Design and Performance Analysis of a Novel Outer-rotor Consequent Pole Permanent Magnet Machine with H-Type Modular Stator

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ABSTRACT In this paper a novel outer-rotor consequent pole permanent magnet machine (OR-CPPMM) with H-type modular stator core is proposed for higher average torque ($T_{avg}$), flux linkage ($\Phi$) and efficiency ($\eta$) whereas low cogging torque ($T_{cog}$), torque ripple ($T_{rip}$) and harmonics content in flux linkage ($\Phi_{THD}$) and back-EMF ($EMF_{THD}$). The proposed OR-CPPMM is investigated with different stator flux gaps width for static and dynamics electromagnetic performances. Analysis reveals that flux gaps in H-type stator core not only improve electromagnetic performance i.e., $\Phi$ is enhanced by 10.23%, $\Phi_{THD}$ is suppressed by 80.65%, diminished $EMF_{THD}$ by 59.37%, truncate $T_{rip}$ by 44.37% and improve $T_{avg}$ by 15.99% but also exhibits better flux focusing effect to enhance flux linkage and diminish harmonic contents. In addition, H-type modular stator structure provide physical isolation of adjacent phase that de-couple the adjacent phase coupling flux which enhance self-inductance and weaken mutual-inductance and hence improve fault tolerant capability. In addition, to elaborate effectiveness of the proposed and justification of OR-CPPMM novelty with H-type modular stator, electromagnetic performance is extensively compared with existing state of the art including E-core and C-core structure. Analysis and comparison with state-of-the-art reveals that proposed OR-CPPMM exhibits $T_{avg}$ higher up to 35.16%, truncate $T_{rip}$ up to 32.88%, enhanced $\Phi$ up to 22.13% and boost $T_{den}$ to 3.41 times at the cost of 2.58% increase in $T_{rip}$.

INDEX TERMS AC Machines, Consequent Pole, flux gap, Outer rotor, Permanent Magnet Machine, Modular stator, H-type stator

I. INTRODUCTION

Flux Switching Machines (FSMs) are proficient candidate for high speed brushless AC applications owing to double-salient robust rotor structure, high torque, and power density. These machines combine features of Switch Reluctance Machine (SRM) and Permanent Magnet Machine (PMM) and based on Permanent Magnet (PM) excitation source; it is termed as Permanent Magnet Flux Switching Machines (PMFSMs) [1]. PMFSMs are extensively appropriate to numerous industrial applications, Electric Vehicles (EVs), Hybrid Electric Vehicles, electric propulsion, electric craft, electric power-assisted steering, renewable and automotive application due to high power and torque density [2]. Majority of the PMFSMs utilize rare-earth Sintered Neodymium-iron-boron (NdFeB) PMs as an excitation source however, due to upsurge in PM demand and potential supply shortage, machine cost grows with PM volume. Consequently, design optimization of PM machines, less or no PM machines for high torque density have been potential research topic in the recent years.

In the recent years, many researchers focused on Consequent Pole Permanent Magnet Machines (CPPMMs) for cost saving and efficient PM utilization. In this regard, rotor consequent pole (RCP) [3-5], stator consequent pole (SCP) [6-8] and both rotor and stator consequent pole in the form of dual modulation have been widely investigated [9]. In dual modulation machine PM volume is double. Moreover, PMs located beside rotor poles suffer from mechanical constraints. In additional SCP machines suppressed lower order space harmonics and associated core loss however, since both PM and armature winding are in stator, electrical loading (slot area) reduces which effects electromagnetic performance. In this regard, RCP topologies play vital role by reducing half of the PM volume in comparison with conventional surface mount PM machines. In Consequent Pole (CP) topologies, PM share same polarity of either N-pole or S-pole whereas salient iron pole act as virtual S-pole or N-pole. CP topology is widely applicable in various types of machines i.e., Hybrid excited machines [10], PM Vernier machines [11] and flux reversal partitioned stator [12]. Moreover, in RCP topologies, radial rotor position regulation is improved. In additional SCP machines suppressed lower order space harmonics and associated core loss however, since both PM and armature winding are in stator, electrical loading (slot area) reduces which effects electromagnetic performance. In this regard, RCP topologies play vital role by reducing half of the PM volume in comparison with conventional surface mount PM machines. In Consequent Pole (CP) topologies, PM share same polarity of either N-pole or S-pole whereas salient iron pole act as virtual S-pole or N-pole. CP topology is widely applicable in various types of machines i.e., Hybrid excited machines [10], PM Vernier machines [11] and flux reversal partitioned stator [12]. Moreover, in RCP topologies, radial rotor position regulation capability as well as radial retaining forces are also improved which make it competent applicant for bearingless PM motor [13-17].
Optimization and performance comparison of surface mounted PM machine (SMPMM) with fractional slot concentrated winding and RCP is investigated in [18] and shows that SMPMM with RCP utilizes 33% reduced PM material to achieve same performance. Furthermore, flux reversal CP PM Machine (FRCPMPM) is proposed for EVs in [19] which produces 26% higher torque than existing state of the art. Comparison of RCP topology with interior PM (IPM) machine for EVs are analyzed in [20]. Analysis reveals that IPM with CP exhibits higher torque density and lower cogging torque and torque ripples at rated condition. In addition, CP IPM shows better flux weakening capability which helps in achieving wide speed range. RCP in hybrid dual PM machine improve torque capability for EVs [21].

However, despite of the above-said various advantages of CP machines, some intrinsic issues i.e., uni-polar leakage flux in shaft, even-order harmonics terms in air-gap flux density and back-EMF etc exists in CP structure. Author in [22] utilizes multi-layer winding for suppression of even-order harmonics in back-EMF whereas author in [3] employed hybrid rotor topologies with different PM polarities for elimination of even-order harmonic in back-EMF and suppression of shaft leakage flux.

The aforesaid machines are non-modular where adjacent phases are physically interconnected therefore, offer poor fault tolerant capability due to high mutual phase coupling. In contrast, considering steel lamination in modular topologies with segmented stator, manufacturing process i.e., winding process is made at ease. Furthermore, modular structure offers thermal, mechanical, and physically magnetic separation between armatures winding hence, on-site maintenance is reduced, and fault tolerant capability is improved.

In this regard, mechanical modular CP rotor exhibits enhanced flux focusing effects and truncate leakage flux near iron-bridge which improve torque density without any influence on efficiency and torque ripples [23]. Various modular stator structure with RCP topologies is investigated for reducing low order space harmonics. Authors in [24] employed flux gap in all and alternate stator teeth of SMPMM forming E/C-core. Despite of more PM usage, detail analysis reveals that flux gaps exhibits positive impact when stator slot number is lesser than pole number while for slot number greater than pole number, electromagnetic performance is degraded. Moreover, the developed modular offer torque density and power density and higher cogging torque and torque ripples.

Hence, this paper combines feature of RCP and modular structure on SMPMM to design a novel outer-rotor consequent pole permanent magnet machine (OR-CPPMM) with H-type modular stator core employing stator flux gap as shown in Figure 1. It is worth mentioning that proposed OR-CPPMM with H-type reduces half of the PM volume compare with SMPMM. Secondly, the developed OR-CPPMM with H-type is converted to modular stator employing stator flux gap decoupling the adjacent phase coupling flux which enhance self-inductance and weaken mutual-inductance and hence improve fault tolerant capability. Moreover, the flux gap (FG) in H-type stator core exhibits better flux focusing effect to enhance flux linkage and diminish harmonic contents. In mechanical aspect, it is noteworthy that combination of RCP with modular stator structure effectively results higher PM utilization and ease manufacturing process, transportation, assembly, and on-site maintenance when design in large dimension for wind power application whereas in electromagnetic analysis, modular structure with RCP has dominant influence on average torque, torque density, power density, torque ripples and efficiency.

This paper, discuss effects of FG width and detailed electromagnetic performance of proposed H-type modular and non-modular OR-CPPMM. Moreover, operating principle of modular CP is discussed based on mathematical modelling whereas torque and back-EMF mechanism are investigated. In addition, to show effectiveness of the proposed OR-CPPMM H-type stator core, electromagnetic performance is thoroughly compared with conventional E-core and C-core CP.

In the following, section II discusses Operating principle of modular CP. Influence of FG on electromagnetic performance is analyzed in Section III. Section IV investigates comparison of conventional and proposed design. Section V compare H-Core machines and finally, some conclusion is drawn in Section VI.

![Figure 1. Proposed OR-CPPMM (a) Cross sectional view (b) Nephogram of magnetic flux density distribution](image-url)
II. Operating principle of modular CP

Design parameters for proposed OR-CPPMM with H-modules is indicated in Figure. 2 and listed in Table I. In stator core, the total active tooth body of stator teeth is kept same regardless in variation of the FGs width to avoid local saturation. Since the focus is on modular structure with FG and H-type stator core, common geometric parameters i.e., air-gap length, rotor back iron, PM thickness, stator tooth width, stator height, stack length and number of turns per phase are kept same for modular as well as non-modular. It is worth noting that for fair comparison, total PM volume is also kept same for modular as well as non-modular. It is worth mentioning that periodicity of the air-gap change with FGs therefore, $N_{sr}$ is introduced to substitute actual stator slot.

Therefore, the air-gap flux density with the PM excited MMF and air-gap permeance produced by PM can be computed as

$$B_{g-pm}(\theta, t) = f_{pm}(\theta, t)A_{g}(\theta, t)$$

where

$$A_{g}(\theta, t) = \sum_{i=0, 1, 2, \ldots}^{\infty} A_{ri} \cos(iN_{r}(\theta - \Omega_{r}t))$$

and

$$A_{s}(\theta, t) = \sum_{j=0, 1, 2, \ldots}^{\infty} A_{sj} \cos[jN_{sr}\theta]$$

Utilizing finite element analysis (FEA) package of JMAG designer, magnetic flux density of the proposed OP-CPPMM is obtained as shown in Figure. 3 with the corresponding harmonic spectra.

Operating principle of modular and non-modular CP is explained with simplified mathematical model. For RCP topologies with PM excitation considering rotor saliency and PM position, MMF generated is generally expressed as [25]

$$f_{pm}(\theta, t) = \sum_{i=1, 2, \ldots}^{\infty} F_{pmi} \cos[iN_{r}(\theta - \Omega_{r}t)]$$

Where $\Omega_{r}$ is rotor rotational speed, $N_{r}$ is rotor pole number, $t$ is time, $\theta$ is stationary coordinate mechanical position and $F_{pmi}$ is $i^{th}$-order generated MMF Fourier coefficients.

Moreover, considering rotor slot, stator slot opening and FGs, air-gap permeance model is expressed in the form of Fourier series as

$$A_{r}(\theta, t) = \sum_{i=0, 1, 2, \ldots}^{\infty} A_{ri} \cos(iN_{r}(\theta - \Omega_{r}t))$$

Where $N_{sr}$ is number of stator slot, $A_{ri}$ and $A_{sj}$ is $i^{th}$ and $j^{th}$-order Fourier coefficients of air-gap permeance accounting rotor pole, stator slot opening and FGs. It is worth mentioning that periodicity of the air-gap change with FGs therefore, $N_{sr}$ is introduced to substitute actual stator slot.

Therefore, the air-gap flux density with the PM excited MMF and air-gap permeance produced by PM can be computed as

$$B_{g-pm}(\theta, t) = f_{pm}(\theta, t)A_{g}(\theta, t)$$

$$= \sum_{i=0, 1, 2, \ldots}^{\infty} \sum_{j=0, 1, 2, \ldots}^{\infty} B_{pm}(i,j) \cos[(iN_{r} \pm jN_{sr})\theta - iN_{r}\Omega_{r}t]$$

Utilizing finite element analysis (FEA) package of JMAG designer, magnetic flux density of the proposed OP-CPPMM is obtained as shown in Figure. 3 with the corresponding harmonic spectra.

Based on air-gap flux density and phase winding function ($N_{pwf}(\theta)$), phase back-EMF is expressed as

$$E_{p}(\theta) = -\frac{d}{dt} \left[ R_{p}I_{s} \int_{0}^{2\pi} B_{g-pm}(\theta, t)N_{pwf}(\theta)d\theta \right]$$

Whereas $R_{p}$ is radius of air-gap, and $N_{pwf}(\theta)$ for single layer winding is expressed as

$$N_{pwf}(\theta) = \sum_{m=1, 3, 5, \ldots}^{\infty} N_{pwf_{m}} \cos(m\theta)$$

According to [25], for PM excited the main harmonic exist at $|iN_{r} \pm jN_{sr}|$ whereas triplen harmonics are cancelled in winding and subsequently, the phase back-EMF can be expressed as
\[
E_p(t) = R_g L_s \sum_{i=1,2,\ldots}^\infty \sum_{j=0,1,2,\ldots}^\infty \sum_{m=1,2,3,\ldots}^\infty E_{p(i,j)} \cos (iN_r \Omega_r t) \tag{8}
\]

It is evident that for both modular and non-modular OR-CPPMM with H-type stator core, the rotor pole pairs \(N_r\), whereas detailed of the associated harmonics contributing in fundamental back-EMF is shown in Figure. 4.

\[
\begin{align*}
E_{p(i,j)} &= \cos (iN_r \Omega_r t) \\
E_{p(i,j)} &= \cos (iN_r \Omega_r t)
\end{align*}
\]

Figure 4. Phase back-EMF (a) waveform and (b) Harmonics spectra

III. Influence of FG on electromagnetic performance of OR-CPPMM

Electromagnetic performance is analyzed under different condition with key matric function as phase flux linkage with harmonics spectra and harmonics components, back-EMF with harmonics spectra and harmonics components, Instantaneous and cogging torque, average torque, torque ripple \(T_{rip}\), core losses, efficiency \(\eta\), self-inductance and mutual inductance. It is worth mentioning that the aforesaid key performance indicators are investigated under various FG width in different sections as follows whereas the key matric functions are calculated as

\[
T_{rip} = T_{max} - T_{min}
\]

\[
\eta = \frac{P_{out} - P_{loss}}{P_{in}} \times 100\%
\]

Whereas \(T_{max}\) is the maximum torque, \(T_{min}\) is the minimum torque, \(P_{out}\) is mechanical output power, \(P_{in}\) is input power and \(P_{loss}\) is losses.

A. Open-circuit performance

Variation of the open-circuit performance includes phase flux linkage with harmonics spectra, and variation of harmonic components, phase back-EMF with harmonics spectra and harmonics components, Instantaneous and cogging torque which are shown in Figure. 5 to Figure. 10 respectively.

From Figure. 5, analysis reveals that FGs have positive impact phase flux linkage of OR-CPPMM. It can be clearly seen in enlarge section of Figure 5(a) that with increase in FGs width, magnitude of the phase flux linkage increases whereas the harmonics spectra indicates that the dominant 3\(^{rd}\) order harmonics are effectively reduced as shown in harmonics spectra of Figure. 5(b). This impact on phase flux linkage increases the magnitude of fundamental and peak to peak phase flux linkage and reduction in total harmonic distortion (THD) as shown in Figure. 6. It is worth noting that proposed modular OR-CPMM, the increase in phase flux linkage is due to the increase in fundamental harmonics component with decrease in the influence of 3\(^{rd}\) order harmonics as shown in Figure. 6(a) whereas the peak-to-peak phase flux linkages increase and THD decreases as shown in Figure. 6(b).

Quantitative performance analysis reveals that FG have improved peak to peak phase flux linkage by 10.51%, enhanced fundamental working component by 1.28%, reduces 3\(^{rd}\) order harmonics influence by 99.1% with overall 80.65% reduction in THD.

In additional, influence of the FG width on back-EMF waveform and spectra is shown in Figure. 7 whereas variation of the harmonic’s components is displayed in Figure. 8. Analysis reveals that as soon as the width of the FG increases, the back-EMF waveform becomes more sinusoidal (as shown in Figure. 7(a)) whereas the harmonics spectra (as shown in Figure 7(b)) reveal that FGs diminishes the influence of the 3\(^{rd}\) order harmonics components successfully. Figure. 8(a) shows that magnitude of fundamental component of phase back-EMF first increases and then slightly decreases with the increase in the FG width whereas the dominant 3\(^{rd}\) order harmonics magnitudes are effectively curtailed whereas Figure. 8(b) clearly shows that THD is decreased. Quantitative analysis reveals that fundamental back-EMF component is improved by 0.6% whereas 3\(^{rd}\) order harmonics and THD are effectively reduced by 46.38% and 59.35% respectively.
It is noteworthy that if magnitude of fundamental phase back-
EMF continue to increase, this mean that FGs have flux
focusing effects. This flux focusing effects can be obtained with
appropriate FGs width. From harmonic spectra of Figure. 8, it
can be clearly seen that flux focusing effect can be obtained in
modular OR-CPPMM with FGs width of 0-2 mm. Various
harmonics order contributing to fundamental phase back-EMF
are $|i_{N_{r}} \pm jN_{s}p|$. 

Despite of the fundamental phase back-EMF, harmonic
component of 5$^{th}$ and 7$^{th}$ order need to be clearly investigated
as it contributes to torque ripples ($T_{rip}$) as shown in Figure. 9(a).
From harmonic spectra, it is found that 5$^{th}$ order harmonics first
increase with FGs and then decreases whereas 7$^{th}$ order
component is effectively suppressed. This effect of the torque
ripples can be seen in Figure. 9(a). Despite of back-EMF and
$T_{rip}$, it is important to analyse cogging torque ($T_{cog}$) because
5$^{th}$ and 7$^{th}$ harmonic is dominant factor of $T_{cog}$ as shown in
Figure. 9(b) (peak to peak values) and Figure. 10(a) shows its
waveform. This cogging torque contributes to the torque
ripples. This is explained with periodic cycles of cogging torque
which can be computed as $LCM(k_{p}N_{s})/N_{r}$ whereas $N_{s}$
is stator slot, LCM is least common multiple and $k_{p} = 1$ for CP.
As a result, for non-modular OR-CPPMM with H-type stator
core, there are 12 periodic cycle in each electrical period
whereas in modular stator structure with, this periodic cycle is
reduced to half.

**B. On-load performance**

At rated condition of 15 A/mm$^2$, instantaneous torque (as
shown in Figure. 10(b)) whereas average torque ($T_{avg}$) and $T_{rip}$
of proposed modular H-type stator core with different FGs are
shown in Figure. 11(a). It can be clearly seen that FGs have
positive impact on $T_{avg}$ and $T_{rip}$ as shown in Figure. 11(a). It
can be further analyzed that $T_{avg}$ first decreased at FG=1 mm
however, with further increase in the FG i.e., 2-4 mm, $T_{avg}$
increases due to the flux focusing effects and effectively
suppressed $T_{rip}$ which is mainly due to 5$^{th}$ and 7$^{th}$ harmonic
as explained.

In addition, comparison of non-modular with modular
structure shows that, FGs introduces dummy slots in stator
structure causing variation in air-gap permeance and have
impact on the core losses as shown in Figure. 11(b). In proposed
H-type modular OR-CPPMM, it can be clearly seen that there
are twelve FGs that results reduction in core losses regardless
of the rotor pole and stator slot combinations as shown in
Figure. 11(b). This reduction is mainly due to the fact that with
the increase in the FGs width, the magnitude of both 5th and 7th order harmonics decreases. In additional, stator core losses are due to dominant working harmonics, since working harmonics reduces, therefore stator core losses are reduced.

Figure 11. Effect of FGs on (a) $T_{avg}$ and $T_{rip}$ and (b) core loss and $\eta$

In design stage of electric machine, efficiency is key factor that play major role in dynamic performance analysis. Therefore, effect of FGs width on efficiency of proposed OR-CPPMM with H-type stator core are calculated and shown in Figure. 11(b). Analysis reveals that FGs have positive impact on efficiency of modular structure. It can be clearly seen that efficiency increases which is mainly due to improvement in open-circuit and on-load performance as discussed.

Quantitative performance analysis reveals that with the introduction of the FG, $T_{rip}$ is suppressed by 44.4%, $T_{avg}$ is improved by 16%, core loss is truncated by 22.35% and $\eta$ is enhanced by 5.1%.

C. Fault tolerant capability

Inserting FGs in stator core introduces dummy slots in stator structure causing variation in air-gap permeance which alters distribution of magnetic flux density inside the stator core which ultimately modifies magnetic flux paths. This modification in flux paths distinct mutual flux coupling of neighbouring phase results in variation of the self and mutual inductance. Accounting influence of PM, self-inductance and mutual inductance can be expressed as

$$L_i = \frac{\Phi_i - \Phi_o}{I_i} \quad (11)$$

$$M_{ij} = \frac{\Phi_j - \Phi_o}{I_i} \quad (12)$$

Whereas $L_i$ and $M_{ij}$ are self and mutual inductance respectively, $\Phi_i$ is self-phase flux linkage of phase $i$, $\Phi_j$ is mutual-phase flux linkage of phase $j$, $\Phi_o$ is open circuit phase flux linkage due to PMs and $I_i$ is injected DC current in phase $i$.

The phase self-inductance and mutual inductance is calculated for various FGs width by injecting DC current in armature winding. Since the self and mutual inductance for all phases remain the same, therefore only phase A is illustrated. The phase self-inductance and mutual inductance with varying FGs width are shown in Figure. 12. It can be clearly seen that both self and mutual inductance varies with rotor position as well as with FG width. Analysis concludes that with insertion of the FGs, self-inductance drastically increases whereas mutual inductance reduces because FG stop mutual coupling of phase flux linkage as shown in Figure. 13. This greatly diminished ratio of mutual and self-inductance as a result of which ultimately improve fault-tolerant capability because FG provide physical separation of the adjacent phases. Moreover, during short circuit condition, higher self-inductance mitigate short circuit current and lower mutual inductance suppresses fault interaction between faulty and healthy phase. In additional despite of fault tolerant capability, modular stator structure with FGs physical separates three phase armature winding and provides open path between adjacent phases for air circulation, therefore, offer better cooling of stator in comparison of non-modular structure.

Figure 12. Influence of FGs on (a) self-inductance and (b) Mutual inductance

IV. Comparison of conventional and proposed design

In order to highlight effectiveness of the proposed OR-CPPMM with H-type stator core, electromagnetic performance with key performance metric i.e., phase flux linkage (\(\Phi\)), phase flux linkage THD (\(\Phi_{THD}\)), back-EMF, back-EMF THD (EMF\(_{THD}\)), $T_{avg}$, $T_{rip}$, $T_{den}$, and core losses (\(l_{core}\)) is thoroughly compared with conventional C-core and E-core CP PMFSM as shown in Figure. 14 [26]. It is noteworthy that H-core stator, C-core and E-core structure share same design parameters whereas different stator structure and rotor orientation. The aforesaid topology of proposed H-core is compared with conventional C-core and E-core for varying FGs width as listed in table III to table V whereas waveform and harmonic spectra are shown in Figure. 15 and Figure. 16.
Quantitative analysis and comparison as listed in table III, table IV and table V reveal that with H-core stator structure, the $\Phi$ is improved to 0.253 Wb whereas C-core and E-core offer $\Phi$ of 0.154 Wb and 0.169 Wb respectively. Furthermore, H-core reduces $\Phi_{THD}$ to 2.36% from 12.24% whereas C-core and E-core exhibits minimum $\Phi_{THD}$ of 7.23% and 5.13% respectively.

Figure 14. Cross sectional view of conventional CP PMFSM with (a) C-core and (b) E-core

Back-EMF profile with harmonic spectra for C-core and E-core conventional CP PMFSM under various FG width is shown in Figure. 16. Figure. 16(a-b) shows that with introduction of FGs, magnitude of fundamental working harmonic component slightly decreases for C-core whereas it increases for E-core CP PMFSM. Moreover, harmonics spectra in Figure. 16(c-d) shows that in case of C-core CP PMFSM 3rd order harmonics first increases and then decreases whereas 5th, 6th and 7th order
harmonics continue to decrease with the increase of the FG. In case of the E-core all the higher order harmonic content i.e., 3rd, 5th, 7th and 9th decrease with the increase in FG width in the stator core.

Quantitative analysis and comparison of conventional C-E-core CP PMFSM with H-core OR-CPPMM reveals that minimum $EMF_{THD}$ offered by C-core is 18.78% whereas E-core exhibits 12.38% and proposed H-core shows minimum of 10.44% $EMF_{THD}$ in case of FG=4 mm.

Quantitative performance comparison of proposed OR-CPPMM with C/E-core CP PMFSM reveals that proposed H-core offer 44.40% lower $EMF_{THD}$ than C-core CP PMFSM and 15.67% lower $EMF_{THD}$ than E-core CP PMFSM.

Electromagnetic performance analysis results that maximum $T_{avg}$ for H-core stator is 7.917 Nm with $FG = 4$ mm. Comparing with maximum $T_{avg}$ of C-core and E-core i.e., 4.13 Nm and 4.28, respectively, analysis concluded that OR-CPPMM with H-core results $T_{avg}$ higher by 91.69% when compared with C-core and 84.97% higher $T_{avg}$ in comparison with conventional E-core CP PMFSM.

**Quantitative Electromagnetic Performance of Proposed H-core OR-CPPMM**

| Flux gap width | 0 | 1 | 2 | 3 | 4 | Unit |
|----------------|---|---|---|---|---|------|
| $\Phi$ | 0.229 | 0.238 | 0.244 | 0.249 | 0.253 | Wb |
| $\Phi_{THD}$ | 12.241 | 9.103 | 6.283 | 3.763 | 2.368 | % |
| $EMF_{THD}$ | 37.981 | 29.612 | 22.358 | 17.063 | 10.44 | % |
| $T_{avg}$ | 6.825 | 6.539 | 6.776 | 6.741 | 7.917 | Nm |
| $T_{rip}$ | 0.302 | 0.169 | 0.218 | 0.177 | 0.168 | % |
| $T_{den}$ | 0.3480 | 0.333 | 0.345 | 0.343 | 0.4036 | kNm |

**Quantitative Electromagnetic Performance of C-core CP PMFSM**

| Flux gap width | 0 | 1 | 2 | 3 | 4 | Unit |
|----------------|---|---|---|---|---|------|
| $\Phi$ | 0.154 | 0.148 | 0.149 | 0.143 | 0.143 | Wb |
| $\Phi_{THD}$ | 8.485 | 7.23 | 8.75 | 11.55 | 11.55 | % |
| $EMF_{THD}$ | 23.523 | 18.78 | 25.16 | 32.03 | 32.01 | % |
| $T_{avg}$ | 4.13 | 3.59 | 3.68 | 3.53 | 3.52 | Nm |
| $T_{rip}$ | 0.738 | 1.06 | 0.94 | 0.98 | 0.97 | kNm |
| $T_{den}$ | 0.091 | 0.079 | 0.081 | 0.078 | 0.077 | % |
| $I_{core}$ | 20.52 | 18.16 | 20.21 | 19.37 | 19.85 | W |
Quantitative performance analysis results that minimum $T_{\text{rip}}$ for H-core stator is 0.168% Nm with $FG = 4$ mm. Comparing with minimum C-core and E-core $T_{\text{rip}}$ of 0.738% and 0.681% respectively, analysis unveil that H-core diminish $T_{\text{rip}}$ by 77.23% and 75.33% when compared with C-core and E-core CP PMFSM respectively. Similarly, comparing $T_{\text{den}}$ of proposed H-type stator core with C-core and E-core CP PMFSM, analysis reveals that $T_{\text{den}}$ is improved 4.43 and 4.29 times, respectively.

To sum up, comparison of conventional C/E-core with proposed H-core OR-CPPMM reveals that proposed H-core design results $\Phi$ higher up to 65.35%, suppressed $\Phi_{THD}$ up to 67.24%, truncates $EMF_{THD}$ up to 44.40%, enhanced $T_{\text{avg}}$ up to 91.69%, diminished $T_{\text{rip}}$ up to 77.23% and boost $T_{\text{den}}$ to 4.43 times.

V. Comparison of H-type Machines

The effectiveness of the proposed H-Core OR-CPPMM is further elaborated by comparing the proposed design with existing H-core machines. Since proposed OR-CPPMM is newly developed, therefore performance comparison is performed with H-core in Permanent Magnet Flux Switching Machines (PMFSM) categories. For detailed investigation purpose, inner rotor PMFSM (IR-PMFSM) and dual rotor PMFSM (DU-PMFSM) with H-core are opted for investigation as shown in Figure 17 [27-28] whereas quantitative electromagnetic performance is listed in Table VI. It is noteworthy that both IR-PMFSM and DR-PMFSM are designed under same designed parameters i.e., stator outer diameter, stack length, electrical loading, and magnetic loading to ensure fair comparison.

Analysis and comparison of the OR-CPPMM under $FG = 0$ with IR-PMFSM reveals that $\Phi$ is enhanced by 33.13%, improve $T_{\text{avg}}$ by 35.16%, diminished $T_{\text{rip}}$ by 32.88%, reduces $l_{\text{core}}$ by 4.12% and boot $T_{\text{den}}$ to 3.41 times at the cost of 92.77% increase in $\Phi_{THD}$ whereas OR-CPPMM under $FG = 0$ with DR-PMFSM reveals that $\Phi$ is enhanced by 9.04%, improve $T_{\text{avg}}$ by 17.87%, reduces $l_{\text{core}}$ by 28.82% and boot $T_{\text{den}}$ to 2.74 times at the cost of 92.77% increase in $\Phi_{THD}$ and 2.58% increase in $T_{\text{rip}}$. Based on quantitative analysis of the proposed H-core OR-CPPMM with IR-PMFSM and DR-PMFSM as listed in table III and table IV, it is evident that proposed design offers comparatively better performance than the existing state of the art.

VI. Conclusion

In this paper a novel outer-rotor consequent pole permanent magnet machine with H-type modular stator core is proposed to achieve higher average torque and low cogging torque, torque ripple and harmonics content in flux linkage and back-EMF. The proposed design is investigated with different stator flux gaps width where analysis concludes that flux gaps in H-type stator core not only improve electromagnetic performance but also exhibits better flux focusing. Moreover, due to insertion of

![Cross sectional view of H-core (a) IR-PMFSM and (b) DR-PMFSM](image)
the FG in stator core, modular stator provides physical isolation of adjacent phase that de-couple the adjacent phase coupling flux hence improve fault tolerant capability. Finally, detailed investigation concludes that proposed design offers higher average torque up to 91.69% and exhibits lower cogging and torque ripples. Furthermore, comparison with the base reference concludes that due to physical isolation of the adjacent phase winding, the proposed design offer better fault tolerant capability.

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