Comparative study of stator consequent-pole permanent magnet machines

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Abstract
A comparative investigation is made of stator consequent-pole (SCP) machines with different permanent magnet (PM) arrangements. Compared with conventional surface-mounted PM (SPM) configurations, SCP configurations produce more orders of air-gap field harmonics. Due to asymmetrical PM magnetomotive force (MMF) distributions and the double-side slotting effect, SCP machines exhibit multiple air-gap field harmonics, especially relatively enhanced low-order field harmonics, for torque production. As a consequence, improved torque capability can be obtained over that of conventional SPM counterparts. Machine topologies and operating principles are described. The design parameters of four SCP machines with different magnet arrangements are globally optimised. The key electromagnetic performances, including open-circuit performance, torque quality, field-weakening capability, and efficiency, are comprehensively investigated and compared by the finite element (FE) method. Finally, some experimental measurements on an optimally selected SCP machine prototype are carried out to validate the theoretical and FE analyses.

1  INTRODUCTION

Owing to its high torque/power density, simple salient rotor, and good thermal management, the stator permanent magnet (PM) machine [1–3] is widely recognised as a potential candidate for wind turbine, electric vehicle use, and aircraft applications. According to their PM position, stator PM machines can generally be categorised as interior PM [4–13] and surface-mounted PM (SPM) [14–28] structures. The former type mainly includes switched flux [4–9], doubly salient [10,11], and stator slot PM structures [12,13]. The latter mainly consists of flux reversal [14–32] and biased PM flux topologies [33–35]. With the advantages of simple manufacturing and high reliability, stator SPM machines [14–26] are preferred for practical applications.

Various stator SPM machines using dual stator [15], linear structure [16], and hybrid excited [17] topologies have been developed and investigated in recent years. In addition, the design issues of stator SPM machines, including the effects of magnet polarities [18,19], PM number [20], winding configurations [21,22], asymmetrical stator pole [23], stator/rotor combinations [24] etc., and their effects on electromagnetic characteristics have been presented. Furthermore, investigations of the working mechanism have demonstrated that only fundamental rotor permeance and PM magnetomotive force (MMF) components are responsible for torque generation in stator SPM machines [25,26]. Nevertheless, serious PM flux leakage [27,28], relatively high PM cost [29], and the risk of potentially irreversible demagnetisation [30] are major concerns for existing stator SPM machines.

To address the aforementioned issues, stator SPM structures were extended to stator consequent-pole (SCP) machines in [31–36]. Because of the asymmetrical magnetic pole design of SPM machines [31], more even-order PM MMF harmonics were obtained. This indicates that higher effective low-order air-gap flux density harmonic magnitudes can be obtained with the SCP design, hence improving torque capability. Thus, the SCP configuration exhibits much higher torque than that of the SPM case [32]. In addition, the electromagnetic performance of SCP flux reversal machines with different stator/rotor pole combinations was studied in [33], with the finding that torque improvement of the SCP machine is largely influenced by rotor pole number.
In order to validate the merits of torque improvement and magnet cost reduction, four flux reversal machines with different PM piece configurations were compared and investigated in [34]. In addition, SCP machines with closed-slot and semi-closed-slot structures were comparatively studied in [35], which demonstrates that the closed-slot structure provides more effective PM magnetic circuit, which results in improved torque capability.

However, a comprehensive performance comparison of SCP machines with different PM arrangements remains hitherto unreported. Therefore, in order to provide an insightful and general design guideline for selecting an appropriate structure for the SCP machine, the electromagnetic characteristics of four SCP topologies with different PM configurations are comparatively studied. The machine topologies, working principles, and analytical modelling are provided in Section II. To perform an impartial comparison, the design parameters of the four different types of SCP machines are globally optimised in Section III. Then, the main electromagnetic performances of the optimised SCP machines are investigated and compared by the finite element (FE) method. In Section IV, to validate the theoretical analyses, the SCP-IV configuration with optimal overall performance is selected for prototype manufacturing and experimental validation. Finally, some general conclusions are drawn in Section V.

2 | MACHINE TOPOLOGIES AND WORKING MECHANISM

2.1 | Machine topologies

The evolution of SCP topology is shown in Figure 1. The consequent-pole (CP) configuration evolved from the conventional SPM structure [35] by replacing one of the two adjacent PM poles with an iron pole. $N_s$ and $N_{PM}$ are defined as the number of stator teeth and the number of pole pairs of stator PMs, respectively. By rotating the magnets by $\pi/N_s$ degrees in Figure 1a, a regular flux reversal machine with a CP structure [32] can be obtained, as shown in Figure 1b. To reduce flux leakage and further improve the PM utilisation ratio, a semi-closed-slot configuration is employed, as illustrated in Figure 1c [32]. By shifting the sided magnets to the centre of the corresponding stator teeth, a new SCP machine configuration is obtained, as shown in Figure 1d [36]. Furthermore, two SCP machines with semi-closed and closed-slot structures [35] can be obtained by shifting the magnets in Figure 1d by $\pi/N_s$ degrees, as shown in Figure 1e, f, respectively. The illustration of the structural evolution reflects the underlying relation of those SCP topologies.

Four SCP machines with four typical PM arrangements were selected and investigated, as illustrated in Figure 2. To perform an impartial comparison, all four SCP machines have the same 6 PM pole pairs and 11-rotor poles. It can be seen that all of the SCP machine configurations have the armature windings and homopolar magnets in the stator side and a simple salient rotor structure, which means that good thermal management and high rotor robustness can be achieved.

![Image](https://example.com/image1.png)

**FIGURE 1** Evolution of stator consequent-pole (SCP) machine topologies. (a) Regular SCP machine derived from conventional biased flux surface-mounted permanent magnet machine [25] (SCP-I), (b) Flux reversal machine with consequent-pole (CP) and closed-slot structure, (c) Flux reversal machine with CP and open-slot structure (SCP-II), (d) Flux reversal machine with permanent magnets on the stator teeth middle (SCP-III), (e) SCP machine with semi-closed-slot [35], (f) SCP machine with closed-slot (SCP-IV) [28]

![Image](https://example.com/image2.png)

**FIGURE 2** Topologies of stator consequent-pole (SCP) machines with different permanent magnet configurations. (a) SCP-I, (b) SCP-II, (c) SCP-III, (d) SCP-IV
2.2 | Working principle

The magnetic field distributions of the four SCP machines under different rotor positions are shown in Figure 3. The corresponding flux linkage waveforms of coil A1 are shown in Figure 4. The SCP-I machine exhibits unipolar flux linkage, while the others have bipolar flux linkage. In addition, the SCP-II, III, and IV machines have higher fundamental flux linkage amplitudes than the SCP-I case. Therefore, the SCP-II, III, and IV arrangements are expected to provide higher torque capability than the SCP-I case, as presented in the following analyses.

\[ F_{PM} = F_{PM0} + \sum_{i=1}^{\infty} F_{PMi} \sin(iN_{PM}\theta) \]  \hspace{1cm} (1)

where \( F_{PM0} \) and \( F_{PMi} \) are the \( 0^{th} \) and \( i^{th} \) Fourier coefficients, respectively, which can be expressed as

\[
F_{PM0} = \frac{N_{PM}}{2\pi} \frac{B_r h_{PM}}{\mu_0 \mu_r} \theta_{PM}
\]

\[
F_{PMi} = 2\frac{N_{PM}}{i\pi} \frac{B_r h_{PM}}{\mu_0 \mu_r} \sin(i\frac{\theta_{PM}}{2})
\]

where \( B_r \) is the remanence, \( h_{PM} \) is the PM thickness, \( \mu_0 \) is the permeability of vacuum, \( \mu_r \) is the relative permeability of the PM, and \( \theta_{PM} \) is the PM pole-arc.

For a doubly salient structure, the air-gap permeance can be obtained by considering a slotless stator and rotor, respectively. The air-gap permeance function can be expressed as [37,38]
where \( \Lambda_s \) and \( \Lambda_r \) are the air-gap permeance functions that refer to the stator and rotor slotting effects, respectively. Thus, \( \Lambda_g \) can be further simplified as \[38\]

\[
\Lambda_g = \frac{1}{\frac{1}{\Lambda_s} + \frac{1}{\Lambda_r}} = \frac{\mu_0 \Lambda_s}{\mu_0 \Lambda_s + \frac{\mu_0}{g} \Lambda_r \frac{1}{\mu_0}} \times \frac{\mu_0 / g}{\Lambda_s + \frac{\mu_0}{g} \Lambda_r} \tag{3}
\]

where \( g \) is the air-gap length. The stator and rotor permeance functions can be represented by series as

\[
\Lambda_s(\theta) = \Lambda_{s0} + \sum_{m=1}^{\infty} \Lambda_{sm} \cos(mN_{PM}\theta) \tag{5}
\]

\[
\Lambda_r(\theta, t) = \Lambda_{r0} + \sum_{n=1}^{\infty} \Lambda_{rn} \cos [nN_r(\theta - \theta_0 - \Omega_r t)] \tag{6}
\]

where \( N_r \) is the rotor pole number, \( \Omega_r \) is the rotor angular speed, \( \Lambda_{s0} \) and \( \Lambda_{r0} \) are the zero-order stator and rotor permeance Fourier coefficients, respectively, \( \Lambda_{sm} \) and \( \Lambda_{rn} \) are the \( m^{th} \) and \( n^{th} \) stator and rotor permeance Fourier coefficients, respectively, and \( \theta_0 \) is the initial rotor position. For the single-side saliency structure, the coefficients of the air-gap permeance function can be obtained by employing the conformal mapping method [37–39]:

\[
\Lambda_0 = \frac{\mu_0}{g} \left( 1 - 1.6 \frac{b_0}{t_0} \right) \tag{7}
\]

\[
\Lambda_k = \frac{\mu_0}{g} \frac{4\lambda}{3\pi} \left[ 0.5 + \frac{(b_0/t_0)^2}{0.78125 - 2(b_0/t_0)^2} \right] \sin \left( 1.6\pi \frac{b_0}{t_0} \right) \tag{8}
\]

\[
\lambda = 0.5 - 1 \sqrt{1 + \frac{(b_0/t_0)^2}{2t_0/g}} \tag{9}
\]

where \( b_0 \) and \( t_0 \) are the slot opening and slot pitch, respectively. By considering only zero and fundamental stator and rotor permeance harmonics, \( \Lambda_g \) can be rewritten as

\[
\Lambda_g = \frac{g}{\mu_0} \Lambda_{s0}\Lambda_{r0} + \frac{g}{\mu_0} \Lambda_{s0}\Lambda_{r1} \cos(N_{PM}\theta) + \frac{g}{\mu_0} \Lambda_{s1}\Lambda_{r0} \cos [N_r(\theta - \theta_0 - \Omega_r t)] + \frac{g}{2\mu_0} \Lambda_{s1}\Lambda_{r1} \cos(N_{PM} - N_r)\theta \mp N_r(\theta_0 + \Omega_r t) \tag{10}
\]

According to the MMF-permeance-based model [39], the no-load air-gap flux density can be derived in terms of (1) and (6), that is,

\[
B_g(\theta, t) = F_{PM}(\theta) \Lambda_g(\theta, t) = \frac{g}{\mu_0} \Lambda_{s0}\Lambda_{r0} \sum_{i=1,2,3...} F_{PMi} \sin(iN_{PM}\theta) + \frac{g}{2\mu_0} \Lambda_{s0}\Lambda_{r1} \sum_{i=1,2,3...} F_{PMi} \sin [(iN_{PM} \pm N_{PM})\theta] + \frac{g}{4\mu_0} \Lambda_{s1}\Lambda_{r1} \sum_{i=1}^{\infty} F_{PMi} \sin \left( \pm N_r(\theta_0 + \Omega_r t) \right) \tag{11}
\]

Because stationary air-gap flux density harmonics are not responsible for torque production, those components will be neglected in the following derivation. Taking the main order of the PM MMF harmonic into consideration, the main effective \( B_g \) can be simplified as

\[
B_g = B_{[2N_{PM} - N_r]} \sin [(2N_{PM} - N_r)\theta + N_r(\theta_0 + \Omega_r t)] + B_{[N_{PM} - N_r]} \sin [(N_{PM} - N_r)\theta + N_r(\theta_0 + \Omega_r t)] + B_{[3N_{PM} - N_r]} \sin [(3N_{PM} - N_r)\theta + N_r(\theta_0 + \Omega_r t)] + B_{[2N_{PM} + N_r]} \sin [(2N_{PM} + N_r)\theta - N_r(\theta_0 + \Omega_r t)] + B_{[2N_{PM} + N_r]} \sin [(2N_{PM} + N_r)\theta - N_r(\theta_0 + \Omega_r t)] = \sum_{j=1} B_j \sin \left( P_j \theta \pm N_r(\theta_0 + \Omega_r t) \right) \tag{12}
\]

where \( B_j \) and \( P_j \) are the \( j^{th} \) air-gap flux density amplitudes and pole pairs, respectively. The amplitudes and speeds of the main air-gap flux density harmonics are summarised in Table 1.

The flux linkage, \( \psi_A(t) \), of phase A can be obtained as

\[
\psi_A(t) = r_g I_{ahl} \int_0^{\pi} B_g(\theta, t) N_s(\theta) d\theta \tag{13}
\]

where \( r_g \) is the air-gap radius and \( l_{ahl} \) is the active stack length. \( N_s(\theta) \) is the winding function, which can be expressed as

\[
N_s(\theta) = \sum_{b=3}^2 \frac{2}{b\pi} N_b k_{sh} \cos(b\theta) \tag{14}
\]

where \( N_b \) is the series-connected winding turns per phase and \( k_{sh} \) is the winding factor of the \( b^{th} \) air-gap flux density. Thus, the back electromotive force (EMF) of phase A can be expressed as

\[
e_A(t) = -\frac{d\psi_A(t)}{dt} \tag{15}
\]

The electromagnetic torque can be derived as
TABLE 1 The main air-gap flux density harmonic characteristics in stator consequent-pole machines

| Pole pairs                  | Amplitudes                                        | Speed |
|-----------------------------|---------------------------------------------------|-------|
| \([2N_{PMr}N_{r}]\)         | \(B_{[2N_{PMr}N_{r}]} = \frac{\mu}{\Omega_{r}}\Lambda_{w}N_{PMr}F_{PM} + \frac{\mu}{\Omega_{r}}\Lambda_{r}N_{PMr}F_{PM} \) | \(N_{r} \times \) |
| \([N_{PMr}N_{r}]\)          | \(B_{[N_{PMr}N_{r}]} = \frac{\mu}{\Omega_{r}}\Lambda_{w}N_{PMr}F_{PM} + \frac{\mu}{\Omega_{r}}\Lambda_{r}N_{PMr}F_{PM} \) | \(N_{r} \times \) |
| \([3N_{PMr}N_{r}]\)         | \(B_{[3N_{PMr}N_{r}]} = \frac{\mu}{\Omega_{r}}\Lambda_{w}N_{PMr}F_{PM} + \frac{\mu}{\Omega_{r}}\Lambda_{r}N_{PMr}F_{PM} \) | \(N_{r} \times \) |
| \([N_{PM} + N_{r}]\)        | \(B_{[N_{PM} + N_{r}]} = \frac{\mu}{\Omega_{r}}\Lambda_{w}N_{PM}F_{PM} + \frac{\mu}{\Omega_{r}}\Lambda_{r}N_{PM}F_{PM} \) | \(N_{r} \times \) |
| \([2N_{PM} + N_{r}]\)       | \(B_{[2N_{PM} + N_{r}]} = \frac{\mu}{\Omega_{r}}\Lambda_{w}N_{PM}F_{PM} + \frac{\mu}{\Omega_{r}}\Lambda_{r}N_{PM}F_{PM} \) | \(N_{r} \times \) |

TABLE 2 Harmonic amplitudes, torque contributions, and torque proportions of the main air-gap flux density components in four stator consequent-pole machines

| Items                          | SCP-I | SCP-II | SCP-III | SCP-IV |
|-------------------------------|-------|--------|---------|--------|
| \([2N_{PMr}N_{r}]\)_1^{st}    | Amplitude (T) | 0.074 | 0.093 | 0.017 | 0.152 |
| Torque (Nm)                   | 0.21  | 0.42   | 0.67    | 5.385  |
| Proportion (%)                | 7.92  | 8.45   | 21.13   | 68.78  |
| \([N_{PMr}N_{r}]\)_5^{th}    | Amplitude (T) | 0.224 | 0.245 | 0.187 | 0.224 |
| Torque (Nm)                   | 1.76  | 3.08   | 1.50    | 1.587  |
| Proportion (%)                | 66.42 | 61.97  | 47.31   | 20.29  |
| \([3N_{PMr}N_{r}]\)_7^{th}   | Amplitude (T) | 0.002 | 0.056 | 0.073 | 0.062 |
| Torque (Nm)                   | 0.01  | 0.50   | 0.42    | -0.314 |
| Proportion (%)                | 0.38  | 10.06  | 13.25   | 4.03   |
| \([N_{PM} + N_{r}]\)_1^{st}  | Amplitude (T) | 0.284 | 0.257 | 0.232 | 0.240 |
| Torque (Nm)                   | 0.66  | 0.95   | 0.54    | 0.500  |
| Proportion (%)                | 24.91 | 19.11  | 17.03   | 6.47   |
| \([2N_{PM} + N_{r}]\)_3^{rd} | Amplitude (T) | 0.127 | 0.088 | 0.023 | 0.028 |
| Torque (Nm)                   | 0.01  | 0.02   | 0.04    | 0.045  |
| Proportion (%)                | 0.38  | 0.40   | 1.26    | 0.43   |
| Sum (100%) (Nm)               | 2.65  | 4.97   | 3.17    | 6.95   |
| FE-predicted (Nm)             | 2.72  | 5.06   | 3.28    | 7.00   |

Abbreviations: FE, finite element; SCP, stator consequent-pole.

\[
T_e = \sum_{j=1}^{3} B_{j} k_{wj} I_{\text{max}} n_{p} n_{r} \times \frac{B_{[2N_{PM}-N_{r}]} k_{w2N_{PM}-N_{r}}}{[2N_{PM}-N_{r}]} + \frac{B_{[N_{PM}-N_{r}]} k_{w[N_{PM}-N_{r}]} N_{PM}}{[N_{PM}-N_{r}]} + \frac{B_{[3N_{PM}-N_{r}]} k_{w3N_{PM}-N_{r}}}{[3N_{PM}-N_{r}]} + \frac{B_{[N_{PM}+N_{r}]} k_{w[N_{PM}+N_{r}]} N_{PM}}{[N_{PM}+N_{r}]} + \frac{B_{[2N_{PM}+N_{r}]} k_{w2N_{PM}+N_{r}}}{[2N_{PM}+N_{r}]} \\
= 3r_{f} I_{\text{max}} n_{p} n_{r} \sum_{j=1}^{3} B_{j} k_{wj} P_{j} = \sum_{j=1}^{3} T_{\text{avgj}}
\]

(16)

where \(e_{A}, e_{B},\) and \(e_{C}\) are the back-EMFs of phases A, B, and C, respectively; \(i_{A}, i_{B},\) and \(i_{C}\) are the phase currents of phases A, B, and C, respectively; \(k_{wj}\) is the winding factor of the \(j^{th}\) air-gap flux density harmonics; \(I_{\text{max}}\) is the maximum value of phase current; and \(T_{\text{avgj}}\) is the average torque generated by the \(j^{th}\) air-gap flux density. From (16), it can be found that average torque can be enhanced by improving the low-order harmonics, that is, the first \(([2N_{PMr}N_{r}])\) in this case. In order to confirm this advantage, the open-circuit air-gap flux densities of the four SCP arrangements are shown in Figure 5. The main-order working harmonics of the four SCP machines are illustrated in Figure 5b. The SCP-III machine shows the lowest low-order air-gap flux density magnitude, that is, the first-order one. The SCP-IV configuration exhibits the highest first-order harmonic magnitudes, which means that the highest torque capability can be obtained in the SCP-IV topology, as presented in the subjacent analyses.

The proportion of the average torque produced by the \(j^{th}\) air-gap field harmonic is defined as
\[ \lambda_j = \frac{T_{\text{avg}}}{T_{\text{avg}}^{100\%}} \]  

The main working harmonic amplitudes, torque contributions, and torque proportions of the four SCP machines are given in Table 2. It can be seen that SCP-IV exhibits the highest \( |2N_{\text{PM}}-N_r| \) low-order harmonic magnitude, hence resulting in the highest torque proportion, 68.85%. That is to say, its torque capability is enhanced more significantly by improving low-order harmonics than is the case for other SCP machines.

4 | ROTOR POLE SELECTION

For an impartial comparison, the four SCP machines have the same PM pole pair number, stator outer radius, active stack length, air-gap length, PM volume, and current density, as shown in Table 3. The design parameters of the four SCP configurations are globally optimised. In order to select the optimal rotor pole number, the torque performances of the four SCP machines with different rotor poles are given in Figure 6. It can be found that the SCP-IV machine exhibits the highest torque capability regardless of rotor pole number, which is mainly attributed to the higher effective low-order air-gap flux density harmonics for torque production, as evidenced in Table 3.

Considering average torque and torque ripple, the 11-rotor pole is subsequently selected for the subjacent analyses. In order to optimise the design parameters, the multi-objective genetic algorithm [40–43] embedded in the JMag 17.1 software package is employed. The optimisation objectives are to maximise the average torque and minimise the torque ripple, of which the corresponding weight factors are set as 1 and 0.5, respectively. The resultant scatter diagrams of average torque against torque ripple of the four SCP machines with 11-rotor poles are illustrated in Figure 7. The resultant Pareto front curves of the four SCP machines are shown in Figure 7 with blue lines. To maximise average torque and minimise torque ripple, the design parameters of the optimal case of the four SCP machines are selected as tabulated in Table 1.

5 | PERFORMANCE COMPARISON

5.1 | No-load performance

The no-load magnetic field distributions of the four SCP machines are illustrated in Figure 7. It can be seen that the stator teeth tips exhibit serious magnetic saturation in the four SCP machines, which is mainly due to the flux leakage in CP

| Design Parameters | SCP-I | SCP-II | SCP-III | SCP-IV |
|-------------------|-------|--------|---------|--------|
| Stator slot number, \( N_s \) | 12    | 12     | 6       | 6      |
| Pole pairs of PMs, \( N_{\text{PM}} \) | 6     |        |         |        |
| Rotor pole number, \( N_r \) | 11    |        |         |        |
| Stator outer diameter, mm | 100   |        |         |        |
| Active stack length, mm | 50    |        |         |        |
| Stator inner diameter, mm | 59.4  |        |         |        |
| Stator yoke thickness, mm | 4.9   |        |         |        |
| Stator teeth thickness, mm | 5.6   |        |         |        |
| Stator PM thickness, mm | 4     | 4      | 4       | 3.1    |
| Stator slot thickness, mm | 0.8   | 1.4    | 0.9     | -      |
| Stator thickness, mm | 3.2   | 4.9    | 1.9     | 3.5    |
| Air-gap length, mm | 0.5   |        |         |        |
| Rotor outer diameter, mm | 58.4  |        |         |        |
| Rotor outer teeth radius, deg | 10.4  |        |         |        |
| Rotor inner teeth radius, deg | 22.1  |        |         |        |
| Rotor teeth length, mm | 8     |        |         |        |
| Rotor inner diameter, mm | 24    |        |         |        |
| Steel grade | 50CS350 |        |         |        |
| PM grade | N35SH |        |         |        |
| PM volume, ml | 22.4  |        |         |        |
| Turns per phase | 130   |        |         |        |

Abbreviations: PM, permanent magnet; SCP, stator consequent-pole.
The phase back-EMFs of the four SCP machines are shown in Figure 8. Because it has the largest effective low-order air-gap flux density harmonics, the SCP-IV configuration exhibits the highest back-EMF fundamental amplitude, as shown in Figure 9b. The SCP-I structure has the lowest back-EMF fundamental amplitude, which is mainly attributed to its unipolar coil flux linkage and resultant stator core saturation effect. Because of the compensation effect [44], the even-order harmonics of back-EMFs are suppressed in the four SCP machines, as shown in Figure 9b. However, due to the doubly salient structures, multiple air-gap field harmonics will be induced, resulting in relatively high odd-order EMF harmonics, as illustrated in Figure 9b. Total harmonic distortion (THD) for each of the four SCP machines is 13.8%, 13.9%, 13.2% and 8.7%, respectively. Because it has the largest fundamental component, SCP-IV exhibits the lowest THD of the four machine configurations.
The torque performances of the four SCP machines are illustrated in Figure 10. It can be seen that the four SCP machines reach peak torque at approximate current

### Table 4

| Items       | SCP-I | SCP-II | SCP-III | SCP-IV |
|-------------|-------|--------|---------|--------|
| $L_s$, mH   | 1.44  | 3.06   | 3.54    | 4.12   |
| $\psi_m$, mWb | 19.38 | 38.53  | 19.58   | 53.28  |
| $L_s/\psi_m$ | 0.074 | 0.079  | 1.807   | 0.077  |

Abbreviation: SCP, stator consequent-pole.

### Figure 12

**B-H** curves of the N35SH with different temperatures.

### Figure 13

Flux density distributions and selected minimum flux density points in the four stator consequent-pole (SCP) machines at field-weakening operating condition with different speeds (80°C). (a) SCP-I, (b) SCP-II, (c) SCP-III, (d) SCP-IV.

5.2 Torque and power factor characteristics
angles of 5, 10, 5, and 10 electrical degrees, respectively, as shown in Figure 10a. Figure 10b shows steady-state torque waveforms at the rated phase current. Because it has the highest low-order air-gap flux density harmonic magnitude, as shown in Figure 5b, the SCP-IV configuration exhibits the highest average torque of the four configurations. As a consequence, the highest overload capability can be achieved in the SCP-IV arrangement, as illustrated in Figure 10c.

The power factors of the four SCP machines are compared and shown in Figure 11. Because the reluctance torque is very low and can be neglected, the $i_d = 0$ control is adopted in the four SCP machines. If resistance is neglected, the power factor can be expressed as

$$PF = \frac{1}{\sqrt{1 + \left(\frac{L_s I_{rms}}{\Psi_m}\right)^2}}$$  \hspace{1cm} (18)

where $L_s$ is the synchronous inductance, $I_{rms}$ is the root mean square phase current, and $\Psi_m$ is the PM flux linkage. The inductance and PM flux linkage parameters of the four SCP machines at rated load are illustrated in Table 4. Because it has the highest $L_s/\Psi_m$, the SCP-III machine exhibits the lowest power factor of the four machines. The SCP-I machine exhibits a relatively higher power factor than the SCP-II and SCP-IV cases in overload conditions, which is mainly due to its lower $L_s/\Psi_m$, as shown in Table 4.

5.3 Demagnetisation characteristics

The PM material and working temperature are set as N35SH and 80°C, respectively. The B–H curves of the N35SH at different temperatures are shown in Figure 12. It can be seen that the reference knee flux density is approximately -0.1 T at 80°C. In order to examine the PM's demagnetisation-withstanding capability, the flux density distributions of the four
SCP machines at field-weakening operating condition with different speeds are shown in Figure 13. The corresponding flux density variations of the minimum flux density points of PMs are respectively illustrated in Figure 14. It can be seen that all the flux density results of the selected PM points are higher than the threshold value, which indicates that good demagnetisation-withstanding capability can be obtained in the four SCP machines.

### 5.4 Field-weakening capability, loss, and efficiency

To present a fair comparison, the four SCP machines share the same DC voltage of 120 V. The average torque and output

![Figure 16](image1.png)  
**Figure 16** Iron and permanent magnet eddy-current losses against speed curves. (a) Iron losses, (b) PM eddy-current losses.

![Figure 17](image2.png)  
**Figure 17** Efficiency maps of the four stator consequent-pole (SCP) machines. (a) SCP-I, (b) SCP-II, (c) SCP-III, (d) SCP-IV, $I_{rms} = 10A, u_{dc} = 120$ V.

| Items                        | SCP-I | SCP-II | SCP-III | SCP-IV |
|-----------------------------|-------|--------|---------|--------|
| Iron loss (W) Rotor         | 11.98 | 5.56   | 5.54    | 3.30   |
| Stator                      | 3.13  | 2.70   | 4.48    | 5.22   |
| PM eddy-current loss (W)    | 2.50  | 1.10   | 1.63    | 0.34   |
| Copper loss (W)             | 24.32 |        |         |        |
| Total loss (W)              | 41.93 | 33.68  | 35.97   | 33.18  |
| Maximum efficiency (%)      | 85.02 | 92.31  | 87.47   | 93.28  |
| High-efficiency Over 80%    | 45.60 | 47.13  | 26.62   | 41.13  |
| Over 90%                    | 0     | 22.39  | 0       | 25.31  |

Abbreviations: PM, permanent magnet; SCP, stator consequent-pole.
power versus speed curves of the four SCP machines are illustrated in Figure 15. The SCP-IV structure has the highest peak power output, and all four SCP machines show good ability to maintain constant power in the high-speed range. Figure 16 shows iron and PM eddy-current losses against speed curves. The SCP-III case shows the highest iron and PM eddy-current loss regardless of speed, which is mainly attributed to its pronounced localised iron magnetic saturation and the eddy-current density in PMs, respectively. The detailed loss data are tabulated in Table 5. The corresponding efficiency maps are shown in Figure 17. The SCP-IV machine exhibits the highest peak efficiency and largest high-efficiency region (over 90%) of the four cases, as shown in Figure 17 and Table 5, a result that is due to its the relatively lower iron and PM eddy-current losses and because it has highest output power capability.

6 | EXPERIMENTAL VALIDATION

An optimised 6-slot/11-rotor pole SCP-IV machine was manufactured and tested to validate the FE analyses. The stator and rotor assemblies and the test rig of the prototype are shown in Figure 18. The 2-D and 3-D FE-predicted, as well as measured back-EMFs, are plotted in Figure 19. A relatively higher mismatch between the 2-D FE results and measurements can be seen. This is mainly attributed to the pronounced end flux leakage effect occurring in the CP structure [46]. In addition, the end-effect is not considered in the 2-D FE analyses, which is also responsible for the discrepancy compared with the measured results. Moreover, it can be seen that rivet holes and separated stator teeth tips are adopted in the prototype, as shown in Figure 17b, which inevitably result in some mechanical tolerances for the measured results. The measured average torques are shown in Figure 20 and compared with the 2-D and 3-D FE predictions at different phase currents. Again, because of mechanical tolerances, the measured values are slightly lower for 3-D FE-predicted torques. The measured and FE-predicted average torque and output curves are shown in Figure 21. The measured results are slightly lower than the FE predictions due to mechanical tolerances. In addition, the measured and FE-predicted efficiency against rotor speed curves are given in Figure 22. The mismatch between the tested and FE-predicted efficiency results is mainly due to the mechanical loss that is neglected in the FE model. In summary, the back-EMF and average torque of the proposed machine are all verified by prototype test results.

7 | CONCLUSION

Four SCP machines with different PM configurations were comparatively studied. A simplified PM MMF-permeance-based model was employed to reveal the torque generation mechanism, which showed the feasibility of the SCP designs...
for torque improvement from the biased flux modulation effect. In addition, the torque contributions of the various working harmonics quantified by unified torque equation showed that torque capability can be significantly enhanced by enhancing low-order flux density magnitude in the SCP machines. The performance comparison results suggest that the SCP-IV machine has the highest torque capability and largest high-efficiency region of the four cases mainly because of its more pronounced biased flux effect, which is caused by the asymmetric MMF distribution. Finally, the satisfactory agreement between the FE-predicted and experimental results validates the theoretical analyses.

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APPENDIX: Magnetic Asymmetry

In order to illustrate magnetic asymmetry, the air-gap flux densities of the four SCP machines with slotless rotors are shown in Figure 23. It can be seen that the air-gap flux density waveforms of the four SCP arrangements appear to be asymmetric, as shown in Figure 23a, which is mainly due to the unipolar PM MMF distributions in CP structures. As a result, a series of air-gap field harmonics with even-order multiples of PM pole pairs, that is, $iN_{PM}$ ($i = 2, 4, 6, \ldots$) can be produced in the four SCP configurations, as shown in Figure 23b, which indicates that various air-gap field harmonics are responsible for torque production compared with their stator PM counterparts with symmetrical magnet arrangements [31]. In addition, the SCP-IV structure exhibits the strongest pronounced biased flux effect, that is, the magnitude of $2N_{PM}$ order harmonic is the highest, which indicates that higher effective low-order air-gap field harmonics and better torque capability can be achieved.

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![Figure 23](image-url)