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Review of Variable-flux Permanent Magnet Machines

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Abstract – Variable-flux permanent-magnet machines (VFPM) are of great interest and many different machine topologies have been documented. This paper categorizes VFPM machine topologies with regard to the method of flux variation and further, in the case of hybrid excited machines with field coils, with regard to the location of the excitation sources. The different VFPM machines are reviewed and compared in terms of their torque density, complexity and their ability to vary the flux.

Keywords: Electric machines, Hybrid-excitation, PM machines, Review, Variable-flux

1. Introduction

Variable-flux permanent-magnet (VFPM) machines are those which include some means of adjusting the level of permanent magnet flux and are of interest today as they allow flexibility in terms of optimizing efficiency across a machine operation cycle. Many examples of VFPM machines have been studied and documented including hybrid-excited machines with field coils[1]-[34], machines with mechanical adjustment [34]-[43], or those that involve other means of varying the flux [44]-[50]. This paper reviews documented VFPM machines and categorizes them as described above and as further shown in Fig. 1. The following sections look at each category in turn. Throughout the review it has been attempted to quantify, where possible, the torque density of the machines and their ability to enhance and weaken the permanent magnet flux from the literature. This has been tabulated along with a judgment, in the case of machines with field coils, as to whether the path of the field coil flux poses an inherent risk of demagnetization.

2. Hybrid-excited Machines with Field Coil Excitation

Hybrid-excited permanent-magnet machines with wound field coils are one primary category of VFPM machines. They have been studied extensively particularly in terms of their potential to extend the flux-weakening range of permanent magnet machines and to improve efficiency. As shown in Fig. 1, hybrid-excited machines have been further grouped based on the location of the excitation sources and the configuration of the permanent-magnet and field-coil flux paths.

2.1 Series flux path hybrid-excited machines

Although parallel flux path machines are more common as they minimize the risk of permanently demagnetizing the permanent-magnets, some series flux path hybrid-excited machines have been investigated. These have the following general attributes:

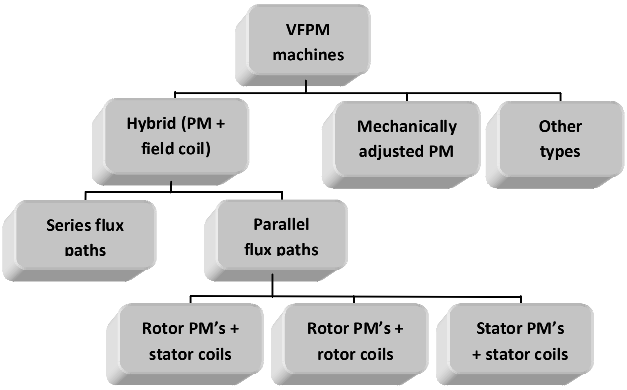

Fig. 1. Categorization of VFPM machines

- Generally have risk of magnet demagnetization
- Generally simple structure
- Good flux regulation capability, both weakening and boosting
- Generally hybridization has little effect on torque density

The doubly excited synchronous machine (DESM) [2] and one type of doubly salient permanent magnet (DSPM) machine [3]-[4], Fig. 2(a)-(b) are series flux path hybrid-excited. Another machine that can be classified as a series or parallel flux path hybrid-excited machine is based on a hybrid stepper motor [5]-[6] and is shown in Fig. 2(c). This does not have the same potential for demagnetization because the DC coil flux passes through the magnets only in the direction of the magnet flux. The DESM machine has both excitation sources in the rotor with permanent-magnets fixed to the end of rotor teeth that are wound with DC field-

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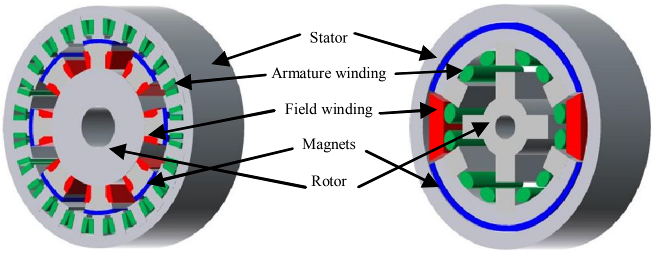
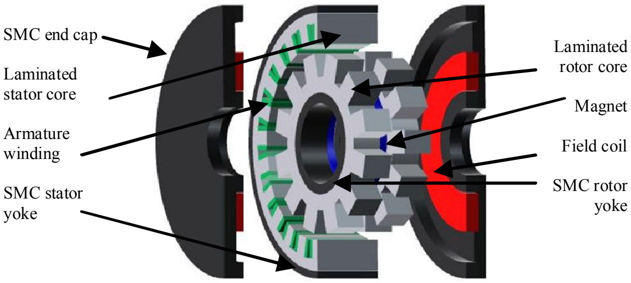
coils, whereas the DSPM machine has both sources in the stator, avoiding the need for slip rings. The DSPM topology has a large area for the permanent–magnets and utilizes flux-focusing, allowing the use of cheaper grades of magnet such as ferrite. Both these machines show reasonable flux boosting and weakening capabilities, but do have the potential for permanent demagnetization of the magnets as the weakening flux of the DC coils passes through them. The hybrid stepper machine utilizes a soft magnetic composite (SMC) to provide the flux path for the field coil, through the end-caps and stator and rotor yoke. The permanent magnet is toroidal in shape, axially magnetized and sandwiched between the two rotor sections. In [5] this topology was presented, having good weakening capability but no strengthening capability, however in [6] an improved design provides both boosting and weakening.



(a) DESM (b) DSPM



(c) Hybrid stepper

Fig. 2. DESM, DSPM and hybrid stepper series flux path hybrid-excited machines

Table 1. Series hybrid machine comparison

	Torque density	Flux weakening	Flux boosting	Demag?
DSPM	1.326Nm/kg	≈50%	≈25%	✓
DESM	?	≈55%	≈45%	✓
Hybrid Stepper	1.2Nm/kg (0 field current) 4.9Nm/kg (+ve field current)	≈100%	≈98%	×

2.2. Parallel flux path hybrid-excited machines

Parallel path hybrid-excited machines can be further grouped in terms of their configuration as shown in Fig. 1. These categories will be looked at in turn starting with those machines which have magnets in or on the rotor and coils housed in the stator.

Rotor permanent-magnets and stator field-coils

The majority of hybrid-excited permanent magnet machines are found in this category [7]-[21]. They include permanent-magnets on the rotor, but the field coils are contained within the stator thereby ensuring that slip rings and brushes are not required. General characteristics of this type of hybrid are:

- Complicated structure to analyze and manufacture
- No inherent risk of demagnetization
- Potentially good torque density
- Reasonable/good flux boosting and weakening

The CPPM machine utilizes a short, large diameter solenoidal field coil sandwiched in the stator back iron. Both axial [7]-[8] and radial [9]-[10] (Fig. 3) flux designs have been investigated. The rotor has alternating permanent-magnets and consequent iron poles and the stator is split into two sections, with the field-coil sandwiched between the two. A reasonably wide range of control is possible, but the machines are relatively complicated to manufacture. Increasing the ratio of magnet to consequent pole can increase the torque density of CPPM machines [11], but this comes at the cost of significantly reducing the regulation capability.

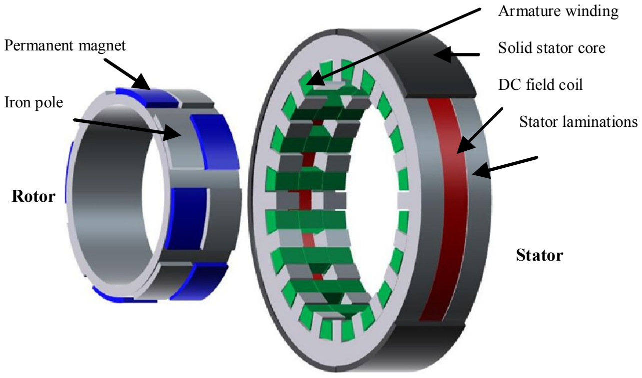


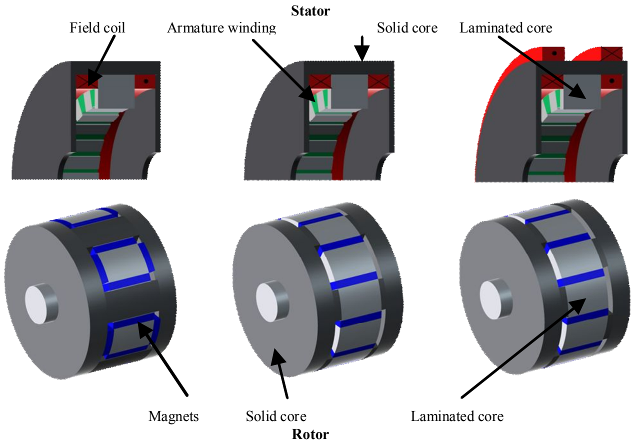
Fig. 3. Radial flux CPPM machine

Much research in France has been undertaken on the topologies shown in Fig. 4. Topology (a) is introduced in [12], whilst (b) and (c) are introduced and compared with (a) in [13]-[14]. They contain circumferentially magnetized ferrite magnets embedded in the rotor. These machines are also relatively complicated to manufacture, however a good range of flux control can be achieved by the DC field-coil and in [15] it is shown that good torque output is achieved in comparison with a SPM machine with NdFeB magnets.

The imbricated hybrid-excited machine was also developed in France [16]. The rotor has two magnetically isolated parts: an outer cylinder, and an inner core which includes the permanent magnets and has teeth which extend to the rotor surface through holes in the cylinder. The stator also has two parts joined by a yoke. The field-coil is once again solenoidal and is located adjacent to the stator yoke.

Claw-pole rotor machines [17]-[19] also utilize solenoidal windings, which are stationary, but located inside the rotor structure. The rotor is a claw-pole type with PM's either on or on and between the claw poles and the structure is as shown in Fig. 5.

The HSUB machine, introduced in [20]-[21] is a form of IPM machine with a solenoidal field coil included in the stator. Axial and radial HSUB machines have been investigated based on the principle that well positioned permanent magnets can prevent leakage from the DC field flux. In general, the HSUB machine is capable of very good boosting performance (100% or more), with slightly poorer weakening performance. Without flux strengthening from the field coil the torque density is not very high, however in general cheaper injected permanent magnet materials rather than rare earth PM's have been used.



(a)Homopolar (with axial PM's) (b)Homopolar (c)Bipolar

Fig. 4. Homopolar and bipolar embedded PM hybrid-excited topologies

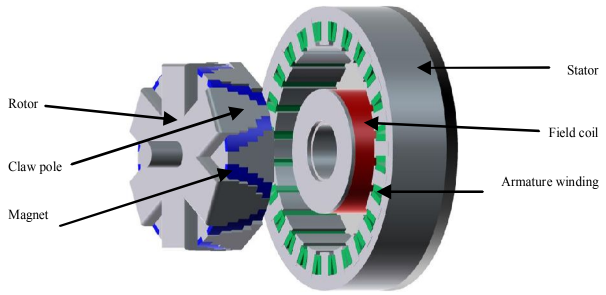


Fig. 5. Claw-pole machine

Table 2. Rotor Magnets/Stator Coils Parallel Hybrid Machine Comparison

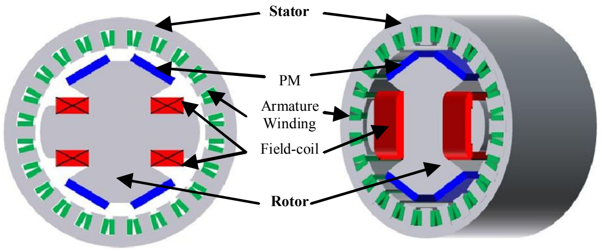
	Torque density	Flux weakening	Flux boosting	Demag?
CPPM axial	?	✓	✓	×
		87% combined range		
CPPM radial	?	≈40%	≈40%	×
Homopolar	?	≈70%	≈35%	×
Bipolar	?	≈70%	≈90%	×
	Similar to SPM [HLI 08]	Less than above	Less than above	
Imbricated	?	≈50%	≈120%	×
Clawpole	?	≈25%	≈25%	×
HSUB	Poor without field strengthening	OK	>100%	×

Rotor permanent-magnets and rotor field-coils

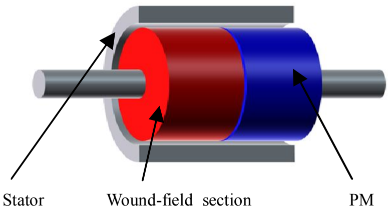
Hybrid-excited machines with field-coils on the rotor are less common as they require slip rings and brushes in order to excite the field-coils. However, there are examples of this type of hybrid-excited machine the SynPM [22]-[23] machine and the dual-rotor machine [25]. These machines have the following characteristics:

- Slip rings required
- Relatively simple topology
- Low torque density as PM volume is sacrificed for the field coil

The SynPM machine is shown in Fig. 6(a). The rotor has both wound DC field-coils and PM poles. A variant on the SynPM machine which includes interior permanent magnets has been shown in [24]. The dual rotor machine (Fig. 6(b)) also includes both field-coils and permanent magnets on the rotor, however in this case the two excitation types are on axially separated sections of the rotor within a common stator. In [25] a machine of this type is presented with a 2-pole rotor. Results show a wide range of control is possible with a small amount of DC current.



(a)SynPM machine



(b)Dual rotor machine

Fig. 6. Hybrid- excited machines with rotor permanent-magnets and rotor field coils

Table 3. Rotor Magnets/Rotor Coils Parallel Hybrid Machine Comparison

	Torque density	Flux weakening	Flux boosting	Demag?
SynPM	?	✓ 87% combined range	✓	×
Dual-rotor	POOR	≈100%	≈400%	×

Stator permanent-magnets and stator field-coils

This type of hybrid excited permanent magnet machine is limited to three machine types; the doubly salient permanent magnet (DSPM) machine[26]-[30], the switched-flux permanent magnet (SFPM) machine[31]-[33] and the doubly-excited, dual-stator permanent-magnet (DEDSPM) machine [34]. They share these characteristics:

- All excitation sources in the stator
- Simple, robust rotor
- Generally good flux regulation comes at the cost of torque density

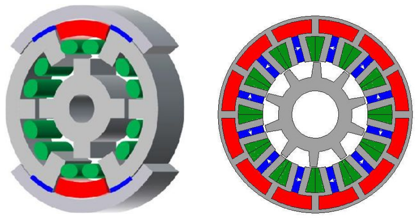
Several hybrid DSPM machines have been investigated, incorporating distributed [26]-[29](e.g. Fig. 7(a)) or solenoidal [30] field coils and utilizing a relatively small amount of magnet material. Hybrid SFPM machines have been shown in [31]-[32]. Field coils have been incorporated as a direct replacement for some of the magnet material [32] or by increasing the machine volume [31], therefore field regulation very clearly comes at the expense of torque density, as the field coils cannot compete with the PM's in terms of torque density. This is further shown in [33] where the magnets have entirely been replace with field coils. The DEDSPM machine [34] is configured as an external rotor machine. The stator is in two parts, with the excitation sources on the inner part and the armature winding on the outer. A wide range of control is shown, with peak airgap flux density ranging from 0.1T-0.9T.

3. VFPM Machines with Mechanical Adjustment

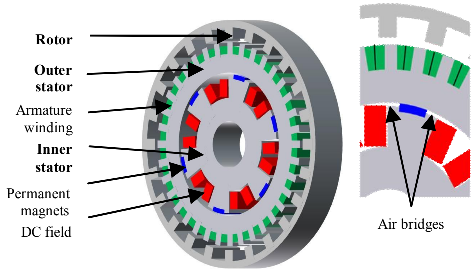
The machines in this section are PM machines which have mechanical flux regulation, i.e. the mechanical structure of the machine is altered to regulate the flux. Machines can be altered by:

- Rotating rotor sections [35],[37]-[40]
- Rotating stator sections [36]
- Axially adjusting the airgap [41]
- Adding leakage paths [42]-[43]
- Adjusting flux barriers (IPM machines) [44]-[45]

In the majority of these methods only flux weakening is possible as the original PM excitation is weakened by providing a leakage path or misaligning the flux path.



(a) DSPM machine [26] (b) SFPM machine [31]



(c)DEDSPM [33]

Fig. 7. Example of DSPM and SFPM hybrid excited machines

Table 4. Stator Magnets/Stator Coils Parallel Hybrid Machine Comparison

	Torque density	Flux weakening	Flux boosting	Demag?
DSPM	?	≈50%	≈100%	×
SFPM	OK - 60% of conventional SFPM	≈20%	≈20%	×
	OK - ≈1.27Nm/kg *2.2Nm/kg* *(with DC current)*	≈35%	≈90%	
DEDSPM	Potentially GOOD as all the additional parts are contained within the original machine dimensions	Wide range of airgap flux density– 0.1T to 0.9T		×

3.1. Machines with adjustment of rotor or stator sections

Axial machine with weakening caused by rotating rotor or stator sections

A mechanical hybrid topology based on an axial flux surface mounted permanent magnet machine which consists of a slotless stator containing the armature winding, sandwiched between two rotor disks [35] is shown in Fig. 8(a). The two rotor sections can be misaligned by displacing them in opposite directions so that less flux links the stator coils. A similar machine where multiple stator sections are displaced is introduced in [36] as shown in Fig. 8(b). In the case of the rotor displacement, it is shown in [37] that this could be achieved with very little extra weight by using simple speed or torque dependant mechanical devices. Using this type of device therefore ensures a very similar torque density to a standard axial flux PM machine. In the stator case an additional linear actuator is required which will impact on overall torque density, complexity, weight and cost.

Other machines with rotor displacement

Other methods of flux weakening by displacing rotor sections are shown in Fig. 9. In [38] (Fig. 9(a)), a machine type is introduced based on a standard surface mounted PM machine but with the rotor split axially and mounted on a screw thread shaft. This allows one of the rotor sections to be rotated away from the other by a servo actuator, misaligning it to reduce the flux that links the armature coils. In Fig. 9(b) another machine [39] that involves rotor displacement of an SPM machine is shown. In this case the rotor has two magnet sections separated by an SR type section. This middle section can be rotated so that the teeth form a leakage path between north and south pole magnets. Both machines could provide good torque density and flux weakening performance, however the added weight, power demand and complexity caused by the additional servo actuator must be considered. Fig. 9(c) shows a machine [40] that has two radial layers of rotor magnets which can be displaced similarly to cause field weakening. When the magnets are misaligned they partially cancel out flux causing the flux linking the coils to drop.

3.2. Airgap adjustment

Adjustment of the airgap length to provide field strengthening and weakening is introduced in [41] (Fig. 10), with an axial flux PM machine which uses the current in the stator armature coils and the spring and hinge set up shown to control the machine air gap. Results show good performance in terms of flux adjustment, however the complex mechanism will affect torque density and manufacturability. Several patents have also been filed highlighting other potential methods of airgap adjustment.

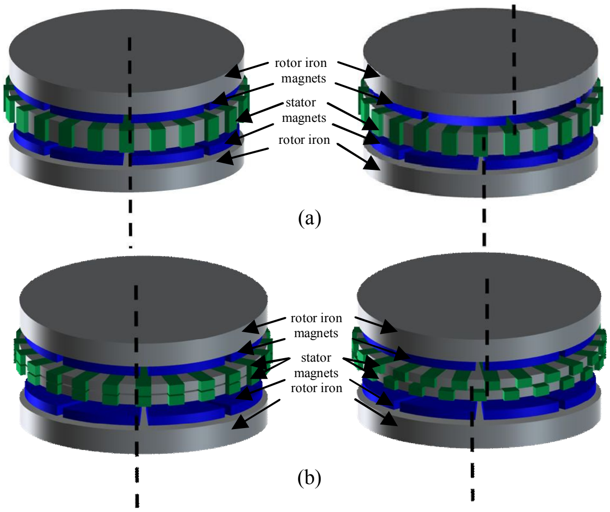
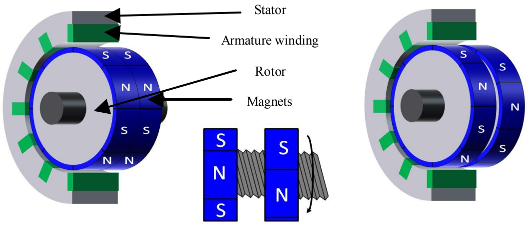
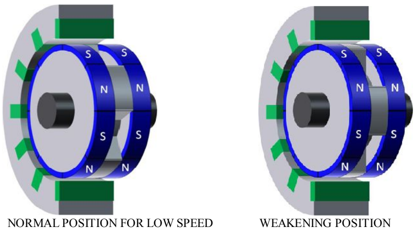


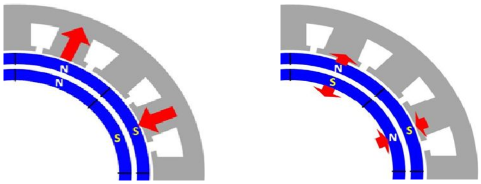
Fig. 8. Axial Machine with weakening caused by rotating rotor or stator sections: (a) rotor displacement, (b) stator displacement



(a) 2-piece rotor on a screw thread shaft



(b) PM machine with rotating SR type rotor segment



(c) Radially divided rotor sections

Fig. 9. Other examples of rotor adjustment

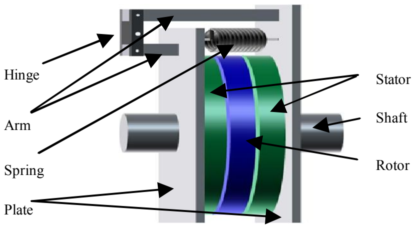


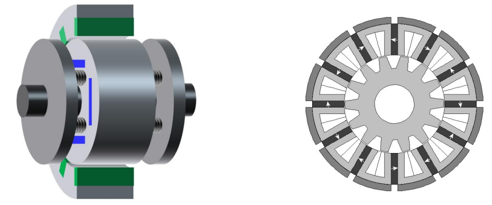
Fig. 10. Machines with axial airgap adjustment [40]

3.3. Endplate adjustment and other leakage paths

An IPM machine is introduced in [42] and shown in Fig. 11, which involves endplates that cause a short circuit leakage path in the rotor. For normal operation the plates are held far from the rotor by springs to prevent leakage, but when flux weakening is required, the plates can be pushed against the rotor by actuators to provide a leakage path to reduce the PM flux. An SFPM machine with a leakage path added to the stator is introduced in [43] showing significant adjustment in the PM flux.

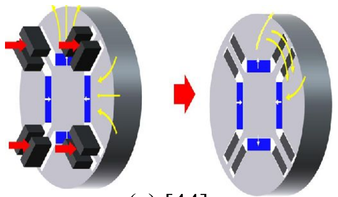
3.4. IPM flux barrier and magnet adjustment

Investigations have also been made into altering the leakage path in the flux barriers of the rotor of IPM machines. In [44] flux weakening is achieved by inserting an iron section into the flux barrier axially, whereas in [45] an iron flux leakage bridge is moved into position when centrifugal forces overcome the magnetic repulsion of two magnets. In the first case, shown in Fig. 12(a), at low speed the iron segments are located outside of the flux barriers, but as the rotor speed increases, the segments are pushed into the barriers providing a leakage path for the PM flux. In the second case (Fig. 12(b)), an iron flux bridge is controlled by two opposing magnets. As the speed increases the centrifugal forces overcome the magnetic repulsion and the bridge moves to form a short circuit path.

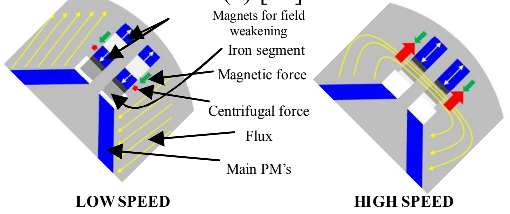


(a)Machine with moveable endplates (b) SFPM with stator leakage path

Fig. 11. Machines with additional leakage paths



(a) [44]



(b) [45]

Fig. 12. Machines with flux barrier adjustment

4. Other machines with Flux Adjustment

There are some machines which offer adjustment of flux which do not fit neatly into the above categories of hybrid-excited machines, nor are they mechanically adjusted. They provide adjustment of magnet flux but by other means rather than the use of a field coil or a specific mechanical adjustment. [46] presents a PM machine which has two sets of 3-phase armature windings. Then to control the flux either both sets of windings can be connected in series or only one set is utilized.

The memory motor, introduced in [47]-[48], uses Alnico magnets, which can be demagnetized and re-magnetized easily with a short pulse of negative d-axis current. This enables the flux to be varied very effectively. The machine has been extensively modeled [49], the effect of the shape of the Alnico magnets has been investigated [50] and a machine of this type with a combination of NdFeB and Alnico magnets has been proposed [51]. [52] proposes a machine similar to the DEDSPM machine of [34], but utilizing Alnico magnets like a memory motor, as a starter generator for HEV's.

Table 5. Mechanical hybrid machine comparison

	Torque density	Flux weakening	Flux boosting	Demag?
Axial machine with rotor displacement	GOOD – As the original axial PM m/c with minor additional mass, 2.35Nm/kg	GOOD	×	×
Axial machine with stator displacement	OK – Additional actuator required for mechanical operation	GOOD	×	×
Screw-type rotor displacement	OK - Additional machine required for mechanical operation	GOOD	×	×
Radially divided magnets	OK – Dependant on method of mechanical action	GOOD	×	×
Airgap manipulation	POOR – Large apparatus required for adjustment	OK – 15% shown	GOOD – 40% shown	×
Endplates	POOR – Endplates, springs and actuators to move them required	GOOD	×	×
Flux barrier adjustment	OK/GOOD – As IPM m/c but dependant on the adjustment mechanism	OK – 15% shown [42]	×	×

5. Conclusions

A review of VFPM machines has been presented including hybrid-excited machines with field coils, mechanical variable flux machines and machines with other means of varying the flux.

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