A Novel Variable Flux Spoke Type Permanent Magnet Motor With Swiveling Magnetization for Electric Vehicles

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\textbf{ABSTRACT} This article proposes a novel variable-flux spoke-type permanent magnet synchronous motor (VFS-PMSM), whose air gap flux density can be adjusted by “swiveling” magnetic pole directions in permanent magnet (PM). This is distinctive from conventional methods that require a large magnetizing field to magnetize and demagnetize (or partially) rotor PM along the same axis for variable flux motors. This paper first compares the proposed VFS-PMSM with two other typical types, i.e., series and parallel arrangements combining high- and low-coercivity PMs to achieve variable flux. It is found that the magnetic circuit of the proposed motor is identical to that of the series type at flux enhancing and to that of the parallel type at flux weakening. Therefore, the wide flux regulation range of the parallel type motors and the excellent on-load demagnetization-resisting capability of the series type motors can both be achieved in the proposed design. Another benefit of the proposed design is that the flux produced by the low-coercivity magnet constantly or aligns with that produced by the high-coercivity one whether the motor is flux enhanced or weakened. This allows the low-coercivity magnet to maintain its operating point within a safe range. These features make the proposed design suitable for electric vehicle tractions. Finite element analysis is used to compare the performance of various types of motors and highlight the advantages of the proposed VFS-PMSM. Experiments are conducted to validate the feasibility of the low-coercivity magnet to be magnetized with the method proposed in this paper. It is found that the field strength to magnetize or demagnetize the rotor can be significantly reduced, which improves the feasibility of this design.

\textbf{INDEX TERMS} Electric vehicle, variable flux motor, magnetization, spoke type, permanent magnet synchronous motor.

\section{I. INTRODUCTION}
In recent years, significant effort has been input into the development of green transportation technology in response to the rising environmental protection consciousness. Many automobile manufacturers have started to develop or produce electric vehicles (EVs). Traction motors greatly affect the performance of EV powertrains, and permanent-magnet synchronous motors (PMSMs) have been extensively employed in EV tractions for their advantage of high torque/power density and high efficiency \cite{1}–\cite{4}. Having been equipped with strong permanent magnets (PMs), the speed range of PMSMs could be limited without flux weakening control \cite{5}, \cite{6}. Flux weakening requires a negative direct-axis (d-axis) field to depress the field generated by permanent magnet (PM) and thereby the electromotive force (EMF) at high speed can be reduced. However, flux weakening not only increases unnecessary copper loss but also diminishes efficiency at high speed. This would then reduce the cruise range and limit the maximum speed of electric vehicles. These weaknesses associated with flux weakening using negative d-axis current should be improved to enhance traction motor performance.

In addition, EV traction motors are required to achieve a wide operating range for various driving conditions, i.e., high torque at low- to medium-speed (e.g., hill climbing)
and low torque for high-speed cruise. To expand the speed range, the ability of flux weakening becomes critical as previously mentioned. However, different approaches should be considered other than weakening the flux by d-axis current. In this regard, various types of motors have been proposed [7]–[12]. Fodorean [8] proposed a doubly-excited synchronous motor with field windings in the rotor and the speed range could be improved to 2.8 times the base speed. However, slip rings and brushes are needed and copper loss is still inevitable when performing flux weakening, which are considered the main drawbacks of this motor [8]. Instead, wireless power transfer devices can be adopted to power the rotor field winding [13] but this again results in additional cost and complexity. Tapia proposed a consequent-pole PM (CPPM) machine which has inherent field weakening capability [14]. The control for this motor is conducted by injecting a dc current into a stationary field winding located in the central portion of the stator. This improves the speed range and requires no slip rings; however, the structure and materials of the stator need a special design. A set of controlled dc power sources are also required.

Other than the application of field windings, regulation of air-gap flux density can also be performed by mechanical devices [10], [11]. For example, Zhou [10] developed a variable flux motor that mechanically performs field weakening. It can control air gap flux density accurately and effectively extend speed range. However, the maintenance cost for the device may increase. Ostovic proposed the concept of variable flux motor (VFM), also called the variable flux memory motor (VFMM) [15], [16], where a pulse current generated by stator windings is utilized to change the magnetization state (MS) of the magnet. The VFMM usually uses low coercive force (LCF) magnets (e.g., AlNiCo) to bring the pulse current needed down to magnetize or demagnetize the magnet [17]–[20]. To prevent unexpected demagnetization of the LCF magnets during motor operation, Kato et al. [21], [22] proposed a variable-flux flux-intensifying interior permanent magnet machine (VFI-IPMM), whose d-axis inductance was designed to be greater than q-axis inductance. In most operating conditions of VFI-IPMM, the d-axis current is positive and thus demagnetization can be avoided.

The VFMs often possess a relatively low torque density due to the utilization of LCF magnets. To improve this, a hybrid permanent magnet variable flux motor (HPM-VFM) combining high coercive force (HCF) magnets and LCF magnets was proposed [23]–[35]. Regulation of air-gap flux density in HPM-VFM can be achieved by applying a pulse current whose copper loss is considered negligible. The HPM-VFM can also maintain high torque and high power density, almost equivalent to general PMSMs. Due to these advantages, various rotor topologies have been developed, the most typical of which are series [23], [25]–[28] and parallel [29], [30] HPM-VFMs. These two types of rotor topologies possess their own strengths and weaknesses. For example, the parallel HPM-VFM is prone to unexpected demagnetization [24], [31] but with a wide flux regulation range. Therefore, many hybrid magnetic-circuit variable flux motors have been further proposed [25], [32]–[34] based on these two types. They aimed at operating the LCF magnet at safe and healthy operating points (e.g., as the series type) and simultaneously providing a magnetic leakage bypass (e.g., as the parallel type) to expand an adjustable flux range. To successfully combine these advantages and maintain high torque, high power density and high efficiency for EVs would further enhance the feasibility of the VFMs [1]–[4], [36].

Therefore, in this paper, to make use of the strengths of the parallel and series HPM-VFMs for EVs, a novel variable flux spoke-type permanent magnet synchronous motor (VFS-PMSM) is proposed. In this design, the air gap flux density can be adjusted by “swiveling” the direction of the PM magnetic pole instead of reversing it by applying a strong magnetizing field. Through this new method, the pulse current magnitude required to magnetize and demagnetize the PM can be reduced and safe operating points for the LCF magnet in both enhanced and weakened modes can be guaranteed. Compared with the series and parallel HPM-VFMs, the proposed design does not require additional mechanisms, such as field windings or mechanical structures to regulate the field. The material cost for LCF magnets would be lower than that of HCF ones, and therefore not much would be added to the overall motor cost. Most importantly, the proposed design can enhance the value of vehicles with an expanded operating range.

This paper develops the equivalent magnetic circuits (EMCs) of the proposed VFS-PMSM and compares them with that of the series and parallel HPM-VFMs. An index for flux regulation ability denoted flux regulation ratio (FR) for the three types of motors is derived via the developed EMCs. Then, experiments are conducted to verify the feasibility of the proposed method of switching MS. The maximum torque, torque ripple, efficiency map, and other key parameters of the three types of motors are compared with finite element analysis (FEA). For a more comprehensive analysis, two other interior PMSMs (IPMSMs) are also used to compare with the proposed VFS-PMSM.

This paper is organized as follows. In Section II, the characteristics of the series, parallel, and the proposed VFS-PMSM configurations are analyzed and compared, and their features are explained in detail. The developed EMC models for the three configurations are analyzed and the FR is derived in Section III. In Section IV, the feasibility of the VFS-PMSM concept is validated by experiments. The electromagnetic characteristics of the VFS-PMSM are simulated and compared with the other types of motors in Section V, followed by Section VI to conclude this paper.

II. VARIABLE FLUX PM MOTOR TOPOLOGIES AND PROPOSED VFS-PMSM

By combining LCF and HCF magnets, the rotor topology can be categorized into the series and parallel types, which are both called the conventional types here. To explain the
difference between the conventional types and the proposed VFS-PMSM, their configurations and features are introduced and compared here. For convenience, the two conventional types of HPM-VFMs are called the “Series type” and “Parallel type” in what follows.

A. SERIES TYPE TOPOLOGY
The schematic of the series hybrid permanent magnet variable flux motor (SHPM-VFM) is shown in Fig. 1. The stator of the SHPM-VFM is identical to common interior permanent magnet synchronous motors but the rotor configuration is different. The MS of the LCF magnet between two pieces of HCF magnets is indicated in Fig. 1 and can be changed by the magnetizing current provided by the stator. To satisfy the need for high torque and high speed, the SHPM-VFM basically operates in two modes, i.e., flux enhancing and weakening. In the flux enhancing mode, as shown in Fig. 1(a), the flux produced by the HCF magnet joins that of the LCF magnet and links with the stator windings. This helps the LCF magnet stabilize its operating point and avoid unexpected demagnetization under heavy load or high-temperature conditions. In contrast, in the flux weakening mode shown in Fig. 1(b), the flux direction of the HCF magnet is opposite to that of the LCF magnet. Comparing the above two modes, it is apparent that to change the direction of the HCF magnet poles, flux enhancing requires a smaller magnetizing pulse current magnitude than the weakening mode due to the influence of the HCF magnet.

B. PARALLEL TYPE TOPOLOGY
The principles of enhancing and weakening modes in the parallel hybrid permanent magnet variable flux motor (PHPM-VFM) are respectively shown in Figs. 2(a) and (b). The LCF magnet of the PHPM-VFM is used to block the flux of the HCF magnet from flowing through the leakage bypass to increase the air gap flux density and thus the flux direction of the LCF magnet is parallel to that of the HCF magnet in the enhancing mode. This indicates that the PHPM-VFM does not possess the advantage of stable operating points for the LCF magnet as in the series type in the enhancing mode, as shown in Fig. 2(a). Even under no-load conditions, the LCF magnet still needs to resist the magnetic field produced by the HCF magnet. Consequently, the risk of demagnetization in the parallel type is higher than that in the series type. As shown in Fig. 2(b), the LCF magnet will guide part of the flux produced by the HCF magnet to flow through the leakage bypass so that the air gap flux density can be reduced in the weakening mode. One advantage of the parallel type is that this leakage bypass can be easily created by changing the MS of the LCF magnet. This allows the parallel type motor to gain a better ability to adjust the air gap flux density than the series type. The MS of the parallel type is switched in a different way to that of the series type such that a higher magnetizing pulse current is required when switching from weakening to enhancing mode and a smaller current for switching to weakening mode. Despite the advantage of excellent flux regulation in the parallel type, the series type is often adopted due to its low risk of demagnetization in LCF magnet during operations.

C. PROPOSED VFS-PMSM TOPOLOGY
The topology of the proposed VFS-PMSM is shown in Fig. 3, which aims at overcoming the weaknesses of conventional VFMs while keeping their strengths. Note that the magnetization directions in Fig. 3 are ideal and only used for explaining the concept of swiveling magnetization.
The actual flux direction of the LCF magnet may be deflected by the strong HCF magnet, resulting in uneven magnetization operations in the LCF magnets. The proposed VFS-PMSM possesses three major features. First, the biggest difference lies in the magnetization and demagnetization approach to the LCF magnet for flux regulation. In conventional types of rotors, the magnets are magnetized and demagnetized along the same axis. However, with a different approach, the air gap flux density of the proposed VFS-PMSM is regulated by swiveling the poles of the LCF magnet through external magnetizing fields. Fig. 4(a) shows a schematic diagram that explains the external magnetizing field to switch the LCF magnet MS indicated by the three unit vectors. In these vectors, the one on the positive Y-axis is the original MS, on the negative Y-axis is the MS switched using the conventional approach and on the negative X-axis is the swiveled MS by the proposed method. To switch the MS along the same axis (Y-axis), the required external magnetizing field could be around twice the unit vector as indicated. However, for the proposed motor, the magnet pole direction is swiveled from one axis (e.g., positive on Y-axis) to another (e.g., negative on X-axis), and thus the required external magnetizing field would become smaller ($\sqrt{2}$ times the unit vector instead of twice, i.e., 29.3% less), as indicated in Fig. 4(a). This significantly reduces the magnetizing current required from the stator, which is different from conventional methods [21]. This will be detailed and validated in Section IV.

The second feature of the VFS-PMSM is the strong flux guidance ability to the flux generated by the HCF magnets. In Figs. 4(b)(c), the solid arrows on the magnets indicate their magnetic pole directions and the dashed arrows on the LCF magnets indicate the direction of the magnetizing field required to be produced by the stator to switch the original MS (solid arrows) to another. In Fig. 4(b), part of the flux generated by the HCF magnet can be guided through the air gap instead of leaking through any leakage bypass, as shown by the solid arrows. Therefore, higher air-gap flux density can be maintained in the flux enhancing mode. In Fig. 4(c), the LCF magnet guides part of the flux produced by the HCF magnet through the leakage bypass (mainly formed by the two LCF magnets) to reduce the air gap flux density and achieve flux weakening. To verify this feature, a simulation using FEA software (ANSYS) is conducted and the result is shown in Fig. 5. As can be seen, most of the flux is guided to the stator in the enhancing mode. Therefore, the leakage flux in the leakage bypass is much less, where the average flux density is only 0.55 T. In contrast, in the weakening mode shown in Fig. 5(b), as indicated by a red circle, the leakage flux passing through the LCF magnet and bypass help reduce the flux density on the stator teeth and yoke and thus the flux linkage. The average flux density is 0.96 T in the leakage bypass in the weakening mode, where the leakage flux increases nearly double compared with the enhancing mode.

The third important feature is the ability to maintain the operating point of the LCF magnet in both flux weakening or enhancing modes. The flux of the HCF magnet passing through the LCF magnet in the two modes is shown in Fig. 5.
As can be seen, the no-load operating points on the LCF magnets in the two cases are both in good condition, and they are averagely 0.695 T and 0.807 T in the enhancing and weakening modes, respectively. These are much higher than the knee point flux density, 0.4 T, of the demagnetization curve of the LCF magnet. In this way, the LCF magnet will operate safely and will not be easily demagnetized as in the conventional topologies. In addition, saturation only occurs in the ribs of the VFS-PMSM as shown in Fig. 5(c), which does not affect the motor operation. In the weakening mode, the flux of the magnets is mostly confined within the rotor, which is thus saturated. Instead, the flux density in the stator is low, even at the on-load condition, as shown in Fig. 5(d). However, the saturated rotor can reduce the air gap flux to achieve the objective of weakening the flux. Therefore, saturation in any operating mode does not affect the VFS-PMSM operation.

To explicitly confirm the stability of the LCF magnet operating points in the proposed design, the back EMF of the VFS-PMSM is simulated before and after the load is applied and then released. Note that the operating points of the LCF magnets can be tracked throughout the simulations. The results are shown in Fig. 6, where the phase voltage (also representing the back EMF at no load) remains at 20.5 V after the load is applied and released at 1500 rpm. Therefore, the stable operations of the LCF magnet are confirmed.

As mentioned above, in order to rotate (or “swivel”) the pole direction of the LCF magnet, the stator needs to generate a magnetizing field as the dashed arrows indicated in Fig. 4(b)(c) on the LCF magnet. To achieve this, the LCF magnet for the VFS-PMSM is arranged to be different from that of the conventional types, as can be observed from a comparison between Figs. 1, 2, and 3. FEA is carried out here to verify whether or not the stator can generate the magnetic field required for the transition of MS. The simulation for stator current with a phase advance of 90 degrees is shown in Fig. 7(a) and that for -90 degrees is shown in Fig. 7(b). As shown in Fig. 7(a), the magnetizing field for switching the MS is in the same direction as the dashed arrows shown in Fig. 4(b). In Fig. 7(b), the magnetizing field direction matches that in Fig. 4(c).

These results indicate that the flux enhancing and weakening modes can be properly switched by stator current. It should be noted that it is difficult to obtain the magnitude of the magnetizing field strength for the transition during magnetization via simulation. This is because the simulation involving magnetization of the PM along the Y-axis and demagnetization along the X-axis from weakening to enhancing mode cannot be simultaneously performed in the FEA software. Therefore, it will be verified experimentally and reported in a later section.
III. EQUIVALENT MAGNETIC CIRCUITS OF VFS-PMSM

To further compare the characteristics of the three types of motors discussed in Section II, their equivalent magnetic circuit (EMC) models are derived. Note that the reluctance of the stator is assumed to be much smaller than that of the air gap. Therefore, it is negligible in the EMCs.

A. EMC FOR SERIES TYPE

As previously discussed, the LCF magnet is in the flux path of the HCF magnet for the series type motor, and the HCF magnet can help the LCF magnet maintain at a higher operating point and avoid unexpected demagnetization. According to the EMCs shown in Figs. 8(a) and (b), the air-gap flux $\Phi_{s+}$ and $\Phi_{s-}$ in the flux enhancing and weakening modes can be formulated as

$$\Phi_{s+} = \frac{F_c (R_r + R_v) + 2F_v R_r}{2R_r R_v + (2R_g + R_r)(R_r + R_v)} \tag{1}$$

$$\Phi_{s-} = \frac{F_c (R_r + R_v) - 2F_v R_r}{2R_r R_v + (2R_g + R_r)(R_r + R_v)} \tag{2}$$

where $F_c$ and $F_v$ are magnetomotive force (MMF) of the HCF and LCF magnet, respectively; $R_v$ and $R_r$ are reluctance of the HCF and LCF magnet; $R_g$ is reluctance of air gap; $R_r$ is reluctance of rotor core.

The flux regulation ratio of the series type (denoted FR$_S$) is defined as the ratio of the air-gap flux in the enhancing mode to that in the weakening mode, as given by

$$\text{FR}_S = \frac{\Phi_{s+}}{\Phi_{s-}} = \frac{F_c (R_r + R_v) + 2F_v R_r}{F_c (R_r + R_v) - 2F_v R_r} \tag{3}$$

Note that the MMF changes for the enhancing and weakening modes are indicated in Figs. 8(a) and (b). The flux regulation ratio is an important parameter for variable flux motors to characterize the control range of air gap flux.

B. EMC FOR PARALLEL TYPE

The biggest difference between the parallel type and the series type is that the parallel type possesses significant and active flux leakage bypasses. As shown in Fig. 9, in the enhancing mode of the parallel type rotor, the LCF magnet will resist the flux produced by the HCF magnet to avoid leakage and add to the air gap flux. In contrast, the flux of the LCF magnet, together with part of leakage flux from the HCF magnet will be guided through the bypass to reduce the air gap flux. In contrast, the flux of the LCF magnet, together with part of leakage flux from the HCF magnet will be guided through the bypass to reduce the air gap flux and flux linkage in the weakening mode. This implies that the flux regulation ability of the parallel type is better than that of the series type.
FIGURE 9. Equivalent magnetic circuits of parallel type: (a) in enhancing mode; (b) in weakening mode; (c) parallel configuration matching the equivalent circuits.

According to the EMCs shown in Figs. 9(a) and (b), the air-gap flux $\Phi_{P+}$ and $\Phi_{P-}$ in the flux enhancing and weakening states can be formulated by

$$\Phi_{P+} = \frac{F_v R_v + F_r R_c}{R_v R_c + (R_g + R_r)(R_c + 2R_v)}$$

$$\Phi_{P-} = \frac{F_v R_v - F_r R_c}{R_v R_c + (R_g + R_r)(R_c + 2R_v)}$$

The flux regulation ratio of the parallel type, i.e., $\text{FR}_P$, is given by:

$$\text{FR}_P = \frac{\Phi_{P+}}{\Phi_{P-}} = \frac{F_v R_v + F_r R_c}{F_v R_v - F_r R_c}$$

C. EMC FOR PROPOSED VFS-PMSM

Differing from the two conventional types previously discussed, in the proposed VFS-PMSM, the magnetizing field is aimed at swiveling the pole direction of the LCF magnet by around 90 degrees rather than simply magnetizing and demagnetizing the magnet on the same axis. The flux of the HCF magnet is guided to regulate air gap flux density by the LCF magnet whose pole direction swivels according to operating modes (enhancing or weakening). This implies that it can possess the advantages of both series and parallel types of motors. Fig. 10 shows the EMC of the proposed VFS-PMSM in the enhancing and weakening modes. In the enhancing mode, the LCF magnet not only blocks the HCF flux to avoid leakage but also helps to improve the flux linkage. Only negligible flux would leak through the bypass. In contrast, in the weakening mode, a large portion of flux from the HCF magnet is guided through the leakage bypass by the LCF magnet to achieve the same effect as the PHPM-VFM. This guarantees that the flux of the HCF magnet will flow through the LCF magnet in its magnetization direction in any operating mode. Therefore, the operating point of the weaker LCF magnet can be maintained and the risk of accidental demagnetization can be avoided. This is a significant difference to the conventional types of motors which are vulnerable to demagnetization in either enhancing or weakening modes. As can be seen in Figs. 10(a) and (b), the EMC of the VFS-PMSM is the same as that of the series
type in the enhancing mode and as that of the parallel type in the weakening mode. Based on the EMCs of the VFS-PMSM, the air-gap flux $\Phi_{N+}$ and $\Phi_{N-}$ in the flux enhancing and weakening modes can be respectively formulated as:

$$\Phi_{N+} = \frac{F_c (R_r + R_c) + 2F_v R_r}{2R_r R_v + (2R_g + R_r)(R_r + R_c)}$$  \hspace{1cm} (7)

$$\Phi_{N-} = \frac{F_c R_v - F_v R_c}{R_r R_c + (R_g + R_r)(R_c + 2R_r)}$$  \hspace{1cm} (8)

The flux regulation ratio of the VFS-PMSM (denoted $FR_N$) is given by:

$$FR_N = \frac{\Phi_{N+}}{\Phi_{N-}} = \frac{(F_c (R_r + R_c) + 2F_v R_r) R_c / 2R_r}{F_c R_v - F_v R_c}$$  \hspace{1cm} (9)

Equation (9) can be further simplified to be:

$$FR_N = \frac{(R_c / 2R_r) (F_c R_r) + F_v R_c + F_c R_v / 2}{F_c R_v - F_v R_c}$$  \hspace{1cm} (10)

The air-gap flux of the VFS-PMSM in the enhancing mode, $\Phi_{N+}$, is the same as that in (1) and $\Phi_{N-}$ for the weakening mode is the same as in (5). Ideally, the VFS-PMSM can achieve high torque output as the series type in the enhancing mode and have the advantage of excellent flux regulation ability as the parallel type. The parallel type has a leakage bypass and a better flux regulation ability than the series type. Therefore, the flux regulation ratio of the parallel type and VFS-PMSM, i.e., $FR_P$ and $FR_N$, is compared through (10) and (6). It can be found that, with $R_r$ smaller than $R_c$ (reluctance of the HCF magnet), $FR_N$ should be greater than $FR_P$ when assuming all the parameters, i.e., reluctances and MMFs are the same. This implies that the proposed VFS-PMSM should possess better flux regulation ability than the parallel type. However, as will be discussed in the following, an isotropic and weaker LCF is used in the proposed VFS-PMSM and consequently, the flux regulation is not as good as expected.

### IV. FEASIBILITY VERIFICATION OF VFS-PMSM

Experiments are conducted to verify the feasibility of the magnetization method proposed in this paper and demonstrate whether the pole direction of the isotropic AlNiCo magnet can be successfully rotated by 90 degrees.

Fig. 11 shows the experimental setup, including the magnetizer, magnetizing fixture, Gaussmeter, and the magnet to be magnetized. The magnet and the magnet holder are placed inside the magnetizing fixture. The specifications and properties of the main equipment (magnetizer), device (magnetizing fixture), and materials (magnet) used in this experiment are listed in Table 1.

In the experiment, the linearity of the magnetizer and fixture is first verified and thus the relationship between voltage, magnetizing current, and field intensity generated by the magnetizing fixture is measured and determined. The measured results are then compared with the calculation. The relationship between voltage and current can be calculated by the common circuit theory. The relationship between voltage and magnetizing field strength can be obtained by the Biot-Savart law [37].
As shown in Fig. 12, the relationship between the voltage and current or the voltage and the field strength is linear for both the calculation and measurements. Their results agree well, and this confirms the reliability of the magnetizer and magnetizing fixture.

Then, the magnetizing field strength required for magnetization and demagnetization for the typical series or parallel types should be confirmed. The initial magnetization curve of the isotropic AlNiCo magnet LNG13 is first measured. The flux density inside the magnetizing fixture was measured with and without a magnet when the magnetizing field was applied. The flux density was first measured for each magnetizing field strength applied when the magnet was placed in the magnetizing fixture. Then the flux density generated by the fixture was again measured when the magnet was removed. The results from the two cases were subtracted to obtain the initial magnetization curve of the LCF magnet (AlNiCo LNG13) [38], as shown in Fig. 13, where it can be observed that a field strength beyond 577 kA/m is needed to sufficiently magnetize the magnet.

From the measurement previously presented, the MS (expressed by magnetization percentage), the rotation angle (X-axis is set as the reference) of the magnet pole direction, and the magnetizing field strength required for magnetization are shown in Fig. 15. Note that, as can be seen in Fig. 13, the magnetizing field strength required for full magnetization of the series or parallel type can be set at 577 kA/m. However, only 433.8 kA/m is needed to successfully rotate the magnetic pole direction of the magnet and reach the maximum MS, as shown in Fig. 15. This reduces 25% of the required magnetizing field strength for full magnetization in the initial magnetization curve. This result confirms that the magnetization axis of the magnet can be successfully rotated with a smaller magnetizing field using the proposed...
swiveling magnetization. Moreover, the LCF magnet can be fully magnetized at 90 degrees to the original magnetization direction. Therefore, the MS of the LCF magnet can be effectively switched and the flux can be more easily regulated in this way.

V. MOTOR PERFORMANCE SIMULATION

To investigate the strengths and weaknesses of the series, parallel, and the proposed VFS-PMSM, simulations (using ANSYS Maxwell) are compared in terms of back electromotive force (BEMF), torque output, and efficiency maps in Section V.A. In Section V.B, the proposed VFS-PMSM is compared with two conventional IPMSMs. For a fair comparison, the stator and rotor dimensions, winding layouts, number of slots and poles, and the amount of usage of the LCF and/or HCF magnets are set to be all the same for the above three types of motors and the conventional IPMSMs.

The parameters of the motors and their material properties are listed in Table 2. It is well known that the AlNiCo magnet possesses excellent temperature stability. However, the HCF magnet used in this paper is N32H, whose working temperature is limited to 120 °C. Therefore, the cooling system should be carefully designed. Note that the series and parallel types often employ anisotropic LCF magnets (e.g., LNGT40) to enhance the flux in certain directions; instead, the proposed VFS-PMSM uses isotropic LCF magnets (LNGT18) for easily swiveling the magnetic pole directions. Note that for the conventional IPMSMs, only HCF magnets are used and the amount of usage of HCF magnets is the same as that in the proposed VFS-PMSM. In Section V.C, the VFS-PMSM is further optimized, aimed at improving the maximum torque.

A. COMPARISON OF SERIES, PARALLEL TYPES AND VFS-PMSM

The simulation results of BEMF for the three types of motors are shown in Fig. 16. In the enhancing mode, the BEMF of the proposed VFS-PMSM is almost the same as that of the series type. The torque performance is also similar (Fig. 17). However, as shown in Figs. 16 (b)(c), there are more harmonics in the BEMF waveform in the enhancing mode for the parallel type and in the weakening mode for the series type. This may result from the situation where the flux directions of the LCF and HCF magnets are opposite in these two cases, causing unsmooth air gap flux distributions. This feature is rarely discussed in the literature. The characteristics of the VFS-PMSM are such that the flux of the HCF magnet passes through the LCF magnet without opposite flux in any operating modes. Therefore, the BEMF harmonics of the VFS-PMSM are less than that for the series and parallel types, as shown in Fig. 16 (a).

As shown in (3)(6)(9), the flux regulation can be expressed by the ratio of the flux in the enhancing mode to that in the weakening mode. The flux at no load can be treated as proportional to the BEMF. Therefore, the flux regulation can also be expressed by the ratio of BEMF in the two operating modes. As listed in Table 3, $E_+\, E_-$ are the back EMF magnitudes in the enhancing and weakening modes and $E_r$ is the ratio of $E_+\, E_-$. As can be seen, the parallel type seems to possess the best flux regulation (with the largest BEMF ratio of the enhancing to weakening modes). However, the parallel type suffers a high risk of accidental demagnetization in the enhanced mode, and thus it is difficult to maintain the ideal performance. With a smaller magnetizing pulse current required, the risk of accidental demagnetization is lower than that of the parallel type, and the flux regulation

| Item | Value |
|------|-------|
| DC link voltage Udc (V) | 48 |
| Phase Current (peak) (A) | 60 |
| Power (kW) | 2 |
| Rated Speed (rpm) | 1500 |
| Outer diameter of stator (mm) | 160 |
| Outer diameter of rotor (mm) | 112 |
| Air gap (mm) | 0.5 |
| Stack length (mm) | 36 |
| Winding turns per phase | 36 |
| HCF PM grade | N32H |
| LCF PM grade (Series & Parallel / VFS-PMSM/ Conventional PM -1 & 2) | LNGT40 / LNGT18 / X |
| HCF PM coercivity (kA/m) | 886 |
| HCF PM remanence (T) | 1.146 |
| LCF PM coercivity (kA/m) | LNGT40 / LNGT18 |
| LCF PM remanence (T) | 115.7 / 100.5 |
| Stator & rotor steel | 25CS1500HF |
FIGURE 16. Back-EMF of (a) VFS-PMSM; (b) parallel type; (c) series type in enhancing and weakening modes.

TABLE 3. Comparison of BEMF in enhancing and weakening modes.

|          | VFS-PMSM | Parallel | Series |
|----------|----------|----------|--------|
| $E+$ (V) | 20.72    | 20.83    | 20.97  |
| $E-$ (V) | 12.47    | 8.09     | 13.11  |
| $E_r = E+/E-$ | 1.66    | 2.57     | 1.60   |

ability is better than that of the series type. This implies that the proposed VFS-PMSM is more suitable for practical application.

The BEMF harmonics may affect the torque ripple. As can be seen in Fig. 17, the torque ripple of the VFS-PMSM is smaller than that of the parallel and series types. For the average torque in the enhancing mode, the VFS-PMSM can achieve nearly the same torque as the series and parallel types. Figs. 18, 19, and 20 respectively show the efficiency maps of the VFS-PMSM, parallel, and series types in the enhancing and weakening modes. Note that the efficiency of all the operating points in the efficiency map is calculated by

$$\eta = \frac{P_{out}}{P_{out} + P_{loss}}$$  \hspace{1cm} (11)

where $\eta$ is efficiency, $P_{out}$ and $P_{loss}$ are respectively output power and loss of the motor. The loss consists of magnet loss, copper loss, and iron loss of the stator and rotor without considering mechanical loss and windage loss. For a simple
and clear comparison, the efficiency map of the VFS-PMSM is simplified and placed on top of that of the parallel type and series type. Note that only the ≥80% and ≥90% efficiency ranges for the VFS-PMSM are indicated with purple and pink curves, respectively, to avoid complexity. As can be seen in Figs. 19 and 20, the high-efficiency operating range of the proposed VFS-PMSM is almost the same as that of the parallel type and larger than that of the series type at high speed in the enhancing mode. In the weakening mode, the efficiency ranges for ≥80% and ≥90% of the VFS-PMSM are larger than that of the parallel type at low speed but lower at high speed. The reason could be that the maximum torque per voltage (MTPV) control is used for the parallel type motor to operate at high speed, which results in smaller PM eddy current loss. Therefore, the parallel type has a large high-efficiency range at high speed. However, the VFS-PMSM can operate at high speed without the complex MTPV control and maintain high torque at high speed. The high-efficiency operating range of the proposed VFS-PMSM is almost the same as that of the series type but larger than that of the parallel type at high speed in the enhancing mode. In the weakening mode, the efficiency ranges for ≥90% efficiency range of the VFS-PMSM are slightly smaller than that of the series type, but the ≥80% efficiency range and the speed range are larger.

Table 4 shows the losses in the VFS-PMSM, parallel, and series type motors at the based speed in the enhancing and weakening modes. For a fair comparison, the losses in Table 4 are all obtained under maximum voltage and current. As can be seen, the total loss of the VFS-PMSM in the enhancing mode is lower than that of the parallel type and higher than that of the series type. In the weakening mode, the total loss of the VFS-PMSM is lower than that of both the parallel and series types. As can be seen in Table 4, the PM loss of the three cases is quite different, which is the possible cause for the difference in the total loss.

|                  | Enhancing Mode |          | Weakening Mode |          |
|------------------|----------------|----------|----------------|----------|
|                  | VFS-PMSM       | Parallel | Series         | VFS-PMSM | Parallel | Series |
| Copper loss (W)  | 86.41          | 86.41    | 86.41          | 86.41    | 86.41    | 86.41  |
| Iron loss (W)    | 10.32          | 6.46     | 7.04           | 5.18     | 5.55     | 6.07   |
| PM loss (W)      | 10.21          | 24.82    | 6.39           | 22.89    | 27.8     | 39.34  |
| Total loss (W)   | 106.94         | 117.69   | 99.84          | 114.48   | 119.76   | 131.82 |
In summary, the proposed novel VFS-PMSM has a slightly lower output performance than the series type but is similar to the parallel type. Most importantly, the proposed VFS-PMSM can effectively reduce the field strength required for magnetization and demagnetization. Note that a weaker (isotropic) LCF magnet is used in the proposed motor than that of the two conventional types and the potential demagnetization problem under load for the parallel type is not considered here.

B. COMPARISON OF CONVENTIONAL IPMSM AND VFS-PMSM

For a more comprehensive analysis, the simulation results (using ANSYS Maxwell) of the VFS-PMSM and the two conventional IPMSMs (denoted IPMSM-1 and IPMSM-2) are compared. For a fair comparison, the conventional IPMSMs are designed as the construction of spoke-type motors. The parameters of the spoke-type IPMSMs and their material properties are listed in Table 2 and the schematics are shown in Fig. 21. The difference to the VFS-PMSM is that the IPMSMs do not contain LCF magnets, and therefore, the operating range may be limited due to their strong PM field even with field weakening control.

The torque-speed curves of the three motors are compared in Fig. 22. As can be seen, the VFS-PMSM only needs to sacrifice part of the maximum torque to make the operating range much broader than that of the spoke-type IPMSMs even in the enhancing mode. As shown in Table 5, the three motors are compared in terms of maximum torque, maximum speed, maximum efficiency, power density, and loss at the base speed using simulation. It should be noted that the calculation of maximum efficiency only considers motors themselves, and the power density is calculated based on the active volume without taking into account of other components such as housing.
From the simulation results presented in Table 5, since the two spoke-type IPMSMs maintain the air gap flux density at a high level, the leakage flux is minimized, and the torque is maximized compared to the VFS-PMSM. However, the VFS-PMSM can achieve a maximum speed of 14,000 rpm through the flux adjustment ability, which is much higher than that of the two conventional IPMSMs. The maximum efficiency, power density, and loss of these three are almost the same. The VFS-PMSM has a slightly higher loss at the base speed and the main cause can be that the VFS-PMSM uses additional LCF magnets, so there could be more PM eddy current losses. However, this can be mitigated by segmenting the magnet.

C. OPTIMIZATION OF VFS-PMSM

The VFS-PMSM uses an isotropic magnet, resulting in a slightly lower maximum torque. Therefore, optimization is conducted to improve the maximum torque of the VFS-PMSM. To simplify the analysis, the built-in Genetic Algorithm (GA) in ANSYS is used for optimization. The main variables for optimization are the angle and width of the LCF magnet indicated in Fig. 23 and denoted $\theta_L$ and $W_L$. Note that the varying range of $\theta_L$ and $W_L$ should be limited to avoid any possible difficulty in magnetization when considering the magnetizing field pattern produced by the stator, as shown in Fig. 7.

As shown in Fig. 24, the torque of the VFS-PMSM can be improved to 12.5 Nm with optimization. Compared with the original design, $\theta_L$ and $W_L$ are respectively adjusted from 5.5 deg and 6 mm to 5.21 deg and 6.99 mm. This results in a slight increase in the maximum torque from 12.17 Nm to 12.5 Nm. This is greater than that of the parallel type and close to that of the series type. The possible reason is that this adjustment may affect the flux guided by the LCF magnet and thus slightly enhance the stator flux linkage and the maximum torque of the VFS-PMSM.

VI. CONCLUSION

In this paper, a new type of variable flux motor without additional structures has been proposed where the magnetization and demagnetization are performed by rotating the pole direction of the LCF magnet. It has been demonstrated that the field strength required to switch between the enhancing and weakening modes can be reduced compared to conventional configurations. In addition, the LCF and HCF magnets do not have opposite flux in all the operating conditions. Thus, the HCF magnet can help maintain the operating point of the LCF magnet without causing accidental demagnetization. The torque ripple of the proposed motor has been shown to be smaller than that of the series and parallel types. The flux regulation ability has been demonstrated to
be better than that of the series type and close to that of the ideal parallel type. In addition, in comparison with general spoke-type IPMSMs, the VFS-PMSM also has equivalently wide speed range. These demonstrate the advantages of the proposed VFS-PMSM for EV applications.

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