are Permanent Magnet Flux Switching Motor (PMFSM), Field Excitation Flux Switching Motor (FEFSM), and Hybrid Excitation Flux Switching Motor (HEFSM). Both PMFSM and FEFSM has only Permanent Magnet and Field Excitation Coil (FEC), respectively as their main flux sources, while HEFSM combines both PM and FEC as their main flux sources.

PERMANENT MAGNET FLUX-SWITCHING MACHINES (PMFSM)

The principle of flux switching was first proposed in 1955 as a single-phase flux-switching alternator. However, it was not until the late 1990s when a classical structure of a three-phase 12-stator-slot/10-rotor-pole FSPM machine was presented. After that, there has been a substantial increase in the investigation of subjects ranging from different excitation modes and structure variants to control strategies and operation principles. .PMFS machines recently attracted considerable attention due to the advantages of high power (torque) density, robust mechanical structure, good flux-weakening capability, and essential sinusoidal back-electromotive-force waveforms and high efficiency, favorable for cooling and high speed operation. Therefore, the PMFS machines are perfectly suitable for EV and HEV applications. All the PMs in PMFS machines are magnetized in alternative opposite directions to produce the “flux focus” effect. In addition, each stator pole includes two adjacent stator teeth with a magnet sandwiched and a concentrated armature coil wound around, called “all teeth-wound” windings. However, the stator poles can also be wound by the concentrated armature winding coils alternately, which means only half stator poles are wound and the other half are unwound, which can be called “half-teeth-wound” windings.

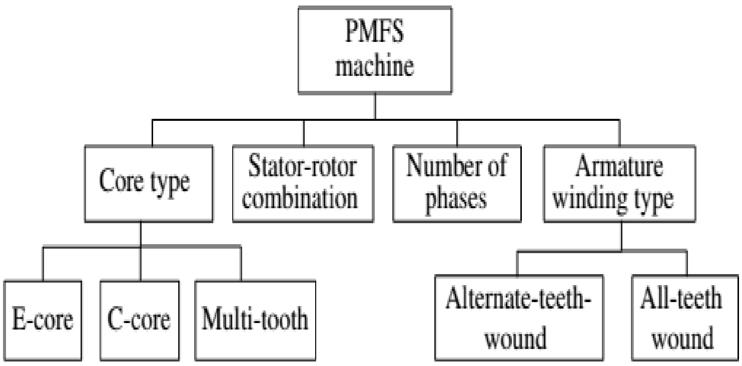

Fig. 3: *Classification PMFSM*

It should be emphasized that the characteristics of PMFS machines, such as fault-tolerant capacity, are influenced significantly by “all-teeth-wound” or “half-teeth-wound” windings. On the other hand, compared with the conventional

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rotor-PM machines having magnets in the rotor, the placement of both PMs and armature windings in the stator is favorable for cooling and desirable for aerospace and EV applications, where the ambient temperature may be high. Finally, the end part of the winding coils of the PMFS machines can be obviously reduced with the concentrated armature coils, instead of distributed ones.

PRINCIPLES OF OPERATION OF PMFSM

The so-called "flux-switching" principle is illustrated in Figure 5. When the rotor moves from the position in Figure 4(a) to that in Figure 4(b), the PM flux due to magnets only linked by the armature coil changes the direction from "toward the rotor" to "toward the stator," that is, from positive peak value to negative peak value as shown in Figure 4(c), and realizes the "flux switching." Consequently, as the rotor moves continually, the coil PM flux linkage in the coils of windings will change periodically in both polarities and magnitudes; meanwhile, the inducted EMF of each coil will change periodically as well. Since the flux due to armature reaction in a PMFS machine does not pass through the magnets, the irreversible demagnetization withstand capability of the PMFS machines is high, which makes it particularly suitable for flux-weakening operation.

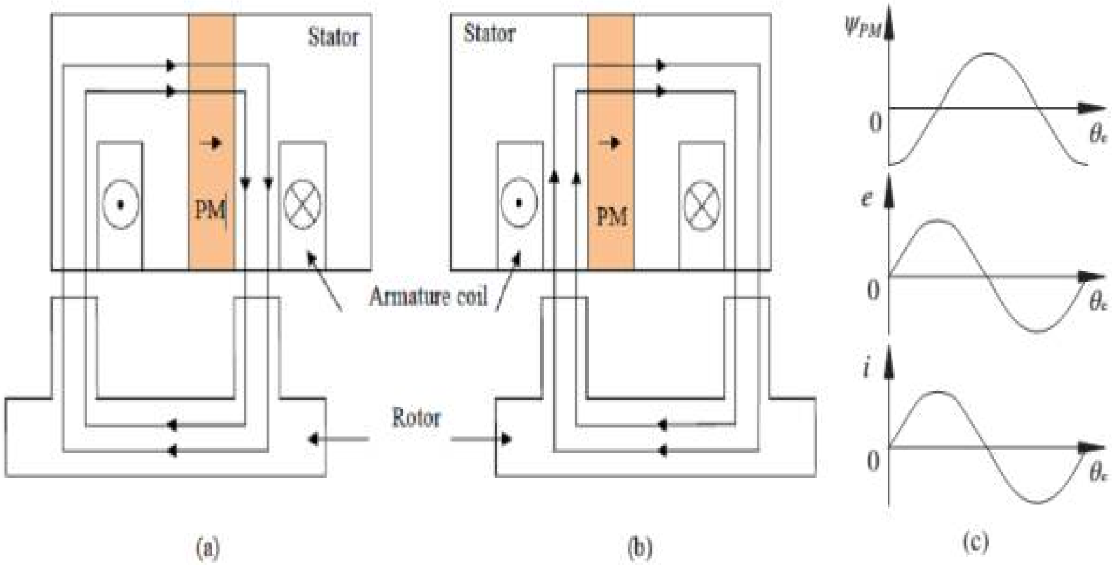

***Fig. 4:** Principle of operation of PMFSM*

Over the last ten years or so, many novel and new flux switching machine topologies have been developed for various applications, ranging from low cost domestic appliances, automotive, wind power, to aerospace, etc. Some of them are shown in fig. (5).

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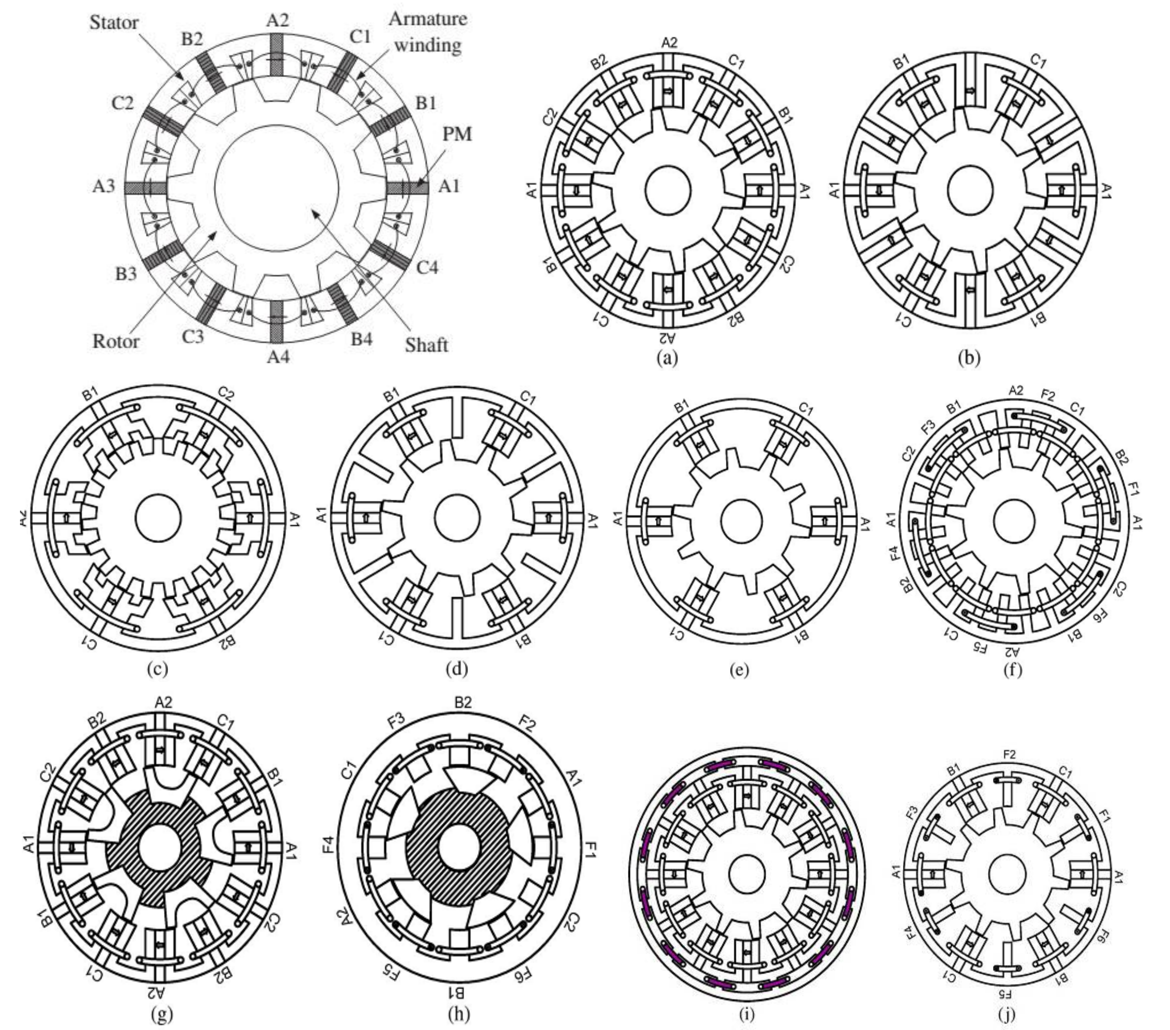

Fig.-5. *Topologies of flux-switching (FS) machines-**(a)** Conventional FSPM machine with all poles wound, **(b)** Conventional FSPM machine with alternate poles wound. **(c)** Multi-tooth FSPM machine. **(d)** E-core FSPM machine. **(e)** C-core FSPM machine. **(f)** DC winding excited FS machine. **(g)** Modular rotor FSPM machine. **(h)** Modular rotor DC winding excited FS machine. **(i)** Hybrid excited FSPM machines. **(j)** Hybrid excited E-core FSPM machine.*

HYBRID EXCITED FLUX-SWITCHING MACHINES (HEFSM)

A flux-switching machine comprises a non-wound rotor devoid of permanent magnets and a stator comprising phase windings and excitation windings or permanent magnets. Hybrid excitation flux switching machines (HEFSM) are those which utilize primary excitation by permanent magnets (PM) as well as DC field excitation coil (FEC) as a secondary source in an electric motors The AC voltage at the terminals of the phase windings is produced by the switching of the flux following the rotation of the rotor. In a known flux-switching machine, each groove receiving conductors of an excitation winding and the two adjacent grooves receiving conductors of phase windings constitute a basic cell. The excitation coils and the phase coils each cover two teeth pitches on the stator, that is to say the grooves

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which receive said windings are separated by two teeth. These machines are generally characterized by the use of a significant quantity of copper or other conductor material in order to form the excitation windings so as to limit the losses sustained due to the Joule effect and the effects thereof on the output.

Permanent magnet flux switching machines (PMFSM) have relatively poor flux weakening performance but can be operated beyond base speed in the flux weakening region by means of controlling the armature winding current. By applying negative d-axis current, the PM field can be counteracted but with the disadvantage of increase in copper loss and thereby reducing the efficiency, reduced power capability, and also possible irreversible demagnetization of the PMs. Thus, HEFSM is an alternative option where the advantages of both PM machines and DCFEC synchronous machines are combined. As such HEFSMs have the potential to improve flux weakening performance, power and torque density, variable flux capability, and efficiency which have been researched extensively over many years. Various combinations of stator slot and rotor pole for HEFSM have been developed, for example, a 6S-4P, 6S-5P, and 6S-7P model, most of the PM flux flows into the stator iron around the FEC, while 100% flux of PM flows around the FEC for 6S -8P model. This will give advantages of less cogging torque and almost no back-emf at open-circuit condition.

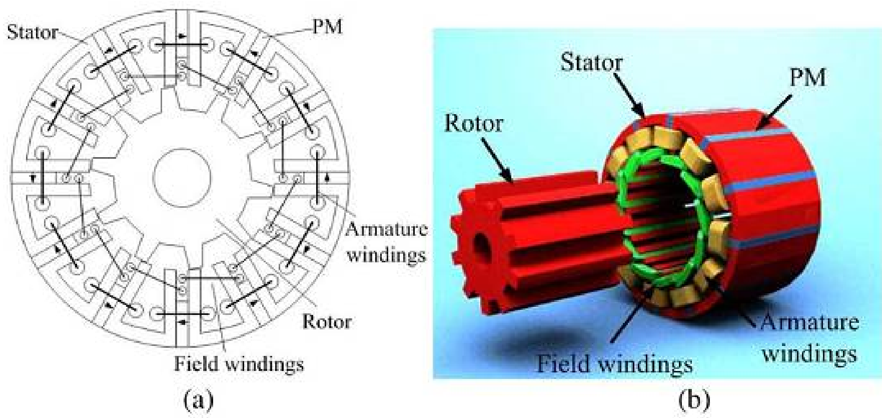

Fig. 6: *Topology of HEFSM (a) Cross-section. (b) Configuration.*

CLASSIFICATION OF HYBRID EXCITATION FLUX-SWITCHING MACHINE (HEFSM)

A. The first type consists of both PM and FEC at rotor side such as combination rotor hybrid excitation (CRHE) machine and synchronous/PM hybrid AC machine.

B. The second type consists of PM in the rotor while FEC is in the stator.

C. The third type consists of PM in the rotor while the FEC is in the machine end.

D. Finally, the fourth type of HEM is the machine, which has both PM and FEC in the stator.

It should be emphasized that all HEMs mentioned in the first three have a PM in the rotor and can be categorized as “hybrid rotor-PM with field excitation machines” while the fourth machine can be referred as “hybrid stator-PM with field excitation machines”. Based on its principles of operation, the fourth machine is also known as “hybrid excitation flux switching machine (HEFSM)” which is getting more popular recently. The presence of excitation coil makes these types of machines more attractive in terms of modulating the PM flux. Among various types of HEFSSM, the machine with both permanent magnet (PM) and field excitation coil (FEC) on the stator has the advantages of robust rotor structure together with variable flux control capabilities that make this machine becoming more attractive to apply for high-speed motor drive systems. For HEFSM, all the active parts are located on the stator with the armature while PM (DC field winding) placed in alternate stator teeth. The machine is suitable for high speed applications because it possess robust rotor structure. Furthermore, the flux generated can be controlled using the FEC. For solely PMs excited machines, it is a traditional contradiction between the requests of high torque capability under the base speed (constant torque region) and wide speed operation above the base speed (constant power region). Hence, hybrid-excitation flux-switching machines (HEFSM) are proposed in which the magnet dimensions were reduced to save room for the introduced field excitation coil (FEC) windings. It is obvious that with variable dc FEC, the air gap field of HEFSM can be easily controlled and is favorable for Electric Vehicle (EV) applications.

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It should be emphasized that for the HEFS machine, the DC field winding coils are located on the stator, so it does not require slip rings. The magnetic circuit associated with the DC excitation may be either in series or in parallel with the magnetic circuit associated with the PM excitation. The series excitation is simple and requires a higher excitation MMF due to the low recoil permeability of the magnets. Meanwhile, the parallel excitation is more electromagnetically effective. Overall, the DC excitation winding enables the air-gap flux, and hence the torque capability, to be enhanced at low speed, to be reduced at high speed to facilitate extended speed operation, and to be optimized over the entire speed range to improve the efficiency. But HEFS machines also suffer the drawback of reduced torque density compared with PMFS machines.

WOUND-EXCITED FLUX-SWITCHING MACHINES (WEFSM OR FEFSM)

Although compared with permanent magnet-free (PM-free) machines the above PMFS and HEFS machines have higher torque density and efficiency, the characteristics of these two kinds of flux-switching machines are still compromised by the following reasons:

- The price and supply uncertainties of permanent magnets, particularly for NdFeB.
- The irreversible demagnetization for PMs is still possible at high temperature.
- The mechanical strength is relatively weak for their stators, which are divided into many segments by the corresponding PMs.
- The air-gap flux density is dominated by PM excited field and the flux regulation capability is limited.

Hence, WEFS machines are proposed, where the magnets are removed, for example, PM-free, and both the field and armature windings are located on the stator. Obviously, the costs of the WEFS machines are greatly reduced and the foregoing problems concerning PMs can be easily solved in this way.

OPERATION PRINCIPLES

A typical topology of WEFS machines, as shown in Figure 7, is similar to a traditional PMFS machine, in which both the armature windings and the field excitation windings are located on the stator. The armature coils in WEFS machines are wound in the same manner as in PMFS machines, whereas the DC field windings functioning as PMs are placed in the radial direction. It should be noted that the DC excitation fields due to field windings are in alternative opposite directions as PMs in PMFS machines. The operation principles of WEFS machines are the same as typical PMFS machines, as illustrated in Figure 8.

As the salient-pole rotor moves continuously, the field flux (flux linkage) linked in an armature winding coil will change periodically not only the amplitudes but also the polarities. Consequently, the corresponding EMF will be induced in each armature coil. As a result of the coupling reaction between the field-excited flux and the armature reaction flux, an electromagnetic torque can be produced and drives the rotor to rotate. Since the topology is similar to that of the PMFS machines, the WEFS machines possess the same operation principles as PMFS machines. However, different from the PMFS machines, the air-gap field can be easily weakened or strengthened in the WEFS machines as it is generated by controllable DC currents. Therefore, the WEFS machines can be considered as a good compromise between the requirements of high torque density and wide speed regulation range as well as costs.

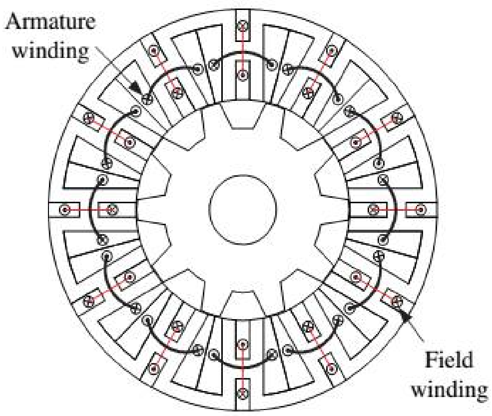

Fig. 7: *Cross-section of WEFSM*

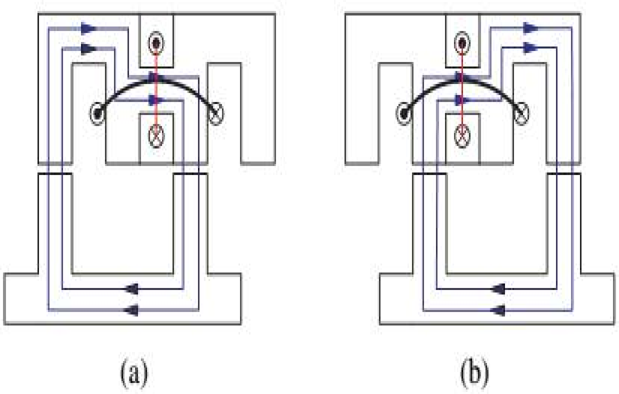

Fig. 8: *Principle of operation of WEFSM*

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II. EVALUATION OF FLUX-SWITCHING MACHINES

A comprehensive comparison between the three typical flux-switching machines, namely, PMFS, HEFS, and WEFS machines, has led to a series of significant conclusions, which are summarized below.

Table 1: General comparison of flux switching machines

Design issue	PMFS	HEFS	WEFS
PM volume	Maximum	Medium	None
Torque density	Maximum	Medium	Minimum
Field regulation	Minimum	Medium	Maximum
Overload ability	Minimum	Medium	Maximum
Copper loss	Minimum	Medium	Maximum
Efficiency	Maximum	Medium	Minimum
Cogging torque	Maximum	Medium	Minimum

V. REVIEW OF LITERATURE

Z. Q. Zhu, *et. Al*., *2005,* developed a nonlinear adaptive lumped parameter magnetic circuit model, to predict the electromagnetic performance of flux-switching machines, taking account of magnetic saturation and flux leakage. The predicted air-gap field distribution, back-EMF waveform, winding inductances, and electromagnetic torque are validated by both two-dimensional (2-D) and three-dimensional (3-D) finite-element analyses.

Yacine Amara, *et. Al.*, *2005,* presented the electromagnetic design and comparison of different flux-switch machines for an aircraft oil breather application. A preliminary design procedure applied to two configurations, one with rare earth magnets (SmCo) and the other with ferrite magnets, is first presented. Due to their relatively low maximum operating temperature NdFeB magnets have not been considered. This particular structure uses the principles of both flux-switch and flux concentration.

Wei Hua, *et. al*., 2009, proposed a novel hybrid excitation flux-switching (HEFS) motor, in which the air-gap field can be easily controlled and is favorable for hybrid vehicles. The preliminary topology, operation principle, design and static characteristics including phase flux-linkage, back-EMF waveforms under different excitations as well as cogging torque are evaluated based on finite element (FE) analysis. The results confirm the excellent field-regulation capability of a “proof-of-principle” HEFS motor.

Richard L. Owen, *et. al.*, 2010 proposed topologies of hybrid-excited flux-switching PM machines incorporating iron flux bridges to enhance the effectiveness of the field coil excitation. A simple lumped parameter magnetic circuit model is developed to predict the effect of adjusting various parameters. Two-dimensional finite-element analysis has also been used to predict the machine performance, while a prototype machine has been built and tested to validate the predicted results.

Wei Hua, *et. al.*, 2011 proposed a nonlinear magnetic network model, to predict the performance of HEFS machines. Particular attention is paid to the locations of the MMF due to magnets and field windings. It is confirmed that the proposed NMNM can predict the air-gap flux density distribution and the flux linkages of armature and field windings under different excitations with satisfied accuracy. All the results from the NMNM are validated by FE analysis.

Gan Zhang, *et. al.*, 2011, analyzed the oversaturated phenomenon in hybrid excited flux-switching permanent magnet machines and the effect on electromagnetic performance. Then, an effective stator-tooth-width coefficient is defined, which can be used in both initial and optimal designs of HEFS machines. Moreover, the proposed oversaturated effect can also be used to analyze the relation between the air-gap flux density, magnet length, and flux-linkage in armature windings.

Juan de Santiago, *et. al.*, 2012, presented an up-to-date review of EV drivelines based on a survey of commercial EVs and reviews the history of the EV with emphasis on future electric motors. He also describes the mechanical parts of the driveline in EVs and discusses the advantages and disadvantages of technology trends.

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Yu Wang and Zhiquan Deng, 2012, compared and analyzed the electromagnetic performance of different hybrid excitation stator PM machines according to different combination modes of PMs, excitation winding, and iron flux bridges. Then, the control strategies for voltage regulation of dc power systems are discussed based on different critical control variables including the excitation current, the armature current, and the electromagnetic torque. Furthermore, an improved direct torque control (DTC) strategy is investigated to improve system performance. A parallel hybrid excitation flux-switching generator employing the improved DTC which shows excellent dynamic and steady-state performance has been achieved experimentally.

Weizhong Fei, et. al., 2012, proposed a novel permanent-magnet (PM) flux switching (PMFS) machine with an outer-rotor configuration for in-wheel light traction applications. The geometric topology of the outer-rotor PMFS machine is introduced, and the analytical sizing equations are derived to determine the main design parameters of the machine. Two-dimensional finite-element analysis (FEA) models are developed to investigate and optimize the machine performance. Furthermore, the flux-weakening capability of the machine is analyzed and further improved by segmental PMs with iron bridges.

Yu Wang, and Zhi-Quan Deng, 2012, analyzed the basic design dimensions and electromagnetic performance of the EEFS machines and those of the EEDS machines are also given for comparison. Compared with the EEDS machine, the EEFS machine exhibits bipolar stator flux-linkage and sinusoidal back-EMF waveforms as well as larger torque density. Then, control schemes of the two machines for voltage regulation of dc power systems are discussed, and in order to improve the steady state and dynamic performance of the EEFS generator dc power system, an improved direct torque control scheme is presented. It develops the strictly linear relationship between the torque and sinusoidal value of the torque angle, and can regulate the instantaneous torque directly and smoothly without current loop. Besides, the flux weakening control of the proposed scheme is also studied.

Daohan Wang, et. al., 2012, investigated cogging torque principle in FSPM by analyzing the flux density distribution and a simple cogging torque reduction technique, i.e., teeth notching. Various kinds of notching schemes and their influence on cogging torque are examined along with instantaneous torque and average output torque at different load conditions. Numerical optimization process combined with finite-element analysis, which gives more preciseness to calculations, is performed to minimize cogging torque. The results show that the cogging torque circle depends on the real flux density distribution in the machine rather than the number of stator/rotor poles and the presented method can greatly reduce the torque ripple at only slight cost of average output torque.

E. Sulaiman, et. al. (2013), presented design study and flux interaction analysis of a new 12S-10P and 12S-14P FEFSM with single direction of DC FEC winding are presented. Initially, design procedures of the FEFSM including, parts, drawing, materials and conditions setting, and properties setting are explained. Then, coil arrangement tests are examined to confirm the machine operating principle and position of each armature coil phase. Finally, flux interaction between DC FEC and armature coil, FEC flux capabilities at various current condition, induced voltage and initial torque are also analyzed.

E.Sulaiman, *et. al.*, (2013), presented design study and flux interaction analysis of 24S-10P FEFSM with single direction of FEC winding. Initially, design procedures of the FEFSM including parts drawing, materials and conditions setting and properties setting are explained. Then, coil arrangement tests are examined to confirm the machine operating principle and position of each armature coil phase. Finally, the flux interaction between DC FEC and armature coil, FEC flux capabilities at various current condition, and initial torque are also investigated.

Benjamin Gaussens, *et. al.*, (2014), presented a new topology of hybrid-excited flux-switching machine with excitation coils located in stator slots (or inner dc windings). It is demonstrated that the air-gap field can be easily controlled, which is interesting for variable-speed applications. Finally, a prototype having 12 stator poles and different rotor tooth numbers (10 or 14) was built. Finally, the thermal behavior of the prototype machine is investigated through experiments. It is shown that, up to 12 000 r/min, the thermal stabilization is achieved, making this topology an excellent candidate for high-speed applications.

Wei Hua, *et. al.*, (2014) proposed two five-phase hybrid-excitation flux-switching (HEFS) machines with different stator topologies and analyzed with the identical stator outer diameters and stack lengths. The electromagnetic performances, including the conventional static characteristics, such as phase flux, back-EMF, inductance, cogging torque and electromagnetic torque, and so on, are presented first. Then, both the flux-strengthening and flux-weakening capabilities are evaluated in detail according to the electromagnetic torque characteristics under different field currents with the help of 2-D finite element analysis. The corresponding predictions and conclusions indicate that the U-core topology is preferred for the five-phase HEFS machines.

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Gan Zhang, et. al., (2015) proposed an improved topology to enhance the flux-regulation capability based on the basic HEFSM by reversing current direction in one of the field slots. Therefore, the improved topology shares identical structure with the basic one but has different field current directions in some field slots and thus different field winding accommodations. Comparisons of the FEA predictions indicated that both armature no-load flux-regulation capability and armature load torque capability in the improved HEFS machine are much better than those in the basic one. Finally, the FEA results are validated by experimental measurements on two prototyped HEFS machines.
Gan Zhang, et. al., (2015) proposed the design of two six-phase hybrid-excited flux-switching (HEFS) machines with E-core and C-core stator laminations, respectively. The iron bridges are adopted in each machine and the influences on performance are investigated. In addition, alternative-tooth-wound armature windings are employed in the C-core one to obtain physical and magnetic isolations between armature phases. A comprehensive comparison of the two designs is carried out. Then, more attention is paid to fault tolerant operating capabilities when open-circuit fault occurs to only one phase and two phases of armature windings, respectively. The positive field current can be applied in C-core machine under fault-tolerant operating conditions, thus the post-fault armature current can be reduced whilst maintaining torque output. Finally, the FEA-based studies are validated by experimental measurements on two HEFS machine prototypes.
Dongjae Kim, et. al., (2016) proposed a double-stator flux-switching permanent magnet (DS-FSPM) machine using ferrite to replace an interior permanent magnet synchronous motor (IPMSM) on hybrid electric vehicles. A conventional FSPM machine is designed, and its torque characteristic is analyzed by a frozen permeability method. It is verified that magnetic saturation causes the reduction of flux linkage generated by PM and leads to the deterioration of electromagnetic torque. A DS-FSPM machine is effective for magnetic saturation because of its unique structure and makes the improvement of efficiency and power density. The proposed DS-FSPM machine achieves distinct performance enhancement compared with an IPMSM, even by utilizing ferrite PM.
Agathe Dupas, et. al. (2016) presented a new structure for a hybrid excitation, flux-switching synchronous machine. The particularity of this machine is its global excitation winding component that creates a three-dimensional (3-D) excitation flux path to control the global air gap flux. Both 3-D finite-element analysis and a comparison with experimental results are provided. This model makes it possible to: show the excitation flux path, explore the flux-regulation capability of a new structure, and identify the influence of material characteristics.

VI. CONCLUSION

With the emergence of energy related issues in the automotive sector, there is a tendency to find new efficient solutions to replace existing electrical machinery. Flux switching machines are at a first glance very promising alternatives to replace PMSM (e.g., BLDC) and SRM. In this study, a particular attention is paid to the topology and principle of operation of various flux switching machines. Flux-switching machines are similar to switched reluctance machines, which make them more suitable to high-speed operation. Flux-switching machines have significant potential for applications, including domestic appliances, power tools, automotives, aerospace, and wind power generation, etc.

REFERENCES

[1]. Tapia, J.A., F. Leonardi, T.A. Lipo, "Consequent-pole permanent magnet machine with extended field-weakening capability," IEEE Trans. on Industry Applications, 39(6): pp. 1704-1709, 2003.
[2]. Z. Q. Zhu, Y. Pang, D. Howe, S. Iwasaki, R. Deodhar and A. Pride, "Analysis of Electromagnetic Performance of Flux-Switching Permanent-Magnet Machines by Nonlinear Adaptive Lumped Parameter Magnetic Circuit Model," IEEE Transactions On Magnetics, Vol. 41, No. 11, pp.4277-4287, 2005.
[3]. Yacine Amara, Emmanuel Hoang, Mohamed Gabsi, Michel Le ´crivain and Sylvain Allano, "Design and comparison of different flux-switch synchronous machines for an aircraft oil breather application," European Transactions On Electrical Power; 15: pp.497–511, 2005.
[4]. J. F. Bangura,"Design of high-power density and relatively high efficiency flux-switching motor," IEEE Trans. Energy Convers., vol. 21(2), pp. 416-424, Jun. 2006.
[5]. Y. Pang, Z. Zhu, D. Howe, S. Iwasaki, R. Deodhar and A. Pride, "Eddy current loss in the frame of a flux-switching permanent magnet machine," IEEE Trans. Magn., vol. 42 (10), pp. 3413 3415,Oct. 2006.
[6]. Hoang, E., M. Lecrivain and M. Gabsi, "A New Structure of a Switching Flux Synchronous Poly-phased Machine with Hybrid Excitation," Proceedings of European Conference on Power Electronics and Applications, Aalborg, Denmark, 2007.
[7]. Fodorean, D., A. Djerdir, I.A. Viorel and A. Miraoui, "A double excited synchronous machine for direct drive application-Design and prototype tests," IEEE Trans. on Energy Conversion, 22(3): 656-665, 2007.
[8]. Wei Hua, Ming Cheng, and Gan Zhang, "A Novel Hybrid Excitation Flux-Switching Motor for Hybrid Vehicles," IEEE Transactions On Magnetics, Vol. 45, No. 10, pp. 4728-4731, 2009.
[9]. Amara, Y., L. Vido, M. Gabsi, E. Hoang, A.H. Ben Ahmed and M. Lecrivain, "Hybrid excitation synchronous machines: Energy-efficient solution for vehicles propulsion," IEEE Trans. Veh. Technol., 58(5): pp. 2137–2149, 2009.
[10]. Owen, R.L., Z.Q. Zhu and G.W. Jewell, "Hybrid Excited Flux-switching permanent Magnet Machines", Proc. 13th European Conf. on Power Electronics and Applications, EPE, Barcelona, Spain, 2009.

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[11]. Richard L. Owen, Z. Q. Zhu, Fellow, IEEE, and Geraint W. Jewell, "Hybrid-Excited Flux-Switching Permanent-Magnet Machines With Iron Flux Bridges," IEEE Transactions On Magnetics, Vol. 46, No. 6, pp. 1726-1729, 2010.
[12]. Kosaka, T., M. Sridharbabu, M. Yamamoto and N. Matsui, "Design studies of hybrid excitation motor for main spindle drive in machine tools", IEEE Trans. Ind. Electron., 57(11): pp. 3807-3813, 2010.
[13]. Wei Hua, Gan Zhang, Ming Cheng, and Jianning Dong, "Electromagnetic Performance Analysis of Hybrid-Excited Flux-Switching Machines by a Nonlinear Magnetic Network Model," IEEE Transactions On Magnetics, Vol. 47, No. 10, pp. 3216-3219, 2011.
[14]. Gan Zhang, Ming Cheng, Wei Hua, and Jianning Dong, "Analysis of the Oversaturated Effect in Hybrid Excited Flux-Switching Machines," IEEE Transactions On Magnetics, Vol. 47, No. 10, pp. 2827-2830, 2011.
[15]. Sulaiman, E., T. Kosaka and N. Matsui, "A New Structure of 12Slot-10Pole Field-Excitation Flux Switching Synchronous Machine for Hybrid Electric Vehicles", Proc. of 14th European Conference on Power Electronics and Applications, Birmingham, 2011.
[16]. Sulaiman, E., T. Kosaka, N. Matsui and M.Z. Ahmad, "Design Improvement and Performance Analysis of 12slot-10pole Permanent Magnet Flux Switching Machine with Field Excitation Coils", Power Engineering And Optimization Conference (PEOCO), 2011.
[17]. Sulaiman, E., T. Kosaka and N. Matsui, "A Novel Hybrid Excitation Flux Switching Machine for Hybrid Electric Vehicles", Proc. of The 14th International Conference on Electrical Machines and Systems (ICEMS"2011), Beijing, 2011.
[18]. Juan de Santiago, Hans Bernhoff, Boel Ekergård, Sandra Eriksson, Senad Ferhatovic, Rafael Waters and Mats Leijon, "Electrical Motor Drivelines in Commercial All-Electric Vehicles: A Review," IEEE Transactions On Vehicular Technology, Vol. 61, No. 2, 2012.
[19]. Yu Wang and Zhiquan Deng, "Hybrid Excitation Topologies and Control Strategies of Stator Permanent Magnet Machines for DC Power System," IEEE Transactions On Industrial Electronics, Vol. 59, No. 12, 2012.
[20]. Weizhong Fei, Patrick Chi Kwong Luk, Jian Xin Shen, Yu Wang, and Mengjia Jin, "A Novel Permanent-Magnet Flux Switching Machine With an Outer-Rotor Configuration for In-Wheel Light Traction Applications," IEEE Transactions On Industry Applications, Vol. 48, No. 5, 2012.
[21]. Yu Wang, and Zhi-Quan Deng, "Analysis of Electromagnetic Performance and Control Schemes of Electrical Excitation Flux-Switching Machine for DC Power Systems," IEEE Transactions On Energy Conversion, Vol. 27, No. 4, pp. 844-855, 2012.
[22]. Daohan Wang , Xiuhe Wang , and Sang-Yong Jung , "Reduction on Cogging Torque in Flux-Switching Permanent Magnet Machine by Teeth Notching Schemes," IEEE Transactions On Magnetics, Vol. 48, No. 11, pp. 4228-4231, 2012.
[23]. E. Sulaiman, M. F. M. Teridi, Z. A. Husin, M. Z. Ahmad and T. Kosaka, "Performance Comparison of 24S-10P and 24S-14P Field Excitation Flux Switching Machine with Single DC-Coil Polarity," IEEE 7th International Power Engineering and Optimization Conference (PEOCO2013), Langkawi, Malaysia, 2013.
[24]. N.A. Jafar, E., Sulaiman, "Design Analysis of 12S-10P Hybrid-Excitation Flux-Switching Permanent Magnet Machines for Hybrid Electric Vehicle", Power Engineering and Optimization Conference (PEOCO), Langkawi, 2014.
[25]. Benjamin Gaussens, Emmanuel Hoang, Michel Lécrivain, Philippe Manfe, and Mohamed Gabsi, "A Hybrid-Excited Flux-Switching Machine for High-Speed DC-Alternator Applications," IEEE Transactions On Industrial Electronics, Vol. 61, No. 6, 2014.
[26]. Wei Hua, Xiaomei, Yin, Gan Zhang, and Ming Cheng, "Analysis of Two Novel Five-Phase Hybrid-Excitation Flux-Switching Machines for Electric Vehicles," IEEE Transactions on Magnetics, Vol. 50, No. 11, 2014.
[27]. Sulaiman, E., T. Kosaka and N. Matsui, "Design and Analysis of High-power/high-torque Density Dual Excitation Switched-Flux Machine for Traction Drive in HEVs", Renewable & Sustainable Energy Reviews 34: pp. 517-524, 2014.
[28]. Y. J. Zhou and Z. Q. Zhu, "Comparison of wound-field switched-flux machines," IEEE Trans. Ind. Appl., vol. 50, pp. 3314 3324, Sept./Oct. 2014.
[29]. Gan Zhang, Wei Hua, Ming Cheng, Jinguo Liao, Kai Wang, and Jianzhong Zhang, "Investigation of an Improved Hybrid-Excitation Flux-Switching Brushless Machine for HEV/EV Applications," IEEE Transactions On Industry Applications, Vol. 51, No. 5, pp. 3791- 3799, September/October, 2015.
[30]. Gan Zhang, Wei Hua, Ming Cheng and Jinguo Liao, "Design and Comparison of Two Six Phase Hybrid-Excited Flux-Switching Machines for EV/HEV Applications," IEEE Transactions On Industrial Electronics, 2015.
[31]. Dongjae Kim, Hongsik Hwang, Sungwoo Bae, and Cheewoo Lee, "Analysis and Design of a Double-Stator Flux-Switching Permanent Magnet Machine Using Ferrite Magnet in Hybrid Electric Vehicles," IEEE Transactions On Magnetics, Vol. 52, No. 7, 2016.
[32]. Agathe Dupas, Sami Hlioui, Emmanuel Hoang, Mohamed Gabsi, and Michel Lecrivain, "Investigation of a New Topology of Hybrid-Excited Flux-Switching Machine with Static Global Winding: Experiments and Modeling," IEEE Transactions On Industry Applications, Vol. 52, No. 2, March/April, 2016.
[33]. Faisal Khan, Erwan Sulaiman & Md Zarafi Ahmad, "Review of Switched Flux Wound-Field Machines Technology," IETE Technical Review, pp. 2016

BIOGRAPHY

Arvind Kumar received B.Tech. degree from S.R.M.S. CET, Bareilly affiliated to UPTU, Lucknow, U.P. and M.Tech. degree from GBPUA&T, Pantnagar. Currently, he is pursuing Ph.D. in the department of Electrical Engineering at GBPUA&T, Pantnagar, Uttarakhand.

Ajay Srivastava received B.E. degree from Madan Mohan Malviya Engineering College (MMMEC) Gorakhpur and M.Tech. from GBPUA&T, Pantnagar and Ph.D. from GBPUA&T, Pantnagar. Currently, he is working as Professor in the Department of Electrical Engineering at GBPUA&T, Pantnagar, Uttarakhand.