Double-Stator Permanent Magnet Vernier Machine: A Review

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Abstract— **This paper reviews the current state of the double-stator permanent magnet vernier (DS-PMV) machine technology. At first, the recent advances in PMV machines are presented. In the following, the classification of various PMV machines' configuration is elucidated. In general, this review covers the principle of better understanding of the novel PMV machines' topologies using different windings configurations, flux modulation poles and stator/rotor structures.**

Index Terms— Double-stator, Permanent magnet, Vernier machine.

I. INTRODUCTION

The initial concept of a permanent magnet vernier (PMV) machine was reported in 1957. With the development of PMs, research on PMV machines became more serious than 30 years ago [1]**.** The PMV machines can reach high output torque densities at a slower speed arising from their specific operating law known as "flux modulation" or "magnetic gearing effect" [2]. The magnetic gear effect used in the PMV machine conspicuously causes the production of an improved torque compared with the other types of synchronous machines[3].

This machine is specially used in direct drive (DD) mode with high torque performance at low speed. The PMV machine is derived from the Vernier concept that directly changes the high speed rotational field to a less rotational speed. The high speed rotational field of the armature winding is altered to less rotational speed by flux modulation poles (FMPs) in the air gap (AG). The AG's lower rotational speed created high torque based on the spin interaction with the PM poles of the rotor. Actually, such a PMV machine can be considered an ordinary multi-phase synchronous machine that operates on the vernier scale law simultaneously, according to the reality that the number of stator and rotor pole-pairs is different [4]. Fig. 1 illustrates the PMV machine with FMPs.

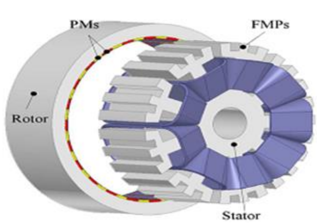

Fig.1. The graphical representation of a PMV machine with FMPs [6]

With this unrivaled feature, the PMV machine is inherently an appropriate alternative for DD usage. The DD system has been extensively utilized in electric vehicles (EVs), aircraft, electric ship propulsion, wind power, and so on [5].

The PMV machine is a promising topology extensively employed for its superior torque density at low speed leading to the broad design of such machines in recent years [7]. Some research works have investigated the torque performance and also improving the power factor (PF) of the PMV machines [8]-[10] with different stator and rotor topologies. Also, several attempts were made for Spoke-type magnet [11]-[14] and high-temperature superconductor (HTS) [15] in the PMV machines. Additionally, other researches have proposed numerous topology for PMV machine such as V-shaped PM [16], [17], U-shaped PM [18], Halbach-array PMs [19], and split-fractional slots [20]-[22], etc.

II .CLASSIFICATION OF PMV MACHINE

Several configurations of the PMV machines have been proposed in recent research works in the area. All those machine structures can be classified into six main categories.

Fig. 2 illustrates the classification of the PMV machine. The classification of the PMV machine is based on the rotor movement type and the position of the rotor and stator. Fig. 3(a) depicts the single excitation PMV (SE-PMV) machine. The SE-PMV machines have two types of outer-rotor and inner-rotor. The linear PMV (LPMV) machine is shown in Fig. 3(b). The linear PMV generator has two types of DD wave energy converters. The first is the Archimedes wave swing, and the second is a buoy-based wave energy generator [23]. The double stator PMV (DS-PMV) machine is demonstrated in Fig. 3(c). The following section reviews the recent advances in DS-PMV machines. Fig. 3(d) shows the double-rotor PMV (DR-PMV) machine. This machine consists of PMs located on the internal and external rotor slots. Moreover, it has double-sided stators in which windings are placed in the stator slots. The double-stator double-rotor (DS-DR) PMV machine artfully combines two machines. The DS-DR PMV machine is illustrated in Fig. 3(e). A parallel doubly stator and a cylindrical outer rotor linear PMV (DS- CORL PMV) machine is demonstrated in Fig. 3(f), incorporating an exterior rotor vernier machine and a cylindrical external rotor linear vernier machine.

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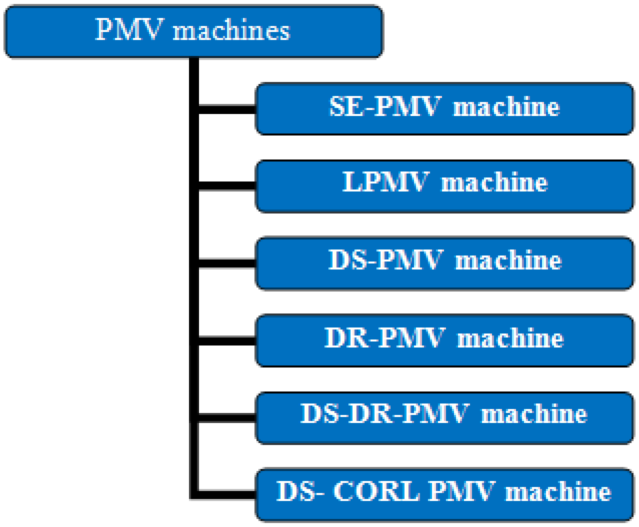

Fig.2. Classification of the PMV machines

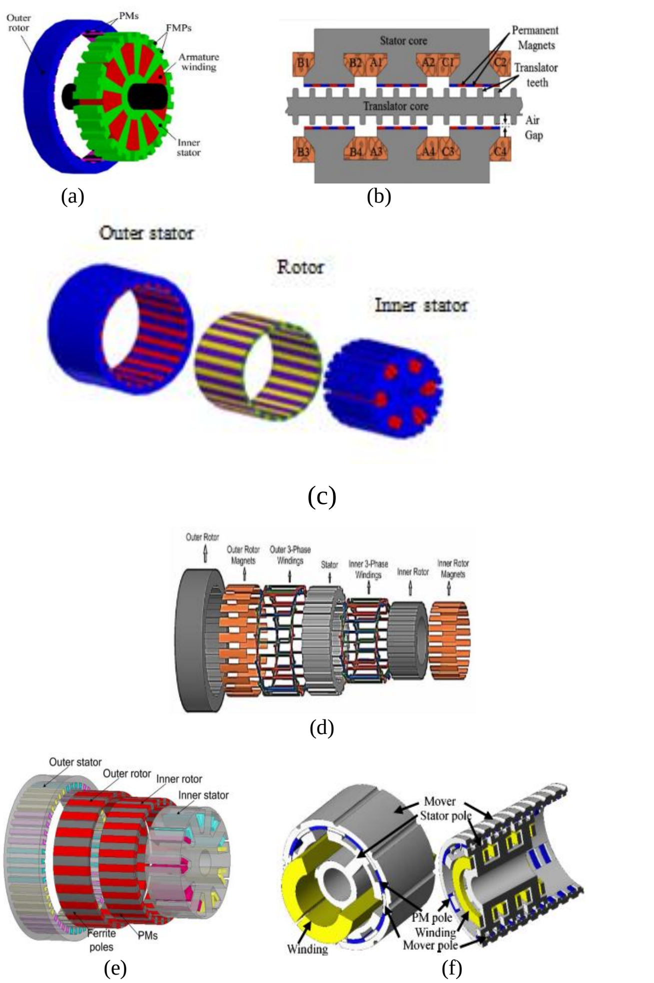

Fig.3. Structures of PMV machines a) SE-PMV machine [24] b) LPMV machine [25] c) DS-PMV machine d) DR-PMV machine [26] e) Double-Stator Double-Rotor PMV machine [27] f) DS- CORL PMV machine [28]

III .DOUBLE STATOR PMV MACHINE

The DS-PMV machine has internal and external stators and a rotor between them. The internal and external surfaces of the rotor are covered by PM and circulated by two exciting fields. The double stator topology has higher energy transfer, torque density, comparable PF, and energy conversion than a single stator PMV type [29]. For these reasons, the DS-PMV machines are the foremost choice for high-efficiency industrial usages such as wind power, robotic arms, servo motors, elevators, and electric vehicles [29], [30].

The following section examines the design features of the seven arrangements pertaining to a DS-PMV machine, i.e. 1) General design, 2) HTS bulks, 3) Stator teeth parameters, 4) Flux-reversal PM arrangement, 5) V-shaped PM arrangement; 6) Halbach-array PMs and 7) Spoke-array PMs.

A. General Design

The concept of public flux-modulated (FM) electric machines is presented in [31] where a unique theory for such types of machines is offered. It can describe the operational laws of a basic vernier machine, a FM machine, a flux-switching machine, and a double-PM-excited machine with PMs on both rotor and stator. A new double-fed DS motor is proposed based on the presented theory.

In [32], the design and multi-mode operation (MMO) of a new DS-PMV machine in collaborative generation performance of the wind turbine and photovoltaic system is suggested. One main challenge related to wind turbines is the variable speed of the wind. To solve this issue and so stabilize the output voltage under different wind speeds, the MMO is proposed better to exploit the electric energy of the hybrid wind-photovoltaic system.

In [33] and [34], two new DS-PMV machines with different design structures and operational parameters are discussed. The proposed machines are utilized for cases such as robots. Also, the machine presents a high output torque density, less power loss, and less torque pulsation. Table I shows the operational comparison of DS-PMV machines introduced in [33] and another one presented in [34].

TABLE I
Comparison of the Performances of a DS-PMV Machine [33] and Another DS-PMV Machine [34]

Item	DS-PMV Machine[33]	DS-PMV Machine [34]
Power efficiency (%)	0.57	0.86
Output power (W)	223	905
Electrical loss (W)	193	152
Torque ripple (%)	3.67	3.5
Torque (N.m)	12.12	43.2

Line-start PMV (LS-PMV) machine increases the self-starting capacity of the PMV machine and improves the output torque density of line-start PM machine. To decrease the extra size, a DS line-start PMV (DSLS-PMV) synchronous machine configuration can achieve the exact aim of the SS capacity. The squirrel cage asynchronous machine (SCAM) is put in the rotor's internal side, and the SCAM's stator is located as the internal stator to form the structure of the DSLS-PMV machine. The operation of the machine in both starting and stable-state conditions can be completely separated such that the machine operates as a typical surface PMV machine in a stable state [35]. The graphical configuration of a DSLS-PMV machine is demonstrated in Fig.5.

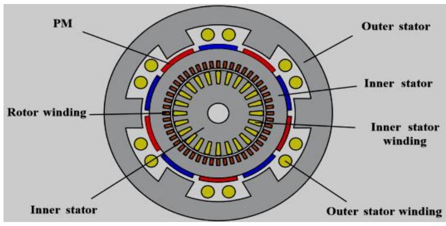

Fig.5. Structure of DSLSPMV machine [35]

Investigation of eddy current losses in the DS-PMV machine has been accomplished in [36]. This way, the multi-pole DS-PMV machine has been proposed for nether-speed DD usage. A study of eddy current losses is performed in both PMs. Moreover, the split-fractional condensed winding is considered to decrease the split number and stator yoke altitude results in space shrinking and enhancing the output torque in the outer stator. In the internal stator, a PMV topology is utilized to decrease the winding spaces and develop the split size to incorporate additional conductors leading to the utilization of the full internal stator area.

In [37], the PMV machine with a double salient pole (DSP) design has been studied in terms of the AG magnetic field (MF). By investigating the effects of the DSP topology on the operating MF, the consequent-pole PMV machine and surface-mounted PMV machine with 12 slots and 10 poles stator windings have been proposed. It was shown that the AG permeance harmonics generated by the rotor split have no effect on the magnetic field owing to the speed of the rotor. Therefore, the stator can be designed on the situation without the split on the rotor. Also, the rotor can be designed similarly.

In the design of the machine introduced in [38], a combination of two DS-PMV machines has been considered. The design difference between the two DS-PMV machines is in the pole pairs of the rotor, external stator, and internal stator. The machine structure has high torque due to its specific operating conditions and lower cost due to the resulting pole configuration and low magnet volume.

In [39], the DS-PMV machine is declared to be an efficient structure to enhance the PF with attention to a turn number allocation of internal and external stator windings. If the inductance of the internal and external stator windings are close to each other or equal, the machine can produce the maximum PF; otherwise, the PF will reach the maximum with the unequal turn number assignment. In addition, allocating a turn number can maximize the machine PF and meet the torque requirement. The performance of the DS-PMV machine with different pole-slit structures has been compared in [40]. The comparative conclusions proposed are as follows: 1) rotating orientation of the operating harmonics of the stator and rotor should be opposing, 2) optimum configuration 24/44, 3) the slot-tooth configuration for the internal stator is not useful to higher torque and structures without joining the extra teeth aiming to attain less harmonic amplitude for back EMF, 4) greater-rate average output torque density, 5) less torque pulsation.

B. HTS bulks

In [41], three types of DS-FMPMV machines, vernier machines with high-temperature-superconductor (HTS) bulks, and magnetic-geared machines are quantitatively compared. The HTS bulks are based on the yttrium barium copper oxide (YBCO) material, which can attain the critical current density up to 104 A/cm^2 in a temperature of 77 K. Compared to the overall performance of the machines, the vernier machine with HTS bulks has the best performance and all the machines have fewer loss.

C. Stator teeth parameters

The research work of [42] aims to explain the effect of the internal stator teeth on the parameters of the DS single winding machine with coils on the external stator and DS doubly winding with the further coils on the internal stator machines. The analytical results demonstrate that the main reason for variation of the electromagnetic torque is a change in the sizes of the internal stator teeth. It is noted that that an additional coil applied to the internal stator has increased the electromagnetic torque by as much as 45%. It has also been proven that the position of the internal stator teeth associated with the external stator can be used to adjust the torque.

D. Flux-reversal PM arrangement

In [43], a new hybrid DS-PMV with flux-reversal (FR-DS) PMV machine is proposed in which the PM arrangement is flux-reversal, so the machine has the specific feature of great torque cost with less torque pulsation and less cogging torque. The FR-DS PMV machine has two types of reverse magnets that are mounted on the teeth of external and internal stators, resulting in increased magnetic fields in indoor and outdoor AGs. From a practical viewpoint, this machine's use in large telescopes has been suggested.

E. V-shaped and H-shaped PM arrangements

The comparative study of three DS interior PMV machines, containing the spoke-array, V-shaped, and H-shaped rotor PM arrangement is presented in [44]. DS collaboration methods are generally more utilized in machine design due to better efficiency. The various parts of the DS-PMV machine experience the practical tests are shown in Fig.6. Comparing these structures proves that the H-shape structure has the weakest magnetic performance and highest cost. Furthermore, the spoke-array has the highest output torque, efficiency, and lowest cost.

F. Halbach-array PMs

Halbach-array corresponds to the placement of PMs in the rotor (Fig. 7(a)), which is capable of providing a good flux adjustment and a high power factor. In [45], a novel DS-PMV machine, structurally demonstrated in Fig. 7(b), is proposed in which the rotor has a consequent-pole structure with Halbach-array PMs. The proposed DS-PMV machine has 1.4% larger efficiency, 16% higher torque, and lower pulsating torque compared to a conventional PMV machine. Furthermore, a novel DS hybrid excited PMV machine with Halbach-array PMs (DS-HPMV) machine has been proposed in [46]. The offered DS-HPMV machine with Halbach–PM has a smaller torque ripple and larger torque density. The DC excitation of the field coil causes good flux regulation capability. Thus, the DS-HPMV machine has a high PF.

Fig.6.Various parts of DS-PMV machine [44]

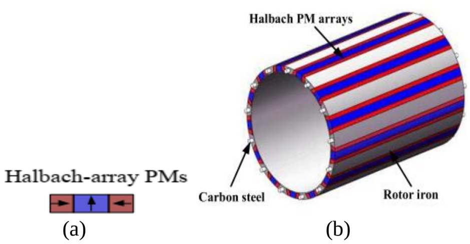

Fig.7. (a) Halbach-array PMs [46] (b) Configuration of the rotor [45]

G. Spoke-array PMs

Four models of DS spoke-type PMV (DSS-PMV) machines were studied in [47] to specify an appropriate prototype for EV systems. The 12 slots and 20 poles with divided winding were considered for appropriate gearless connection, because it offers utmost output torque, less torque ripple, great efficiency, best flux-weakening capacity, and prominent PF.

A single-winding DS spoke-array PMV machine has been taken into account in [48] which has no thermic substance in the internal stator coils. It is shown that the output torque density of the studied machine is bigger than 65kNm/m^3 and its PF in initial design is 0.78 with current density lower than 3A/mm^2. In this case, the torque per PM mass is approximately 120 Nm/kg.

A DS axial-flux spoke-type PMV (DSAFS-PMV) machine encompassing all the advantages of the axial field and the DSS PMV machine is presented in [49]. The DSAFS-PMV machine incorporates the stator's open slot (OS) and the drum winding (DW) with the conductors wrapped around the stator yoke. Although it has a tool the same as ordinary coils due to end of the coil, this type of DW dissolves the difficulty of consolidating the coil in the OS. In this circumstance, the torque pulsations and cogging torque are reduced to a significant level without decreasing the torque of the machine and back EMF. Moreover, the torque ripples are reduced to 4.22% by the presented magnet shape compared with the corresponding value of 8.82% in the basic model. The mentioned value can be further decreased to 3.93% with an optimization process and also 8.53% more reduction in cogging torque [50].

A high PF and high-torque density vernier topology DSS-PMV machine have been proposed in [51]. Hefty magnet flux leakage and low magnet usage have resulted in a low PF up to 50%. The DSS-PMV structure can significantly reduce the leakage flux and all magnets simultaneously contribute to the AG flux density. The internal stator teeth have a half-shift of the teeth relative to the external stator teeth. Therefore, both internal and external teeth compensate for each other effect.

Furthermore, they can create great permeance and leakage flux to help the useful flux from one section to the other section. In addition, the shape of the rotor creates a reluctance torque that can produce great torque density and high PF. In [52], the DSS-PMV machines are detail studied in terms of original design instructions, analytical sizing formula, key geometrical relationship equations, and several fundamental factors such as the stator/rotor pole ratio, slit opening, magnet size, etc.

Additionally, the design procedure of DSS-PMV machines, containing the primary setting of the design parameters, fundamental geometrical relationship rule, analytical sizing equation, stator/rotor pole numbers, different fundamental parameters including pole arc, OS ratio, electric and design parameter optimization is presented in [53]. However, another approach presents a low-speed DSS-PMV motor using ferrite PM [54]. The suggested design of [54] is compared against an industrial inner PM (IIPM) machine utilizing rare-earth magnets and a single AG spoke-array PMV machine. Therefore, the proposed structure of [54] has revealed better output torque, less output torque pulsation, and better efficiency than those of the IIPM machine and the single AG spoke-array PMV machine. A drum rotor (DR) scheme for the DSS-PMV machine is introduced in [55]. The DR is located on both flanks of the machine, stabilizes and strengthens the rotor, and significantly improves the rotor alignment. In [56], an improved DS-PMV (IPMV) machine is presented using ferrite PM matter to properly change an IIPM machine with rare-earth PM industrial usage at a less speed. Fig. 8 (a) shows the conventional DSS-PMV machine with overlapped windings. The IPMV machine design eliminates the internal stator windings, as demonstrated in Fig. 8 (b). Moreover, the cup-rotor (CP) should be connected to the output. Fig. 8(c) depicts the conventional DSS-PMV machine with CP. The DR holds the vacant core of the internal stators, as demonstrated in Fig. 8 (d).

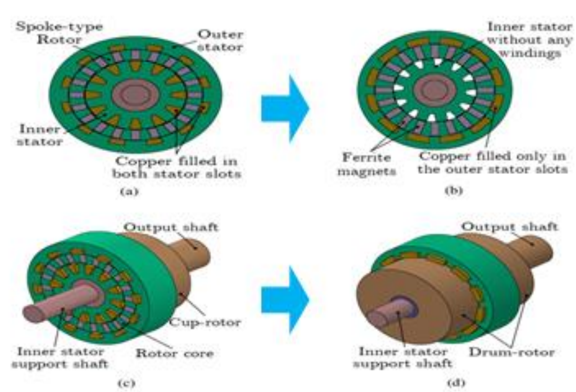

Fig.8. a) Conventional DSS-PMV machine b) Improved DS-PMV (IPMV) machine c) Conventional DSS-PMV machine with CP d) IPMV machine with DR [56].

The study results show that the corrected scheme utilizing ferrite PMs has great torque density, very small torque ripple, reduced cost, and performance than those presented in the IIPM machine with rare-earth magnets.

IV. Conclusion

Two different features specify general PMV machine to other typical machines. One is to offer high torque capability at low speed. The other is that the torque per current is distinctly large. These two characteristics are suitable for a DD. This issue reflects the growing understanding and interest for various types of PMV machines in recent years. PMV machines have different classifications, and a review of the current state of the double-stator PMV machine has been presented in this paper. Double-Stator topology is adopted for large electromagnetic torque capability, high efficiency, fault-tolerant ability, and great flexibility. This topology of vernier machines with different structures has been by researchers in the last decade. Among the various structures for DS-PMV machines, the spoke-array has a better performance than the others, which is modified to eliminate the winding in the internal stator. The future of the DSS-PMV machine is promising and still requires more investigation.

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