



HAL
open science

Using and enhancing the cogging torque of PM machines in valve positioning applications

Samad Taghipour Boroujeni, Nouredine Takorabet, Smail Mezani, Thierry Lubin, Peyman Haghgooie

► **To cite this version:**

Samad Taghipour Boroujeni, Nouredine Takorabet, Smail Mezani, Thierry Lubin, Peyman Haghgooie. Using and enhancing the cogging torque of PM machines in valve positioning applications. IET Electric Power Applications, 2020, 14 (12), pp.2516-2524. 10.1049/iet-epa.2020.0221 . hal-02969798

HAL Id: hal-02969798

<https://hal.science/hal-02969798>

Submitted on 16 Oct 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Using and enhancing the cogging torque of PM machines in valve positioning applications

Samad Taghipour Boroujeni^{1,2}, Nouredine Takorabet², Smail Mezani², and Thierry Lubin², Peyman Haghgooe²

1) Department of Engineering, Shahrekord University, Shahrekord, Iran

2) Université de Lorraine – GREEN, Nancy, France

The corresponding author is S. Taghipour Boroujeni (s.taghipour@sku.ac.ir)

Abstract— In this paper, it is aimed to use the cogging torque of PM machines for providing the load torque in the valve positioning applications. The policy is to use the machine cogging torque to overcome the load torque at the steady-state condition (fixed valve position). Therefore, there is no excitation, and no armature Joule losses at the steady-state condition and consequently lower thermal stress for the machine. To have a more compact actuator, it is tried to increase the machine cogging torque. Two well-known types of PM machines, i.e. Surface-mounted PM (SPM) and Flux-Switching PM (FSPM) machines are studied to be applied in this application. Some techniques such as applying auxiliary slots and PM segmentation (for the SPM machine), and two-part rotor topology (for both SPM and FSPM machines) are proposed to increase the machine cogging torque. The impact of each technique on the developed cogging torque is studied by means of Finite Element Analysis (FEA). Finally, the SPM and FSPM machines are compared together in the terms of the torque density. The validity of the proposed concept of providing the load torque by the cogging torque is investigated by experimental tests.

Index Terms— Cogging torque, Finite element analysis, PM machines, Valve positioning.

I. INTRODUCTION

Usually, servomotors are applied in the positioning applications. In these applications, it is required to lock the rotor and keep it at a fixed position. In such a situation, the locking torque at the zero speed is provided by exciting the armature which results in losses and rising in temperature [1]. For the sake of reducing the energy consumption, the servo-motor could be powered off and the rotor is kept fix through different locking systems such as solenoid electromagnetic braking systems [2] or self-locking gears [3,4]. Equipping the servomotors with the self-locking gears or solenoid electromagnetic brake is a good and efficient solution with precise positioning. However, it increases the size and complexity of the system.

In this paper, it is tried to remove the self-locking systems in the positioning applications by using the cogging torque of the PM servo-motors as the self-locking torque. Although, cogging torque results in torque ripple and noise in non-zero speed

applications, it is not an important issue in the positioning applications which require limited changes in the position and zero steady-state speed working conditions.

In the case of using the machine cogging torque as the steady-state locking torque, some considerations must be taken into account. At first, the machine cogging torque must be high enough to provide the locking torque and provide the load torque at the steady-state condition. Secondly, to change the rotor position, the electromagnetic torque provided by armature current must overcome both of the load and cogging torque. Thirdly, the servo-motor could be stabilized only on some discrete positions, which depends on the cogging torque period. Therefore, to increase the precision of the motor positioning, the period of the machine cogging torque must be decreased. Finally, in the case of changes of the load-torque in a steady-state locked position, there are some changes in the rotor position. The changes in the position by the load variation could be decreased by using a steeper cogging torque waveform. Therefore, in the case of adopting some tolerances in the rotor position, the machine cogging torque may be used to provide the load torque. In such a condition it is not necessary to energize the machine by the external power supply at the steady-state condition; therefore, there is no Joule loss and consequently lower thermal stress on the machine. In addition, in the case of losing the power supply, it is guaranteed that the rotor position is locked. Therefore, such a solution seems good in the terms of torque density, machine efficiency, reliability, and reducing the cost of the supplying inverter.

In most applications, it is tried to reduce the cogging torque as much as possible. However, the used techniques for reducing the machine cogging torque could be applied for increasing it too. The most effective parameter on the machine cogging torque is the combination of the machine slots and poles [5]. However, other design parameters, such as the slot opening and the geometry [6] and the shape [7] of the PMs have significant influences on the machine cogging torque. The machine cogging torque is reduced by means of other well-known techniques such as pole-shifting [8, 9], PM-segmentation [10-12], optimum PM arrangement [13], and applying auxiliary slots [14].

Although the effect of design parameters on the machine

cogging torque is studied deeply in the literature, they are focused on minimization of the cogging torque. In addition, selecting the number of the PM segments or the number of the auxiliary slots is not discussed in the terms of the Cogging Torque Periodicity (CTP). In this paper, two well-known types of PM machines, i.e. Surface Mounted PM (SPM) machine and Flux-Switching PM (FSPM) machines are studied as candidates for the valve positioning application. These machines are extensively researched to obtain a low-value of cogging torque and high electromagnetic torque. However, in this paper, due to the specification of the considered application, high values of cogging and electromagnetic torque is required simultaneously. For the sake of increasing cogging torque two novel works are presented in this paper. The first novelty is increasing the machine CTP in the SPM machines with the fixed slot/pole combination. The second one is using two-part machines to achieve simultaneously high cogging and high electromagnetic torque components in the FSPM machines. It is worth mentioning that the main idea of the work is to evaluate the effectiveness of some techniques on increasing the machine cogging torque, and detailed optimization of the machine geometrical parameters for obtaining the maximum possible cogging torque is out of the scope of the work. The considered techniques include the PM-segmentation, applying auxiliary slots and using two-part rotor machines.

Hereafter, in section 2, a description of the valve positioning application, the concept of using cogging torque in these applications, and the physics of cogging torque is given. In section 3, some techniques for increasing the cogging in the SPM and FSPM machines are presented. The efficacy of the techniques is evaluated by means of Finite Element Analysis (FEA). Finally, the SPM and FSPM machines are compared together in the term of the torque density. The validity of the proposed concept of providing the load torque by the cogging torque is investigated by experimental tests.

II. AIM AND SCOPE

A. Presentation of the application

In the valve positioning applications, it is desired to move the position of the valve to control the flow of oil, air, fuel or etc. Therefore, the position of the valve could be at some discrete angles instead of the exact continuous values. In these applications, the exact positioning may not be really important and some amount of error signal in the position could be tolerable. In addition, in these applications, a gear-box could be used to increase the number of discrete position steps and consequently the precision of the positioning.

In this paper, it is planned to use the machine cogging torque to overcome the load torque at the steady-state condition, i.e., when the valve is fixed (zero rotor speed). However, due to the load variation, for example, the changes in the pressure of the fluid inside the valve, the positioning process is not very exact. In Fig.1 (a) typical waveforms of the machine cogging torque and the load torque are shown, where, τ_c is the period of the cogging torque waveform. Definitely, to implement the proposed idea, the peak value of the cogging torque must be

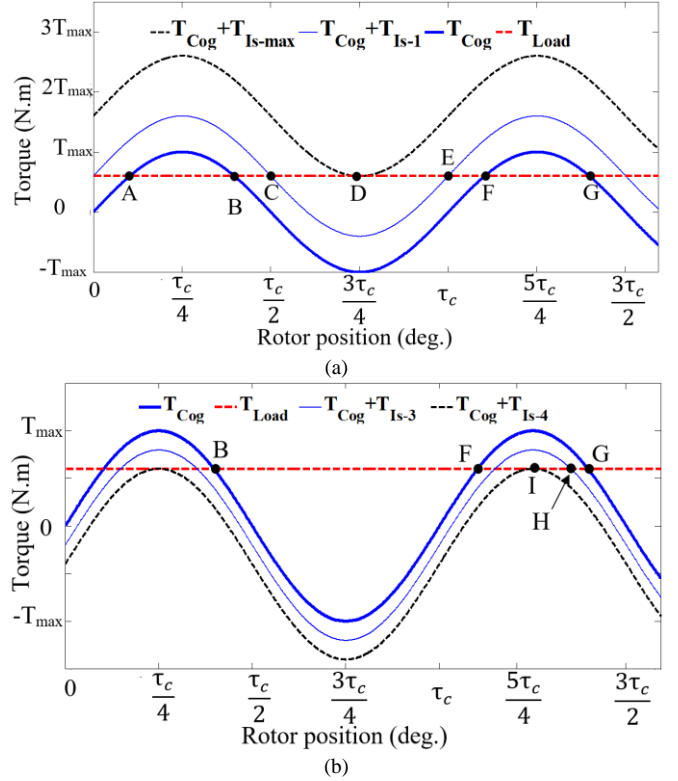


Fig. 1. The load, cogging torque and electromagnetic torque of the PM machine proposed for the valve positioning application (a) forward and (b) backward rotation algorithms.

higher than the maximum of the load torque. When the machine is not energized, the rotor will be located only at points B or G as the stable working points in Fig.1 (a). Therefore, the maximum tolerance of the positioning process is one-half of the cogging torque period ($\tau_c/2$). Actually, τ_c is determined by the combination of the slot and poles of the machine.

In order to move the rotor position about one step forward, some current must be injected in the stator winding. Therefore, positive electromagnetic torque is generated (T_{Is-1}), which shifts up the torque curve, and settles the rotor at point C. Injecting a higher stator current results in a higher electromagnetic torque (T_{Is-max}). In this case, the torque curve touches the load torque at point D. Increasing the provided electromagnetic torque a bit more, the rotor runs away from point D toward the points E and then F. After the point F, even with zero stator current (zero electromagnetic torque) the rotor rotates and hunts point G. To move the rotor position forward for another step, the same algorithm must be followed. To move the rotor back from point G for one step, the stator current must provide a negative electromagnetic torque (T_{Is-3}) to pull back the rotor position to point H. Definitely, higher negative electromagnetic torque (T_{Is-4}) is required to reach point I (see Fig.1 (b)). Finally, by increasing a bit more negative electromagnetic torque, the rotor rotates back toward point F and stabilized in point B as illustrated in Fig.1 (b). Actually, after point F, no stator current is required to rotate back the rotor toward point B. It is worth mentioning that, this simple presented strategy for changing the rotor position is pessimistic because the dynamics of the rotor

TABLE I
THE FIXED DATA OF THE SPM AND FSPM MACHINES

Parameter	Value	
	SPM	FSPM
Stator external diameter	70 mm	70 mm
Stator internal diameter	40 mm	46 mm
Thickness of the PMs	4 mm	3 mm
Slot opening	2.5 mm	4.2 mm
Stator tooth width	5 mm	2.4 mm
Air gap length	0.5 mm	0.5 mm
Height of the stator slots	8 mm	8.9 mm
Machine stack length	10 mm	10 mm
Number of the stator slots	12	12

inertia is not considered. Therefore, changes in the rotor position are possible with the electromagnetic torque lower than T_{Is-max} or T_{Is-4} for the forward and backward rotation, respectively.

As explained, to change the valve angular position, the machine is energized for a short time to provide the electromagnetic torque and settle the valve in the new angular position. Since the machine is excited with an impulse current waveform only in short-time intervals of the rotor transition, a high current density could be adopted inside the coils. This will result in a very compact machine. Applying six-step current waveforms is a good suggestion for providing the rotor transitions. It is worth mentioning that the cogging torque waveform may not be sinusoidal and includes some harmonics. But the shape of cogging torque waveform is not an important matter, because, the main point is that having a stable point cross-section between the load and cogging torque curve. The other thing is that the torque ripple component due to the time- and space-harmonics of the armature flux density is not an important issue in our discussion, because they affect only the electromagnetic torque and have no influence when the machine is unexcited in the steady-state condition (zero armature current, zero speed, and a fixed rotor position).

Since the load torque is provided by the machine cogging torque at the steady-state condition, providing enough cogging torque is a key issue. Furthermore, the precision of the positioning could be improved by reducing the cogging torque period or applying a step-down gearbox.

It is worth mentioning that the policy of using PM magnetic interaction as the steady-state electromagnetic torque is the basic working principle in the magnetic gears [19-21].

B. Physics of the cogging torque

The machine cogging torque is due to the interaction of the PMs edges and the stator teeth in the SPM machine or the interaction of the stator and rotor tooth in the FSPM machine, which are mentioned as magnetic interaction, hereafter. It is a consequence of the basic Electromagnetics law that the generated torque on the rotor desires to reduce the stored magnetic energy as small as possible. In terms of co-energy [15], the machine cogging torque is given in (1), where θ_r is the rotor angular position and W_c is the stored magnetic co-energy inside the whole machine volume.

$$T_{cog}(\theta_r) = \frac{\partial W_c}{\partial \theta_r} \quad (1)$$

The cogging torque could be obtained by the Maxwell stress integration [16] as given in (2), where, B_r and B_ϕ are the radial and circumferential components of the air gap flux density due to the PMs, r is the radius of the considered Maxwell cylinder in the air gap and L_{stk} is the machine stack length.

$$T_{cog}(\theta_r) = \frac{L_{stk} r^2}{\mu_0} \int B_r(\theta_r) B_\phi(\theta_r) d\varphi \quad (2)$$

In addition, the cogging torque could be obtained by integrating the forces on the lateral sides of the machine slots as expressed in (3) [17], where R_s is the stator bore radius, Q_s is the number of the stator slots, θ_{ri} and θ_{li} are the angles of the right and left lateral sides of the i^{th} stator slot.

$$T_{cog} = \frac{L_{stk}}{2\mu_0} \lim_{r \rightarrow \infty} \sum_{i=1}^{Q_s} \left(\int_{R_s e^{j\theta_{ri}}}^{r e^{j\theta_{ri}}} |B|^2 ds - \int_{R_s e^{j\theta_{li}}}^{r e^{j\theta_{li}}} |B|^2 ds \right) \quad (3)$$

However, using (1), (2) and (3) is not a good idea to predict the overall quality of the cogging torque waveform, especially in a machine with high numbers of poles and teeth. Using the general expression of cogging torque in (4) is more useful for evaluating the amplitude of the cogging torque,

$$T_{cog} = GCD(x, Q_s) \sum_{k=1}^{\infty} T_k \sin(LCM(x, Q_s) k \theta_r) \quad (4)$$

where, T_k is the amplitude of k^{th} harmonic of the cogging torque in one CTP of the machine, GCD is the greatest common divisor operator, LCM is the least common multiplier operator, Q_s is the number of the stator teeth. For the SPM and the FSPM machines, x equals to the number of the magnet blocks and the number of the rotor teeth, respectively. The value of $GCD(x, Q_s)$ determines the CTP. Physically, the CTP shows the number of magnetic interactions in the machine with exactly identical cogging torque waveforms. It means a machine with higher CTP has the potential of producing a greater cogging torque. As well as the CTP, the value of the resultant cogging torque in one CTP of the machine is an important factor too. It depends on the level of the coherency of the magnetic interaction waveforms in one CTP of the machine. A higher level of coherency results in greater cogging torque. Actually, the level of coherency between the magnetic interactions in one CTP of the machine depends on geometrical parameters such as the slot-opening, the teeth arcs, and PM arcs. However, the CTP has a more significant impact on the machine cogging torque. Therefore, the cogging torque of the machine could be increased in two separate steps. At first, the CTP must be increased as much as possible by using an appropriate combination of the number of slots and poles. In the second step, coherency between the magnetic interactions in one CTP of the machine must be maximized by optimizing the geometrical parameters such as slot opening and PM or tooth arcs. It should be noted that the attempt of the presented work is focused on the first step, and increasing the level of coherency between the magnetic interactions in one CTP of the machine is not the scope of the paper. The mentioned steps are studied extensively and applied in literature to minimize the cogging

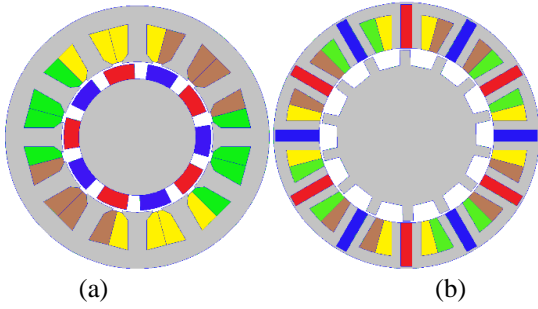


Fig. 2. Geometry of the 12-slot (a) 10-pole SPM and (b) 14-rotor tooth FSPM machines

torque of the PM machines. The first novelty of the presented work is increasing the CTP of the SPM machines with the fixed slot/pole combination.

Actually the pole/slot combination in the SPM machine and the stator-/rotor-teeth number in the FSPM defines the machine periodicity. In comparison with the integral-slot SPM machines, in the existing fractional-slot SPM machines, the machine periodicity, its CTP and, consequently the cogging torque is small [5]. Similarly, the proposed FSPM machines in the literature have a fractional ratio between the stator and the rotor teeth [17]. Therefore, the extant fractional-slot machines may not be good solutions for the valve positioning application. However, the other merits of fractional-slot machines, such as using concentrated coils with simple manufacturing and high value of slot filling factor, still encourage us to use fractional-slot machines for the valve positioning application. Since in the positioning applications a high amount of cogging torque is required, in the following, some techniques are proposed to increase the machine cogging torque in the fractional-slot SPM and FSPM machines.

III. INCREASING THE COGGING TOQUE

To study the impact of applying different techniques on increasing the cogging torque, two types of PM machines, i.e., SPM and FSPM machines are considered. As mentioned, the aim of the work is not to increase the level of the coherency between the magnetic interactions in one periodicity of the cogging torque. Actually, it is tried to increase the CTP of the SPM machine with predefined slot/pole combination. Therefore, the stator geometry is kept fix. The fixed data of these machines stators are given in Table 1. The geometry of these machines is shown in Fig.2. In addition, it is desired to achieve the cogging torque equal to 3 N.m and its period less or equal to 15° .

Hereafter, in the influence of the number of the PM segments in each pole and the number of auxiliary slots on the cogging torque of the SPM machine is investigated. Since it not possible to apply the mentioned methods in FSPM machines, the effect of applying another technique, i.e. using a two-part rotor is studied on the cogging torque of both SPM and FSPM machines. In order to have an insight into the efficacy of each method on increasing the machine cogging torque, at first the existing cogging torque waveforms of the SPM and FSPM machines with variant design parameters are obtained.

The cogging torque of the SPM machine with 4-, 8- and 10-

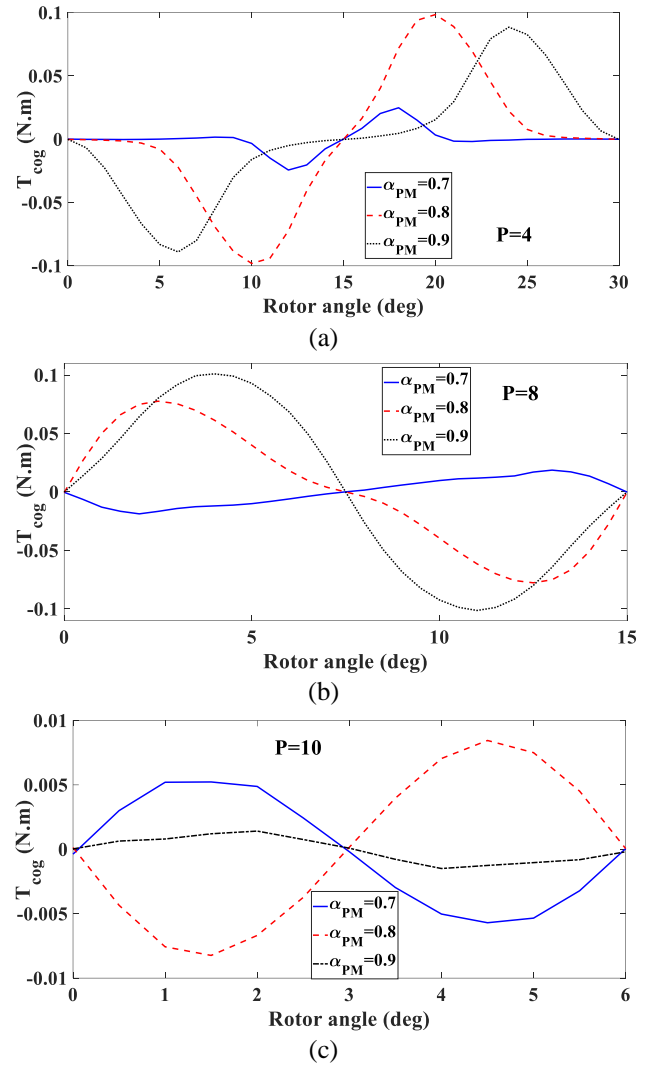


Fig. 3. Cogging torque waveforms of (a) 4-pole, (b) 8-pole and (c) 10-pole SPM machine.

poles and different ratios of the PM arc to the pole pitch (α_{PM}) are illustrated in Fig.3 (a)-(c). The CTP of the 4-, 8- and 10-pole machines are 4, 4, and 2, respectively. Since in one CTP of the 4, 8, and 10-pole SPM machine, there are 1, 2, and 5 number of the magnet blocks with 2, 4, and 10 number of the PM edges, there will be 2, 4, and 10 number of magnetic interaction between the PM edges and slots., respectively. Although the number of magnetic interactions in one CTP of the machine is higher in the 10-pole machine in comparison with the 4- and 8-pole machines, they are not coherent waveforms. Therefore, it is expected that the amplitude of the resultant cogging torque in 4- and 8-pole machines is much higher than the 10-pole machine. On the other hand, the 4-pole machine is not interested, because it is not only an integral-slot machine but also its cogging torque period is higher than the supposed maximum angle tolerance (15°). Therefore, the 4- and 10-pole machines are not good candidates for the considered valve positioning application. Although, the electromagnetic torque density and the winding factor of the 12-slot 8-pole machine is lower than the 12-slot 10-pole machine [18], due to its higher cogging torque this machine is considered for the valve

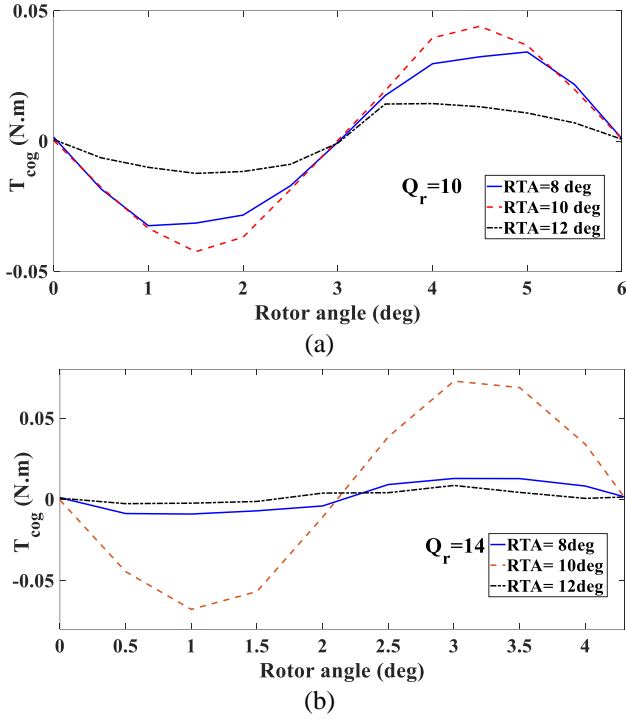


Fig. 4. Cogging torque waveforms of FSPM machine with (a) 10, (b) 14 rotor teeth.

TABLE II

THE CHANGES IN CTP AND THE MAXIMUM COGGING TORQUE OF THE SPM MACHINES WITH AUXILIARY SLOT

No. of poles	GCD((d+1)Q _s ,2p)		T _{cog-max} (N.m)	
	d=0	d=1	d=0	d=1
P=4	4	4	0.10	0.10
P=8	4	8	0.10	0.17
P=10	2	2	0.008	0.004

TABLE III

THE CHANGES IN CTP AND MAXIMUM COGGING TORQUE OF THE SPM MACHINES WITH SEGMENTED PMs

No. of poles	GCD(Q _s ,2sp)				T _{cog-max} (N.m)			
	s=1	s=2	s=3	s=4	s=1	s=2	s=3	s=4
P=4	4	4	12	4	0.10	0.08	0.30	0.02
P=8	4	4	12	4	0.08	0.04	0.28	0.03
P=10	2	4	2	4	0.008	0.001	0.011	0.011

positioning application, hereafter. From Fig.3 (b), it can be found that for providing 3 N.m locking (load) torque about 300mm stack length of the 8-pole machine is required.

In addition, the machine cogging torque in the FSPM machine with the rotor teeth number of 10 and 14 and different ratios of the Rotor Teeth Arc (RTA) are illustrated in Fig.4 (a) and (b). As seen in Fig.4 to provide 3 N.m locking (load) torque about 750mm/430mm stack length of the 10-/14-rotor teeth machine is required.

The CTP of the FSPM machines with 10 and 14 is 2. On the other hand, the phases of the magnetic interaction of the rotor and stator teeth waveforms in one CTP of the machine are not coherent. Therefore, as expected and discussed previously, the

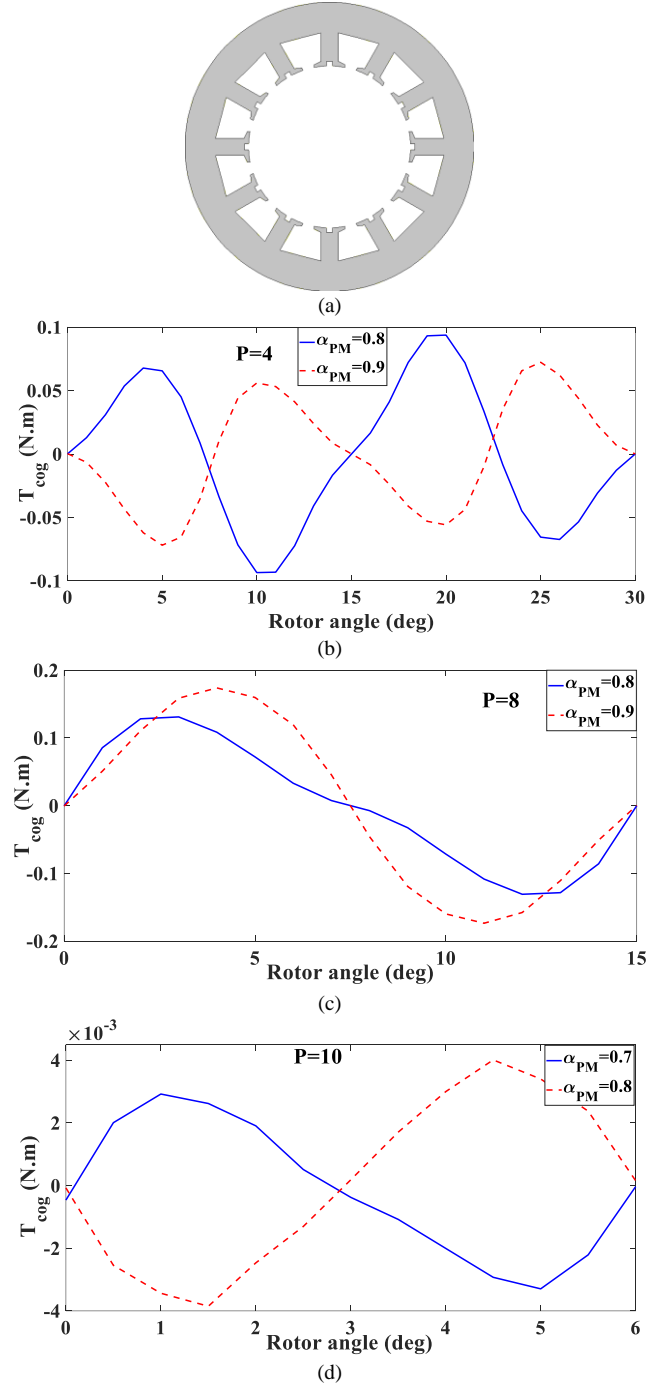


Fig. 5. The stator geometry with auxiliary slots, and the cogging torque waveforms of (a) 4-pole, (b) 8-pole and (c) 10-pole SPM machine with auxiliary slots.

cogging torque of these FSPM machines is too small, and this machine seems not to be a good candidate for valve positioning applications. Since the FSPM is supposed to be a symmetrical three-phase machine, other rotor geometries with higher CTPs (rotors with 9, 12, 15, and 18 number of the rotor teeth) could not be applied. So at the first look FSPM machine is not a good candidate for valve positioning applications. Hereafter, it is tried to increase the cogging torque of the SPM and FSPM machine.

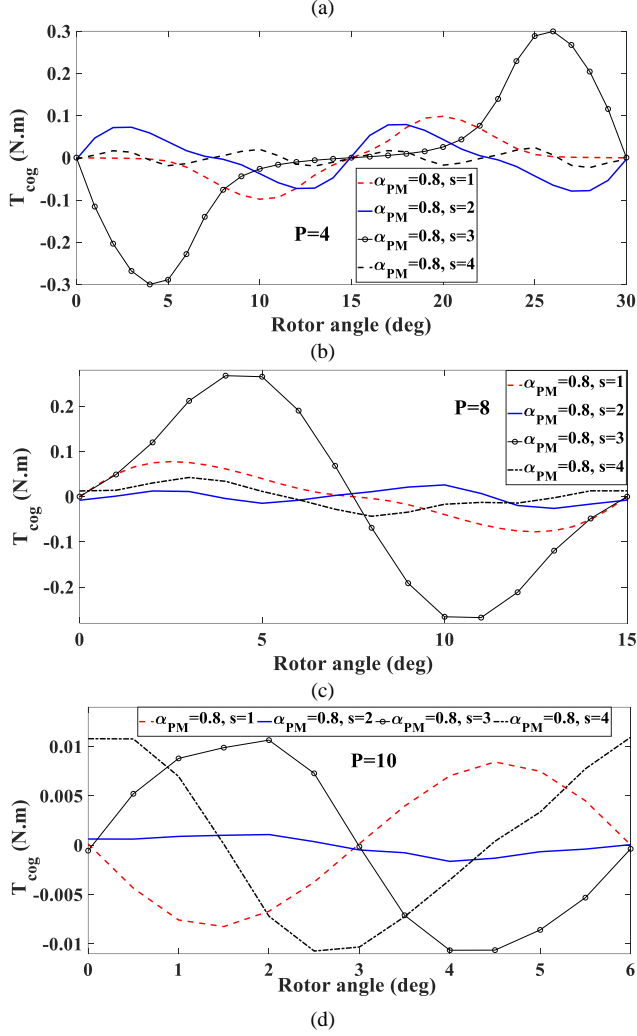
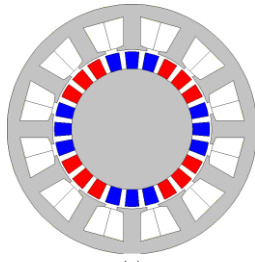


Fig. 6. The SPM machine with 8-pole and 3-segment PMs rotor (a) and the cogging torque waveforms of (b) 4-pole, (c) 8-pole and (d) 10-pole SPM machine with segmented PMs.

A. With Applying auxiliary slots in the SPM machine

In this section, one auxiliary slot is considered in each stator tooth. In the [14-15], applying auxiliary slots is presented as a technique for reducing the machine cogging torque, however, the possibility and condition of increasing the cogging torque is not investigated. The shape of the stator of the SPM machine with auxiliary slots is shown in Fig.5 (a). The cogging torque of the 4-, 8- and 10-pole SPM machines is obtained by FEA and shown in Fig.5 (b)-(d), respectively. It should be noted that the auxiliary slots are provided in all stator teeth uniformly with the width of the real slot openings and the height of 1mm. The GCD of the all stator slots and the rotor poles, and the maximum

obtained cogging torque for the 4-, 8- and 10-pole SPM machines are given in Table 2, where, $d+1$ is the number of the slots per stator slot pitch.

As seen in Table 2, by applying the auxiliary slots, the $GCD(2p, (d+1)Q_s)$ in the 4-pole and 10-pole machines does not change while in the 8-pole machine it increases two times. In other words, the number of coherent interactions between the PMs and stator teeth increased. Therefore, it is expected that against the 4- and 10-pole machines, the machine cogging torque is increased by applying auxiliary slots in the 8-pole machine. From the cogging torque waveforms in Fig.5, it is seen that applying auxiliary slots does not change the period of the cogging torque in 8-pole machine because the LCM of the slots and poles does not change, while, in the 4-pole SPM machine the period of the cogging torque is halved because the LCM value is doubled by applying auxiliary slots. Finally, it could be stated that applying the auxiliary slots can increase the machine cogging torque if the value of GDC ($2p, d+1$) is increased (or the number of all teeth is a multiplier of the rotor poles). As seen in Fig.5 to provide 3 N.m locking (load) torque about 170mm stack length of the 8-pole SPM machine with auxiliary slots is required.

B. Segmentation of the PMs in the SPM machine

PM segmentation is a well-known technique to mitigate the cogging torque in the SPM machines [8-12]. However, here, it is used to increase the cogging torque. For this aim, the uniform segmentation, i.e., the similar equidistance magnet blocks, is adopted. The geometries with $s=2, 3$ and 4 are considered hereafter, where s is the number of PM segments per pole. The shape of the 8-pole SPM machine with 3 segments per pole is shown in Fig.6 (a). The cogging torque of the segmented PM machines with 4-, 8- and 10-pole SPM machines are given in Fig.6 (b)-(d), respectively. The GCD of the stator slots and the rotor PM segments and the maximum of the cogging torque waveform for the 4-, 8- and 10-pole SPM machines are given in Table 3.

As seen in Table. 3, against the other segmented machines, in the 4- and 8-pole SPM machines with 3 segments PMs per pole, the number of PM pieces is an integer number of the stator slots and the $GCD(Q_s, 2ps)$ is increased significantly (the maximum possible value i.e., 12), therefore, in these machines, the cogging torque increases very much. In this condition, the number of coherent interactions between the PMs and stator teeth is increased, considerably. From the cogging torque waveforms in Fig.6, it is seen that the PM segmentation does not change the period of the cogging torque. Comparing the cogging torque waveforms in Fig.6 by the ones in Fig.5, it is found that the PM segmentation technique is more effective than applying auxiliary slots on increasing the machine cogging torque. As seen in Fig.5 to provide 3 N.m locking (load) torque about 110mm stack length of the 8-pole SPM machine with 3 magnet segments per pole is required.

C. Using two-part machines

In the previous sections, the cogging and electromagnetic torque components are generated simultaneously in the whole

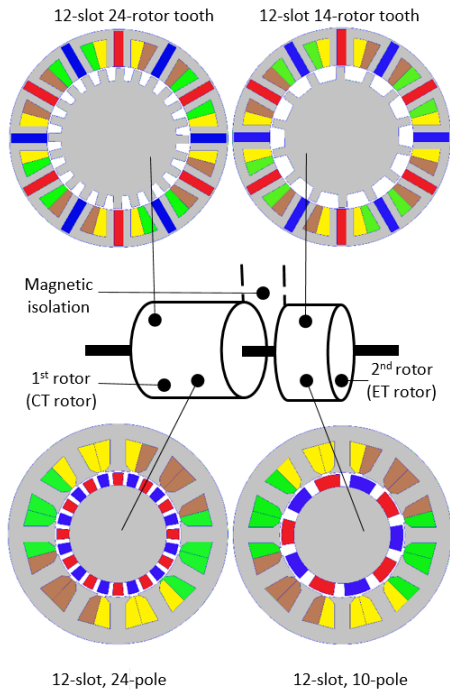


Fig. 7. The layout of the two-part SPM and FSPM machines.

axial length of the machine. Although considering this idea and applying PM segmentation is an efficient method in increasing the SPM machine cogging torque, it cannot be applied to the FSPM machines effectively. In this part of the study, it is tried to separate the rotor of the machines in two axial parts and provide the cogging and electromagnetic torques separately in each axial part of the machine. The two parts include the same stator geometry (for the sake of simplicity in manufacturing), while they contain different rotor geometries which are magnetically isolated by applying an air distance between them to avoid 3D effects. The configuration of the two-part machine is illustrated in Fig.7. In the proposed two-part machine SPM or FSPM machines could be applied. The first part of the rotor provides a big amount of cogging torque which is required in the steady-state condition. This part of the rotor is named CT rotor hereafter. The second part of the rotor mentioned as ET rotor produces the electromagnetic torque. ET rotor is responsible for rotating the rotor during transitions. Therefore, the number of rotor poles/teeth in the SPM/FSPM machine can be selected to maximize the CTP of the machine and consequently, increase the machine cogging torque with no concern regarding the balanced three-phase condition or the electromagnetic torque. Therefore, 24-pole SPM or 24-rotor tooth geometries could be applied for the CT rotor. In addition, the number of the rotor poles/teeth in the ET rotor of the SPM/FSPM machine is selected as 10/14, the normal SPM/FSPM machines, to provide balance three-phase condition with a high-value electromagnetic torque and a small amount of cogging torque. Hereafter, both SPM and FSPM machines are considered for the design of two-part machines.

1) Providing a high cogging torque

A rotor with a high-level of CTP should be selected for the CT rotor section. Since the CT rotor is not supposed to

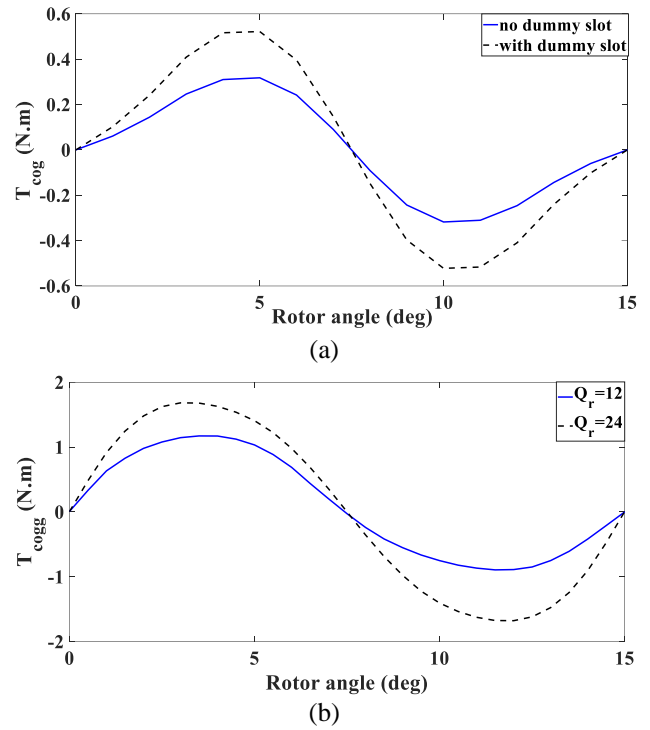


Fig. 8. Cogging torque developed by the CT rotor in (a) 24-pole SPM machines with $\alpha_{PM}=0.8$ and (b) FSPM machines with rotor tooth arc of 7° .

contribute on producing the electromagnetic torque as a 3-phase and symmetrical machine, there are more variant alternatives for the rotor topology. In other words, a very huge cogging torque could be produced by selecting an appropriate number of PMs and the rotor teeth in the SPM and FSPM machines, respectively. Actually, the number of the rotor poles (in the SPM machine) and the rotor teeth (in the FSPM machine) must be an integer number of the stator slots to reach a high CTP value. In this study, a 12-pole rotor is not selected because the period of its cogging torque is 30° , which is higher than the minimum acceptable period for the cogging torque waveform. Therefore, a 24-pole rotor with $\alpha_{PM}=0.8$ is selected and the cogging torque waveforms with and without applying auxiliary slots in the stator are obtained and shown in Fig.8 (a). In this case, the CTP of the machine is 24 and 12 for the machines with and without auxiliary slots, respectively. By comparing the cogging torque waveforms of the 24-pole rotor machine (without using auxiliary slots) in Fig.8 (a) and the 8-pole SPM machine with 3 segments per pole in Fig.6 (b) (as the machine with highest cogging torque), it is inferred that the using two-part rotors does not increase significantly the cogging torque in the SPM machines. Alternatively, as shown in Fig.7, for the CT rotor of the FSPM machine the number of the rotor teeth may be selected as 12 and 24, respectively. The cogging torque waveforms of the FSPM machines with 12 and 24 rotor teeth are shown in Fig.8 (b). By comparing the cogging torque waveforms in Fig.8 (b) with the waveforms in Fig. 4, it is found that using the two-part rotor is an effective technique that results in a very high cogging torque in the FSPM machines even more than SPM machines. As seen in Fig.8 (a) and (b) to provide 3 N.m locking (load) torque about 100, 60, and 20mm

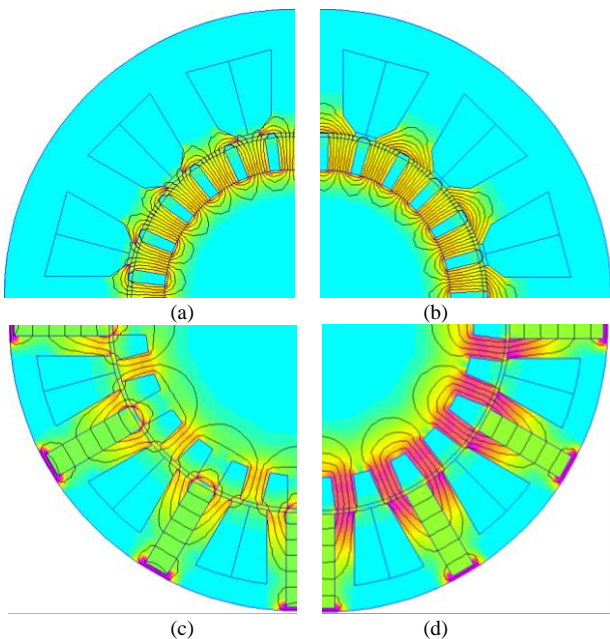


Fig. 9. Flux density distribution for the rotor position of 0°(a), 7.5° (b) for the 4-pole SPM, and 0°(c) and 7.5° (d) for the FSPM machines.

stack lengths are required in the CT rotor of the by SPM with and without auxiliary slots and FSPM machines, respectively. For providing 3N.m locking torque, using a two-part SPM machine is not a good idea because it needs 60mm axial length only for providing the cogging torque. However, using the 3-segment PM rotor is a very nice idea in the SPM machines (110mm axial length for providing both cogging and electromagnetic torque components). Against the SPM, in the FSPM using a two-part rotor is logical (20mm for CT rotor).

The flux density distribution in the first part of the SPM and FSPM machines for two rotor positions are given in Fig.9 (a) and (b), respectively. It is understood from Fig.9 that in the first part of machines there is no flux linkage and back-EMF inside the stator coils due to the PMs and, consequently, this part of the machine has no influence on the electromagnetic torque production.

2) Providing a high electromagnetic torque

The ET rotor is responsible for providing the required electromagnetic torque in the transient conditions. Therefore, the well-known classical fractional-slot SPM or FSPM with very low cogging torque and high electromagnetic torque density could be applied in the EM rotor. As shown in Fig. 8, a 10-pole rotor for the SPM or a 14-tooth rotor in the FSPM machines could be applied. Hereafter The stators of the SPM and FSPM are excited and the behavior of the provided torque in the CT and ET rotors of these machines are investigated separately. Considering the same current density inside the stator slots of the SPM and FSPM machines, the electromagnetic torque waveforms for DC and synchronized six-step armature currents in the second part of the machine are obtained by means of FEA and shown in Fig.10 (a) and (b), respectively.

To investigate the contribution of the first rotor part in the torque production in the transients, the stator of the first part of

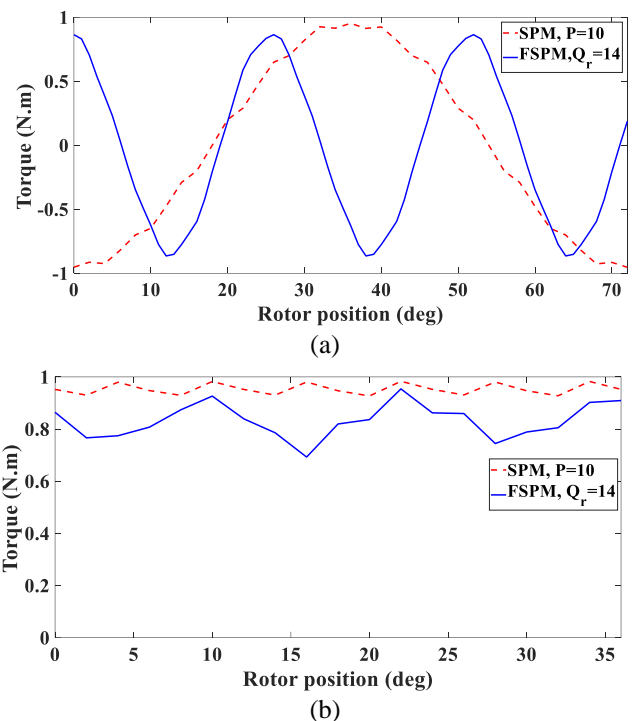


Fig. 10. The total torque in the second part of the 10-pole SPM and 14-rotor teeth FSPM machines with (a) DC and (b) six-step synchronized currents.

the SPM and FSPM machines are excited by the DC and six-step synchronized currents and the obtained torque waveforms are shown in Fig.11 (a) and (b), respectively. Comparing the static, synchronized torque waveforms with the cogging torque of the first parts of the machines in Fig.11 (b), shows that no electromagnetic torque is generated by the interaction of the armature currents and PMs in the first part of the machines. The same result (having no PM flux linkage and consequently no electromagnetic torque component in the first part of the machine) is obtained from Fig.9.

Finally, from the easiness of manufacturing point of view, it should be noted that using PM segmentation (with magnet blocks with similar dimensions) and applying two-part machines are applicable and straightforward techniques and could be implemented without applying changes in the stator laminations or coil windings. Regarding using auxiliary slot techniques in the SPM machines, although, it could be applied in the existing stator laminations, it requires some mechanical modifications efforts.

IV. CONCEPT VERIFICATION

To evaluate the applicability of using cogging torque as the load torque experimental tests are applied. The test rig is shown in Fig.12a. In the test rig, an interior PM machine is used to provide the cogging torque, a synchronous reluctance machine is used to implement the load torque and the DSPACE MicroBox controller is used to control the PWM inverters. The measured cogging torque is illustrated versus the rotor position in Fig.12b. In the test, the synchronous reluctance machine is controlled to provide a constant torque of 0.3 N.m. By exciting the phases of the PM machine with DC voltages ($\pm 5V$), the rotor

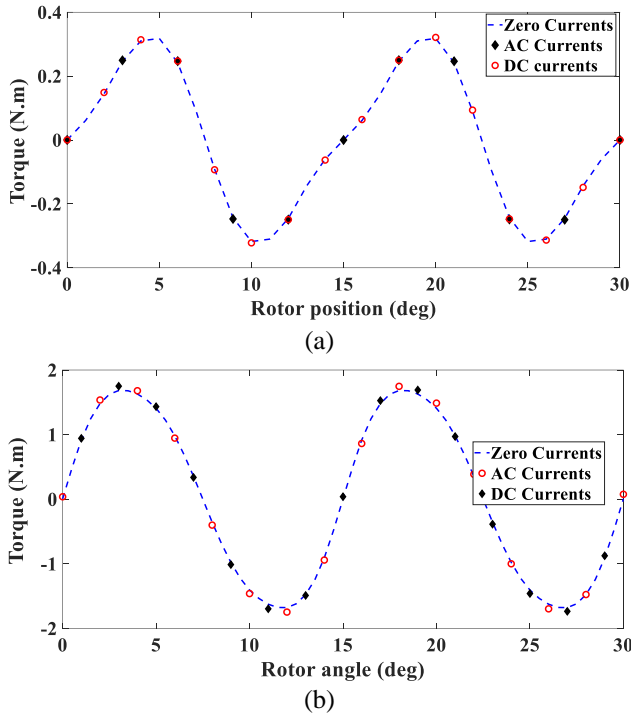


Fig. 11. The total torque in the first part of the (a) 24-pole SPM and (b) 24-rotor teeth FSPM machines with DC and six-step synchronized currents.

position is changed as shown in Fig.12c. The sequence of the applied DC voltages is presented in Fig.12c. The waveform of the measured torque is given in Fig.12d. As seen in Fig.12c after changing the rotor position, the stator terminals of the PM machine is short-circuited and the machine cogging torque provides the load torque.

V. CONCLUSION

In this paper, it is proposed to use the machine cogging torque to provide the load torque at the steady-state condition (i.e., zero speed and the fixed rotor position) in the valve positioning system. Therefore, it is tried to increase the machine cogging torque as much as possible. Two types of PM machines, i.e., SPM, and FSPM machines with a fixed stator geometry is considered. The first novelty of the work is focused on increasing the machine CTP in an SPM machine with a fixed number of slot/pole combination. The influence of PM segmentation and using auxiliary slot techniques on increasing the CTP of the SPM machines are investigated. It is shown that PM segmentation is a more effective approach. It is shown that to increase the cogging torque in the PM-segmented SPM machines, the number of the rotor poles and the PM segments must be selected such that $GCD(Q_s, 2p_s)$ is high as possible. In addition, it is found that in the case of applying auxiliary slots to reach a high value of the cogging torque, the number of the rotor poles and the auxiliary slots must be selected such that $GCD((d+1)Q_s, 2p)$ is high as much as possible. Finally, since increasing the machine CTP is not applicable in the FSPM machine, applying two-part machines is proposed and used to increase the cogging torque of FSPM machines. It is found that using a two-part machine in the FSPM results in a very high

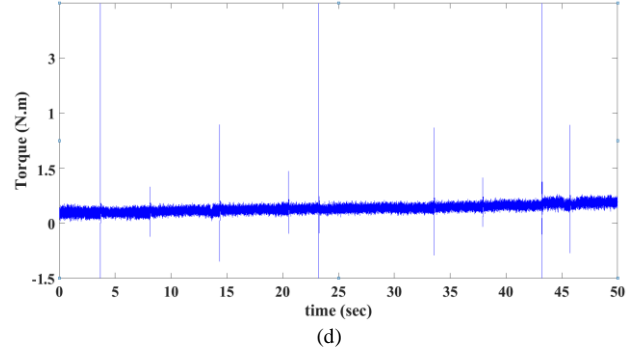
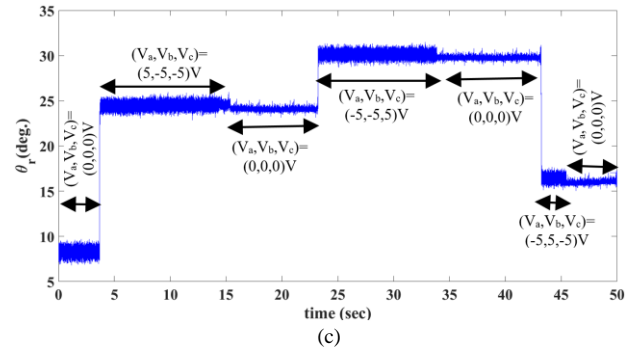
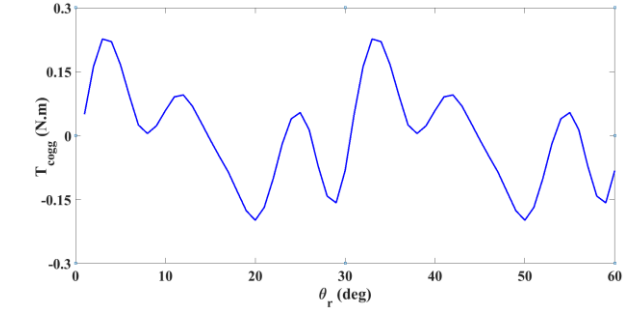
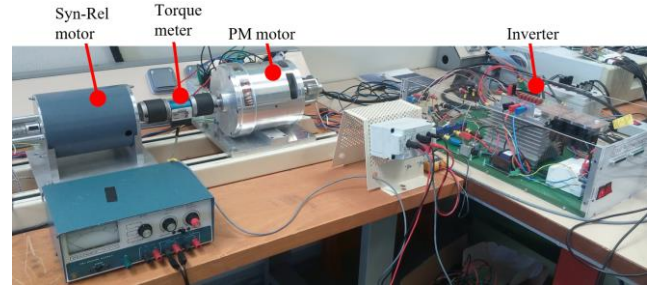


Fig. 12. (a) the experimental test rig, (b) the measured cogging torque, (c) the rotor position and (d) the electromagnetic waveforms

cogging torque. Using FEA, it is shown that the CT rotor in the first part of the machine produces only the cogging torque even in the case that stator armature is excited. During the rotor transitions, the stator current must be injected inside the armature coils to provided electromagnetic torque in the second part of the machine with the ET rotor. Finally, the concept of providing the load torque by the cogging torque is verified by experiments.

REFERENCES

- [1] G. Yu, Y. Xu, J. Zou, L. Xiao, and H. Lan, "Development of a Radial-Flux Slotted Limited-Angle Torque Motor with Asymmetrical Teeth for

- Torque Performance Improvement, *IEEE Trans. on Magn.*, vol.55, no.7, July 2019, ID. 8203305
- [2] B. V. R. Kumar, K. Sivakumar, Y. S. Rao, S. Karunanidhi, "Design of a new Electro-magnetic brake for actuator locking mechanism in Aerospace vehicle," *IEEE Transactions on Magnetics*, Vol. 53, No.11, Nov. 2017, ASN: 8002606.
 - [3] H. Deng, X. Xu, W. Zhuo, A. Zhang, "Current-Sensor-Based Contact Stiffness Detection For Prosthetic Hands," *IEEE Access*, vol. 8, pp. 29456-29466.
 - [4] J. U. Chu, D. H. Jung, and Y. J. Lee, "Design and Control of a Multifunction Myoelectric Hand with New Adaptive Grasping and Self-locking Mechanisms," *IEEE International Conference on Robotics and Automation*, CA, USA, May 19-23, 2008, pp.743-748.
 - [5] P. Jalali, S. T. Boroujeni, J. Khoshtarash, "Expansion of the Feasible Slot/Pole Combinations in the Fractional Slot PM Machines by Applying Three-Slot Pitch Coils," *IEEE Trans. Energy Convers.*, vol. 34, no. 2, pp. 993-999, June. 2019.
 - [6] J. Ping, F. Shuhua, S. L. Ho, "Distribution Characteristic and Combined Optimization of Maximum Cogging Torque of Surface-Mounted Permanent-Magnet Machines", *Magnetics IEEE Transactions on*, vol. 54, no. 3, pp. 1-5, 2018
 - [7] Boroujeni, S. T., and Zamani, V., "Influence of magnet shaping on cogging torque of surface-mounted PM machines", *Int. J. Numer. Model.*, vol. 29, no.5, pp. 859-872, Sep. 2016.
 - [8] Bianchi, N., and Bolognani, S., "Design techniques for reducing the cogging torque in surface-mounted PM motors", *IEEE Trans. Magn.*, vol.38, no.5, pp. 1259-1265, Sep. 2002.
 - [9] S. Chaithongsuk, N. Takorabet, F. Meibody-Tabar, "On the Use of Pulse Width Modulation Method for the Elimination of Flux Density Harmonics in the Air-Gap of Surface PM Motors *IEEE Transactions on Magnetics*," *IEEE Trans. Magn.*, vol.45, no.3, pp. 1736-1739, March. 2009.
 - [10] Ramdane Lateb, Nouredine Takorabet, and Farid Meibody-Tabar "Effect of Magnet Segmentation on the Cogging Torque in Surface-Mounted Permanent-Magnet Motors," *IEEE Trans. Magn.*, vo. 42, no. 3, March 2006, 442-445
 - [11] M. Ashabani, J. Milimonfared, S. Taghipour, "Cogging force mitigation of tubular permanent magnet machines with magnet dividing," *International Conference on Electrical Machines and Systems (ICEMS)*, OCT. 2007, pp. 810-814
 - [12] V. Zamani, S. Taghipour and N. Takorabet, "Optimum arrangement of PMs in surface-mounted PM machines: cogging torque and flux density harmonics," *Elec. Eng. Springer*, has been accepted for publication
 - [13] C. Xia, Z. Chen, T. Shi, and H. Wang, "Cogging torque modeling and analyzing for surface-mounted permanent magnet machines with auxiliary slots," *IEEE Trans. Magn.*, vol.49, no.9, pp. 5112-5123, Jul. 2013.
 - [14] F Ebadi, M Mardaneh, A Rahideh, N Bianchi, "Analytical Energy-Based Approaches for Cogging Torque Calculation in Surface-Mounted PM Motors," *IEEE Transactions on Magnetics*, Vol. 55, No.5, Apr. 2019, pp. 1-10.
 - [15] ST Boroujeni, P Jalali, N Bianchi, "Analytical modeling of no-load eccentric slotted surface-mounted PM machines: Cogging torque and radial force," *IEEE Transactions on Magnetics* 53 (12), 1-8
 - [16] D. Žarko, D. Ban, and T. A. Lipo, "Analytical calculation of magnetic field distribution in the slotted air gap of a surface permanent-magnet motor using complex relative air-gap permeance," *IEEE Trans. Magn.*, vol. 42, no. 7, pp. 1828-1837, July. 2006.
 - [17] J. T. Chen, Z. Q. Zhu, "Winding Configurations and Optimal Stator and Rotor Pole Combination of Flux-Switching PM Brushless AC Machines," *IEEE Trans. Energy Convers.*, vol. 25, no. 2, pp. 293-302, June 2010.
 - [18] K. Wang, Z. Q. Zhu, G. Ombach, "Synthesis of High Performance Fractional-Slot Permanent-Magnet Machines With Coil-Pitch of Two Slot-Pitches," *IEEE Trans. Energy Convers.*, vol.29, no.3, 2014, pp.758-770.
 - [19] L. Jing, Z. Huang, J. Chen, and R. Qu, "An Asymmetric Pole Coaxial Magnetic Gear with Unequal Halbach Arrays and Spoke Structure," *IEEE Trans. Appl. Superconductivity*, vol.30, no.4, pp.1-4, 2020.
 - [20] L. Jing, Z. Huang, J. Chen and R. Qu, "Design, Analysis and Realization of a Hybrid-Excited Magnetic Gear during Overload," has been accepted for publication in *IEEE Trans. On Ind.* doi: 10.1109/TIA.2020.3004425.
 - [21] A Rahideh, A. A. Vahaj, M. Mardaneh, T. Lubin, "Two-dimensional analytical investigation of the parameters and the effects of magnetisation patterns on the performance of coaxial magnetic gears," *IET Electrical Systems in Transportation*, vol. 7, no.3, 2017, pp. 230-245.