Effect of End-winding on Electromagnetic Performance of Fractional Slot and Vernier PM Machines with Different Slot/pole Number Combinations and Winding Configurations

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ABSTRACT In this paper, the effects of end-winding on electromagnetic performance of surface mounted permanent magnet machines (SPMMs) (including vernier machines) with different slot/pole number combinations and winding configurations are analyzed and compared. By using genetic algorithm based on finite element analysis, SPMMs with different coil pitches are optimized for maximum average torque under fixed copper loss or fixed copper and iron losses, with/without considering the influence of end-winding. The effects of coil pitch and stack length on torque and torque density are investigated, and the optimal coil pitch for each slot/pole number combination is obtained. The efficiencies, inductances, and power factors of optimized SPMMs are also compared. The torques of optimized SPMMs considering iron loss decrease, especially at high speed and larger rotor pole number. It is found that the end-winding has significant effect on torque, torque density, winding inductance, and power factor etc. Compared with the fractional slot concentrated winding SPMMs with the same lamination stack length but slot number higher than pole number, the integer-slot distributed winding SPMMs with pole number higher than slot number have higher torques due to field modulation effect, but lower torque densities due to longer axial end-winding lengths.

INDEX TERMS Copper loss, end-winding, iron loss, optimization, permanent magnet machine, slot/pole combination, vernier machines, winding configurations.

I. INTRODUCTION

Owing to high torque density and efficiency, permanent magnet (PM) machines have been extensively employed in various applications, e.g. aerospace, domestic appliance, electric and hybrid electric vehicles, wind power generation, etc. [1]-[4]. Amongst different types of PM machines, radial-field rotor PM machines are the most common topology in terms of electromagnetic performance, manufacturability, and cost, etc. For radial-field rotor PM machines, PMs could be located either on the surface or the interior of the rotor. To date, the surface-mounted PM machines (SPMMs) are widely used due to simple structure since the PMs are mounted on the rotor surface and adjacent to the airgap. Meanwhile, SPMMs are also more preferred in ultra high-speed applications although a rotor sleeve is required to withstand the centrifugal force [3] [5].

From perspective of winding configurations, the SPMMs can be configured by either overlapping distributed windings (DW) or overlapping/non-overlapping concentrated windings (CW). On the one hand, integral slot (IS) SPMMs, having integral slot numbers per pole per phase, could achieve high winding factors by using the DW configurations, i.e. they could achieve the largest fundamental harmonic winding factor for maximum average output torque. Since an ISDW SPMM has more sinusoidal winding magnetomotive force (MMF) waveform with fewer higher order harmonics, it is beneficial for reducing iron and PM eddy current losses [6] [7]. On the other hand, fractional slot (FS) PMMs which have fractional slot numbers per pole
per phase have been extensively investigated so far. In comparison to ISDW SPMMs, FSCW SPMMs have the advantages of high power and torque densities, high efficiency, lower torque ripple, and enhanced flux weakening capability [1], [7]. Meanwhile, it has shorter end-winding and lower copper usage. However, FSCW SPMMs result in abundant sub-harmonic field contents, which lead to higher iron and PM losses [8], [9].

Furthermore, to tradeoff between the winding factor and the end-winding length, SPMMs with different coil pitches have also been investigated [10]-[13]. In [10], windings with two slot coil pitches are used for PMMs to eliminate and/or reduce undesirable space harmonics resulting from nonoverlapping FSCW. [11] and [12] investigate the feasible slot/pole number combinations of SPMMs with two slot-pitch. The influences of windings with different coil pitches for flux reversal PMMs are compared in [13]. Meanwhile, [14] compares the small-size 6-slot/2-pole high-speed SPMMs with one, two, and three coil-pitch windings and underpins that the two coil-pitch winding is the promising candidate for high-speed PMMs.

Besides, vernier PM machines (VPMMs) are one of the FSCW SPMMs with special slot/pole number combinations, typically with pole number higher than slot number. VPMMs have been gaining more attention recently due to their high torque as a result of field modulation and magnetic gearing effect [15]-[18]. In [19], the FS VPMM having two slot-pitch coils is developed to improve the power factor and achieve a compromise between axial end-winding length and torque capacity. [20] proposes a general instantaneous torque equation of VPMM based on a 12-slot/22-pole ISDW VPMM, which further compares with a 12-slot/10-pole FSCW SPMM in terms of torque and torque density. In [21], the variations of the optimized geometric parameters for VPMMs with different pole ratios and winding pole numbers are presented. The torque production mechanism of VPMMs with different pole ratios and winding pole numbers is investigated and analyzed in [22] [23], but the influences of end-winding on torque density, efficiency, and power factor are not analyzed. Likewise, it has been demonstrated in [24] that the ISDW VPMMs have higher torque per machine volume than the FSCW VPMMs, while the volume of end-winding is also not considered.

To date, there are few papers systematically evaluating the electromagnetic performances of SPMMs considering the influences of end-winding in terms of machine optimization, machine volume, end-winding flux leakage, and power factor simultaneously. Furthermore, in some applications with limited space, torque density is one of the most critical machine design parameters, which is strongly affected by the axial end-winding length. To address this issue, based on the common 12-slot ISDW and FSCW SPMMs (including VPMMs), this paper comprehensively evaluates the influences of different slot/pole number combinations and winding configurations, as well as iron loss at different speeds, on their electromagnetic performances, with particular concerns on the effects of end-winding on torque, torque density, efficiency, inductance, and power factor. Overall, this paper attempts to present a complete procedure from various machine optimization scenarios to electromagnetic performance analysis and provides a comprehensive and informative reference regarding end-winding effects on SPMMs.

This paper is organized as follows. The machine topologies, corresponding electromotive force (EMF) phasor diagrams, and winding connections of the six SPMMs with 12-slot and different pole numbers, i.e. 12-slot/8-pole (12s/8p), 12-slot/10-pole (12s/10p), and 12-slot/14-pole (12s/14p) FSCW SPMMs, and 12-slot/4-pole (12s/4p), 12-slot/20-pole (12s/20p), and 12-slot/22-pole (12s/22p) ISDW SPMMs, are presented in Section II. Then, the six machines are optimized for maximum average torque with the same active lamination stack length with different coil pitches under fixed 40 W copper loss neglecting end-winding by using genetic algorithm (GA) in two-dimensional finite element analysis (FEA) in Section III. The end-winding is taken into consideration during the optimization to determine optimal coil pitches in Section IV and the electromagnetic performances are compared. The effect of stack length on torque and torque density of SPMMs is analyzed in Section V. The SPMMs with optimal coil pitches are further optimized under different speeds with fixed 40 W copper and iron losses in Section VI. The efficiencies are compared in Section VII while the power factors and inductances are compared in Section VIII. This paper is concluded in Section IX.

### II. MACHINE TOPOLOGIES

FSCW and ISDW can be implemented in SPMMs. Typical examples of cross-sections of the SPMMs with different slot/pole number combinations and winding configurations are illustrated in FIGURE 1. The SPMMs with different coil pitches, i.e. 1, 2, and 3 slot pitches, will be investigated in Section III.

The number of slots per pole per phase \( q \) is an integer in ISDW machines while a fraction in FSCW machines according to (1).

\[
q = \frac{N_s}{2mp} \tag{1}
\]

where \( N_s \) is the slot number, \( p \) is the number of pole pairs, and \( m \) is the phase number.

It should be noted that for 12s/20p and 12s/22p, the number of pole pairs in (1) are 2 and 1, respectively, which are the numbers of pole pairs of the armature windings. Therefore, for 12s/8p, 12s/10p, and 12s/14p FSCW SPMMs, the corresponding \( q \) equals 1/2, 2/5, and 2/7, respectively. For 12s/4p, 12s/20p, and 12s/22p ISDW SPMMs, the corresponding \( q \) equals 1, 1, and 2, respectively.
The star-of-slot theory [25] can be used to obtain the winding layout by the phasors of coil EMFs. The coil EMF phasors of the six SPMMs are shown in FIGURE 2. For 12s/8p, the coils of one phase locate in separated slots. For 12s/10p, the phase consists of two adjacent coils with different directions and two opposite coils while the phase sequence for 12s/14p swaps compared with that for 12s/10p. The coil locations of 12s/4p and 12s/20p are the same because their pole numbers of stator armature windings are 4. For 12s/22p, the phase consists of two adjacent coils with same direction and two opposite coils.

![FIGURE 1. Machine topologies and winding connections of SPMMs with different slot/pole number combinations. (a) 12s/4p. (b) 12s/8p. (c) 12s/10p. (d) 12s/14p. (e) 12s/20p. (f) 12s/22p.](image1)

![FIGURE 2. Coil EMF phasors of SPMMs with different slot/pole number combinations. (a) 12s/4p. (b) 12s/8p. (c) 12s/10p. (d) 12s/14p. (e) 12s/20p. (f) 12s/22p.](image2)

### III. OPTIMAL COIL PITCH FOR MAXIMUM TORQUE

The typical winding connections for the six machines have been presented in Section II. Furthermore, the winding connections for machines can be varied with different coil pitches, leading to different winding factors. In this Section, the six SPMMs are optimized for maximum average torque with the same active lamination stack length and different coil pitches to investigate the influence of coil pitch and winding factor on the performance of SPMMs by using GA in FEA.

During the optimization, the stator outer diameter ($d_{so}$), the lamination stack length ($l_{fe}$), the air-gap length ($\delta$), the shaft diameter ($d_{sh}$), the PM volume($v_{pm}$), and the pole arc ($\alpha_p$) are fixed, as listed in Table I, while the stator inner diameter ($d_{si}$), the thickness of stator yoke ($h_y$), the width of stator tooth ($w_t$), and the stator slot opening ($b_{so}$) will be globally optimized under fixed 40 W copper loss in the active part of winding by using GA in FEA. The thickness of the PM ($h_{pm}$) is determined by the stator inner diameter since the volume of PMs is fixed during the optimization.

The dimensional variables during the optimization are shown in FIGURE 3.

![FIGURE 3. Optimization variables.](image3)
TABLE I
FIXED GEOMETRIC AND DESIGN PARAMETERS DURING OPTIMIZATION

| Symbol | Parameters               | Unit | Value       |
|--------|--------------------------|------|-------------|
| Ns     | Number of stator slots   | -    | 12          |
| 2p     | Number of poles          | -    | 4/8/10/14/20/22 |
| dso    | Stator outer diameter    | mm   | 100         |
| lfe    | Lamination stack length  | mm   | 50          |
| Naph   | Number of turns per phase| -    | 184         |
| sf     | Slot filling factor      | -    | 0.28        |
| δ      | Air-gap length           | mm   | 1           |
| dsh    | Shaft diameter           | mm   | 20          |
| vpm    | PM volume                | cm³  | 24.5        |
| αp     | Pole arc                 | Deg. | 180         |
| Br     | PM remanence             | T    | 1.20        |
| μr     | PM relative permeability | -    | 1.05        |

Windings with different coil pitches are illustrated in FIGURE 4. When coil pitch equals 1, the coils of one phase are concentrated and wound on one tooth, and thus, there is no overlapping end-winding part. Otherwise, there may be overlapping parts when coil pitch is larger than 1. It is obvious that the end-winding of non-overlapping FSCW is much shorter than that of overlapping winding.

Taking 12s/4p SPMM as an example, windings with different coil pitches are shown in FIGURE 5. When coil pitch equals 3, ISDW are implemented as shown in FIGURE 1 (a).

The torques of all optimized six SPMMs with different coil pitches are shown in FIGURE 6 (a) and the corresponding winding factors are shown in FIGURE 6 (b). When the SPMMs are optimized for maximum average torque under fixed 40 W copper loss neglecting end-winding, the optimized average torques almost show the same trend with winding factors.

- For 12s/4p SPMM, the optimal coil pitch is 3 due to its highest winding factor.
- For 12s/8p/10p/14p SPMMs, the optimal coil pitch is 1.
- For 12s/20p and 12s/22p SPMMs which are vernier machines, the optimal coil pitch is 3 and 6, respectively, due to their highest winding factors and field modulation effect [18].

FIGURE 6 (c) shows the ratio between average torque and winding factor. The ratio increases significantly with pole number because the magnetic gearing effect increases with the pole number [18], as shown in FIGURE 7, where $T_U$ is the torque component produced by the principle of the conventional electrical machine while $T_M$ is the torque component produced by the principle of the magnetic gearing effect. Meanwhile, the ratio of torque produced by the magnetic gearing effect to the total torque is defined by:

\[ \frac{T_M}{T_{total}} \]
\[ \rho = \frac{T_d}{T_M + T_U} \]  

(2)

FIGURE 6. Optimized average torques, winding factors, and ratios between torque and winding factor of SPMMs with the same active lamination stack length under fixed 40 W copper loss neglecting end-winding with different coil pitches. (a) Average torques. (b) Winding factors. (c) Ratios between torque and winding factor.

FIGURE 7. Torque components of SPMMs with different slot/pole number combinations and ratios of torque produced by magnetic gearing effect. (a) Torque components of SPMMs with different slot/pole number combinations. (b) Ratios of torque produced by magnetic gearing effect.

The optimal torques and coil pitches for all SPMMs are shown in FIGURE 8. According to the optimization results, the optimal coil pitches for 12s/8p, 12s/10p, and 12s/14p SPMMs for maximum average torque are 1 due to the largest winding factor. For 12s/4p, 12s/20p, and 12s/22p SPMMs, the optimal coil pitches are 3, 3, and 6, respectively.

FIGURE 8. Optimized average torques of 12-slot SPMMs with the same active lamination stack length and corresponding optimal coil pitches under fixed 40 W copper loss neglecting end-winding.

IV. GLOBAL OPTIMIZATION CONSIDERING END-WINDING

A. OPTIMAL COIL PITCH CONSIDERING END-WINDING

The coil pitch not only affects winding factor, but also leads to different end-winding lengths. The end-winding length of
ISDW is much longer than that of FSCW, and thus, for fair comparison, the copper loss of end-winding should be taken into consideration during optimization. The end-winding will increase phase resistance and axial length of the machine, which will decrease the torque density. In this Section, the SPMMs are optimized for maximum average torque under fixed 40 W copper loss considering end-winding. Other constraints are the same as Section III. The modelling of end-winding and calculation of end-winding length are shown in Appendix A, and the experimental results of optimized machines are presented in Appendix B.

At first, the six machines with different coil pitches are optimized for maximum average torque under fixed 40 W copper loss considering end-winding. The optimization results are shown in FIGURE 9. Compared with FIGURE 6 (a), the optimized average torques considering end-winding decrease, especially for overlapping windings. When coil pitch equals 1, the end-winding length of FSCW is relatively short, and thus, the torque decreases slightly. The torques reduce more obviously as the coil pitches increase.

The optimized torque reduction ratio increases with the increase of end-winding length. The optimized torques of 12s/8p/10p/14p considering end-winding are 3.88 Nm, 4.31 Nm, and 4.51 Nm, respectively, decreasing about 15% compared with that of neglecting end-winding. However, the torques of 12s/4p, 12s/20p, and 12s/22p decrease significantly because ISDW has longer end-winding length. For 12s/4p SPMM, the torque is 3.07 Nm and decreased by 32%. For 12s/20p and 12s/22p vernier machines, the torques are 4.73 Nm and 5.69 Nm and decreased by 36% and 38%, respectively.

According to the optimization results, the optimal coil pitches for the six SPMMs with fixed 40 W copper loss and 50 mm stack length are selected. For 12s/4p SPMM, the optimal coil pitch for maximum average torque under fixed 40 W copper loss considering end-winding is 3, due to its highest winding factor even though it has the longest end-winding. When coil pitch is 2, the end-winding length will be shorter, but the lower winding factor (0.866) cannot guarantee higher torque. For 12s/8p, 12s/10p, and 12s/14p SPMMs, the optimal coil pitch is 1, due to their shorter end-winding length and high winding factor. For 12s/20p SPMM vernier machine, the optimal coil pitch is 3, due to its highest winding factor and field modulation effect. For 12s/22p SPMMs, when coil pitch equals 4, 5, and 6, the winding factors are 0.837, 0.933, and 0.966, respectively. The corresponding average torques are 5.40 Nm, 5.70 Nm, and 5.69 Nm. Thus, the optimal can be either 5 or 6. In this paper, 6 is selected for 12s/22p.

The optimized average torques of all SPMMs with respective optimal coil pitch considering end-winding and those neglecting end-winding are compared in FIGURE 10. The optimized parameters of all six machines with the same active lamination stack length under fixed 40 W copper loss considering end-winding with different coil pitches are shown in Table II, while the corresponding geometries and on-load flux lines and magnetic field distributions are shown in FIGURE 11.

B. COMPARISON OF OPTIMIZATION RESULTS

FIGURES 12 and 13 show the flux lines and magnetic fields caused by PMs or armature reaction only. It shows that the magnetic fields of 12-slot SPMMs caused by armature reaction increase with the rotor pole number. For 12s/20p and 12s/22p vernier machines, armature reaction has significant influence on on-load flux lines and magnetic field distributions. For other 12-slot SPMMs, armature reaction has...
relatively smaller influence on on-load flux lines and magnetic field distributions.

FIGURE 11. Load flux contour distributions of optimized SPMMs under 40 W copper loss. (a) 12s/4p. (b) 12s/8p. (c) 12s/10p. (d) 12s/14p. (e) 12s/20p. (f) 12s/22p.

FIGURE 12. Flux contour distributions of optimized SPMMs under 40 W copper loss caused by PMs only. (a) 12s/4p. (b) 12s/8p. (c) 12s/10p. (d) 12s/14p. (e) 12s/20p. (f) 12s/22p.

FIGURE 13. Flux contour distributions of optimized SPMMs under 40 W copper loss caused by armature reaction only. (a) 12s/4p. (b) 12s/8p. (c) 12s/10p. (d) 12s/14p. (e) 12s/20p. (f) 12s/22p.
FIGURE 14 compares the optimized average torques, torque densities, and dimensional parameters. The optimized average torques under 40 W copper loss considering end-winding increase with pole number. However, for ISDW vernier machines, the axial length of end-winding is much longer than FSCW SPMMs, the axial end-winding length and torque density are compared in FIGURE 14 (b). The torque densities of 12s/8p, 12s/10p, and 12s/14p FSCW SPMMs are larger than those of 12s/20p and 12s/22p vernier machines, which have relatively longer axial end-windings even though vernier machines can generate higher torque for the same lamination stack length.

The split ratio almost increases with pole number, while the PM thickness is inversely proportional to the split ratio as the PM volumes of all six SPMMs are fixed during optimization. For 12s/8p, 12s/10p, and 12s/14p FSCW SPMMs, the yoke thickness and tooth width decrease with the pole numbers. Therefore, the slot area and current amplitude increase with pole numbers, and the torque increases with pole numbers under fixed copper loss. The yoke thickness of 12s/22p vernier machine is larger than 12s/20p vernier machine. When the vernier machines operate on on-load condition, the armature reactions will affect the magnetic field distribution. For 12s/22p vernier machine, the stator pole number is 2 while the stator pole number is 4 for 12s/20p vernier machine, and thus, the yoke thickness of 12s/22p needs to be larger than that of 12s/20p vernier machine. The optimal slot opening increases with the rotor pole numbers except for 12s/4p SPMM. The ratio of tooth tip width and PM pole pitch increases when the pole number smaller than the slot number, while decreasing when the pole number larger than the slot number, as shown in FIGURE 14 (d).

FIGURE 15 compares the variations of average torque with copper loss to illustrate the overload capability of SPMMs optimized under fixed 40 W copper loss with different slot/pole number combinations. The average torques of VPMMs (12s/20p and 12s/22p) are higher at light load conditions, but VPMMs cannot maintain the advantage in high torque output capacity at heavy load conditions, especially

### TABLE II

RESULTS OF GLOBAL OPTIMIZATION UNDER FIXED 40 W COPPER LOSS CONSIDERING END-WINDING

| Pole number | 4   | 8   | 10  | 14  | 20  | 22  |
|-------------|-----|-----|-----|-----|-----|-----|
| $d_s$ (mm)  | 50.69 | 54.41 | 56.57 | 61.5 | 69.04 | 67.12 |
| $h_y$ (mm)  | 6.61 | 3.85 | 3.41 | 2.66 | 3.02 | 4.64 |
| $w_t$ (mm)  | 6.26 | 7.23 | 7.03 | 5.72 | 3.48 | 2.71 |
| $b_s$ (mm)  | 2.54 | 1.94 | 2.71 | 5.05 | 10.43 | 11.49 |
| $h_{sw}$ (mm) | 3.45 | 3.17 | 3.03 | 2.75 | 2.41 | 2.49 |
| Torque (Nm) | 3.07 | 3.88 | 4.31 | 4.51 | 4.73 | 5.69 |
| $I_{peak}$ (A) | 4.80 | 6.34 | 6.37 | 6.50 | 4.53 | 3.63 |
12s/22p VPMM due to more significant magnetic saturation. In contrast, FSCW SPMMs, especially 12s/10p and 12s/14p SPMMs, have better torque output capacity at heavy load conditions.

As can be seen, the average torque increases with lamination stack length and rotor pole number. The axial end-winding length has adverse effect on torque density. Because the axial end-winding length of FSCW is relatively short compared with stack length, the torque density of FSCW SPMMs decreases with the increase of lamination stack length under fixed 40 W copper loss. However, the end-winding length of ISDW is relatively long when the lamination stack length of the machine is short, and thus, the increase of lamination stack length will eliminate the adverse effect of axial end-winding length on torque density. Therefore, the torque densities of 12s/4p, 12s/20p, and 12s/22p ISDW SPMMs will increase first while increasing the stack length with fixed 40 W copper loss. While further increasing the lamination stack length, the torque density will decrease. The torque densities of 12s/8p, 12s/10p, and 12s/14p FSCW SPMMs are higher than those of 12s/20p and 12s/22p ISDW vernier machines when the lamination stack length is short. While increasing the lamination stack length, the torque density of vernier machines will be higher.

In general, the torque densities of ISDW vernier machines are lower compared with FSCW SPMMs due to long axial end-winding length. However, the vernier machines with long lamination stack lengths can maintain high average torque and torque density simultaneously.

VI. MACHINE OPTIMIZATION CONSIDERING IRON LOSS

Iron loss varies with machine topologies and operating conditions. In some cases, higher iron loss leads to high temperature rise due to higher frequency, which should be taken into consideration during optimization [14].

The iron loss density is computed as [26]:

$$P_r = k_h f B_m + k_e f^{1.5} B_m^{1.5} + k_{ex} f^2 B_m^2$$

(3)

where $B_m$ is the amplitude of the AC flux component, $f$ is the frequency, $K_h$ is the hysteresis core loss coefficient, $K_e$ is the eddy-current core loss coefficient, and $K_{ex}$ is the excess core loss coefficient. The iron loss is calculated by FEA [27], where the coefficients are 109.91W/m³, 0.42W/m³, and 4.94W/m³, respectively.

The iron losses in the optimized SPMMs under different speeds are compared in FIGURE 17. The iron loss increases with the rotor pole number and speed. The iron losses of 12s/20p and 12s/22p vernier machines are much larger than other SPMMs. Hence, in this Section, the iron loss will be considered in the design optimization for fair comparison, especially for high speed SPMMs and SPMMs with large pole number.
The six SPMMs are optimized for maximum average torque under fixed 40 W copper and iron losses accounting for end windings. As the iron loss increases with rotor rotation speed, the SPMMs are optimized under two different specific speeds to illustrate the influence of iron loss in the design optimization.

During the optimization, the fixed parameters are the same as the optimization in previous sections as shown in Table I. Parametric analysis in FEA is used to calculate the electromagnetic performance of all SPMMs with the same active lamination stack length and with different stator inner diameter ($d_{si}$), thickness of stator yoke ($h_y$), width of stator tooth ($w_t$), slot opening ($b_{so}$), and phase current. According to the calculation, the optimal SPMMs with maximum torque are selected from those results with 40 W or less copper and iron losses.

### A. LOW SPEED OPTIMIZATION (400 R/MIN)

The optimized parameters of the SPMMs optimized under fixed 40 W copper and iron losses accounting for end windings at 400 r/min are shown in Table III.

#### TABLE III

RESULTS OF GLOBAL OPTIMIZATION UNDER FIXED 40 W COPPER AND IRON LOSSES AT 400 R/MIN

| Pole number | 4   | 8   | 10  | 14  | 20  | 22  |
|-------------|-----|-----|-----|-----|-----|-----|
| $d_{si}$ (mm) | 51  | 54.5| 57  | 60  | 69.00| 66.5|
| $h_y$ (mm)   | 6.6 | 3.7 | 3.4 | 2.6 | 2.9 | 4.55|
| $w_t$ (mm)   | 6.25| 7.1 | 6.9 | 5.7 | 3.4 | 2.65|
| $b_{so}$ (mm) | 2.50| 2   | 3   | 4.4 | 10.50| 11.50|
| Torque (Nm)  | 3.03| 3.82|4.23 |4.41 |4.61 |5.56 |
| $I_{peak}$ (A) | 4.7 | 6.3 | 6.25| 6.5 | 4.45 |3.6  |

FIGURE 18 shows the optimization results compared with SPMMs optimized under 40 W copper loss. As copper loss plays a dominant role in lower speed condition in FIGURE 18 (e), the optimized dimensional parameters considering iron loss during the optimization in lower speed condition (400 r/min) almost unchanged compared with those optimized under fixed 40 W copper loss, such as split ratio and yoke thickness. The optimized torque and phase current decrease slightly as the total copper loss decreases slightly.
machine under 40 W copper and iron losses is lower than that of 12s/10p and 12s/14p SPMMs due to its higher iron loss. The optimized dimensional parameters considering iron loss during the optimization in higher speed condition (2000 r/min) almost unchanged compared with those optimized results in lower speed condition (400 r/min), such as split ratio and yoke thickness.

**B. HIGH SPEED OPTIMIZATION (2000 R/MIN)**

The optimized parameters of the SPMMs optimized under fixed 40 W copper and iron losses accounting for end windings and 2000 r/min are shown in Table IV.

| Pole number | 4   | 8   | 10  | 14  | 20  | 22  |
|-------------|-----|-----|-----|-----|-----|-----|
| $d_{si}$ (mm) | 50  | 54.5| 57  | 60.5| 67  | 66.5|
| $h_y$ (mm)  | 6.6 | 3.7 | 3.4 | 2.6 | 2.9 | 4.3 |
| $w_t$ (mm)  | 6.25| 7.2 | 6.8 | 5.5 | 3   | 2.6 |
| $b_{so}$ (mm) | 2.5 | 2   | 4   | 7   | 11.5| 12.5|
| Torque (Nm) | 2.81| 3.29| 3.57| 3.62| 3.44| 3.86|
| $I_{peak}$ (A) | 4.4 | 5.4 | 5.3 | 5.4 | 3.6 | 2.5 |

FIGURE 19 shows the optimization results between 2000 r/min and 400 r/min. When the speed increases, the iron loss increases, and the copper loss is no longer the dominant loss especially when the pole number increases, as shown in FIGURE 19 (f). Therefore, the phase current, torque, and torque density decrease. FIGURE 19 (b) shows that the torque reduction ratio between lower speed and higher speed increases with the pole number because iron loss increases with the pole number under the same speed. In general, vernier machines have higher torque output capacity [15]-[20]. However, the optimized average torque of 12s/20p vernier
FIGURE 19. Comparison of the optimization results of SPMMs with the same active lamination stack length and under fixed 40 W copper and iron losses accounting for end windings between 2000 r/min and 400 r/min. (a) Average torque and torque density. (b) Torque reduction ratio. (c) Split ratio. (d) Yoke thickness and tooth width. (e) Slot opening. (f) Loss distribution. (g) Phase current amplitude.

VII. Efficiency

A. SPMMs Optimized with 40 W Copper Loss

As shown in the previous sections, the average torque and iron loss increase with rotor pole number. The PM loss also varies with rotor pole number as shown in FIGURE 20. Therefore, the efficiencies of the optimized machines are compared in this Section.

The efficiency $\eta$ is calculated by

$$\eta = \frac{P_{out}}{P_{out} + P_{Cu} + P_S + P_R + P_{PM}}$$

where $P_{out}$ is the output power, $P_{Cu}$ is the copper loss, $P_S$ is the stator iron loss, $P_R$ is the rotor iron loss, and $P_{PM}$ is the PM loss.

FIGURE 20. Comparison of PM losses of SPMMs under fixed 40 W copper loss and different speeds.

FIGURE 21 compares the efficiencies of SPMMs with 40 W copper loss accounting for end windings and iron loss under different speeds. The efficiencies of SPMMs with larger rotor pole number are higher at lower speed. As the speed increases, the efficiencies of SPMMs with larger rotor pole number become lower than those of SPMMs with smaller rotor pole number because the losses of SPMMs with larger rotor pole number increase faster with the increase of speed, as shown in FIGURE 22.

FIGURE 21. Comparison of efficiencies of SPMMs under fixed 40 W copper loss accounting for end windings and different speeds.

FIGURE 22. Comparison of total losses of SPMMs under fixed 40 W copper loss accounting for end windings and different speeds.

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B. SPMMS OPTIMIZED WITH 40 W COPPER AND IRON LOSSES

As the parameters of the SPMMs optimized with fixed 40 W copper and iron losses at lower speed condition are almost the same with those of under 40 W copper loss, the efficiencies of SPMMs optimized considering iron loss are almost the same with those of optimized with fixed 40 W copper loss.

FIGURE 23. Comparison of efficiencies of SPMMs under fixed 40 W copper and iron losses accounting for end windings and different speeds.

FIGURE 24 compares the efficiencies of SPMMs optimized under fixed 40 W copper and iron losses at 2000 r/min. The efficiencies of SPMMs optimized considering iron loss are slightly higher than those of optimized with fixed 40 W copper loss.

FIGURE 24. Comparison of efficiencies between SPMMs optimized under fixed 40 W copper and iron losses and under fixed 40 W copper loss accounting for end windings at 2000 r/min.

VIII. Inductance and Power Factor

A. INDUCTANCE

Winding inductances have significant effect on the electromagnetic performances of SPMMs. The phase inductance includes synchronous inductance, harmonic leakage inductance, slot leakage inductance, and end-leakage inductance [28] [29]. The differences of end-winding length and disposition between FSCW and ISDW lead to different end-winding leakage inductances. However, end-leakage inductance cannot be calculated in 2D FEA, and thus, the simplified calculation method for end-winding leakage inductance in [29] is used.

\[
L_{\text{end-phase}} = n_{\text{cond}}^2 n_{\text{coils}} K_w (2 l_{\text{end-avg}}) (1.2 \mu_0)
\]  

where \( n_{\text{cond}} \) is the number of conductors per slot, \( n_{\text{coils}} \) is the number of coils per phase, \( K_w \) is the winding factor, and \( l_{\text{end-avg}} \) is the average end-turn length.

The \( d \)-axis inductances \( (L_d) \) of optimized SPMMs with fixed 40 W copper loss and 40 W copper and iron losses at 2000 r/min are similar, as shown in FIGURE 25 (a). The comparison between \( d \)-axis inductances of SPMMs optimized with fixed 40 W copper loss neglecting and considering end-leakage inductance is also shown in FIGURE 25 (b). \( L_d \) of ISDW SPMMS is much higher than those of FSCW SPMMS. As ISDW SPMMS have longer end-winding and overlapping part, the end-winding leakage inductance cannot be ignored for accurate calculation.

FIGURE 25. Comparison of \( d \)-axis inductances of SPMMs with different slot/pole number combinations. (a) \( d \)-axis inductances of SPMMs optimized with different scenarios. (b) Comparison of \( d \)-axis inductances and end-winding leakage inductance with 40 W fixed copper loss.

B. POWER FACTOR

The power factor is calculated by (6) when SPMMs are under \( I_p \neq 0 \) control and the winding resistance is ignored [19] [30].
where $E_i$ is the no-load back EMF, $X_q$ is the $q$-axis inductive reactance, and $I_q$ is the $q$-axis current. In SPMMs, the $d$-axis and $q$-axis inductances (and reactances) are similar.

As the power factor increases with the decrease of the $q$-axis current, the $q$-axis currents of SPMMs optimized with fixed 40 W copper and iron losses at 2000 r/min are adjusted to the same values of currents of SPMMs optimized with fixed 40 W copper loss for fair comparison. The power factors neglecting end-winding leakage inductance of SPMMs optimized with fixed 40 W copper and iron losses at higher speed condition are shown in FIGURE 26. The power factors between SPMMs optimized under 40 W copper loss are almost the same with those of under 40 W copper and iron losses at 2000 r/min. The power factor of 12-slot SPMMs decreases with the rotor pole number, and the power factors of vernier machines are much lower than those of other SPMMs.

FIGURE 26. Comparison of power factors between SPMMs optimized under fixed 40 W copper and iron losses and fixed 40 W copper loss at 2000 r/min.

It can be seen from (6) that the $q$-axis inductance has large impact on the power factor. FIGURE 27 compares the power factors of SPMMs optimized with fixed 40 W copper loss considering end-winding or not. The end-winding leakage inductance will decrease the power factor, especially for 12s/20p and 12s/22p ISDW VPMMs.

FIGURE 27. Comparison of power factors of SPMMs optimized with fixed 40 W copper loss considering end-winding or not. (a) Power factor. (b) Decrement rate.

IX. CONCLUSION

In this paper, three FSCW and three ISDW SPMMs with 12-slots but different slot/pole number combinations are optimized and compared. The effects of coil pitch and end-winding on torque, torque density, efficiency, winding inductance, and power factor of SPMMs with different slot/pole number combinations are investigated. These machines are optimized with the same axial lamination stack length for maximum average torque under fixed 40 W loss for various slot/pole number combinations and different coil pitches, and under various scenarios, i.e. without/with considering end-winding length and/or iron loss, as well as different lamination stack lengths. The optimal coil pitch and winding factor for each slot/pole number combination have been determined for maximum average torque.

It shows that the optimized average torques almost show the same trend with winding factors. The end-winding will decrease the optimized average torque, torque density, and power factor, especially for ISDW SPMMs. As copper loss plays a dominant role at lower speed condition, the optimization results considering iron loss at lower speed condition are almost unchanged. However, the optimized torques reduce obviously while considering iron loss at higher speed, especially for SPMMs with higher rotor pole number. Considering iron loss in machine optimization helps to increase efficiency. In general, the torque densities and power factors of ISDW vernier machines are lower compared with FSCW SPMMs due to long axial end-winding length. However, with long lamination stack length, the vernier machines can maintain high average torque and torque density simultaneously.

Currently, the investigations are being extended to the consequent pole PM machines with different slot/pole number combinations and winding configurations, and the results will be presented in a future paper.
APPENDIX
A. MODELLING OF END-WINDING
FSCW and ISDW have different end-winding structures. In general, the length of end-winding of FSCW is much shorter than that of ISDW. Since end-winding structure is quite complicated and difficult to model accurately, there are several simplified models to calculate the length of end-winding [14], [29], [31]-[36]. The model in [33], [35] uses several serially connected straight lines to model the end-winding in FIGURE 28 (a), which is often used for large AC machines. In most cases, the end-winding is assumed to be circular or semi-circular in FIGURE 28 (b) [29], [34], especially in FSCW machines. In [32], [36], quarter-circles and straight lines are used to model the end-winding in FIGURE 28 (c), whose shape is much closer to the stack.

For double-layer FSCW, the coil center locates in the quadrant of the slot as shown in FIGURE 29, while for single layer ISDW, the coil center locates in the center of the slot. In this paper, two quadrants, two end-winding extensions, and an arc are used to model the half turn of the end-winding, which is shown in FIGURE 28 (c). The corresponding lengths of winding per turn can be calculated by

\[ l_{\text{w}} = 2\tau_c - 4r_{\text{end}} + 2\pi r_{\text{end}} + 4l_{\text{ex}} + 2l_r \]  

(7)

where \( \tau_c \) is the average coil pitch. The end-winding extension can be 0 in this model.

The radius of the center of the coils \( r_{\text{coil}} \) is calculated by:

\[ r_{\text{coil}} = \frac{\text{d_{so}}}{2} - h_z - 0.5h_y \]  

(8)

The end-winding length per turn, \( l_{\text{end}} \), is calculated as

\[ l_{\text{end}} = 2\tau_c - 4r_{\text{end}} + 2\pi r_{\text{end}} + 4l_{\text{ex}} \]  

(9)

For double-layer FSCW, \( \tau_c \) is calculated as

\[ \tau_c = \frac{2\pi r_{\text{coil}}}{N_s} - 0.5w_y \]  

(10)

For single-layer ISDW, \( \tau_c \) is calculated as

\[ \tau_c = \frac{2\pi w_y r_{\text{coil}}}{N_s} \]  

(11)

where \( w_y \) is the coil pitch of slot pitch.

The total winding length per turn \( l_w \) is

\[ l_w = 2l_{\text{ex}} + l_{\text{end}} \]  

(12)

Then, the phase resistance \( r_a \) can be calculated by

\[ r_a = \frac{\rho l_{\text{w}} N_{pk}}{a_i S_i} \]  

(13)

where \( a_i \) is the number of parallel branches while \( S_i \) is the surface area of the coil.

To investigate the torque density, the axial length of end-winding \( l_{\text{ax}} \) also needs to be calculated. For FSCW, the axial length is easy to calculate by (14), where \( t_w \) is the thickness of winding in FIGURE 30 (a).

\[ l_{\text{ax}} = 2l_{\text{ex}} + 2r_{\text{end}} + t_w \]  

(14)

For ISDW, the calculation of axial length is different from the FSCW as there are overlapping parts. As FIGURE 30 shown, the overlapping part of 12s/22p is more than 12s/20p. Therefore, the axial length of ISDW end-winding can be calculated by:

\[ l_{\text{ax}} = 2l_{\text{ex}} + 2r_{\text{end}} + (2n + 1)t_w \]  

(15)
where \( n \) is the number of the overlapping part, 1 for 12s/20p and 2 for 12s/22p.

**FIGURE 30.** End-winding structure. (a) 12s/20p. (b) 12s/22p.

### B. EXPERIMENT VERIFICATION OF FEA RESULTS

In this Section, 12s/14p FSCW and 12s/22p ISDW SPMMs are prototyped and tested [17]. The main dimensional parameters of the prototypes are given in Table V. The prototypes and test rig are shown in **FIGURE 31**.

**FIGURE 31.** Prototypes and test rig. (a) 12-slot stator with FSCW. (b) 14-pole rotor. (c) 12-slot stator with ISDW. (d) 22-pole rotor. (e) Test rig.

The back EMFs and output torques are tested to validate the results calculated by FEA, as shown in **FIGURES 32, 33**, respectively. The static torques of the prototypes are measured [37] by applying DC current to phase A in series connection to the parallel phase B and phase C (\( I_a = -2I_b = -2I_c \)). The static torques within 0-180 electric degrees of the prototypes are measured by rotating the stator housings over 180 electric degrees with fixed steps. The measured results are given and compared with the 2D FEA results in **FIGURE 33**. The back EMFs and torques calculated by FEA show good agreements with the measured results.

**FIGURE 32.** Comparison between measured and FEA predicted back EMFs. (a) 12s/14p. (b) 12s/22p.

**FIGURE 33.** Comparison between measured and 2D FEA calculated back EMFs and torques. (a) Measured vs. FEA. (b) Measured vs. FEA.
FIGURE 33. Comparison between measured and FEA predicted static torques. (a) 12s/14p. (b) 12s/22p.

TABLE V
MAIN DIMENSIONAL PARAMETERS OF PROTOTYPES

| Parameters          | Values   |
|---------------------|----------|
| Slot number         | 12       |
| Pole number         | 14       |
| Stator outer diameter | 100 mm  |
| Lamination stack length | 50 mm   |
| Air-gap length      | 1 mm     |
| PM pole arc         | 180°     |
| Remanence of PM     | 1.2 T    |
| Relative permeability of PM | 1.05 |
| Stator inner diameter | 57 mm   |
| PM thickness        | 3 mm     |
| Slot opening        | 2 mm     |
|                     | 11.5 mm  |

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