Influence of static and dynamic rotor/stator misalignments in axial flux magnetically geared machines

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Abstract: Here, static and dynamic (rotating) misalignments between the low-speed rotor (LSR) and the stator of axial flux magnetically geared machines are studied with the aid of 3-D finite element analysis (FEA). The influence of rotor/stator axis misalignments on machine performance in terms of cogging torque, air-gap flux density, and back-EMF is investigated with reference to the fully healthy condition. The results show that the LSR and HSR cogging torques are significantly affected by such misalignments due to distorted air-gap flux density. However, the amplitude and the harmonics of the back-EMF are only slightly changed. Furthermore, the influence of the misalignments on the machine torque performance is investigated. It is shown that the machine torque is significantly reduced when the LSR axis is misaligned with the axis of the stator. Thus, it is concluded that the torque performance of axial flux magnetically geared machines significantly deteriorates under static and dynamic axis misalignments. In addition, the two types of misalignments have similar effects on machine performance.

1 Introduction
Axial flux permanent magnet (AFPM) machines have desirable advantageous performance for industry applications since they have prominent features of high torque density, short axial length, and compact design, among others [1]. Recently, axial flux magnetically geared machines, in which axial magnetic gears are combined with PM machines, have been proposed and analysed for applications such as wind power generation and hybrid electric vehicles (HEV) [2, 3], due to their improved torque density. In addition, magnetically geared machines are being introduced to realise the power split function in HEVs due to their possession multi-mechanical ports [4, 5]. However, in comparison with conventional PM machines, axial flux magnetically geared machines are more susceptible to manufacturing imperfections and structural deformations which may deteriorate the machines’ electromagnetic performance such as output torque, and introduce vibration and noise [6]. Therefore, it is necessary to investigate the influence of manufacture tolerances on the performance of this type of machine.

For most PM machines, rotor eccentricity is the most common issue, and can be classified into static, dynamic (rotating), or combined eccentricity. Taking a radial flux PM (RFPM) machine as an example, static eccentricity exists when the rotating axis of the rotor is offset from the axis of the stator and the smallest air gap is fixed at one specific position. If dynamic eccentricity exists in the machine, however, the position of the smallest air gap varies as the rotor rotates [7].

The influence of rotor eccentricity in RFPM machine has been widely investigated in recent years. In [7], its influence on back-EMF and torque of a PM brushless machine is analysed. The study indicates that static and dynamic eccentricities result in unbalanced three-phase back-EMFs without affecting their harmonics. In [8], the impact of static and dynamic eccentricities on RFPM machines with different slot/pole combinations is examined. The study states that machines with closely similar numbers of stator slots and rotor poles are more sensitive to the effects of eccentricity than those with a larger difference between stator slot and rotor pole numbers.

In addition to rotor eccentricity and due to their unique geometry, AFPM machines have more possible types of manufacture tolerances, such as rotor/stator axis misalignment, since the stator and rotor are axially arranged. Rotor eccentricity in AFPM machines can be defined as angular rotor misalignments in which the rotor tilts with respect to the stator. On the other hand, when the rotor axis is shifted radially with respect to the stator reference axis, the rotor eccentricity can be defined as rotor/stator axis misalignment [9]. With reference to AFPM machines, the influence of rotor eccentricity has also been investigated in a number of papers [10, 11]. The influence of rotor/stator axis misalignment on AFPM machines is initially investigated in [10]. In [11], the effect of static rotor angle misalignment on air-gap flux density, back-EMF, and the force of a single sided AFPM machine is investigated. The study shows that rotor angular misalignment leads to distorted air-gap flux density distribution, unbalanced back-EMF, and uneven force. The effect of rotor/stator misalignment on the cogging torque of a single-sided AFPM machine is discussed and experimentally verified in [12]. The results reveal that rotor misalignment creates more cogging torque harmonics, which are sidebands of the fundamental harmonic. Furthermore, in [13], the influence of rotor imperfections on the forces and torques acting on the rotors of yokeless and segmented armature (YASA) machines is briefly investigated. The study and experimental results show that the rotor angular and axis misalignments significantly affect the rotor force and torque. Moreover, rotor defects increase the force on the machine stator due to the unbalanced force produced by the rotors. Furthermore, in terms of the YASA machine, the impacts of static and dynamic rotor angular and axis misalignments on no-load performance are investigated in [14]. An analytical method and experimental tests are utilised to analyse the machine back-EMF under rotor misalignments. The study indicates that angular misalignment has a minor effect on the machine back-EMF. However, static and dynamic axis misalignments change the amplitude and the phases of the machine back-EMF.

In this present study, we focus on the axial flux magnetically geared machine presented in [15]. Since rotor misalignment has not been investigated for AF magnetically geared machines, the influence of static and dynamic LSR/stator misalignments on machine performance is investigated using 3-D FEA. The cogging torques of HSR, LSR, and air-gap flux densities as well as back-EMF’s are studied. Performance comparisons of the machine under healthy, static, and dynamic misalignment conditions are conducted. Additionally, the influence of LSR/stator misalignment on the transferred MG torque is studied and compared with the healthy condition. Finally, the on-load machine torque performance is investigated and compared.
respectively. When the modulation pieces are fixed, the machine specifications, optimal dimensions and materials. The machine is comprised of one stator (containing 12 pole iron pieces with concentrated windings) sandwiched between two surface mounted PM axial rotors. By utilising different pole numbers for the two PM rotors, a magnetic gearing (MG) effect can be achieved in the 10-pole HSR, 12-pole iron pieces and the 14-pole LSR. The magnetic flux harmonics and the angular variations of stator slots' air-gap width are uneven. The second is axis misalignment, which occurs when the rotor centre line is offset from the centre line of the stator [11]. Only LSR/stator axis misalignment is considered here. This type of misalignment is further categorised into the following: static axis misalignment and dynamic axis misalignment. Static axis misalignment may occur when the rotor bearing housing flange is defected; therefore, the LSR shaft geometry centre is offset in relation to the stator geometry centre. In this case, the LSR rotates on its shaft's reference axis, as shown in Fig. 2a. Moreover, dynamic axis misalignment may occur, in which the LSR geometry centre is offset with reference to the centre of the stator's geometry and rotor shaft. In this case, the LSR rotates around the stator geometry centre (reference axis) due to a failed connection between the rotor disk geometry and its own shaft, as shown in Fig. 2b [17]. Here, the LSR is offset by 2 mm on the x-axis in both cases, as illustrated in Fig. 2.

3 Static and dynamic LSR/stator misalignments

In general, there are two potential types of rotor/stator misalignments in axial flux machines. The first is angular misalignment, in which the rotor and stator are un-parallel. In this case, the rotor axis is angularly deviated with respect to the centre of the stator, and the air-gap width is uneven. The second is axis misalignment, which occurs when the rotor centre line is offset from the centre line of the stator [11]. Only LSR/stator axis misalignment is considered here. This type of misalignment is further categorised into the following: static axis misalignment and dynamic axis misalignment. Static axis misalignment may occur when the rotor bearing housing flange is defected; therefore, the LSR shaft geometry centre is offset in relation to the stator geometry centre. In this case, the LSR rotates on its shaft's reference axis, as shown in Fig. 2a. Moreover, dynamic axis misalignment may occur, in which the LSR geometry centre is offset with reference to the centre of the stator's geometry and rotor shaft. In this case, the LSR rotates around the stator geometry centre (reference axis) due to a failed connection between the rotor disk geometry and its own shaft, as shown in Fig. 2b [17]. Here, the LSR is offset by 2 mm on the x-axis in both cases, as illustrated in Fig. 2.

4 Influence of LSR/stator misalignment on machine performance

With the aim of investigating the influence of LSR/stator axis misalignment on machine performance, 3-D FEA is usually used. The machine performance (i.e. cogging torque, flux density, back-EMF and torque) is investigated under static and dynamic misalignments with reference to the normal, healthy condition.

4.1 Cogging torque

One of the decisive factors which should be studied in the analysis and design of PM machines is cogging torque. The cogging torque $T_C$ exists in PM machines due to the interaction between the PM magnetic flux harmonics and the angular variations of stator slots' reluctance and can essentially be described as in [18].

$$T_C(\theta_m) = -J_i \phi_k \frac{dR}{d\phi_k}$$  \hspace{1cm} (3)

where $\phi_k$ and $R$ are the air-gap flux and reluctance, respectively, and $\theta_m$ is the rotor position. In addition, the cogging torque waveform of a PM machine can be expressed as in [19].

$$T_C = \sum_{k=1}^{\infty} T_k \sin(kN_c \theta_m + \phi_k)$$  \hspace{1cm} (4)

where $T_k$ and $\phi_k$ are the magnitude and phase of the $k$th harmonic component, respectively; and $N_c$ is the least common multiple between $n_s$ and 2p. The cogging torque amplitude differs depending on the stator and rotor pole combination. It has been shown that PM machines with rotor pole and stator slot numbers differing by one have significantly smaller cogging torque compared to those differing by two at normal condition [7]. Moreover, numerous methods have been investigated for cogging torque minimisation in axial flux machines [20]. However, the cogging torque is significantly exacerbated by the unavoidable manufacturing tolerance [6]. For the introduced magnetic-geared machine, the impact of static and dynamic LSR/stator axis misalignments on two rotors' cogging torque is investigated. To calculate the cogging torque, the magnetic gear average transferred
torque between both rotors should be zero. This can be achieved by aligning one LSR pole with one HSR pole (whereby the relative angle between HSR and LSR is zero). Moreover, the HSR is driven with a constant speed of 400 rpm while the LSR speed is 285.5 rpm. As such, the average torque produced from MG effect between both rotors is always zero. Furthermore, it should be noted that since the machine has two rotors, the LSR and HSR cogging torque periods are calculated with respect to their individual mechanical cycles.

Figs. 3 and 4 show the LSR and HSR cogging torques at static and dynamic misalignments with the reference to the healthy condition, respectively. It is clear that LSR and HSR cogging torques for the healthy model have periodic components with fundamental harmonics of 84th and 60th order, respectively, which can also be estimated by calculating the smallest common multiple between $n_s$ and the rotor pole $2p$ [19]. However, misalignment of the LSR/stator results in LSR and HSR cogging torque modulation in which additional cogging torque harmonics are created. It can also be noticed that native harmonics of the 14th order for LSR and of the 10th order for HSR appear due to static rotor misalignment (the multiple of rotor poles) while the native harmonics of the 12th order for LSR and the 9th order for HSR appear due to dynamic LSR misalignment, as shown in Figs. 3b and 4b.

The cogging torque amplitudes for LSR and HSR at healthy conditions are different due to different number of rotor poles and hence differing air-gap flux, as stated by (3). On the other hand, in terms of rotor misalignment, during the rotation of the HSR and LSR, the timing of LSR pole-slot intersection is not symmetrical due to the shifted position of the rotor axis. Moreover, in terms of dynamic LSR misalignment, the torque arms for each rotor pole vary as the rotor changes its position [12]; therefore, the cogging torque waveform is distorted and the amplitudes of the existing harmonics are changed, which results in additional harmonics. According to (4), the additional harmonics are added to the existing harmonics, which results in obvious changes in the waveform of the cogging torque.

4.2 Air-gap flux density

To reveal the reason for the cogging torque being affected by rotor misalignment, the flux densities at initial rotor position over the middle air gap corresponding to LSR and HSR for all conditions are calculated and compared in Figs. 5 and 6, respectively. It can be seen that the flux density of the healthy condition machine evidences odd harmonics in addition to the fundamental order, e.g. 5th, 9th, 17th and 19th harmonics for LSR air gap and 7th, 15th, 17th and 19th harmonics for HSR. When LSR misalignment exists, the non-uniform reluctance is greater on the side at which the rotor pole is offset over the stator's outer diameter and smaller at the opposite side as a consequence of the fringing effect. Therefore, the non-uniform reluctance results in air-gap flux distortion. The amplitudes of the fundamental harmonics of LSR flux (7th) and HSR (5th) are obviously reduced due to the fringing effect. Moreover, the number of additional field harmonics is increased due to static and dynamic LSR misalignments, as can be seen in Figs. 5b and 6b. The additional flux sideband harmonics around the LSR flux fundamental harmonics (i.e. 6th, 8th) are significantly increased. Moreover, the air-gap flux density waveform shown in Fig. 5a is shifted due to the rotor shifting with respect to the circumferential middle circle over the air gap. On the other hand, the change in the HSR flux density is slighter compared to that of LSR flux density. The fundamental sideband harmonic orders (4th, 6th) are marginally increased, as can be seen in Fig. 6b. Therefore, it can be concluded that for PM machines, the flux distribution in the air gap is essentially non-uniform, which is the reason for cogging torque production. However, the air-gap flux distortion caused by rotor misalignment contributes more undesired harmonic contents, ultimately resulting in an increase in the machine cogging torque.

4.3 Back-EMF

The influence of both static and dynamic LSR axis misalignments on the machine back-EMF is also investigated. Fig. 7 indicates the calculated three-phase back-EMF waveforms and their spectra in the static misalignment case. The back-EMF waveform at static
misalignment is slightly changed compared to healthy back-EMF. Static misalignment results in slightly unbalanced three-phase back-EMF waveforms. More specifically, the amplitudes of three-phase EMFs are unequal: the back-EMF of phase A has the largest amplitude: the largest amplitude phase depends on the direction of rotor/stator misalignment. Unbalanced back-EMF is due to unbalanced flux distribution over the LSR air gap attributable to rotor misalignment. Moreover, as can be shown in Fig. 7b, static axis misalignment only changes the harmonic component amplitude of the back-EMF with no changes to the harmonic contents. On the other hand, for dynamic LSR misalignment, the three-phase back-EMF waveforms are slightly modulated: unbalanced for a full electrical cycle, but balanced with respect to one mechanical cycle in which the three-phase EMF fundamental harmonic amplitudes are equal, as shown in Fig. 8a. From Fig. 8b, it can be seen that dynamic misalignment affects the harmonic amplitude and contents since more harmonics (i.e. 5th and 9th) appear due to rotor rotation at dynamic misalignment. In general, the decreases in three-phase back-EMF amplitudes are slight; therefore, more significant decreases are expected in the case of higher rotor misalignment levels.

4.4 Torque

The HSR and LSR torques produced by both gearing effect and armature reaction of the proposed machine at static and dynamic LSR/stator axis misalignments are studied and compared. The torque transferred by the magnetic gear is calculated at maximum relative angle between both rotors (90°) at no current. Moreover, the machine on-load torque can be obtained when rated current is applied to the stator winding at maximum relative angle between both rotors. Fig. 9 shows the no-load magnetic gear torque response for static and dynamic LSR misalignments compared to the healthy torque performance. When LSR/stator axis misalignment exists, the gearing effect torque of both rotors is significantly decreased, as shown in Fig. 9a. Moreover, the static and dynamic misalignments have the same effect on the torque performance. The decrease in machine torque is due to the decrease in the flux density of the LSR air gap. Furthermore, the torque ripple for the healthy condition of both rotors is relatively small (i.e. 2%); nevertheless, LSR static and dynamic misalignments increase the torque ripple of both rotors (LSR 4%, HSR 6%), as shown in Fig. 9b. On the other hand, the LSR misalignments have

![Fig. 5 Air-gap flux density in the middle of the LSR gap at initial position. (a) Waveforms. (b) Harmonic spectra](image1)

![Fig. 6 Air-gap flux density in the middle of HSR air gap at initial position. (a) Waveforms. (b) Harmonic spectra](image2)

![Fig. 7 3-phase back-EMFs at static LSR axis misalignment. (a) Waveforms (b) Harmonic spectra](image3)
the same effect on machine on-load torque as no-load torque. The change in the machine torque here occurs for the same reason as the no-load case, as can be seen in Fig. 10.

5 Conclusion

In this study, the influence of static and dynamic LSR/stator axis misalignments on the performance of axial flux magnetically geared machine has been analysed using 3-D FEA with reference to the healthy case. It is found that rotor/stator axis misalignment results in additional cogging torque harmonics due to the additional air-gap flux density harmonics. Moreover, air-gap flux density is sensitive to rotor/stator axis misalignment. Furthermore, the amplitude and the harmonic components of the back-EMF are slightly changed in which the degree of such change depends on the stator/rotor axis misalignment distance. In addition, the effect of the LSR misalignment on the magnetic gear torque and on-load torque has been studied. It is shown that the machine torque is obviously decreased by static and dynamic LSR/stator axis misalignments.

6 References

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