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ABSTRACT
Aiming at extending the operating speed range and increasing the machine efficiency, three series-configuration hybrid-permanent-magnet variable-flux machines (HPM-VFMs) with both low and high coercive-force magnets are proposed. The magnetization characteristics of the machine with different dimensions of the high coercive-force (HCF) magnet are investigated. Then, in order to improve the contribution rate of the HCF magnet, two improved topologies are presented. The electromagnetic characteristics of the two proposed machines, including back electromotive force (EMF), maximum torque characteristics, magnetization state (MS) variation range and magnetic field distribution, are comprehensively analyzed and compared. The influence of different types of windings on the performance of the machine is also investigated. Finally, the torque-speed curves of the machine under different MSs are given by finite element method (FEM). The results show that the HPM-VFM can operate over a wide-speed range with high efficiency.

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I. INTRODUCTION
Permanent-magnet (PM) synchronous machines (PMSMs) are widely used in servo systems, traction fields and household applications owing to their high power density and high efficiency.1 However, the unadjustable air-gap flux of the conventional rare-earth PM machine leads to limited constant-power speed range (CPSR), and the efficiency is lower at high speed region which results from the inescapable flux-weakening current.2

To improve this situation, the concept of variable-flux PMSM (VF-PMSM) is proposed.3–10 Since the low coercive-force (LCF) magnet is utilized in the VF-PMSM, the air-gap flux can be changed by applying d-axis current pulse to re/demagnetize the LCF magnet. The magnetization states (MSs) of the LCF magnet can be ‘memorized’ depending on the amplitude of the current pulse, and the copper loss during the re/demagnetization process is negligible. Therefore, high efficiency can be obtained within a wide operating speed range by removing the additional copper loss under flux-weakening control.11 Meanwhile, owing to the controllable back electromotive force (EMF) of the VF-PMSM, CPSR can be extended within limited bus voltage.5,6 Due to the low torque density of VF-PMSMs where the LCF magnet are employed only, hybrid-PM variable-flux machines (HPM-VFMs) are proposed to combine the high torque density of the rare-earth PM machine and flux adjustability of the VF-PMSM.10–16

Generally, HPM-VFMs are classified into parallel and series configuration according to the arrangement of the low and high coercive-force magnets. For parallel-configuration HPM-VFMs, wide range of flux regulation capability can be realized, because the magnetization orientation of LCF magnets can be changed in two directions.10–12 However, the working points of LCF magnets tend to be easily affected by q-axis armature reaction and the high coercive-force (HCF) magnet, so the torque density of parallel-configuration machines is reduced.13–16 Owing to the enhancement of the HCF magnet, the LCF magnet in series-configuration HPM-VFMs can resist the demagnetization effect from the load armature reaction. Therefore, a series-configuration HPM-VFM has been adopted and commercialized in laundry machine.17 Nevertheless, the demagnetization of series configuration is more difficult than that of parallel configuration, so the variation range of no-load air-gap flux density
is limited, which is usually 50–100%\textsuperscript{15,16}. The limited flux variation for HPM-VFMs is undesired for areas requiring wide-speed-range operating ability.

In this paper, three series-configuration HPM-VFMs with reverse saliency are proposed. The air-gap flux variation range of the proposed machine is controllable by changing the bypass flux path, and the variation range can be extended to 0–100%. The topology of the proposed machine is described firstly, and the magnetization characteristics of the machine are investigated. Then, electromagnetic performances of two improved topologies are analyzed and compared. The influence of different windings on the performance of the machine is investigated. Finally, the torque-speed curves of the machine are given.

II. PERFORMANCE ANALYSIS OF INITIAL HPM-VFM

For reverse-salient pole HPM-VFMs, the maximum torque is produced by positive $d$-axis current $I_d$ and $q$-axis current $I_q$. Therefore, the working point of LCF magnets is enhanced by the positive $I_d$, and the demagnetization induced by $I_q$ can be alleviated. On the other hand, the demagnetization effect can be relieved by arranging the LCF and HCF magnet in series configuration.

A. Design criteria and specifications of initial topology

Based on the above analyses, the design criteria of the proposed HPM-VFM includes the following three levels:

1. Topology level: reverse-salient pole and series PM configuration;
2. Magnetization level: wide MS variation range, low magnetization ripple;
3. Electromagnetic performance level: large torque, low torque ripple, high speed-expansion capability.

The initial topology of the proposed HPM-VFM is shown in Fig. 1a. The machine is characterized by reverse-salient pole and series PM configuration, and hence unintentional armature demagnetization of the LCF magnet under load condition can be avoided. The LCF and HCF magnet employed in the machine are AlNiCo and NdFeB, respectively. The bidirectional arrows demonstrate that the MS of the AlNiCo, which behaves as flux adjustors, is changeable. The unidirectional arrows show that the MS of the NdFeB, which acts as stabilizer of the working point of the AlNiCo, is fixed. Q-axis flux barriers are arranged on the rotor core to obtain reverse-salient pole by reducing $L_q$. Small barriers are arranged to reduce the flux leakage of the NdFeB. The specifications of the designed machine are shown in Table I.

B. Contribution rate analysis of NdFeB

The reasonable magnet usage is recognized as a key issue for HPM-VFMs. When the width ($W_A$) of the AlNiCo changes from 5mm to 7mm and the length ($L_A$) changes from 20mm to 26mm, the AlNiCo with 6mm in width ($W_A$) and 24mm in length ($L_A$) is selected, because this size is more suitable for the reverse saliency and torque requirement. The influence of width ($W_N$) and length ($L_N$) of NdFeB on the magnetization of the machine is investigated. The machine is magnetized with the same current pulse under different $W_N$ and $L_N$, and the amplitude of fundamental component of no-load back EMF after magnetization process is selected to evaluate the contribution rate of NdFeB.

The contribution rate of NdFeB $k_{Nd}$ is defined as the increase percent of the no-load back EMF:

$$k_{Nd} = \frac{(V_1 - V_0)}{V_0} \times 100\% \quad (1)$$

### TABLE I. Design specifications for the series-configuration HPM-VFM.

| Parameter                  | Value          |
|----------------------------|----------------|
| Slots/poles                | 36/6           |
| Stator outer diameter (mm) | 175            |
| Stator inner diameter (mm) | 117            |
| Air gap (mm)               | 0.8            |
| Rotor outer diameter (mm)  | 115.4          |
| Stack length (mm)          | 100            |
| Shaft diameter (mm)        | 36             |
| Width of AlNiCo (mm)       | 6              |
| Length of AlNiCo (mm)      | 24             |
| Rated current (A, rms)     | 14.5           |
| Magnetization current (A, amplitude) | 36.7 |
| AlNiCo grade               | AlNiCo 9       |
| NdFeB grade                | N35SH          |

FIG. 1. Topologies of the proposed HPM-VFM. (a) Topology I, (b) Topology II, (c) Topology III.
where \( V_1 \) is the amplitude of fundamental component of no-load back EMF after the HPM-VFM is magnetized under different dimensions of the magnet, \( V_0 \) is the base value when the machine is without NdFeB, which is 84V.

When the \( W_N \) changes from 0mm to 3mm, the amplitude of fundamental component of no-load back EMF is unchanged, so the \( k_N \) is 0%. By replacing the NdFeB with silicon steel, the back EMF remains unchanged. When the \( L_N \) is doubled to 30mm, the no-load back EMF just increases 16.7%. Therefore, increasing the \( W_N \) and \( L_N \) have weak contribution to the magnetization of the machine.

III. PERFORMANCE COMPARISON OF TWO IMPROVED TOPOLOGIES

There are two aspects, which make the contribution of the NdFeB in topology I is weak:

1. The length of the NdFeB \( L_N \), which affects the flux produced by NdFeB.
2. The arrangement of the NdFeB, which makes it harder for the NdFeB flux to pass through the AlNiCo.

Due to the installation size limitation, the shaft diameter is fixed. The method to improve the initial topology is to increase \( L_N \) and change the arrangement of the NdFeB simultaneously. Therefore, the NdFeB is rearranged to different V shapes based on topology I, and the improved topology II and III are proposed, as shown in Fig. 1b and 1c. The \( L_N \) of the topology II and III are 5mm and 3mm longer than that of topology I, respectively. By applying the same magnetization current pulse, the influence of \( W_N \) on no-load back EMFs, torque characteristics and MS variation range are analyzed.

A. No-load back EMFs and torque characteristics

The amplitudes of fundamental component of back EMFs with different \( W_N \) are plotted in Fig. 2a. When the \( W_N \) varies from 0mm to 3mm, the no-load back EMFs of topology II and III have the same increase pattern, and the amplitudes of both topologies increase 73%. The results validate that the contribution of NdFeB to two improved topologies are significantly improved.

The maximum torque and its corresponding current angle are shown in Fig. 2b. The 0\(^\circ\) current angle represents the current is \( q \)-axis current, and the -90\(^\circ\) current angle represents the current is positive \( d \)-axis current. When the \( W_N \) is 0mm, topology II and III become the same reverse-salient non-NdFeB machine. As the \( W_N \) increases, the torque of both machines goes up with the same tendency, but the maximum torque of topology II is larger than topology III. The maximum-torque current angle is increased as \( W_N \) changes, but the increasing slope of topology II is more rapidly. This can be explained by flux paths of two topologies. The position of NdFeB in topology II is only in the flux path of \( d \)-axis, but the position of NdFeB in topology III is in both \( d \) and \( q \) axes, as shown in Fig. 1b and 1c. Consequently, the \( L_q \) of topology III is lower than that of topology II, so the maximum-torque angle of topology III is smaller, which is more suitable for reverse-salient HPM-VFM.

B. MS variation range analysis

The MS variation range is important for the VF-PMFM, which represents the wide-speed operating ability. The MS variation range \( (MS_{VR}) \) is given as follow:

\[
MS_{VR} = \left( \frac{V_m - V_{dm}}{V_m} \right) \times 100% \tag{2}
\]

where \( V_m \) is the maximum amplitude of fundamental component of no-load back EMF after the HPM-VFM is magnetized, \( V_{dm} \) is the minimum amplitude of fundamental component of no-load back EMF after the HPM-VFM is demagnetized.

With the increase of the \( W_N \), the torque density of the machine is increased, but large \( W_N \) will make it difficult to demagnetize the AlNiCo. The \( MS_{VR} \) with different \( W_N \) is shown in Fig. 2c. When the \( W_N \) is lower than 0.3mm, the \( MS_{VR} \) of topology II and III is 100%, but the \( W_N \) is too thin for prototype manufacture. As the increase of the \( W_N \), the \( MS_{VR} \) of both topologies is decreased. However, the \( MS_{VR} \) of topology III is wider than topology II. This can be explained by the bypass flux path.

C. The bypass flux path

When the AlNiCo is magnetized, the NdFeB enhances the working point of the AlNiCo, and the unintended demagnetization caused by load current can be avoided. However, after the AlNiCo

FIG. 2. Influence of the \( W_N \) on performances of the HMP-VFM. (a) Amplitude of fundamental component of no-load back EMFs, (b) Torque characteristics, (c) MS variation range.
is demagnetized, the NdFeB also acts as flux enhancer, which makes the demagnetized AlNiCo be re-magnetized by the NdFeB. Therefore, the $MS_{VR}$ is narrowed and the CPSR is limited, which is unacceptable.

For the demagnetized AlNiCo, the NdFeB produces two kinds of fluxes:

1. The effective flux: this flux maintains the MS of the AlNiCo.
2. The undesired flux: the combination of undesired flux with effective flux makes the AlNiCo be re-magnetized to unintended high-level MS.

Consequently, the flow path of undesired flux should be bypassed when the machine is demagnetized. To illustrate the effectiveness of the bypass flux path, the field distributions of two topologies after re/demagnetization are shown in Fig. 3. When the AlNiCo is magnetized maximally, the field distributions of both topologies in the stator are the same, which indicates that both topologies have the same large-torque low-speed operating ability, as shown in Fig. 3a. However, after the AlNiCo is demagnetized by the same current, the stator flux density of topologies III is much lower than that of topology II, as shown in Fig. 3b. This is because the bypass flux path of topology III, which makes the undesired flux short-circuit in the rotor core, as shown in Fig. 3c. Therefore, topology III has better speed-expansion capability.

In addition, the flow path of undesired flux is controllable by changing the distance $D_N$ of two NdFeB magnets near the AlNiCo magnet, as illustrated in Fig. 1c. When the $D_N$ changes from 4mm to 12mm and the $W_N$ is 2.1mm, the $MS_{VR}$ can be extended from 50% to 100% at the expense of 5% torque. The 100% $MS_{VR}$ rivals that of traditional single PM VF-PMSM in Refs. 5 and 6 and parallel-configuration HPM-VFM in Ref. 10. Compared with traditional series-configuration HPM-VFM in Refs. 15 and 16, the $MS_{VR}$ increases 50%.

IV. PERFORMANCE ANALYSIS UNDER DIFFERENT WINDING CONFIGURATIONS

Based on the above analyses, topology III is more suitable for wide-speed operating areas. Different pole and slot number combination will affect the magnetization characteristics and electromagnetic performance of the HPM-VFM. Therefore, 12 commonly used winding configurations for topology III are analyzed. The 9 slots, 27 slots, 45 slots and 63 slots are fractional double-layer windings, and 18 slots, 36 slots, 54 slots and 72 slots are integer double- and single-layer windings.

A. Magnetization analysis

Taking the maximum magnetization level ($MML$) of AlNiCo of the 9-slot winding as the base value, $MML$s of all the windings are shown in Fig. 4a. The $MML$ is defined as the average value of flux density of the maximally magnetized AlNiCo at each rotor position, so the $MML$ is a function of rotor position. In order to analyze the influence of different slot numbers on the magnetization, the $d$-axis current pulse is changed to a long time constant $d$-axis current with rotating rotor.

It can be seen that the average value of $MML$ of 9- and 18-slot double layer are lower than those of the others. Due to the slot effect, inevitable magnetization ripple will be induced, which makes the magnetization process unstable and uncontrollable. The $MML$ ripples of 9- and 18-slot windings are above 10%. When the slot numbers are bigger than 18, the variation rate of average value of $MML$ and $MML$ ripple versus slot numbers are very small. In addition, the $MML$ ripple of 27 slots is the lowest, and its average value of $MML$ is almost the same as those of windings whose slot number are bigger than 27.

B. Torque analysis

The maximum torques of the 12 machines after magnetizing are analyzed, as shown in Fig. 4b. For integer-slot windings, the torque and torque ripple of each single-layer winding is bigger than that of the same-slot double-layer winding. Apart from 9-slot winding, the torque ripples for the fractional winding are much lower than those of the integer-slot windings, and the torques of fractional winding are almost the same as integer-slot windings.
In general, when the slot number is bigger than 9, the performances of the fractional-slot windings are better than the integer-slot windings. Although the torque ripples of 45- and 63-slot windings are smaller than 27-slot winding, too many slots will increase the magnetization current density. Based on the above analyses, the 27-slot winding configuration is suitable for the proposed HPM-VFM for the wide-speed capability analysis.

C. Torque-speed and efficiency characteristics

The torque-speed characteristics of topology III with 27 slot under 8 MSs are calculated, as shown in Fig. 5. It can be seen that the HPM-VFM has a good speed-expansion capability by changing the MS, and the maximum speed of 30% MS is 3.5 times of that of 100% MS. When the MS of the machine varies, extra torque-speed region is obtained.

The machine efficiency maps for different MSs are investigated. As the MS changes from 100% to 30%, the high efficiency region shifts to the high-speed range, and the high efficiency over the wider torque-speed region can be achieved. This is caused by the decrease of the PM flux, which reduces the iron loss. The copper loss is also reduced because the flux weakening current needed in flux weakening control is replaced by demagnetization current pulse. Therefore, the proposed machine can operate over wide-speed range with high efficiency.

V. CONCLUSION

In this paper, a series-configuration HPM-VFM with AlNiCo and NdFeB is proposed. Two improved topologies are presented to improve the contribution of the NdFeB, and the conclusions of this paper are summarized as follows.

1) The radially placed NdFeB has slight contribution to the magnetization, and the contribution of the NdFeB is improved after the NdFeB is arranged to V shapes. When the NdFeB is in both d and q axes, the $L_q$ of the machine can be further decreased, and higher positive d-axis current can be applied under load condition.

2) The variation range of $MS_{VR}$ of topology III is wider owing to the bypass flux path, which is adjustable by changing the distance of two NdFeB magnets $D_N$ near the AlNiCo. 100% $MS_{VR}$ can be obtained with large $D_N$ at the expense of torque density.

3) 9- and 18-slot windings are not suitable for the 6-pole HPM-VFM due to the large ripple of maximum magnetization level. Apart from 9-slot winding, torque ripples of the fractional-slot winding are much lower than those of the integer-slot winding, and the torques are almost the same as the integer-slot winding.

4) When the MS of the machine varies, extra torque-speed region is obtained, and the high efficiency region moves toward high-speed range, which is desirable for wide-speed-range applications.

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