Received 22 February 2024; revised 31 May 2024; accepted 23 June 2024.
Date of current version 10 September 2024. The review of this article was arranged by Associate Editor Fernando Briz.

Digital Object Identifier 10.1109/OJIA.2024.3430047

Permanent Magnet Rotor Flux Linkage Control Through Direct Axis Field Amplification

DAVID KLINK (Student Member, IEEE), MATTHEW J. BAGNARA (Student Member, IEEE), GREG HEINS (Member, IEEE), AND BEHROOZ BAHRANI (Senior Member, IEEE)

Electrical and Computer Systems Engineering, Monash University, Melbourne, VIC 3800, Australia

CORRESPONDING AUTHOR: DAVID KLINK (e-mail: david.klink@monash.edu)

This work was supported by the Australian Government Research Training Program (RTP).

ABSTRACT Permanent magnets are popular for electric vehicle rotors due to their high energy density, making them excellent candidates for high-torque and high-speed machines. The downside of a permanent magnet machine is the inability to regulate the rotor field, creating nonideal behavior during high-speed or low-load operation, and potentially resulting in high currents and voltages in fault conditions. Several solutions to this have been explored, such as interior permanent magnet (combined reluctance and permanent magnet rotors), "hybrid" wound field and permanent magnet rotors, and variable flux machines with in-situ magnetization control or mechanical field weakening. This article proposes a novel method of regulating the air gap in axial flux machines, allowing for a low-cost mechanism allowing two degree of freedom operation without additional power electronics or modifications to the magnetics. The proposed method uses stacked linear springs to create a nonlinear bias against the attraction force, and then leverages direct axis current to control the air gap. The ideal constant current optimized field weakening spring curve is presented and the proposed concept is experimentally validated on a single-stator single-rotor axial flux machine.

INDEX TERMS Axial flux, field weakening, flux linkage, flux weakening, mechanical, permanent magnet (PM), variable, variable air gap.

I. INTRODUCTION

Typical electric machines for mobility applications include induction machines (IMs), synchronous reluctance (SynRM), wound field (WF), permanent magnet (PM), or hybrid machines, such as interior permanent magnet (IPM), or hybrid PM/WF. These topologies either rely on direct rotor field excitation (through PMs or coils) or indirect excitation (via induction or by utilizing magnetic reluctance torque).

The choice of which type of machine to use depends heavily on factors, such as operating cycle, cost, and performance parameters including specific torque/power and torque/power density. There is no universal solution to the challenge of which machine topology or rotor excitation method to use. These machines can be broadly split into the following three classes based on their rotor field excitation.

1) Direct or indirect controlled excitation.
2) PM rotors with fixed excitation.
3) Variable PM rotors with controlled excitation.

The rotor field in IMs, SynRMs, and WF machines can be regulated via the stator or, in the case of the WF, via the rotor current excitation. This makes them very well suited to applications where rotor field control is desirable, for example, in extended field weakening or low-load/high-speed operation. These variable rotor field characteristics are desirable for traction applications, which typically require extended speed range and efficiency at low load (cruising).

PM machines, on the other hand, utilize a typically uncontrollable fixed excitation. PMs provide a lossless, high-energy-density field. This quality makes them an excellent candidate for high-performance and high-speed machines where reduced rotor mass and loss are desirable [1]. However, due to their permanent excitation, in general, the PM flux linkage cannot be directly controlled, which can result in oversized power electronics, reduced efficiency at low loads and a limited safe constant power speed range (CPSR).

Finally, there is emerging research on a third class of machines: PM machines with discrete or continuously variable rotor flux linkage. These topologies aim to take advantage of the benefits of PMs at high load points, while reducing the excitation to minimize loss and extend speed range at lower loads. This research will focus on this third class of machines.

A. PM MACHINES WITH FLUX LINKAGE CONTROL

Control of the rotor flux linkage in a PM machine can be achieved in many ways. The main mechanisms include the following.

1) *Rotor coils (hybrid PM/WF):* Several groups have explored the merits of this approach [2], [3], [4], [5], [6], [7]. While this is a viable method to control rotor flux it has several drawbacks inherently present in WF machines. This includes a significant increase in the mass and loss of the rotor, reducing operating speeds, dynamic response, increasing bearing loads and providing thermal challenges. The high field strength (coercivity) of these rare Earth PMs, such as NdFeB and SmCo, also makes it difficult to control the flux.
2) *Controlled magnetization and demagnetization through pulses of current:* Similar to the previous, the very high coercivity of PMs can make this very challenging. Hybrid ferrite/AlNiCo and rare Earth rotor structures have been proposed [8], [9], [10], [11], [12], but this results in additional mass, and provides a limited control range. An advantage here is that some of these structures can allow for variable PM flux designs while utilizing less or no rare Earth materials. They also only require a single magnetizing/demagnetizing pulse (no continuous excitation); however, this pulse also typically requires significantly increased inverter voltage/current ratings, reducing the benefits.
3) *Diverting the flux away from the stator:* Ideally through a device in the same rotating reference frame to avoid eddy current and core losses from alternating fields, this has been explored by Urquhart et al. [13], by using an axially adjustable secondary steel rotor to "short circuit" the IPM flux.
4) *Mechanical torque or speed-based flux control:* There are several ideas proposed to phase shift multiple rotors or windings in order to minimize or cancel incident back-emf. Ferraro et al. [14] proposed a mechanical torque-based and speed-based device that changes the relative phase of the two rotors in a double-rotor axial machine to achieve an extended CPSR. A similar arrangement is proposed by Capponi et al. [15], where a coreless double-rotor axial employs a double winding system that is phase-shifted in order to reduce total coil flux linkage as speed increases. An advantage of these approaches is that the mechanical mechanisms can be designed to be fault tolerant; however, a downside is that while the phase shifting cancels the voltage, there is still a significant amount of flux present which will result in high iron and eddy current losses at high speeds.
   Other approaches include spring-loaded magnets or flux shorting blocks that slide in reaction to centripetal force [16], [17], or gear-connected circular magnets, which can rotate to short flux internally rather than pushing it through the stator [18].
5) *Mechanical air gap control with additional actuators:* This solution has been explored by many and is only practically achievable in axial or conical air gap machines due to their planar air gap. Zhao et al. [19] employed a compound axial flux structure with a variable air gap to extend speed range. Several groups demonstrated the speed-extending capability as well as the efficiency and performance benefits of such a system, often including drive cycle-based analysis [20], [21], [22], [23].
   However, as with a lot of the proposed methods above, the downsides of implementing such a system may outweigh the benefits. Some do not provide any details of how the variable air gap behavior is achieved; others provide a theoretical solution but lack experimental validation. Those that do demonstrate operation require expensive actuators or mechanisms, such as ball-screws or other linear actuators, which require additional hardware, power and control mechanisms. In this case, it is typically better to build a bigger or more expensive machine, rather than utilizing one of the above methods to improve performance. In addition, the analyses often incorporate only air gap variation, rather than considering both air gap variation and modulation of the current phase (traditional field weakening).

B. ROTOR POSITION CONTROL WITH DIRECT AXIS CURRENT

Although intended to achieve two-degree of freedom (DOF) actuation or achieve bearingless operation rather than control rotor flux linkage, there have been some concepts exploring variable air gap or variable flux linkage magnetics. Two-DOF "bearingless" rotor topologies that use a force biasing spring to counteract the axial attraction forces and leverage stator currents to independently control air gap and machine torque were proposed by the authors in [24] and [25]. However, they do not explore in detail the design requirements of the force biasing system and how it interacts with the machine under various conditions, such as field weakening for continuous power conversion. Integration into existing machine topologies has also been explored [26], [27], with parallels to these variable air gap machine systems using direct axis current to regulate force—particularly the control and simulation aspects. A similar approach of field weakening by using direct axis current to control mechanical force in order to achieve a rotor phase shift in a split-rotor radial flux machine has also been explored by Capponi et al. [28].

C. RESEARCH GOAL

While air gap adjustment and flux linkage control for the purpose of efficiency optimization and extended speed range have been explored in the past, most solutions provided are either not physically realizable or not economical, requiring expensive actuators or complex mechanisms. This article expands on the existing literature by proposing and evaluating a mechanism for air gap control for continuous power transfer, combining some of the techniques used in bearingless systems and two-DOF machines with variable air gap machines. A mechanically realizable and relatively inexpensive pathway to the rotor PM flux linkage control problem is proposed and experimentally validated on a single-sided axial flux machine, although it is also realizable on double rotor and double stator type machines. This solution utilizes mechanical springs to bias the magnetic axial attraction force of the axial flux machine and uses direct axis current to control the attraction force, thereby controlling the air gap. The implementation is demonstrated experimentally on a purpose built test-machine designed for measurement and adjustability, utilizing simple linear motion and spring components that are commonly integrated into compact mechanisms.

The rest of this article is organized as follows. The challenges associated with variable flux linkage through air gap control are discussed in Section II. Section III explores the characteristics of the system and implementation of the variable air gap system. Experimental validations are presented in Section IV. Finally, Section V concludes this article.

II. PM ROTOR FLUX LINKAGE VARIATION THROUGH AIR GAP CONTROL

A. CHALLENGES

There are four key challenges to overcome when controlling the air gap of axial flux machines. These exist in the steady state but are exacerbated during dynamic operation.

1) *Axial attraction force:* Due to the inherent construction of an axial flux machine, there is a significant attraction force between the rotor and stator disks. This force scales with the square of the axial (Z-axis) flux. Typically, this parasitic effect is discussed in the context of bearings, as the bearings must carry a significant axial loading, which increases the cost, mass and loss. A key benefit of the variable air gap system is that at higher speeds, typically a larger air gap is employed, reducing the axial forces on the bearing and consequently reducing the loss significantly. The force-producing system must be able to overcome the maximum force at minimum air gap continuously and reliably to enable a variable air gap system.
2) *Control:* A standard PM machine system has current (torque), field weakening (flux), speed, and sometimes position controllers. For optimal operation in a variable air gap system, an air gap controller is required. As the torque constant is dependent on the air gap, a change in the air gap will result in a change in output torque at a given current. This introduces cross-coupling effects into the speed controller, as the air gap change will affect the output torque. Furthermore, varying the air gap causes the magnetic flux through the coils to change, resulting in induced voltages that create further disturbances in the current controllers.
3) *Mechanical complexity:* Another topic often explored in the context of axial flux machines is the manufacturability, particularly for YASA-style machines. A large cantilevered air gap means that small angular misalignments and shaft runout can result in large deviations of the air gap and, therefore, magnetic characteristics. This can result in parallel currents flowing, which reduces efficiency. These deviations also add significant unbalanced forces which increase bearing loads and vibrations.

   Furthermore, actively changing the air gap requires new components to be added to the machine, including a bearing system to allow for linear motion, some form of actuation and a feedback mechanism for determining the air gap (although this can be done through sensorless methods). This further adds to the machine's system complexity and mechanical compliance.
4) *Fault tolerance:* Similar to a traditional PM machine operating under field weakening, a fault in the controller or actuation system at high speed can result in significant overvoltages and fault currents, which can cause catastrophic failure of insulation and the power electronics in the inverter. High-impact loading can also damage and reduce the lifetime of bearings.

The benefits of varying the air gap are clear, as outlined in Section I. However, the existing literature does not adequately address their implementation. Prototype systems and literature exploring these topics either employ expensive linear actuators and linear bearings or do not provide a solution for the actuation at all. In addition to being expensive, systems utilizing traditional external actuators often require locking features to reduce loss, maintain steady-state air gaps, and limit air gap collapse in fault situations.

B. REQUIREMENTS

Based on these challenges, dynamic air gap control systems have two major requirements: force biasing and force control. These can be achieved separately or together via various mechanisms, which also influence the fail-safe behavior. Furthermore, axial motion necessitates a linear guide or bearing system.

1) *Force biasing:* To reduce the load on the controlling actuation system and limit controller fault behavior, a passive parallel force biasing system can be employed. A system that perfectly biases electromagnetic attraction force over the air gap curve effectively stores the magnetic potential energy, requiring no work to be done by the force control system.

   This is similar to springs implemented in manufacturing systems where humans are required to lift heavy machinery, by matching the potential energy curves of the springs and masses under the influence of gravity.

2) *Force control:* With a "perfect" passive attraction force biasing system, the demands on the force control system are significantly reduced, allowing for a "zero work" actuator. In this case, the actuator only needs to provide force to overcome the inertial forces required to achieve the desired dynamic response. This reduces the actuation system cost and mass significantly, assuming the passive force biasing system is also cheap and lightweight.
3) *Force producing mechanisms:* Force biasing can be implemented in several ways, for example through nonlinear mechanical, electromagnetic, pneumatic springs, or hydraulic systems. Force biasing can be separate from force control, but certain implementations (such as pneumatic or hydraulic systems) can achieve force biasing as well as force control through control of internal cylinder pressures. In addition, certain methods of force biasing may also provide inherent damping, which reduces the need for active or passive damping systems.
4) *Linear motion:* To accommodate the axial motion of a rotor or stator, a linear bearing or a similar type of linear guide must be implemented to constrain the motion. In the case of a stator system, this must also provide a reaction torque. In a moving rotor system, a moving spline system (for example a ball spline) must be used to accommodate rotational and translational motion.
5) *Fault behavior:* Generally, it is desirable that the system is fail-safe and robust to external disturbances, such as noise, unexpected loads, or a total loss of power. Typically, this means it is desirable to have a system in which the air gap "fails open" to avoid catastrophic failure, particularly during high-speed operation (heavy field weakening).

III. ELECTROMAGNETIC FORCE CONTROL—ROTOR FLUX "AMPLIFICATION"

An economical solution that requires no significant external inputs and expensive actuators is desirable. This can have many implementations depending on budget and integration requirements.

A. ATTRACTION FORCE PROFILE

Before discussing an actuation implementation method, the force profile of an axial flux machine must be understood. A 3-D finite element analysis (FEA) model in Ansys Maxwell is used to simulate an axial flux machine with Neodymium PMs. The machine simulated reflects the machine chosen for experimental validation, outlined in Table 1. Where normalized currents have been used, they have been normalized against the peak condition (20 Arms or 12 Nm with zero direct axis current). The magnetic force versus air gap and flux linkage are shown in Fig. 1. It demonstrates a nonlinear characteristic, suitably matched by a third-order polynomial.

Because the attraction force is dependent on the square of flux density, and the reluctance to the stator core increases linearly with air gap, a second-order polynomial curve would be expected. The third-order behavior is the result of magnetic flux leakage from pole to pole, which reduces the flux linkage to the stator core, an effect which increases with air gap.

TABLE 1. Parameters of the PM Axial Flux Machine

Parameter	Value	Unit
Core outer diameter	100	mm
Peak torque	12	Nm
Rated torque	3	Nm
Rated current density	7	A/mm2
Rated speed	6000	RPM
Torque constant (1mm gap)	0.6	Nm/Arms
Phase inductance	1.4	mH
Phase resistance	450	mOhm

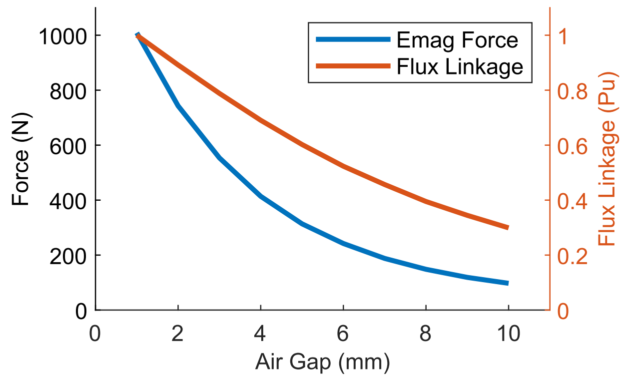

FIGURE 1. Electromagnetic force and normalized flux linkage (back emf constant) versus air gap.

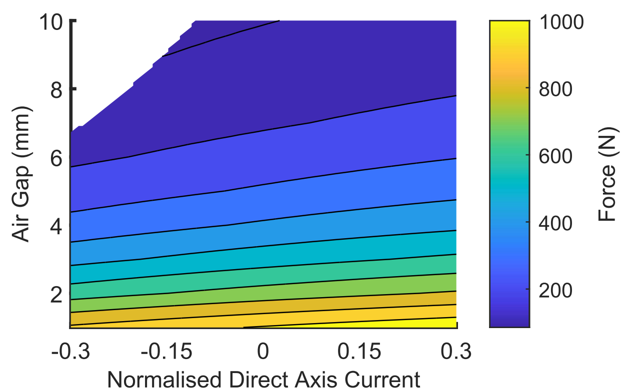

FIGURE 2. FEA electromagnetic force versus direct axis current and air gap.

B. ATTRACTION FORCE CONTROL

Although force control can be achieved with an external actuator, the stator currents can also be leveraged to control the attraction force. This concept is often employed in magnetic bearings. By controlling the phase and magnitude of the current, the stator can attract and repel the rotor, regulating the attraction force, as shown in Fig. 2. The cut-out in the top left-hand corner is omitted as the direct axis current is equal

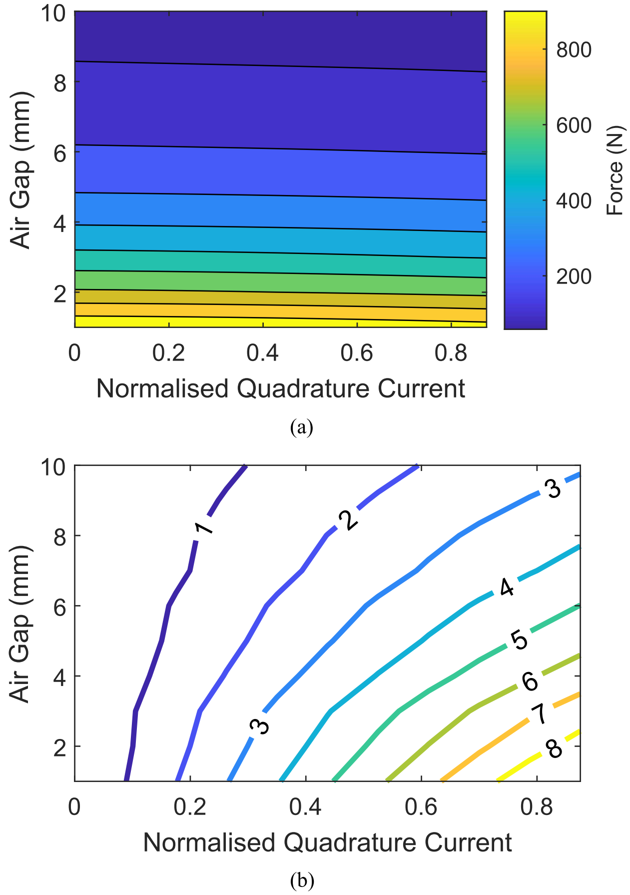

FIGURE 3. **Effect of quadrature current on axial attraction force (a) and torque (b).**

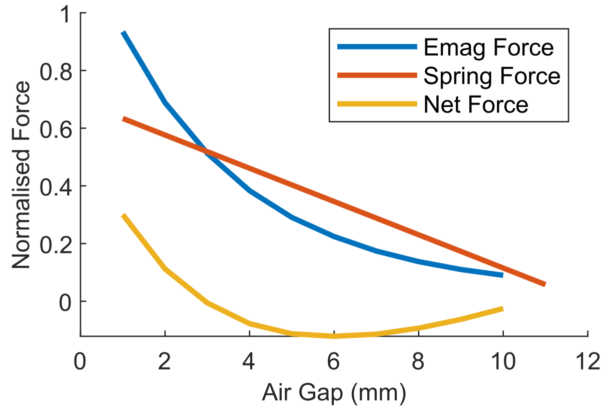

FIGURE 4. **Net *Z*-axis force with linear spring and zero direct axis current.**

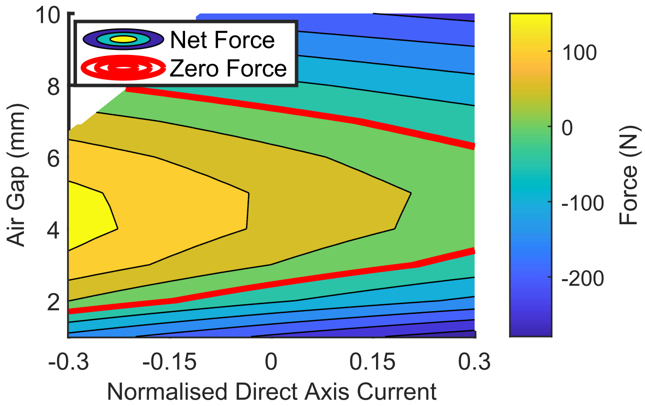

FIGURE 5. **Net *Z*-axis force with a linear bias spring.**

to the characteristic current, therefore flux in this region drops to zero. Any further air gap or field weakening increase results in unnecessary over field-weakening.

In this study, a surface permanent magnet (SPM) rotor without geometric saliency is used. The electromagnetic attraction force of an ideal (linear material) SPM axial flux system is dependent only on the direct axis current and independent of the quadrature axis current. With an ideal (linear core) non-salient rotor, the quadrature axis current only affects torque and does not directly affect the attraction force. At higher current loading, there is a minor impact on the force due to core nonlinearities (saturation). This is demonstrated in Fig. 3.

Typically, in axial flux machines SPM topologies are utilized, however, this air gap variation technique could also be leveraged for an IPM-style rotor. In this case, just as it is possible to generate reluctance torque, a reluctance attraction force will be generated with quadrature current. This behavior is not necessarily a negative and could actually be exploited to create a self-regulating system where a torque-producing current pulls in the rotor. In general, it will influence the characteristics of the spring curve and field weakening behavior but can be considered and adequately compensated for.

C. FORCE BIASING MECHANISMS

The simplest force biasing method is mechanical springs such as coil springs or belleville springs, which store energy in the form of elastic material deformation. The manufacture and use of these springs are well established. They are ubiquitous and can provide a high force with low mass and low cost. However, as opposed to the magnetic attraction force, they are typically linear. One method of creating the required nonlinear spring curve is to use a multispring system with progressive spring engagement.

D. AIR GAP CONTROL WITH PASSIVE SPRING SYSTEMS

If the stator (or rotor) is free to move and preloaded with a passive spring element, the system will reach an equilibrium point where the net force is zero, resulting in no axial rotor acceleration. This equilibrium is demonstrated by Fig. 4 and the zero force line in Fig. 5, where a linear spring has been used to oppose the electromagnetic attraction force. Although the force requirement has been reduced, there is still significant force mismatches needing to be actively regulated. Linear springs require large direct axis currents and also result in nonmonotonic or hysteretic relationships between the direct axis current and air gap.

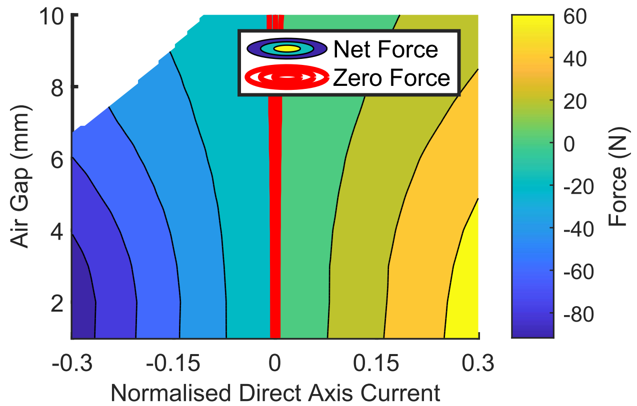

FIGURE 6. **Resultant *Z*-axis force electromagnetic force matched by spring bias. Note—no current is required to move the system in steady state.**

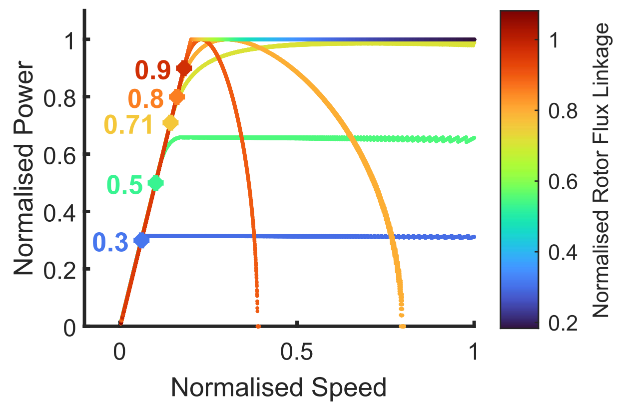

FIGURE 8. **Ideal constant current variable flux linkage machine behavior compared to static flux linkage constant current field weakening curves.**

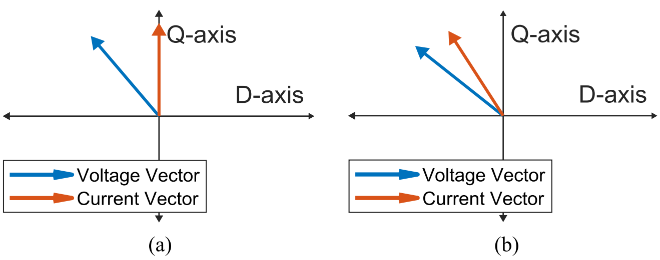

FIGURE 7. **Example of direct and quadrature axis current and voltage vectors with and without field weakening. Increased power factor is demonstrated by reduction of angle. (a) No field weakening. (b) Field weakening.**

E. INFLUENCE OF SPRING CURVE

The "obvious" follow-up approach may be to completely match the electromagnetic attraction force, as shown in Fig. 6. This reduces the current required to change the air gap, which might seem like the most efficient approach. Among other things, this approach results in a system with very low inherent "stiffness"—a small change in direct axis current results in a very large change in the air gap, reducing controller effort but giving poor disturbance rejection. The system is also more prone to manufacturing variations, which affect the attraction force or spring curve. This can be particularly difficult to control in nonlinear spring stacks, which have inherent hysteresis behavior due to the stepped characteristic (stacking of linear spring curves). Another important consideration is how the direct axis currents affect the field weakening behavior of a PM machine system—it is not necessarily desirable to have minimum direct axis current as the power factor increases during field weakening, as seen in Fig. 7. Because of this inherent relationship, the resulting constant current power curves do not exhibit ideal constant power field weakening behavior. In theory, a variable air gap system can adjust rotor flux to achieve the ideal constant power field weakening curve at a given current as demonstrated in Fig. 8. This ideal field weakening behavior also results in highly efficient operation of the machine and inverter at unity power factor, however will operate in a reduced capacity at other current limits (at worst, it performs the same as a static air gap machine).

In general, the spring curve and the resulting direct axis current versus air gap curve are application-dependent, as the optimal spring curve is dependent on the operating cycle and machine characteristics.

F. PASSIVE FORCE BIASING—SPRING CURVE SELECTION

The selection and impact of the field weakening amplification relationship between direct axis current and air gap is nontrivial and is the subject of future work. However given a desired relationship between direct axis current and air gap, a spring curve can be generated to suit it—typically it is desirable to have a monotonic and linear spring.

For the desired direct axis versus air gap relationship, the electromagnetic attraction force along the desired steady state line is evaluated. This represents the force required to put the system into a "steady state" (net zero force) condition. In this case, the system requires only a small proportion of direct axis current to close the air gap, which improves behavior under fault conditions as the system will be "normally open." This (typically) nonlinear spring characteristic is approximated through a set of staged linear spring curves by varying the spring stiffnesses, preloads, and relative displacements. The desired and synthesized curves are shown in Fig. 9.

A few examples of the possible amplification relationships between direct axis current and air gap are demonstrated alongside their required biasing spring curves in Fig. 10(a) and (b). These include the resultant steady-state air gap curves for a linear bias spring configuration, as well as the more generally applicable nonlinear spring configurations. The nonlinear spring configurations demonstrated are generated from: a linear amplification relationship, a nonlinear amplification relationship, as well as the (theoretical) ideal maximum power field weakening behavior introduced previously in Fig. 8.

The resultant power curves are demonstrated in Fig. 10(c) and (d) at rated (5 Arms) and peak (20 Arms) conditions. They

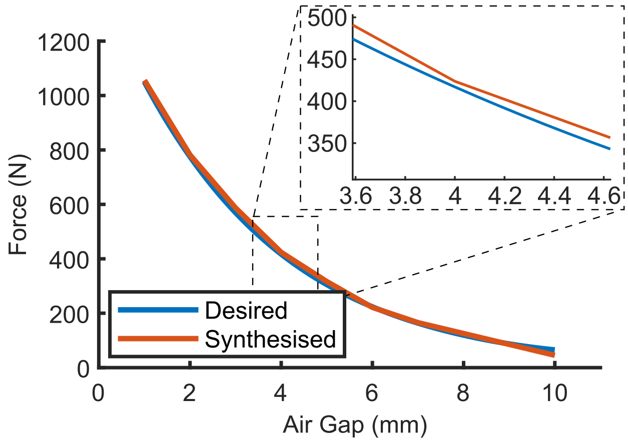

FIGURE 9. Desired and synthesized nonlinear spring curves.

compare the field weakening behavior for a static air gap, ideal variable (optimized for peak condition field weakening) air gap, as well as the arbitrary linear and nonlinear amplification relationships introduced in Fig. 10(a) and (b). A key outcome is that the low-load behavior is relatively independent of spring curve, as the same condition can be hit with a slightly less than optimal field weakening current. This is much more critical if full power is required at high speed, although the low load efficiency benefits are more significant in the steeper and/or normally open curves.

G. PASSIVE FORCE BIASING—SPRING CURVE SYNTHESIS

Once the (typically nonlinear) desired spring curve has been generated, it must be synthesized from linear springs. This is typically done through stepped spring engagement, which approximates the nonlinearity through a set of consequently engaging or disengaging springs, depending on the application. The resultant curve will not match the desired curve perfectly, and will over or undershoot the required force. The result of this is minor hysteresis loops, as well as a distortion of the initially desired direct axis current to air gap relationship. The effect of this nonideal behavior on the zero force system curve is shown in Figs. 11 and 12.

H. ENABLING LINEAR MOTION

For a moving stator (fixed rotor) system, a linear guide must oppose the reaction torque of the stator to inhibit rotational motion. This is preferable in high-speed applications where a fixed rotor enables high stiffness in the bearing assembly, as a moving rotor would also require moving the rotational bearings. A moving stator also requires the cooling lines and phase cables to move freely. A double stator axial flux arrangement would require two moving stator systems, which can compound these cooling and phase cable issues and increase the component count.

In a moving rotor system, the force must either be directly transferred (for example in a fluid moving application) through the rotor, or a linearly moving torque transmission

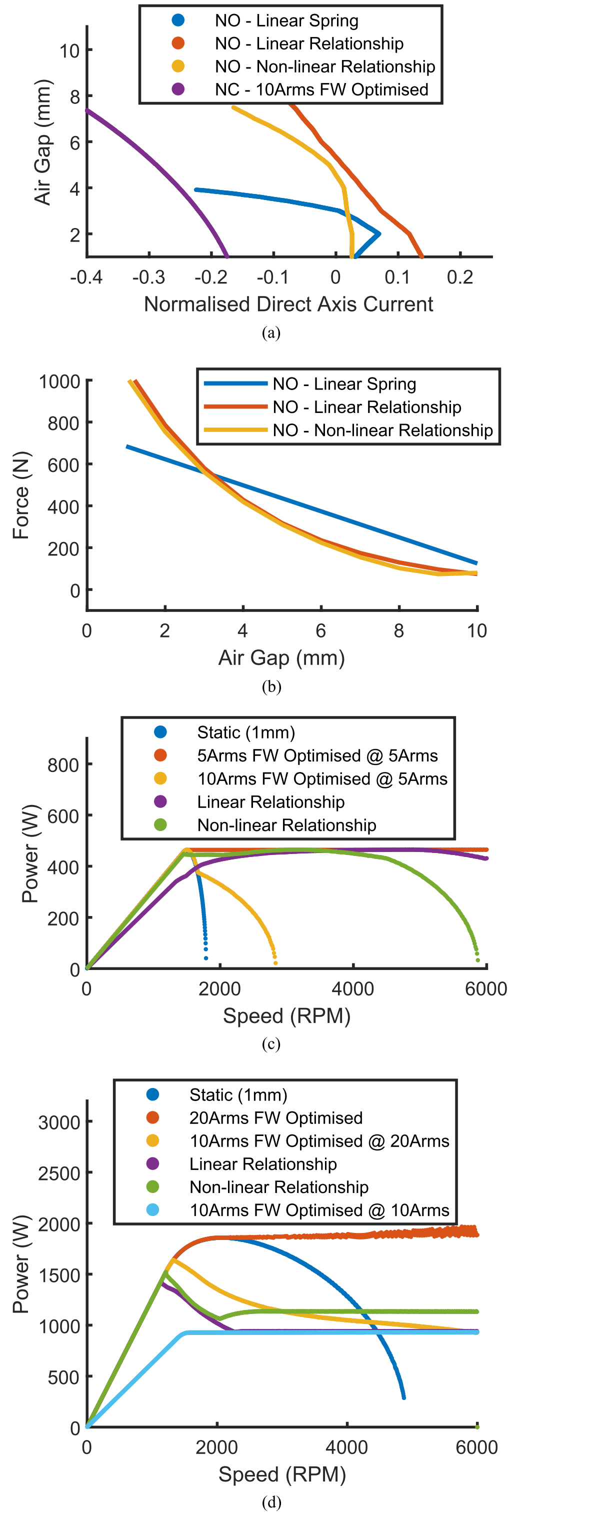

FIGURE 10. Normally open and normally closed systems. Demonstrating linear spring (nonlinear relationship) and nonlinear spring (arbitrary relationship) flux requirements and field weakening behaviors. (a) Steady state air gap behavior as a function of field weakening (direct) current (field weakening amplification relationship). (b) Spring force as a function of displacement ("bias" or "spring" curve). (c) Power curve comparison—5 Arms (rated condition). Optimal field weakening spring curve for 10 Arms (6 Nm) used for comparison. (d) Power curve comparison—20 Arms (peak condition). Optimal field weakening spring curve for 10 Arms (6 Nm) used for comparison.

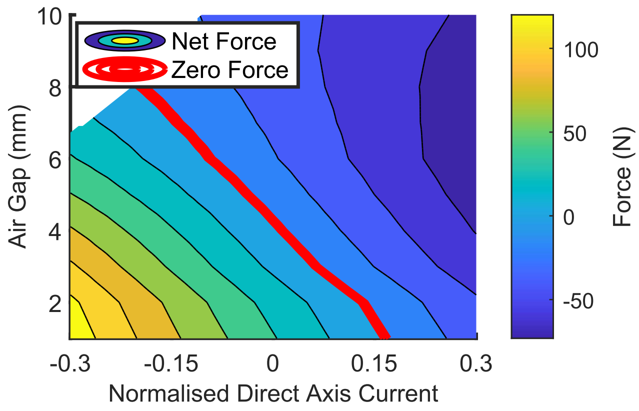

FIGURE 11. Net *Z*-axis force with a monotonic relationship and ideal nonlinear spring.

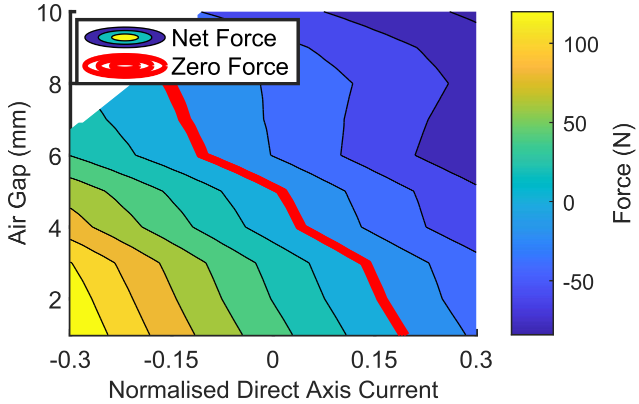

FIGURE 12. Net *Z*-axis force with a monotonic relationship and synthesized nonlinear spring.

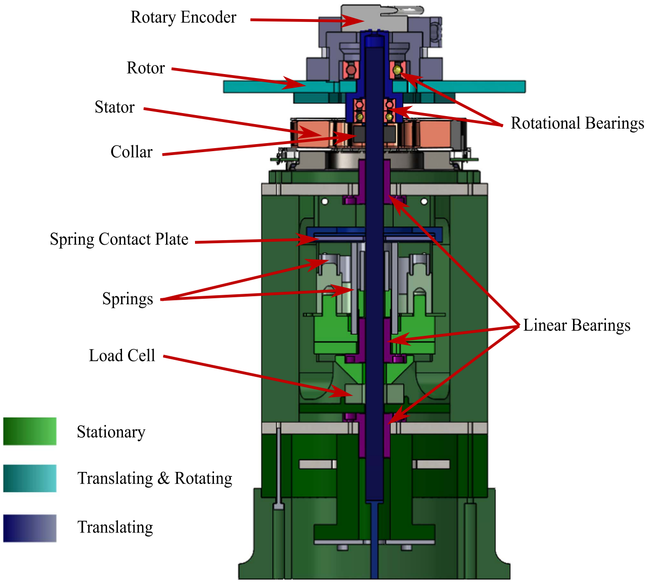

FIGURE 13. Test-machine CAD cross-section.

and force biasing method is required, such as a spring-loaded ball spline. In a double rotor configuration, this requires both rotors to move outwards which makes cooling and stator construction more challenging—compounding existing issues with the construction of double rotor [yokeless and segmented armature (YASA)] machines.

Both systems will also be impacted by inertial forces present in electric vehicles for example, however, the magnitude of these forces is very small compared to the attraction and spring forces present.

I. IMPLICATIONS FOR AXIAL FLUX TOPOLOGY AND PERFORMANCE

A variable air gap necessitates linear motion in the axial direction, requiring linear bearings or another form of linear guide. Depending on the chosen topology, this can be efficiently and compactly realized entirely within the inner volume of the machine—although this is not efficient for testing and tuning due to the restricted access.

Internal packaging is more difficult for smaller, low-power (<2 kW) machines as there is less packaging space in the inner diameter. Axial flux machines also benefit more from diameter increases compared to radial flux machines [29]. Although the mechanism adds weight, cost, and design complexity, it can also significantly reduce costs and improve performance to compensate. There are less manufacturing and performance compromises to make due to the added degree of freedom. The added costs due to manufacturing and design complexity have a higher relative impact on smaller machines at lower power levels. These detriments must be considered and balanced with the cost benefits of reduced power electronics, better efficiency, and lower magnetic requirements.

Although this method was demonstrated on a single rotor, single stator axial flux machine, it is technically possible in both double rotor (YASA) or double stator configurations. Due to the added packaging and motion requirements, variable air gap double rotor/stator configurations exacerbate existing challenges which are easier to deal with in a single stator, single rotor configuration.

In general, the decision of which axial flux topology to use (and whether the air gap is static or variable) is application-dependent [30]. For a variable air gap axial flux system, there are additional considerations regarding bearings and structural stiffness, stator, and rotor thermals, stator mounting, mechanical complexity, and manufacturing and assembly tolerances.

IV. EXPERIMENTAL VALIDATION

A. EXPERIMENTAL SETUP

A test system is manufactured to validate the design, as shown in Figs. 13 and 14. It has been assembled with an industrial single stator/single rotor axial flux machine used in Taran et al.'s [31] work. The machine utilizes copper windings, Nd-Fe-B N50H magnets, and a soft magnetic composite core. The key parameters were previously outlined in Table 1.

FIGURE 14. Assembled test-machine.

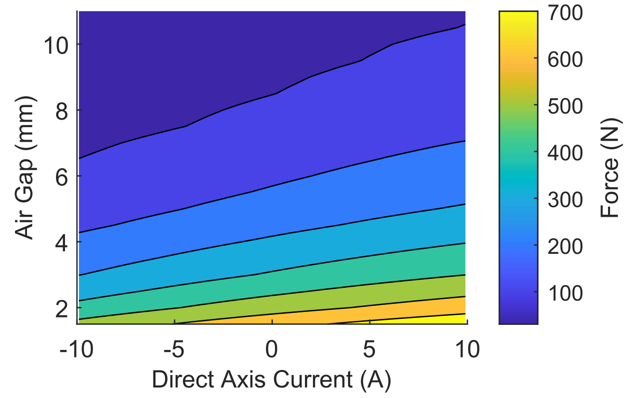

FIGURE 15. Measured combined electromagnetic and weight force versus direct axis current and air gap.

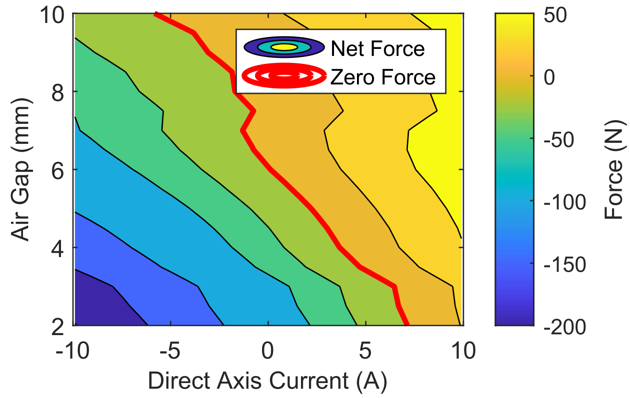

FIGURE 16. Measured net *Z*-axis force versus direct axis current and air gap.

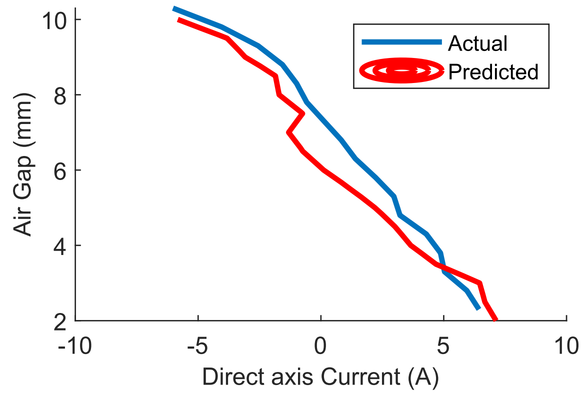

FIGURE 17. Actual and predicted steady-state air gap versus direct axis current.

This system was designed with a constrained scope to easily test and prove key elements of functionality. The PM rotor is supported via a set of deep-groove ball bearings that are concentrically located to a stationary (translating, but not rotating) central shaft. These rotational bearings are axially supported through a shaft collar, which can be easily adjusted during tuning. The shaft itself is further supported via two linear bearings, allowing for constrained axial motion. A steel disc is welded to the shaft, which serves as the contact point between the springs and the translating shaft. The layout facilitates force and displacement sensing while also allowing the springs to be easily tuned and adjusted. However, loaded shaft testing is not possible in this iteration. It is worth noting that these design choices result in a much bigger system than required. In application, the spring and linear bearing system could be significantly smaller and packaged within the inner diameter of the machine.

To achieve the required spring curve, ten linear springs with varying actuation points and spring constants are used, which is deemed sufficient to approximate the required spring curve over the intended air gap range.

A standard two-level three-phase inverter (BOOSTXL-DRV8301) is used to drive the machine with an RM44DC rotary magnetic encoder giving absolute angular position. An IZZE Racing laser distance sensor is used to measure the axial position of the machine and a load cell is placed in series with the spring load path to measure the axial force. Finally, a LAUNCHXL-F28379D DSP is used to process the inputs and control the machine and inverter.

B. VALIDATION OF ELECTROMAGNETIC FORCE

To validate the electromagnetic force, the central spring in the test-machine is replaced with a solid spacer to constrain

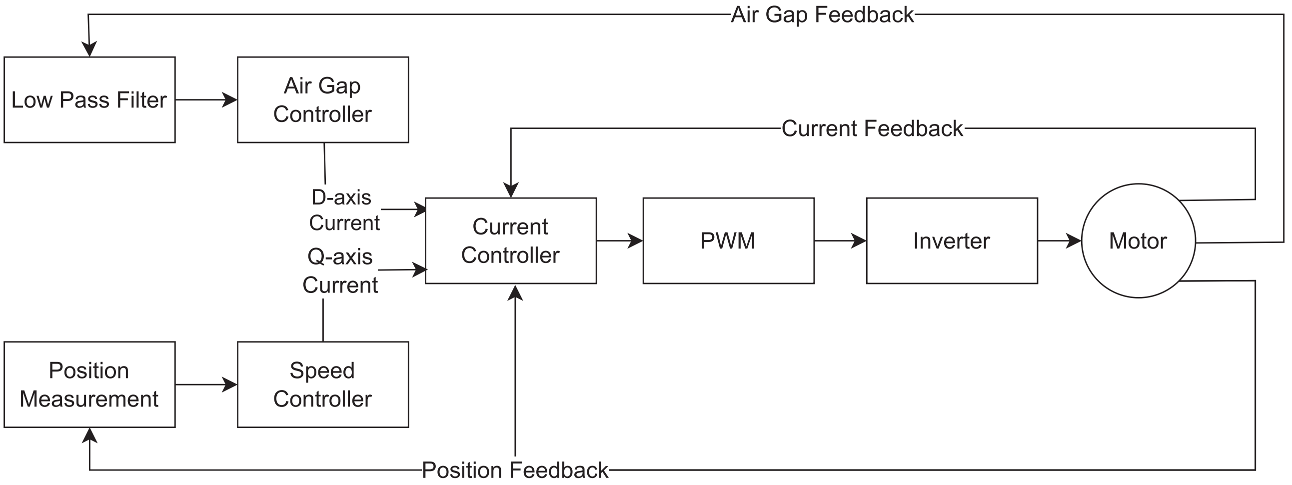

FIGURE 18. Machine drive control flow diagram.

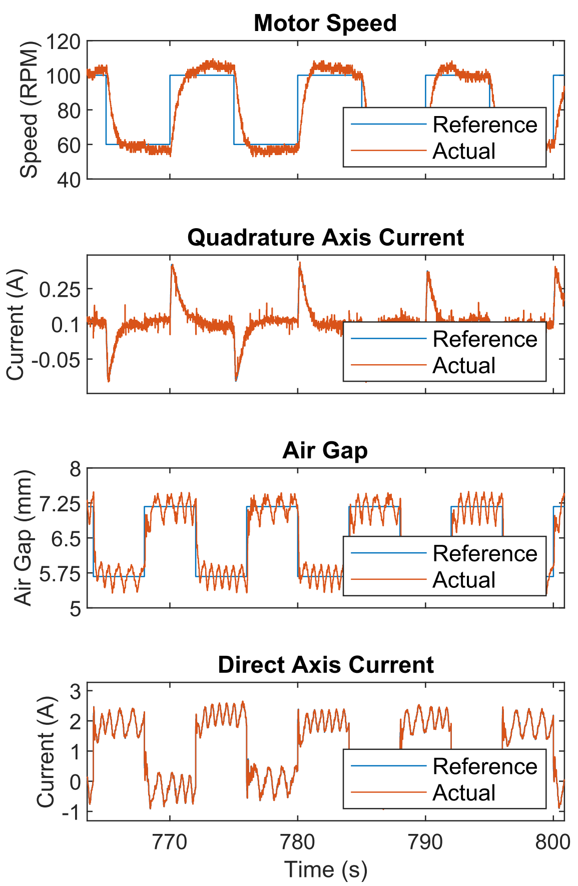

FIGURE 19. Independent closed-loop control of speed and air gap.

the air gap. Shims are used to achieve exact air gaps. The dc bus voltage is set to 20 V, and the machine is set to run at 60 RPM. A sweep of the direct axis current was conducted before changing the air gap and repeating the process. The results can be seen in Fig. 15. While there is some deviation in the results when compared to the FEA results in Fig. 2, the overall shape of the electromagnetic force curves match, supporting the actuation design approach.

C. VALIDATION OF SPRING CURVE

To achieve a suitable spring curve, ten linear springs with varying actuation points and spring constants were used to balance the electromagnetic force, although it would be possible with less (three to five) depending on requirements. A third-order polynomial was fitted to the spring curve to compare it with the electromagnetic force. Fig. 16 demonstrates this configuration of springs achieves an approximately linear relationship from 7 to 2 mm. Above 7 mm, there is a small discontinuity in the linear relationship before the relationship returns to its approximately linear trend. While this curve is not monotonic, further tuning of the springs could rectify this issue, and it may not produce a significant performance detriment in application.

D. SYSTEM VALIDATION

To validate the zero net-force curve in Fig. 16, a sweep of the air gaps used for validating the spring curve in Section IV-C is conducted and the required direct axis current is recorded. The results can be seen in Fig. 17. The results demonstrate a linear relationship between the direct axis current and steady-state air gap as desired. The predicted direct axis current versus steady state air gap relationship obtained from experimental force characterisation, as demonstrated in Fig. 16 is overlaid and is shown to closely match the actual curve.

E. SIMULTANEOUS LOAD AND FORCE CONTROL

To validate the system's controllability, a PI controller is added to the standard field-oriented control structure for PM synchronous machines. This PI controller controls the air gap by regulating the direct axis current supplied to the machine, as shown in Fig. 18. To reduce the impact of noise and rotor eccentricity, a low-pass filter was added to the air gap measurement.

The control test is conducted with a 24 V dc bus, the results are shown in Fig. 19. The air gap controller is capable of tracking the reference air gap even when there are varying speed requests. Small deviations from the reference speed can be seen in the speed of the machine as the air gap changes due to the changing torque constant. The effect of the air gap can also be seen during step speed changes, at a small air gap a smaller quadrature axis controller effort is required to accelerate/decelerate the system. These undesirable coupling effects could be compensated via characterisation and feedforward control.

The required direct axis current to maintain the requested air gap matches the expected values from Fig. 17, with –0.2 A required to maintain a 7.2 mm air gap and 1.9 A required to maintain a 5.7 mm air gap. The ripple seen in the steady-state air gap is due to a slight angular misalignment in the rotor.

V. CONCLUSION

This article reviewed the existing solutions for direct and indirect rotor field control, with a specific focus on variable PM machines. An economically viable variable air gap system was explored and a method of controlling air gap to improve efficiency, speed range and fault behavior was proposed and experimentally validated.

A single-sided axial flux machine was characterized and tested on a custom test-machine. The electromagnetic force at varying air gaps and direct axis currents was validated against the designed electromagnetic force curves and the ability to create a linear relationship between direct axis current and air gap using a combination of linear springs was demonstrated.

A basic PI controller structure was used to control the air gap through direct axis current and speed through quadrature axis current. Independent air gap and load control were demonstrated experimentally, limited due to the inherent coupling between air gap and torque constant. There is significant scope for further development in the areas of control, spring curve, and machine optimization and design.

ACKNOWLEDGMENT

The support of LEAP Australia and Monash University is gratefully acknowledged.

REFERENCES

[1] D. J. Patterson, G. Heins, M. Turner, B. J. Kennedy, M. D. Smith, and R. Rohoza, "An overview of the compactness of a range of axial flux PM machines," in *Proc. 2015 IEEE Int. Electric Mach. Drives Conf. (IEMDC)*, 2015, pp. 96–101.

[2] G. Mörée and M. Leijon, "Overview of hybrid excitation in electrical machines," *Energies*, vol. 15, no. 19, Oct. 2022, Art. no. 7254, doi: 10.3390/en15197254.

[3] Z. Q. Zhu, H. Hua, A. Pride, R. Deodhar, and T. Sasaki, "Analysis and reduction of unipolar leakage flux in series hybrid permanent-magnet variable flux memory machines," *IEEE Trans. Magn.*, vol. 53, no. 11, Nov. 2017, Art. no. 2500604.

[4] M. Ayub, G. Jawad, and B.-i. Kwon, "Consequent-pole hybrid excitation brushless wound field synchronous machine with fractional slot concentrated winding," *IEEE Trans. Magn.*, vol. 55, no. 7, Jul. 2019, Art. no. 8203805.

[5] K. Kamiev, J. Nerg, J. Pyrhönen, V. Zaboin, and J. Tapia, "Feasibility of an armature-reaction-compensated permanent-magnet synchronous generator in island operation," *IEEE Trans. Ind. Electron.*, vol. 61, no. 9, pp. 5075–5085, Sep. 2014.

[6] G. Borocci, F. G. Capponi, G. De Donato, and F. Caricchi, "Mixed-pole hybrid-excitation machine," in *Proc. 2014 Int. Conf. Elect. Mach. (ICEM)*, 2014, pp. 2625–2631.

[7] Y. Amara, L. Vido, M. Gabsi, E. Hoang, A. H. Ben Ahmed, and M. Lecrivain, "Hybrid excitation synchronous machines: Energy-efficient solution for vehicles propulsion," *IEEE Trans. Veh. Technol.*, vol. 58, no. 5, pp. 2137–2149, Jun. 2009.

[8] V. Ostovic, "Memory motors-a new class of controllable flux PM machines for a true wide speed operation," in *Proc. Conf. Rec. 2001 IEEE Ind. Appl. Conf. 36th IAS Annu. Meeting*, 2001, pp. 2577–2584, vol. 4.

[9] T. Kato, N. Limsuwan, C.-Y. Yu, K. Akatsu, and R. D. Lorenz, "Rare Earth reduction using a novel variable magnetomotive force flux-intensified IPM machine," *IEEE Trans. Ind. Appl.*, vol. 50, no. 3, pp. 1748–1756, May/Jun. 2014.

[10] N. Limsuwan, T. Kato, K. Akatsu, and R. D. Lorenz, "Design and evaluation of a variable-flux flux-intensifying interior permanent-magnet machine," *IEEE Trans. Ind. Appl.*, vol. 50, no. 2, pp. 1015–1024, Mar./Apr. 2014.

[11] T. Kato, M. Minowa, H. Hijikata, K. Akatsu, and R. D. Lorenz, "Design methodology for variable leakage flux IPM for automobile traction drives," *IEEE Trans. Ind. Appl.*, vol. 51, no. 5, pp. 3811–3821, Sep./Oct. 2015.

[12] M. Ibrahim, L. Masisi, and P. Pillay, "Design of variable-flux permanent-magnet machines using alnico magnets," *IEEE Trans. Ind. Appl.*, vol. 51, no. 6, pp. 4482–4491, Nov./Dec. 2015.

[13] I. Urquhart, D. Tanaka, R. Owen, Z. Q. Zhu, J. B. Wang, and D. A. Stone, "Mechanically actuated variable flux IPMSM for EV and HEV applications," in *Proc. 2013 World Electric Veh. Symp. Exhib. (EVS27)*, 2013, pp. 1–12.

[14] L. Ferraro, F. Caricchi, and F. Giulii Capponi, "Analysis and comparison of a speed-dependant and a torque-dependant mechanical device for wide constant power speed range in AFPM starter/alternators," *IEEE Trans. Power Electr.,* vol. 21, no. 3, pp. 720–729, May 2006.

[15] F. Giulii Capponi, R. Terrigi, F. Caricchi, and L. Del Ferraro, "Active output voltage regulation for an ironless axial-flux pm automotive alternator with electromechanical flux weakening," *IEEE Trans. Ind. Appl.*, vol. 45, no. 5, pp. 1785–1793, Sep./Oct. 2009.

[16] B. Zhao, B. Li, and Z. Gu, "Research on an axial flux PMSM with radially sliding permanent magnets," *Energies*, vol. 8, pp. 1663–1684, 2015.

[17] C. Li and C. Li, "Research on variable leakage flux function for a self-adaptive passive flux-weakening PMSM," in *Proc. 2015 18th Int. Conf. Elect. Mach. Syst. (ICEMS)*, 2015, pp. 1471–1474.

[18] T. Sun, X. Liu, Y. Zou, C. Huang, and J. Liang, "Design and optimization of a mechanical variable-leakage-flux interior permanent magnet machine with auxiliary rotatable magnetic poles," *CES Trans. Elect. Machines Syst.*, vol. 5, no. 1, pp. 21–29, 2021.

[19] J. Zhao, Y. Yan, Z. Gu, Z. Chen, and P. Zheng, "Research on an axial-axial flux compound-structure PMSM with varying air gap to fulfill field-weakening control," in *Proc. 2014 17th Int. Conf. Elect. Mach. Syst. (ICEMS)*, 2014, pp. 3345–3349.

[20] S. C. Oh, J. Kern, T. Bohn, A. Rousseau, and M. Pasquier, "Axial flux variable gap motor: Application in vehicle systems," in *Proc. SAE 2002 World Congr. I& Exhib. SAE Int.*, Mar. 2002, doi: 10.4271/2002-01-1088.

[21] G. Heins, M. Thiele, D. Patterson, and N. Lambert, "Increase in operating range and efficiency for variable gap axial flux motors," in *Proc. IEEE Energy Convers. Congr. Expo.*, 2014, pp. 5870–5876.

[22] Q. Shen and Q. Xu, "Design of variable air gap axial flux permanent magnet machine for extending the speed region," in *Proc. 2014 17th Int. Conf. Elect. Mach. Syst.*, 2014, pp. 1114–1118.

[23] D. Liu, D. Hari, C. Vagg, L. Ash, S. Akehurst, and C. Brace, "Test and simulation of variable air gap concept on axial flux electric motor," in *Proc. 2013 IEEE Veh. Power Propulsion Conf. (VPPC)*, 2013, pp. 1–6.

[24] S. Ueno and Y. Okada, "Characteristics of axial force and rotating torque and their control of permanent magnet type axial gap self-bearing motor," *Elect. Eng. Jpn.*, vol. 132, no. 1, pp. 81–91, 2000. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/%28SICI%291520-6416%2820000715%29132%3A1%3C81%3A%3AAID-EEJ11%3E3.0.CO%3B2-P

[25] S. Roggia, F. Cupertino, C. Gerada, and M. Galea, "A two-degrees-of-freedom system for wheel traction applications," *IEEE Trans. Ind. Electron.*, vol. 65, no. 6, pp. 4483–4491, Jun. 2018.
[26] J. Asama, Y. Hamasaki, T. Oiwa, and A. Chiba, "Proposal and analysis of a novel single-drive bearingless motor," *IEEE Trans. Ind. Electron.*, vol. 60, no. 1, pp. 129–138, Jan. 2013.
[27] Y. Okada et al., "Mixed flow artificial heart pump with axial self-bearing motor," *IEEE/ASME Trans. Mechatronics*, vol. 10, no. 6, pp. 658–665, Dec. 2005.
[28] F. Lelli, F. Marcolini, F. G. Capponi, and F. Caricchi, "Control of a split rotor SPM synchronous machine for very wide flux weakening operations," in *Proc. IEEE Energy Convers. Congr. Expo.*, 2023, pp. 4797–4804.
[29] M. Lampérth, A. Malloy, A. Mlot, and M. Cordner, "Assessment of axial flux motor technology for hybrid powertrain integration," *World Electric Veh. J.*, vol. 7, pp. 187–194, 2015.
[30] N. Taran, D. Klink, G. Heins, V. Rallabandi, D. Patterson, and D. M. Ionel, "A comparative study of yokeless and segmented armature versus single sided axial flux PM machine topologies for electric traction," *IEEE Trans. Ind. Appl.*, vol. 58, no. 1, pp. 325–335, Jan./Feb. 2022.
[31] N. Taran, G. Heins, V. Rallabandi, D. Patterson, and D. M. Ionel, "Evaluating the effects of electric and magnetic loading on the performance of single- and double-rotor axial-flux PM machines," *IEEE Trans. Ind. Appl.*, vol. 56, no. 4, pp. 3488–3497, Jul.–Aug. 2020.

DAVID KLINK (Member, IEEE) received the B.Eng. (Hons.) degree in mechatronics engineering and science (physics) from Monash University, Melbourne, VIC, Australia, in 2020.

He has worked extensively with electric vehicle technologies in Australia, Germany, and the U.K. As a Ph.D. candidate, he is exploring modern challenges in electrification, focusing on improving specific power and efficiency of electric machines for demanding and variable load applications, such as heavy vehicles, renewable energy, aerospace, and motorsport. His research interests include variable flux linkage machines, additive manufacturing, thermal management, high speed rotors, and electric machine application topology analysis.

MATTHEW J. BAGNARA (Student Member, IEEE) received the B.E. (Hons) degree in 2023 in mechatronics engineering from Monash University, Melbourne, VIC, Australia, where he is currently working toward the Ph.D. degree in control of three-phase machines.

His research focuses on variable speed drives and control.

GREG HEINS (Member, IEEE) received the B.Eng. (Hons.) degree in mechanical engineering and the University Medal from the University of New South Wales, Sydney, NSW, Australia, in 2000, and the Ph.D. degree in electric machine control from Charles Darwin University, Darwin, NT, Australia, in 2008.

He is currently the Director of research and development with Regal Beloit Corporation, Asia Pacific, Beloit, WI, USA. He was a Manufacturing Engineer with Robert Bosch, Clayton, VIC, Australia, and a Senior Lecturer with Charles Darwin University. His research interests include the design, control and manufacture of electric machines, vibration analysis, system modeling, and identification.

Dr. Heins was the recipient of an Australian Learning and Teaching Citation for Outstanding Contributions to Student Learning in 2011.

BEHROOZ BAHRANI (Senior Member, IEEE) received the B.Sc. degree from the Sharif University of Technology, Tehran, Iran, the M.Sc. degree from the University of Toronto, Toronto, ON, Canada, and the Ph.D. degree from the Ecole Polytechnique Federale de Lausanne (EPFL), Lausanne, Switzerland, in 2006, 2008, and 2012, respectively, all in electrical engineering.

Since 2015, he has been with Monash University, Melbourne, VIC, Australia, where he is currently an Associate Professor and the Director of the Grid Innovation Hub. From 2012 to 2015, he was a Postdoctoral Fellow with EPFL, Purdue University, West Lafayette, IN, USA, Georgia Institute of Technology, Atlanta, GA, USA, and the Technical University of Munich, Munich, Germany. His research interests include control of power electronic converters, their applications in power systems, and electric vehicles.