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Comparative review of disk type and unconventional transverse flux machines: performance analysis

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Abstract: Transverse flux machines (TFM) can be designed with high pole numbers, so they are very useful in direct-drive systems with high torque density. Although many TFM models have been proposed to date, no detailed classification and comparison has been made before. Conventional TFMs have a high power and torque density, but low power factors and high cogging torques have prevented them from being widely used. However, especially with the new disk type TFMs proposed in recent years and the methods developed, these drawbacks have been reduced. In this paper, the TFMs proposed in recent years have been classified and their performances in terms of power factor, cogging torque, torque density, and efficiency have been examined. According to the results of this review, the performances of the new generation TFMs are competitive. Especially double-sided disk type TFMs are seen as an important topology with their high magnet utilization and flexibility in design.

Key words: Transverse flux machines, disk type, power factor, cogging torque

1. Introduction

Permanent magnet (PM) machines are classified as radial, axial, or transverse flux machines (TFMs) according to the magnetic flux path. In the TFMs, the magnetic flux path is perpendicular to the direction of movement and to the current passing through the armature windings. Although the term TFM was first put forward by W. M. Morday in 1895 [1], it was first described and named by Weh towards the 90s [2]. The TFM prototype proposed by Weh for use in wind turbines is illustrated in Figure 1a. When the rotor carrying the magnets is moved; the magnet flux encircles the phase windings through the C cores. Therefore, the induced voltage is dependent on the number of C cores and the number of pole pairs. In conventional electrical machines, one phase winding is only enclosed by one pole flux. Conversely, the phase winding can be enclosed by more than one pole in TFMs. As the number of poles increases, the amount of flux surrounding the winding increases too. For example, when the number of poles is increased to 2 times, the number of cores in the stator can be increased at the same rate by reducing their size (Figures 1b and 1c). Another difference from conventional radial flux machine is that the magnets and phase windings do not share the same active surface in TFMs. Therefore, when the magnet volume increases in TFMs, the electrical loading does not decrease due to the slot contraction. In other words, when the designers increase the amount of phase winding, they do not have to reduce the volume of the magnet and thus the magnetic loading. The magnetic loading and the electric loading can be determined independently of each other. Therefore, many different TFM designs have been developed and proposed in the literature.

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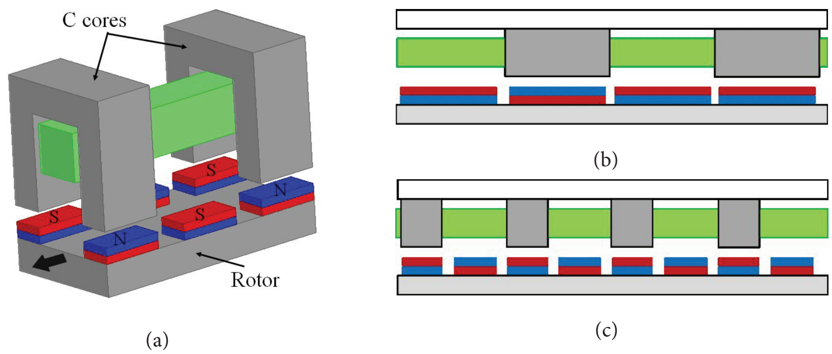


Figure 1. The conventional surface-mounted TFM: (a) 3D model, (b) 2-pole array, (c) 4-pole array.

The fact that the number of poles of TFMs can easily be increased makes them one step ahead in high torque applications. TFMs have contrasted with axial flux and radial flux PMs for different applications in the literature. Three main topologies were compared in terms of efficiency, torque density, and power factor for downhole application (1000 rpm, 105 Nm). In this application, high torque density and efficiency are desired in a small volume where the outer diameter is limited [3]. The TFM considered in the paper was single-sided and consisted of flux-concentrating poles. Consequentially, the conventional radial flux machine and the TFM offered high efficiency, while the TFM stood out for its high torque density. However, the low power factor of the TFM was considered an important drawback. Radial flux motor, axial motor with single stator-single rotor, and single-phase TFM with single-sided were compared in the low speed-high torque application (10 kW, 200 rpm) [4]. Although the torque density of the TFM was low, its efficiency could compete with other topologies. The reason why the torque density of TFM was lower in this comparison is that the optimized radial and axial flux machines were compared with primitive one-sided TFM. The radial flux machine was compared with four TFMs within different topologies by taking into account copper losses, power density, etc. in another paper [5]. It was seen that copper losses of TFMs were generally low, and also some of the TFM topologies performed better than radial flux machine in terms of power density and cost. Another comparison was made between two different TFMs and radial flux machine for the in-wheel application [6]. Although copper losses are similar to the reference radial machine, it has been concluded that "the efficiency of the TFMs due to iron losses and the power factors are low due to leakage flux". All these comparisons show that TFMs are a serious competitor to the traditional machines due to the high torque density in different applications. However, it is necessary to select the appropriate TFM topology and to optimize the power factor.

The motivation of this paper is to examine the new TFM models proposed to improve the low efficiency and power factor, and to compare their performance. This review is expected to give the novel ideas for the development of new TFM models. Therefore, in Section 2, a general classification of TFMs examined in the literature has been made. The untraditional TFMs, which have been proposed to eliminate the disadvantages of traditional TFMs in recent years, have been taken into consideration in this classification. A disadvantage of TFMs is the high cogging torque. The methods used to reduce cogging torque and the cogging torques reported in the literature has been explained in Section 3. The power factor in conventional TFMs is in the range of 0.3–0.5 [7]. Conversely, higher power factors have been reported in new TFM designs, especially disk type, presented in the literature. In Section 4, the components affecting the power factor of TFM have been explained. In addition, the performances of power factor improvement and leakage flux reduction methods have been evaluated. In Section 5, the TFMs examined within the scope of this study have been compared with axial and radial flux PM machine topologies used in similar applications in terms of efficiency and torque density. According to this, the disk type TFMs can be preferred especially for high-torque low-speed applications such as electric vehicles and wind turbines.

2. Classification of the TFMs

There is no detailed study in the literature about the general classification of TFMs. In this paper, TFMs are classified according to their structural characteristics. Besides that, linear, circular, and tubular versions of all the TFM configurations can be mentioned according to the direction of the rotor movement.

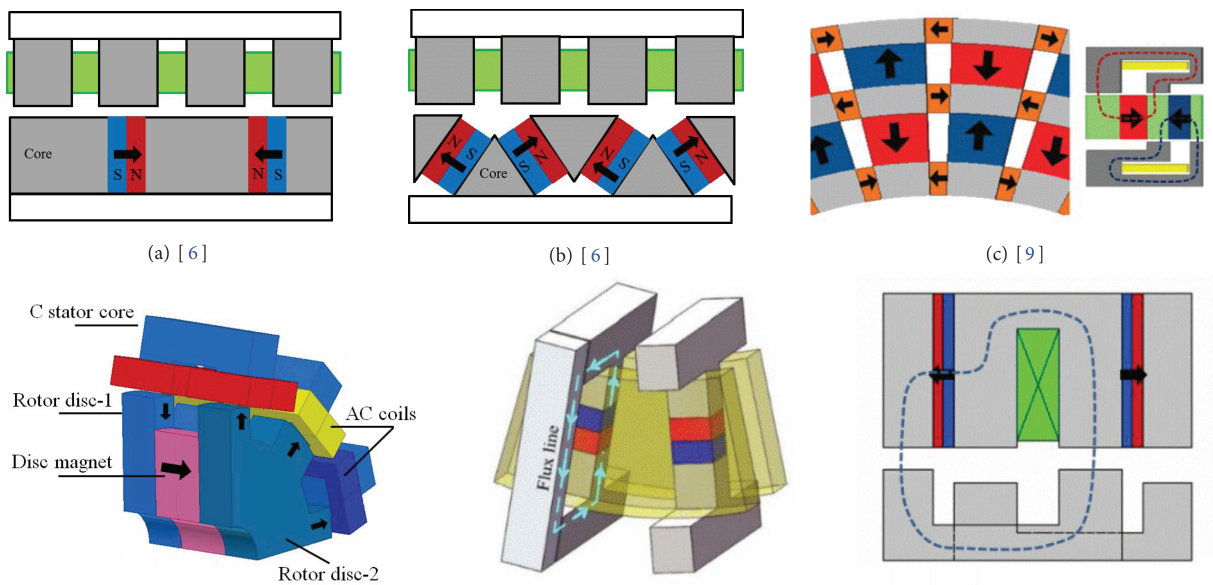
2.1. PM placement

The rotors of conventional flux-concentrating and surface-mounted TFMs are different although the stator structures are the same. The production of the surface-mounted TFMs is easy. However, the effective reluctance is greater along the flux path due to the magnet reluctance. Thus, the air-gap flux density is not high. Because the active air-gap is reduced, the amount of leakage flux is significantly reduced by a good design approach in the flux-concentrating TFM. PM is usually magnetized parallel to the air-gap in the flux-concentrating TFMs (Figure 2a). As shown in Figure 2b, the use of triangular cores is also possible [8]. Consequently, the machine weight reduces since fewer cores are used. The flux-concentrating rotor production is difficult since segmented cores are used. To facilitate production, using a toothed rotor was proposed [9]. The magnets can also be produced in the trapezoidal form, together with the appropriate core structure, to secure the magnets more firmly to the core [10].

Different embedded magnet arrays have been proposed to increase the use of PMs and reduce leakage fluxes between magnets in flux-concentrating TFMs. As shown in Figure 2c, interpolar leakage fluxes are reduced with Halbach magnets [11]. However, it is an important problem for the production that the rotor structure is multisegmented and complex. In a simpler machine structure, one toroidal PM is located between two toothed disks [12]. However, 3D flux paths are passed in the rotor disks. and so use of the SMC material is required (Figure 2d). The PMs are generally placed on the rotor in TFMs, but it is also possible to place them in the stator core for a more robust rotor structure [13–16]. The presence of PMs in the stator [13] or rotor does not affect the power factor of the surface-mounted TFM. However, in flux-concentrating TFMs where PMs are in the stator [14], the power factor is remarkable. Figures 2e and 2f show the TFM models using a robust rotor with axial air-gap [14] and radial air-gap [15, 16], respectively.

2.2. Active air-gap

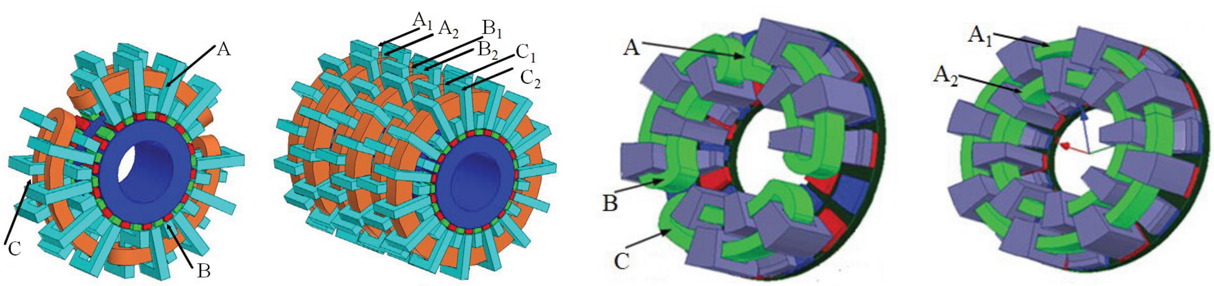
It is possible to separate the circular moving TFMs as those using axial and radial air-gaps. Radial TFM topology predominates the performance improvement research of new TFMs and new machine model propositions in recent years. The fact remains that the disk structure provides an advantage in wind turbine applications. However, as shown in Figures 3a and 3b, it is possible to develop an axial air-gap version of a TFM model with radial air-gap [17, 18]. This approach can be adapted to many new generations of the radial TFMs examined in this review.



(a) [6] (b) [6] (c) [9]

(d) [10] (e) [12] (f) [13]

Figure 2. Flux-concentrating TFMs.



(a) [15] (b) [16]

Figure 3. Radial and axial air-gap TFMs of identical structure.

2.3. Single-sided or double-sided TFMs

TFMs are classified according to whether they use single or both sides of the stator or rotor [19]. PM utilization rate is very low in traditional single-sided surface-mounted TFMs. When a pair of PMs is fully aligned with the stator core, the magnetic flux of the other PMs cannot be actively used [20]. Double-sided TFMs have been proposed for the use of all magnets [21, 22]. U and I cores are used in the stator disks placed on both sides of the coreless rotor (Figure 4a). The magnetic flux of the PM closes through the U-core of the stator on a single side of the rotor and the I-core on the other side of the rotor [21]. Thus, all magnets are actively used. In another model using two stator disks for single-phase, H-shaped cores and embedded magnets in the core are used instead of a coreless rotor [14]. Figure 4b shows the application of single-stator double-rotor disk TFM configuration [22]. The U cores, which are arranged side by side with opposite directions, are used around the toroidal phase winding in the stator. In this way, when the magnets are aligned with the stator cores, all the magnets contribute to torque generation. The long active air-gap in the magnetic flux path must be carefully designed to prevent leakage fluxes. When the U-cores in the stator of the same structure are rotated by 90° (C-core), a wide operating air-gap is not needed. In this case, the use of magnets is reduced. Because the flux of the magnets on one rotor disk completes its circuit path over the C cores, the magnets on the other rotor disk become short-circuit through the next C core's yoke [23, 24]. Figure 4c shows a 3-phase double-sided TFM using C cores [24].

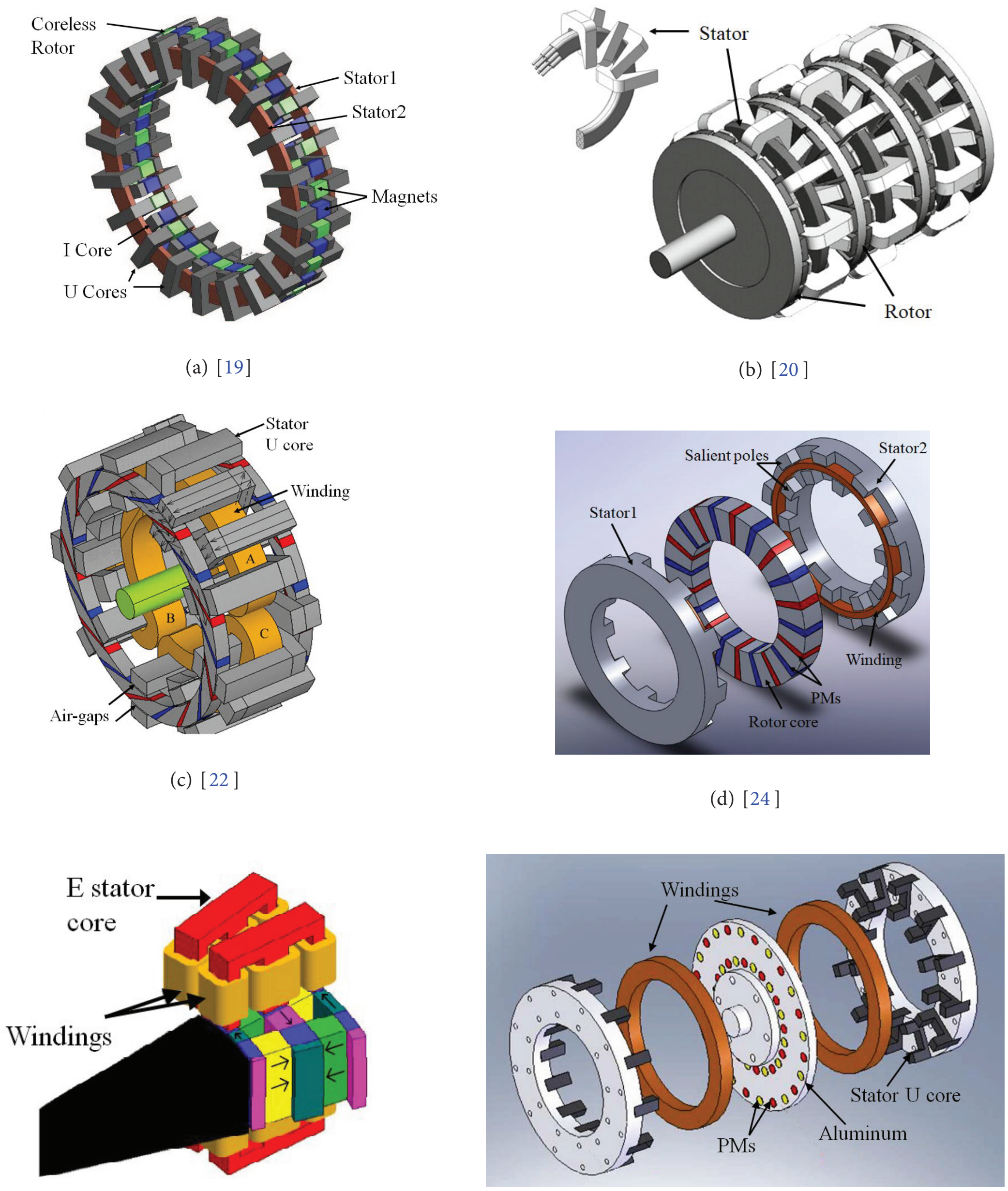
TFMs designed like NN-type axial flux PM machines use one rotor and two stators [25, 26]. There is not a common magnetic path between the two sides. In other words, the magnetic fluxes on both sides are independent of each other. Therefore, even if there is a problem with one stator disk, the TFM can continue to operate (Figures 4d and 4e). Since both stator cores use the same rotor magnets and cores, the axial length of the rotor disks are slightly greater than the configuration in Figure 4a. In the case of the NS-type double-sided TFM (Figure 4f), the magnetic path crosses two air-gaps and completes through the stator U-core on the other side of the rotor [27].

2.4. Types of the using core

Stator cores generally consist of U/C-shaped cores or claw poles in the conventional TFMs. Laminated sheet cores are commonly used in TFMs, but SMC is preferred when 3D flux path is required [10, 15, 28]. Operating at high frequencies and low iron losses are important advantages of SMC. Since the magnetic flux density and magnetic permeability of SMC materials is low, the torque density decreases in TFMs using SMC compared to the use of laminated sheets. In addition, when the cost and heating problems are taken into consideration, laminated sheet cores are preferred if possible [23].

SMC material is generally used as the stator core in the claw-pole TFM, but it is also possible to use the SMC-laminated material combination [29]. The cores with salient poles can also be used in the stator instead of the claw pole. Such machines are generally called "modulated pole machines" [30, 31]. Figure 5a shows the structure of flux-concentrating single-phase TFM using tooth stator core. If three of the structures are arranged with 120° electrical shifted on one shaft, 3-phase TFM is achieved. These three disks are magnetically independent of each other. However, a more compact 3-phase TFM has been produced with the use of a common magnetic path as in [31]. Although the active weight of this machine is higher, the torque density has been increased by the use of the common magnetic path. When the tooth cores are used on the rotor-side (Figure 5b) as with hybrid step motors, the use of only one toroidal magnet is sufficient [12, 32]. If the PMs are also taken to the stator core, there remain only salient poles on the rotor. Thus, a more robust TFM structure is obtained [16, 33, 34]. This rotor structure is especially important for high-speed operation such as 10000 rpm [33]. Figure 5c shows an outer-rotor TFM with salient poles. The inner-rotor version of the machine was examined in [16]. Figure 5d shows another single-phase TFM consisting of E-shaped cores and PMs in the stator. The rotor has salient poles and one ring in the middle of them [34]. Axial disc type versions of all the radial TFM models in Figure 5 can be developed.

The use of cores with salient poles increases the weight of the active material. At this point, TFMs with coreless rotor have been developed for minimum active material [35, 36]. The rotor can be axial [35] or radial [36]. Although the magnetic circuit structure is very similar to the conventional TFM, these machines have less leakage flux (Figure 6). The fact that only one PM is used on the magnetic path also reduces the cost. With these advantages, TFMs using coreless rotors show remarkable performance in terms of power factor and efficiency.



(a) [19]

(b) [20]

(c) [22]

(d) [24]

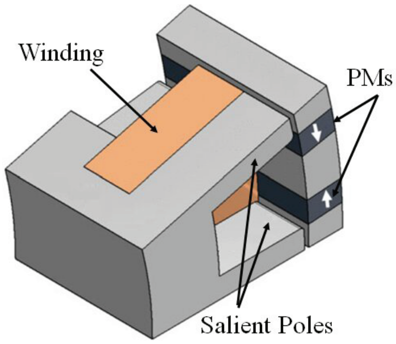
(e) [23]

(f) [25]

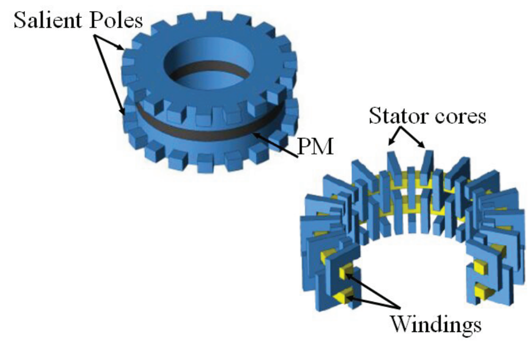
Figure 4. Disk-type double-sided TFMs.

3. The cogging torque of the TFMs

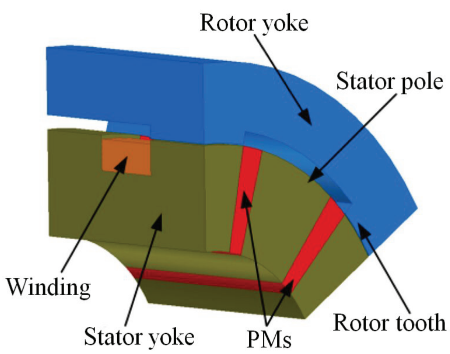
TFMs have ordinarily, high cogging torque due to the change in the air-gap reluctances encountered by PMs during machine rotation [21]. The cogging torque is intolerable in the single-phase TFMs. However, when 3-phase TFM is produced by combining three single-phase TFMs, placed on the same shaft with 120° electrical phase shift, the cogging torque is significantly reduced [13, 46]. In the TFM, not all phase windings need to be in the independent sections. Moreover, phase windings can be distributed on the one disk structure. In this case,



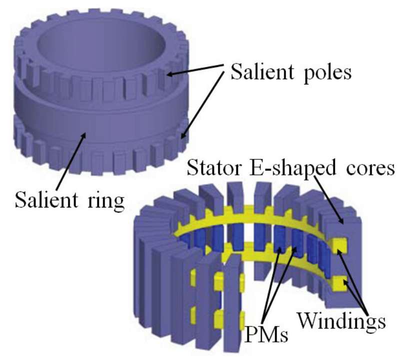
(a) [29]



(b) [30]



(c) [31]



(d) [32]

Figure 5. The use of salient pole in TFMs.

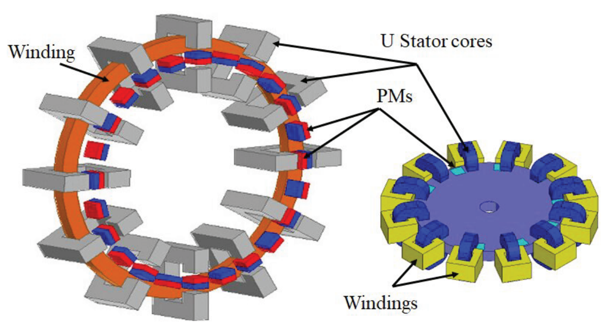


Figure 6. TFMs using a single PM in one magnetic flux path [35, 36].

TFMs with higher phase numbers can be designed. For example, in a 5-phase TFM, the cogging torque can be very low as in [47]. Apart from the methods applied in traditional machines, the topology-specific method such as using magnetic shunt can also be used in order to reduce cogging torque in TFMs. Performance comparison of the examined methods are given in Table 1.

Table 1. The performance of cogging torque reduction methods used in TFMs.

	Method	Reduction effect (%)	Cogging torque (%)	Rated torque (Nm)	Power (Watt)	Changing rated torque (%)	Air-gap (mm)
Flux-concentrating	Magnet Shape [16]	33	∼3.8	1.8	678*	negligible	0.5
	Pole width and pole skew [49]	90	2	29.27	1173	–9	1
	Using slant-pole [52]	58.44*	10.2*	62.7	3300	–21.03	1.25
	Pole shape [47]	85.3*	3*	10.38	-	6.7*	-
	Pole skew [32]	90	∼1	28.65*	1500	–3.3	-
	Pole skew [53]	88.5	-	-	-	-	-
	Un-equal pole pitch [53]	79.1	-	-	-	-	-
	Pole skew and un-equal pole pitch [53]	97.6	-	-	-	-10	-
	Un-equal pole pitch [57]	74	5.81*	7.67	-	3	0.4
Surface mounted TFM	Un-equal pole pitch [51]	91	-	-	64	-	1
	Stepping pole [51]	95.3	-	-	64	-	1
	Tooth notching [51]	negligible	-	-	64	-	1
	Magnet skew [18]	48.39*	1.57*	50.92*	2000	-	0.5
	Two-stepping magnet [54]	97	-	-	2000	–8	-
	Two-stepping pole [55]	89	0.8	-	-	–3.8	-
	Non-symmetrical two-stepping pole [55]	96	0.291	-	-	–7.7	-
	Magnetic shunt [41]	∼55	∼6	∼150	-	-	-
	Magnetic shunt [59]	75	-	-	-	-	1

*Calculated

3.1. Types of the poles and PMs

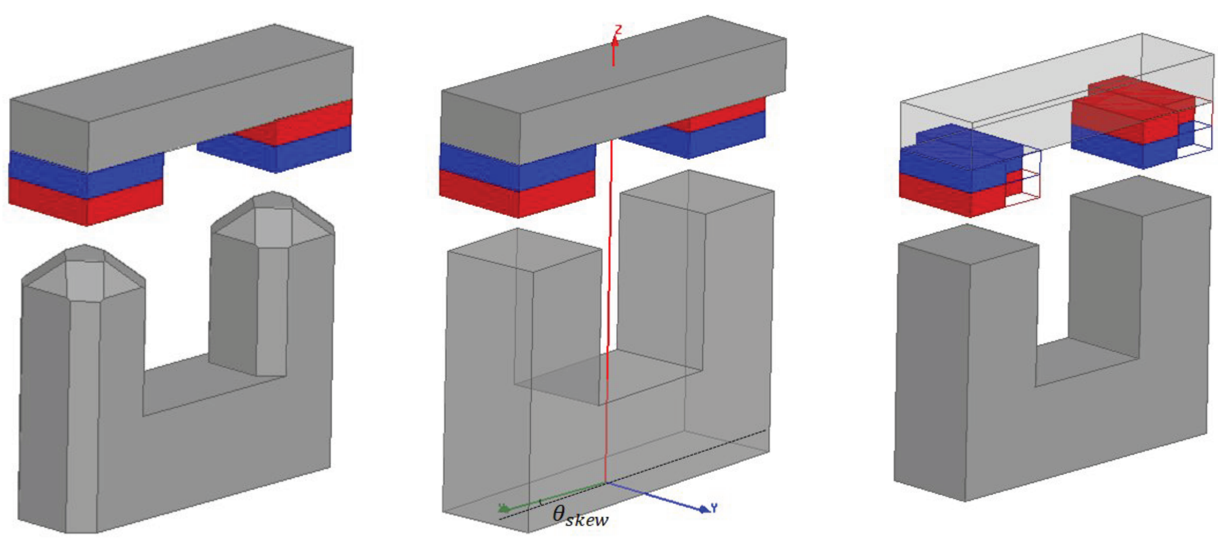
The cogging torque is caused by the interaction between poles and PMs in the stator and rotor. It is, therefore, directly influenced by the shape and size of the poles and PMs. Since the flux density is higher in the flux-concentrating TFMs, as the higher the number of poles, the greater the impacts of the cogging torque [10]. Thus, the shape, type, and dimensions of the magnet are important. For example in [16], the calculated peak value of the cogging torque was less in the ratio of 1/3 by using the rectangular magnets instead of trapezoidal. The optimization of the stator and rotor pole widths results in a relatively reduced magnitude of the cogging torque [48, 49]. This method cannot achieve the desired effect alone. In addition to the stator pole width, the pole shift method was examined and the hybrid optimization was performed in [49]. The optimization of the depth and width in the notch applications has decreased the cogging torque in the TFMs [50, 51] like in the traditional PM machines. By using the chamfered core in the stator, the cogging torque was reduced by 58.44%, while the average torque was reduced by 21.03% [52]. This reduction in the average torque is remarkable. Reducing the contact surface of the pole in the air-gap reduces cogging torque, but the average torque is also significantly reduced, as the amount of effective magnetic flux is also significantly reduced. Therefore, when looking for suitable pole shapes, the effective surface area should be considered. The effect of different rotor pole shapes on the cogging torque was investigated in [47]. Cutting the edges and corners of the pole at an angle reduces the cogging torque (Figure 7a). However, some proposed pole structures do not allow the use of laminated sheets.

3.2. Skewing of stator/rotor poles

Skewing in the stator or rotor is a relatively simple process for the conventional PM machines. However, this process is complex due to the high number of poles in TFMs [10]. For instance, the cogging torque was reduced by 48.4% with a rotor skew angle of 16° in the relatively low pole TFM [18]. Skewing the salient poles in the TFM consisting of tooth poles can be less costly and easy. The cogging torque was decreased by 90% with skewing application at the salient rotor poles [32]. Unacceptable decreases in the average torque may occur if the skew angle is too wide. For this reason, the optimum skewing angle should be determined. Although difficult to produce (Figure 7b), the effect of the θ_{skew}, skew angle applied in the TFM constituted by U stator cores was also investigated [53].

3.3. Use of pole pitch and magnet

The bulge and dent in the back-emf can be reduced by optimizing the shape of the poles in disk-type TFMs. Thus, the cogging torque is reduced [13]. Using multistep poles and magnets in the stator or rotor is one of the effective methods for reducing cogging torque in the PM machines. The cogging torque was reduced with the use of two-step magnets in [54] as shown in Figure 7c. Using segmented stator cores instead of segmented magnets makes production easier [55]. When the shifting between two levels equals 1/6 of the tooth width, the cogging torque is calculated as 0.803% of the rated torque. In addition, the rated torque reduction is only 3.8%. However, multistep and complex skew applications have not been studied in TFMs due to the high number of poles.

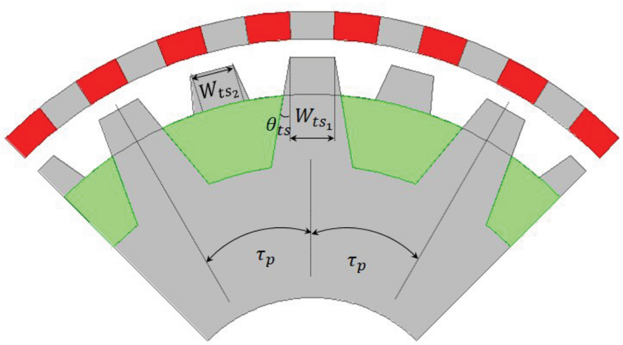


(a) [24] (b) [23] (c) [25]

Figure 7. Different cogging torque reduction methods.

3.4. Use of unsymmetrical pole

In TFMs consisting of the flux-concentrating rotor and the stator disks with teeth, the stator tooth widths W_{ts1} and W_{ts2} can be optimized to reduce cogging torque. The pole angle θ_{ts} also affects the cogging torque (Figure 8a). In [56], the widths of the stator tooth and rotor pole shapes were optimized to reduce cogging torque and improve efficiency. As shown in Figure 8b, the cogging torque can be reduced by shifting the stator disks. Here one pole pitch is $\tau_p + \alpha$, the other pole pitch is $\tau_p - \alpha$. The shifting in the stator disks also reduces the electromagnetic torque [57]. If the unequal stator teeth are used together with the pole shifting method, higher electromagnetic torque than that of the reference TFM can be achieved [58].

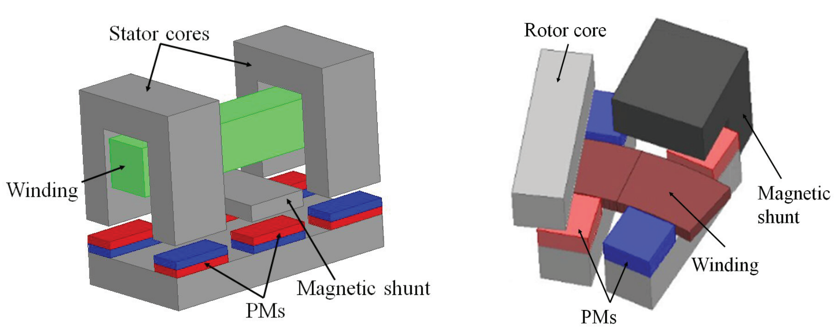


(a) (b)

Figure 8. Cogging torque improvement in the TFMs that consist of stator disk with teeth.

3.5. Use of magnetic shunt

The magnetic shunts are used to block inactive magnet fluxes and to reduce the cogging torque in the TFM (as seen Figure 9a). For example, the use of the magnetic shunts in the three-phase TFM resulted in a 1/2 reduction in the cogging torque [41]. On the other hand, this method increases the active weight of the machine. Therefore, instead of short-circuiting two inactive magnets, it can be also preferable to block only one magnet using a smaller magnetic shunt as shown in Figure 9b [59].



(a) (b) [57]

Figure 9. Different magnetic shunt applications in TFMs.

4. Power factor of TFMs

The low power factor of the traditional TFMs is due to the high flux leakage and 3D flux paths. Since the synchronous reactance is very large in conventional synchronous machines, the winding resistance can be neglected. Since the d-axis current does not contribute to torque generation, it is tried to be eliminated in the control methods. In this case, the angle Theta can be found from (1). Accordingly, the power factor is written as (2) or (3).

$$\varphi = \tan^{-1}(\frac{I_q X_q}{E}) \tag{1}$$

$$\cos\varphi = \cos(\tan^{-1}(\frac{I_q X_q}{E})) \tag{2}$$

$$\cos\varphi = \sqrt{(1-(\frac{I_q X_q}{E})^2)} \tag{3}$$

The low power factor means a high VA source requirement. Therefore, the power factors need to be improved in order for TFMs to compete with traditional PM machines. The power factor can be enhanced by optimizing the number of poles and magnet dimensions [6, 21, 37–40]. As the number of poles increases, the distance between the poles decreases; therefore, the leakage between the poles increases [21]. On the other hand, with the increase in the number of poles, the amount of flux that encloses the phase winding at the same time; thus, the magnitude of induced voltage increases (4) and (5), where N, p, and f are the turn number of the armature phase winding, the number of poles, and the frequency of the induced voltage, respectively. p is, therefore, proportional to the torque density. As a result, it may be necessary to decrease the torque density a little to improve the power factor.

$$E = -N\frac{d(p\phi_{(t)})}{dt} \tag{4}$$

$$E_{rms} = \frac{2\pi}{\sqrt{2}} Npf\phi_{max} \tag{5}$$

There are as many stator cores as the number of pole pairs in the conventional TFMs using U stator cores. When the stator cores are aligned with the magnets, the other pair of magnets cannot be actively used, and also they have the weakening effects on the phase flux-linkage. The I cores called “bridge” or “magnetic shunt” are used to reduce the negative effect of unused magnet fluxes [4, 41]. For example in [41], when the magnetic shunts were added to the TFM model, the power factor increased from 0.5 to 0.8. However, in models whose power factor is relatively high compared to the conventional TFMs [36], the use of I cores does not have the same effect.

The flux-concentrating TFM has higher magnet utilization ratio compared to the surface-mounted TFM using the magnetic shunts. In other words, the amount of leakage flux is lower. Therefore, the flux density of the air gap is higher in the same magnet volume [42]. When the pole structure is examined especially in the disk type TFMs, using the arc-shape poles increases the power factor relatively [25]. However, there is a slight decrease in efficiency and torque density. The use of dummy coils as another method will also reduce leakage flux. Not all the TFM structures are suitable for dummy coils. Besides, the dummy coil cannot eliminate all the leakage flux in the stator, and even leads to a reduction in flux linkage [38]. In addition to the main magnets in TFMs, the use of auxiliary magnets to reduce leakage fluxes between the poles was also proposed [37].

5. Efficiency and torque density of TFMs

Copper losses of TFMs are similar to or even less than those of conventional PM machines. The electrical frequency is high due to the design with high pole numbers. Therefore, iron losses are high in the TFMs. When the efficiencies of radial, axial, and 3-phase conventional TFM machines were compared, higher efficiency was calculated in the TFM than in the axial machine [3]. However, in another comparison of claw-pole TFM, modulating-pole TFM, and the radial flux machine, the efficiencies of the TFMs were calculated in the range of 60%–70% [6]. This contrast reveals that the machine torque density should also be taken into account during efficiency analysis. The efficiency of the TFM machine can be optimized by compromising its torque density. Therefore, the efficiency and torque densities must be evaluated together. In Table 2, the efficiency of the TFMs examined in this study and the traditional PM machines with the same rated power and speed can be seen. When the disk type TFM [27] and the axial flux PM machine [61] with similar power and speed value are compared, it is seen that the efficiency and power factors are quite close. If the objective function is maximum efficiency in the optimum design of any machine, the torque density may not be very good. On the other hand, it may be necessary to waive efficiency or torque density to improve the power factor. Therefore, power factor and torque density should also be examined for a complete efficiency comparison in TFMs.

In the axial flux machines, the torque density increases as the number of poles increases. Therefore, axial flux machines are more suitable for low-speed applications [68]. As explained in the introduction, when the number of poles in TFM increases, the torque density increases as in the axial flux PMs. The torque density in the 50-pole TFM has been reported as 26.9 kNm/kg [46]. Of course, as the power of the machine increases, the torque density will increase too. Therefore, the machines with identical power and speed values should be compared. For example, the switched reluctance machine recommended for in-wheel electric vehicle application [68] and the TFM machine proposed in [19] have identical characteristics. This exhibits that disk-type TFMs can compete with other topologies in terms of torque density and efficiency in low-speed applications.

6. Conclusions

Although the adventure of transverse flux machines has exceeded one century, there has been no significant improvement in their performance until recent years. The aim of this study is to classify the new TFM models proposed in recent years and to present the performances of these models to the interest of researchers. In addition, the proposed methods against the low-power-factor and high cogging torque, which are the structural problems of TFMs, have been discussed and compared. In this review, the methods of improving the performance of the traditional TFMs, and the performance of newly proposed TFMs have been examined in detail. According to this;

- In terms of torque densities, TFMs are superior to conventional PM machines. Since the number of poles can be quite high, they are an important option for use in low-speed, high-torque applications, such as electric vehicles and wind turbines.
- TFMs were accepted as low-power-factor machines in many machine comparisons. However, the power

Table 2. Efficiency and torque density comparison of the TFMs and identical traditional PM machines.

	Ref	Power (Watt)	Speed (rpm)	Slot/pole number		Power factor	Efficiency (%)	Torque density (kNm/m^3)	(kNm/kg)
TFMs	[3]	3570	1000	-		-	94.9	8.68	-
	[11]	816	300	30		0.317*	85	9.3	3.5
	[12]	3100	3000	12	8	0.92	76.5*	-	-
	[13]	330	125	24		0.5	71.3	8.22	-
	[14]	180	2500	24		0.81	95	-	-
	[16]	~ 680	3600	12		-	84	9.85	-
	[17]	-	100	30		-	-	10.88	-
	[18]	2000	375	16		0.708	-	-	-
	[19]	1200	400	-		0.676	88.23	-	3.28
	[25]	~ 1100	400	30		0.638	90.9	-	3.28
	[27]	400	2500	24		0.8985	90	-	-
	[28]	100	1200	24		0.82	82	-	1.78
	[30]	523	250	-		-	87	-	6.9
	[31]	-	285	-		-	-	-	2.01
	[36]	200	1500	24		0.874	86	-	-
	[32]	1500	500	36		-	-	-	-
	[37]	1000	400	30		-	~ 84	-	3.28
	[38]	570	260	32		0.82	80	10.4	-
	[40]	1200	400	30		0.202	75*	-	-
	[41]	1000	-	24		~ 0.84	~ 90	-	-
	[46]	1500*	100	50		-	-	-	26.9
	[60]	7400	1100	12	16	-	93.7	-	-
Radial and axial flux PMs	[60]	390	3000	12		0.958	84.3	-	-
	[62]	275	375	12		0.96*	86.3	-	-
	[63]	3770	143	54	42	-	92	17.55	5.64
	[64]	1020	500	12	14	-	93.4	-	-
	[65]	3500*	320	24	22	0.57	86	31.9	-
	[66]	1000	900	12	8	0.9	90	-	-
	[67]	1380	600	12	26	-	90.4	-	3.25

*Calculated

factors of TFMs proposed in recent years have been competitive with traditional permanent magnet machines. In other words, while the power factors of TFMs were between 0.3 and 0.5 until recently, they are nowadays between 0.62 and 0.92.

- The high cogging torque of the TFMs in the initial designs can be reduced by using the same methods applied in the conventional PM machines. In the TFMs consisting of the flux-concentrating rotor and stator disks with tooth, it is remarkable that the cogging torque can be reduced without any decline in the average torque.

- The iron losses of TFMs are relatively high due to the high number of poles. Nevertheless, according to the results of the review, the rated efficiency of the new TFMs is competitive with traditional PM machines.

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