

# **Comparison of Fractional Slot Concentrated Winding and PM Assisted Synchronous Reluctance Motors for Class IV Electric Vehicles**

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## **Summary**

The design and comparative analysis of three 200 kW motors, a fractional slot concentrated winding machine (FSCW) and two permanent magnet-assisted synchronous reluctance machines (PMa SynRM) have been considered for a Class IV step van electric vehicle application. Different results comparing the performances of each machine have been presented using electromagnetic, thermal and acoustics-related analyses as well as vehicle dynamic simulations for various urban drive cycles. The presented results show that all three motors are suitable for a Class IV electric vehicle. Also, the relative merits indicate that the FSCW machine has a cost advantage in terms of the required inverter size, while the PMa SynRMs benefit from a smaller size.

*Keywords: Motor Design, Optimization, EV (electric vehicle), finite element calculation, powertrain.*

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## **1. Introduction**

The design, optimization and comparison of three 200 kW electric motors have been performed for a single-speed Class IV electric step van application. The two motor topologies that are studied here are the fractional slot concentrated winding machine (FSCW) [1], [2], [3] and the multiple-barrier permanent magnet-assisted synchronous reluctance machine (PMa SynRM) [4], [5], [6]. Both topologies have been selected because they are currently being researched and developed as potential candidates for the drivetrain's power-plant in Class II electric and hybrid electric vehicles. FSCW machines have desirable characteristics suitable for traction applications, such as high power density, high efficiency at low speeds, high fill factor due to the use of segmented stators and wide constant power speed range (CPSR). On the other hand, pure SynRMs benefit from simple rotor manufacturing and low material cost due to the lack of rare-earth PMs which have recently seen fluctuations in their price and supply [5]. However, they fail to directly compete with high performing machines such as FSCW and interior permanent magnet (IPM) topologies. It is possible to address the pure SynRM's performance limitations by inserting low-cost PMs inside its rotor structure to give rise to a PM-assisted SynRM. Despite the advantages and high speed performance of PMa SynRMs and FSCW machines, neither have yet been

considered for a Class IV electric vehicle application for which the maximum speed constraint can be much lower than that of Class II vehicles. Hence, this work aims to use design optimized versions of PMa SynRM and FSCW machines in a Class IV electric vehicle and compare their relative performances.

Indeed, the comparison of distinct motor topologies is a complex proposition due to multiple design choices and outcomes which may render drawing general conclusions difficult. To address this problem, two major assumptions are made. First, the stator's outer diameter of the studied motors was considered to be approximately the same, while the stack length was set as a design parameter for a given constraint. This reasonable assumption allows for a geometric size comparison in terms of volume and mass for each motor type. Second, choosing the viable number of pole-slot combinations for each motor type can be numerous [7] with each resulting in different design solutions. The pole-slot combinations of the FSCW machine and PMa SynRMs were first selected based on potential industrially relevant choices based on winding options, manufacturability, etc.

This paper has been structured in the following order. Section 2 presents the performance requirements for the FSCW machine and PMa SynRMs before discussing their design and optimization. The electromagnetic performances of the machines have been presented in Section 3.1. In Section 3.2 the thermal analysis of the motors under various load conditions using electromagnetic-thermal simulations have been presented. Some elementary noise, vibration and harshness (NVH) characteristic or acoustic related results are shown in Section 3.3. Section 3.4 displays the vehicle dynamic simulation results for a number of commercial drive cycles. Conclusive remarks are finally stated in Section 4.

## 2. Design and Optimization

The performance requirements and constraints of the motors to be designed and optimized were determined for a Class IV vehicle (14001–16000 lbs. or 6351–7257 kg). Certain aspects were based on the speed-torque-efficiency characteristics of industrially produced motors that may be used in this vehicle class [8]. These electrical, mechanical and thermal specifications are summarized below in Table 1.

Table 1: Summary of motor performance requirements

| Performance Requirement                                       | Unit       | Target                   |
|---------------------------------------------------------------|------------|--------------------------|
| Maximum speed                                                 | RPM        | 6000                     |
| Base speed                                                    | RPM        | ~1500                    |
| Peak power at 20% of maximum speed at nominal voltage for 36s | kW         | 190 - 200                |
| Continuous power                                              | kW         | 100 - 105                |
| Operating DC bus voltage                                      | V          | 400 - 650 (~450 nominal) |
| Efficiency at rated speed                                     | %          | > 95                     |
| Maximum peak-to-peak torque ripple (w.r.t. average torque)    | %          | < 10                     |
| Cooling type                                                  |            | Liquid (ethyl glycol)    |
| Coolant temperature                                           | °C         | 105                      |
| Coolant flow rate                                             | liters/min | 10                       |

## 2.1. Fractional Slot Concentrated Winding (FSCW) Machine

In the past decade, there has been a great deal of research and development on the design of FSCW machines [3]. These range from in-depth analysis of FSCW characteristics all the way to optimum design strategies and challenges. The FSCW motor designed for this paper used the approaches and recommendations of many recent works in combination with conventional methodologies [7]. The design procedure may be summarized as follows: motor sizing (choice of pole-slot combination, material selection for the lamination stack and permanent magnets, motor geometrical cross-section determination and winding design), performance evaluation (power output, efficiency calculations, torque ripple, power factor, cogging torque, etc.) and design iterations to meet the requirements specified in Table 1. These steps were followed by a design optimization study and multi-physics simulations such as electromagnetic-thermal and acoustic characteristic determination.

Based on the relative merits presented in [3] for various pole-slot combinations of FSCW machines, the 12-slot 10-pole configuration was selected because of its relatively high winding factor (93%) and manufacturing advantage of utilizing a segmented stator structure. Analytical results similar to those in [9], which constrain the d and q-axis voltages, currents and inductances for reducing the machine characteristic current below its rated current, were used to design the motor's winding and select the PM grade to satisfy a CPSR value of 4. Once the initial cross-section and winding were designed, the machine's electromagnetic performance was evaluated using FEA-based transient simulations at startup, base speed (nominal rating) and maximum speed as well as under peak power operating conditions. This process was repeated until a satisfactory base design met the performance criteria. In addition, reducing the PM eddy current losses at high speeds is a significant design challenge for FSCW machines. To reduce these losses and ensure that the FSCW motor can safely operate without the risks of demagnetization, a rotor structure with four segments per PM was used. The number of segments was determined based on coupled electromagnetic-thermal simulations discussed in Section 3.2 which guarantees that, under rated condition, the steady state magnet temperature would be below 100°C.

As a final step, the base design was optimized with respect to the rotor, stator and magnet geometrical dimensions. The optimization parameters included the rotor's back iron depth, magnet width and height, stator's tooth dimensions (tooth width, tang depth, tang angle, slot gap width), stator's back iron depth and stack length. A recently developed multi-objective optimization algorithm by Freitas et al. [10] and Silva et al. [11] was used to design optimize the motor. The significant feature of this procedure is its ability to consider a relatively high number of design objectives, as 16 of them were chosen initially. It applies a novel scheme to reduce the total number of objectives with minimal loss of optimal design candidates. This is an advancement compared to conventional optimization approaches since the computational requirement grows exponentially with the number of objectives. Typically, only four design objectives (average torque, efficiency, torque ripple and material cost associated with motor size) have been the previously attempted for design optimization. By using the method developed by [10], [11] and the surrogate modeling algorithm of [12], the base design was optimized with respect to 8 performance criteria, including average torque, torque ripple, efficiency, PM mass, stator's core mass, power factor, PM loss and winding loss. From the optimal set of design candidates, a final solution was selected which minimized the PM eddy current losses, operated at low torque ripple and satisfied all other target criteria. A summary of this motor's parameters are shown in Table 2. It should be noted that all design-related calculations were carried out using the FEA based MotorSolve software from Infolytica Corporation [13].

## 2.2. Permanent Magnet–Assisted Synchronous Reluctance Machine (PMa SynRM)

As discussed in the literature [5], [14], [15], pure SynRMs have certain disadvantages such as lower power factor, limited CPSR and high torque ripple. These limiting conditions require inverter kVA oversizing thus increasing the system costs, which suggests a negative perspective in meeting the technical targets set down in Table 1. A simple, yet effective approach to alleviate the low power factor and CPSR problems is to insert low-cost magnets within the rotor to give rise to a PMa SynRM. Although this topology resembles an IPM motor, it relies more on producing reluctance torque than PM torque. This procedure follows after optimizing the SynRM's reluctance torque with respect to the rotor geometry of the flux barriers using design methodologies in [16], [17].

As with FSCW machines, the initial design decisions required choosing the number of stator slots and rotor poles of a pure SynRM. To consider motors of similar sizes to that of the FSCW, the 10-pole and 8-pole cases were chosen. Next, the number of stator slots were selected: the 48-slot version resembles the IPM stator in the 2010 model of the Toyota Prius and has a good slot number due to its industrial relevance, relatively low cogging torque and parasitic air gap harmonic content. Since torque ripple is a major design challenge for SynRMs based on the results presented in [17], the 33-slot version was selected as a second choice. As suggested in [18], an asymmetric flux barrier arrangement with respect to the stator slots results in lower ripple torque values which occur for both the pole configurations (48/10 = 4.800, 33/8 = 4.125). These two pole-slot combinations resulted in winding configurations with high relative winding factors for both motors (95.6%, 95.4%).

Initially, a single-barrier rotor was designed with respect to average torque and torque ripple using a surrogate-based optimization procedure described in [17]. Through a magnetic circuit decomposition, the rotor's single flux barrier and carrier were divided into two to reduce the torque ripple [16] by distributing the main flux lines. Once the rotor geometry was designed to optimize the reluctance torque, a right amount of low cost bonded NdFeB PMs was added to the rotor flux barriers to maintain a good CPSR. An iterative procedure was then carried out to minimize the motor volume and mass (which reduces the material cost) while meeting the required startup, continuous and maximum ratings using accurate FEA simulations [13]. The RMS current density in the stator slots of both PMa SynRMs was constrained to be similar to the FSCW machine. A design summary of both the 48-slot and 33-slot PMa SynRM parameters are shown below in Table 2.

## 2.3. Efficiency Maps and Design Summary

In order to find the efficiency maps of each synchronous motor, different control strategies were applied to compute the maximum torque envelope for a range of operating speeds [19]. To calculate the Maximum-Torque-per-Ampere (MTPA) operation point at a given current magnitude  $I_s$ , the quadratic equation in (1) was solved to find the optimal current advance angle  $\gamma^{MTPA}$ . The parameters used were the rotor saliency ratio  $\xi$ , the PM flux linkage  $\lambda_m$ , the d-axis inductance  $L_d$  and the characteristic current due to PMs  $I_m$ . The dq-axis convention follows [17], where the q-axis inductance  $L_q$  is larger than  $L_d$  for salient pole machines.

$$\begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} 2I_s(\xi - 1) \\ I_m \\ -(\xi - 1)I_s \end{bmatrix} \rightarrow a(\sin \gamma^{MTPA})^2 + b(\sin \gamma^{MTPA}) + c = 0, \quad I_m = \frac{\lambda_m}{L_d}, \quad \xi = \frac{L_q}{L_d} \quad (1)$$

For motor speeds higher than its base, the MTPA strategy cannot be used because the induced voltage in the motor windings rises above the maximum battery voltage  $V_{dc}$ . Hence, a Flux Weakening (FW) strategy was

imposed to intersect the current circle and the voltage ellipse in the dq-current plane using (2). Here the optimal  $\gamma^{FW}$  is found for a given  $I_s$  and motor speed, where the maximum radius of the voltage ellipse  $I_e$  depends on the maximum phase voltage  $V_s^{MAX}$  and the electrical angular frequency  $\omega_e$  linked to the motor speed.

$$\begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} I_s^2(\xi^2 - 1) \\ 2I_m I_s \\ I_e^2 - I_m^2 - \xi^2 I_s^2 \end{bmatrix} \rightarrow a(\sin \gamma^{FW})^2 + b(\sin \gamma^{FW}) + c = 0, \quad I_e = \frac{V_s^{MAX}}{\omega_e L_d} \quad (2)$$

At even higher speeds when the voltage ellipse gets even smaller but is still constrained within the current circle, a Maximum-Torque-per-Volt (MTPV) strategy was used to find the optimal d-axis flux linkage  $\lambda_d^{MTPV}$  through (3) shown below using the maximum stator flux linkage  $\lambda_s^{MAX}$ . This  $\lambda_d^{MTPV}$  value was then used to calculate the optimal MTPV ( $I_s^{MTPV}, \gamma^{MTPV}$ ) point.

$$\begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} 2\left(\frac{1}{\xi} - 1\right) \\ \lambda_m \\ -\left(\frac{1}{\xi} - 1\right)(\lambda_s^{MAX})^2 \end{bmatrix} \rightarrow a(\lambda_d^{MTPV})^2 + b\lambda_d^{MTPV} + c = 0, \quad \lambda_s^{MAX} = \frac{V_s^{MAX}}{\omega_e} \quad (3)$$

The design parameters of the FSCW motor and PMa SynRMs are shown in Table 2 below. A main difference between the two motor types is the smaller size of the PMa SynRM which is an attractive feature for traction applications. Roughly speaking, this results in a lower material cost based on the reference costs presented in [14]. Figure 1 also illustrates the respective efficiency maps and geometric cross-sections of all three motors.

Table 2: Design summary of three studied motors

| Parameter/Dimension            | Unit                              | FSCW        | PMa SynRM 1    | PMa SynRM 2    |
|--------------------------------|-----------------------------------|-------------|----------------|----------------|
| Number of poles/slots          |                                   | 10/12       | 10/48          | 8/33           |
| DC bus voltage                 | V                                 | 450-650     | 650            | 650            |
| Stator's outer diameter        | mm                                | 360         | 355            | 355            |
| Rotor's outer diameter         | mm                                | 199         | 260            | 240            |
| Active stack length            | mm                                | 245         | 135            | 125            |
| Magnet width                   | mm                                | 50.1        | -              | -              |
| Magnet thickness               | mm                                | 14.3        | -              | -              |
| Airgap thickness               | mm                                | 1.15        | 1.00           | 1.00           |
| Rated RMS line current         | A <sub>rms</sub>                  | 255         | 320            | 375            |
| Number of turns/parallel paths |                                   | 28/4        | 6/1            | 3/1            |
| Cont. current density          | A <sub>rms</sub> /mm <sup>2</sup> | 10.0        | 10.1           | 10.1           |
| Peak current density           | A <sub>rms</sub> /mm <sup>2</sup> | 30.0        | 30.2           | 27.2           |
| Stator + Rotor core mass       | kg                                | 67.4 + 17.9 | 28.2 + 23.3    | 36.8 + 16.8    |
| Copper winding mass            | kg                                | 58.2        | 22.9           | 17.3           |
| Magnet mass                    | kg                                | 11.5        | 4.5            | 4.9            |
| Total mass                     | kg                                | 155.0       | 78.9           | 75.8           |
| Magnet material                |                                   | NdFeB 32/16 | MQP-B+ 897/780 | MQP-B+ 897/780 |
| Core material                  |                                   | M-19 29 Ga  | M-19 29 Ga     | M-19 29 Ga     |
| Cooling method                 |                                   | liquid      | liquid         | liquid         |

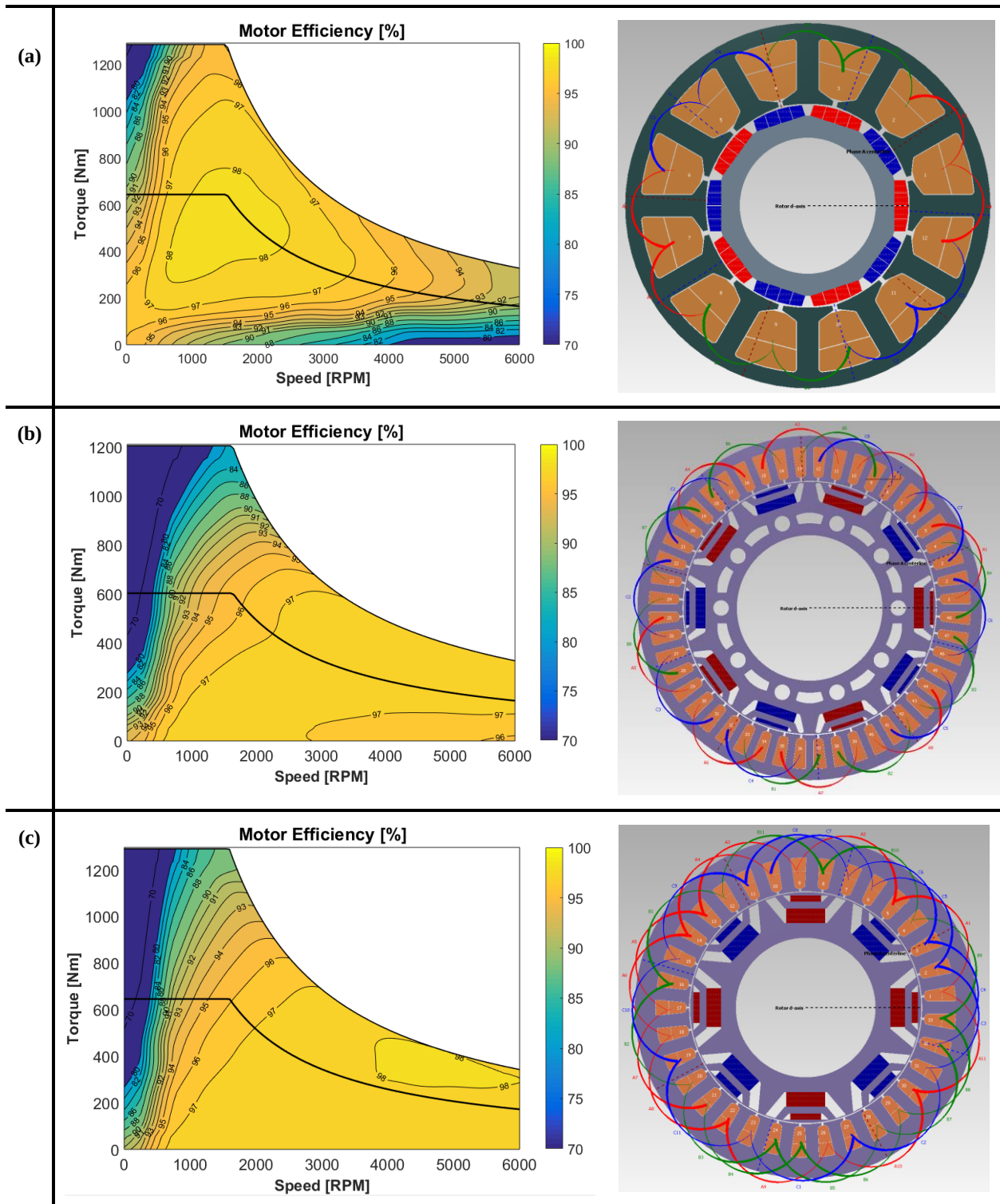


Figure 1: Motor efficiency maps and cross-sectional geometries:  
 (a) 12-slot 10-pole FSCW machine, (b) 48-slot 10-pole PMa SynRM, (c) 33-slot-8-pole PMa SynRM

### 3. Performance Comparison

The subsections below comparatively analyze the performances of the FSCW machine and the two PMa SynRMs using electromagnetic, thermal, NVH and vehicle dynamic simulations.

#### 3.1. Electromagnetic Analysis

Table 3 summarizes the electromagnetic performances of the studied motors. All three machines satisfied the continuous torque and peak power requirements (Figure 1) as well as other performance criteria. The three motors have a nearly negligible cogging torque. Also, Figure 2 and Figure 3 display the torque waveforms and different loss components at base speed respectively. As expected, FSCW PMs have significantly higher eddy current losses compared to PMa SynRMs which, given the relatively low thermal conductivity of rare earth magnets lead to segmentation requirement of these machines.

Table 3: Electromagnetic analysis summary

|                                    | Performance         | Unit | FSCW  | PMa SynRM 1 | PMa SynRM 2 |
|------------------------------------|---------------------|------|-------|-------------|-------------|
| No load operation                  | Max. cogging torque | Nm   | 1.73  | 0.12        | 0.02        |
| Continuous operation at base speed | Average torque      | Nm   | 653.2 | 641.6       | 615.0       |
|                                    | Torque ripple       | %    | 2.40  | 7.78        | 5.39        |
|                                    | Efficiency          | %    | 98.2  | 95.2        | 96.1        |
|                                    | Power factor        |      | 0.811 | 0.570       | 0.651       |

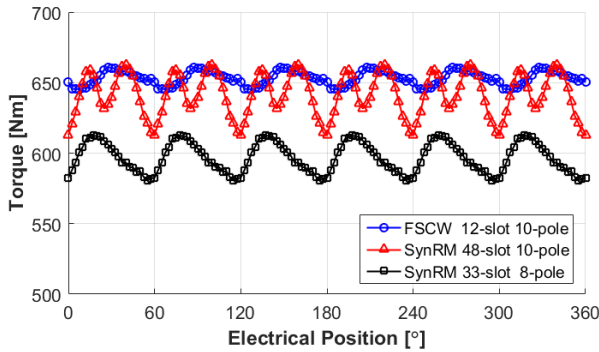


Figure 2: Instantaneous torque waveforms at continuous current and base speed operation

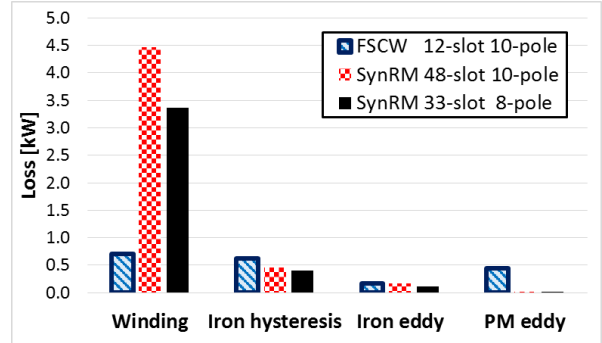


Figure 3: Electromagnetic loss components at continuous current and base speed operation

#### 3.2. Thermal Analysis

The motors presented in Table 2 and Figure 1 were designed to be liquid cooled using ethyl glycol. During the electromagnetic design phase, the cooling criterion was applied to keep the continuous and peak current densities below 12 and 30 A/mm<sup>2</sup> respectively. These two limits were used based on the recommendations in [7]. To ensure that the temperatures of various motor segments such as the stator windings, rotor core and permanent magnets were within the acceptable limit and to compare the relative cooling costs, coupled electromagnetic-thermal simulations were performed to calculate the temperature rise in these machine parts under variable load conditions (applied as a function of time) at the rated speed. Spiral duct cooling (using 8 ducts) and spray cooling (using engine oil) were applied to the stator and its end windings respectively. Identical cooling conditions were imposed on each motor to directly compare the thermal performances. All analyses were performed using the thermal simulation module of the FEA-based MotorSolve software [13]. Figure 4 shows the temperature-versus-time plots of the stator coil, rotor core and PMs in each motor under various load conditions. Constant

temperatures values recorded at 900 minutes of the thermal analyses are given in Table 4. The results clearly indicate that the PM temperature is higher for the FSCW machine when compared to the PMa SynRMs. In fact for FSCW machines, segmenting the rotor PMs is essential. Otherwise, a high temperature in the magnets would cause them to demagnetize and adversely affect the motor's expected performance.

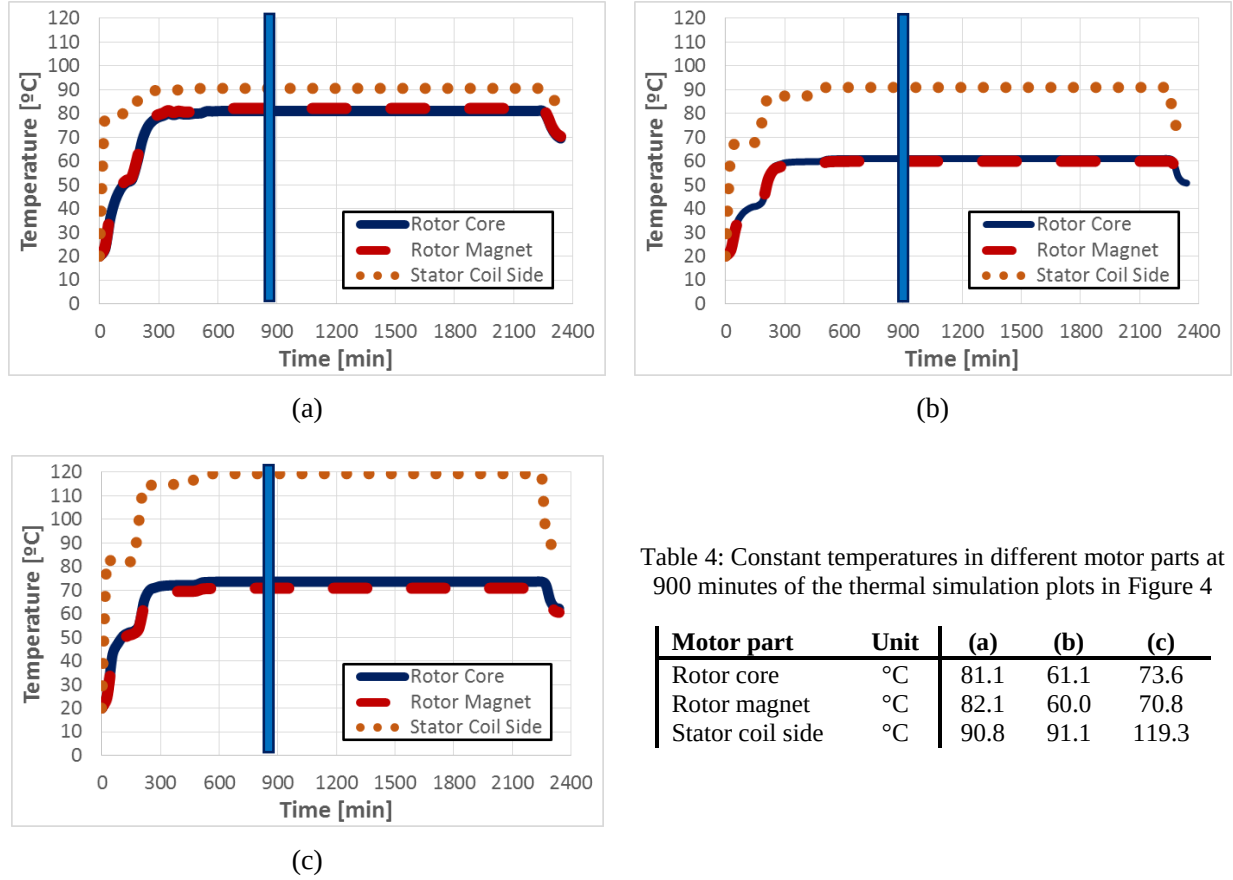


Table 4: Constant temperatures in different motor parts at 900 minutes of the thermal simulation plots in Figure 4

| Motor part       | Unit | (a)  | (b)  | (c)   |
|------------------|------|------|------|-------|
| Rotor core       | °C   | 81.1 | 61.1 | 73.6  |
| Rotor magnet     | °C   | 82.1 | 60.0 | 70.8  |
| Stator coil side | °C   | 90.8 | 91.1 | 119.3 |

Figure 4: Thermal simulation results: (a) 12-slot 10-pole FSCW, (b) 48-slot 10-pole and (c) 33-slot-8-pole PMa SynRMs

### 3.3. Noise, Vibration and Harshness (NVH) Analysis

The accurate calculation of noise and vibration levels in an electric machine is quite complex as there are multiple sources of these phenomena (electromagnetic, mechanical, etc.) that are difficult to model. However, using a few simplifying assumptions [20], it is possible to estimate the noise level from electromagnetic sources in electric machines. Using the methodology in [20], the air gap pressure wave harmonics of the three machines have been calculated under rated condition. Since the normal component of the air gap pressure wave is dominant over its tangential counterpart, the normal component is calculated using  $P_n(\theta) \approx B_n(\theta)^2 / (2\mu_0)$  where  $B_n$  is the normal component of the air gap flux density and  $\mu_0$  is the permeability constant of free space. It has been shown in [20] that the machine's stator can be modeled as a constrained cantilever beam whose displacements are inversely proportional to the fourth power of the mode amplitudes. Hence, if the amplitude of the low order pressure wave harmonics are significant, then the noise level in the machine would also be substantial. Considering the Fourier series harmonic amplitudes illustrated in Figure 5 for  $P_n$ , it is observed that the noise level in all three motors is unlikely to be significantly different. It should be noted that calculating the loudness value in dB requires FEA-

based structural analysis which was not performed in this study. Only a qualitative comparison based on the results in Figure 5 is presented.

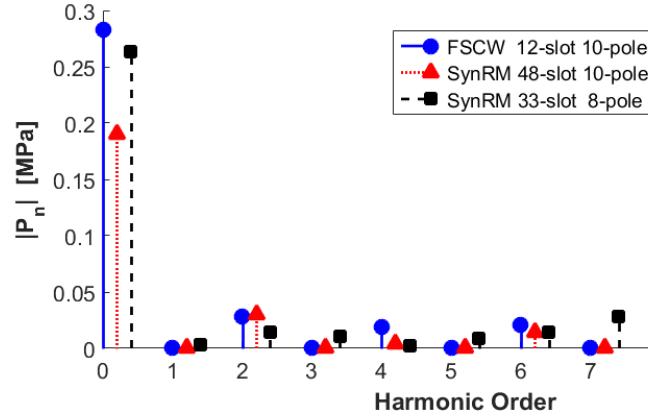


Figure 5: Fourier series harmonic amplitudes of air gap pressure wave (normal component)

### 3.4. Vehicle Dynamic Analysis

In order to realistically compare the operating performance of the three motors, vehicle dynamic simulations using the ADVISOR software within the MATLAB computing environment were carried using a single-speed electric vehicle with a 6.5 gear ratio, 1:1 differential and over 30% gradeability for a number of standard drive cycles. A summary of the vehicle performance data is shown in Table 5. The vehicle parameters and an example of the 48-slot 10-pole PMa SynRM's operating points is demonstrated in Table 6 and Figure 6 respectively.

Table 5: Summary of vehicle dynamic analyses

| Drive Cycle | Performances      | Unit  | FSCW   | PMa SynRM (1) | PMa SynRM (2) |
|-------------|-------------------|-------|--------|---------------|---------------|
| HTUF4_short | Consumption       | Wh/km | 630.4  | 606.4         | 602.6         |
|             | Range             | km    | 108.0  | 112.4         | 113.1         |
| NYCC        | Consumption       | Wh/km | 815.2  | 852.4         | 837.3         |
|             | Range             | km    | 84.6   | 80.9          | 82.4          |
| OCC         | Consumption       | Wh/km | 659.2  | 659.9         | 656.4         |
|             | Range             | km    | 103.6  | 103.5         | 104.1         |
| UDDS        | Consumption       | Wh/km | 664.7  | 643.8         | 641.2         |
|             | Range             | km    | 102.5  | 105.9         | 106.3         |
| UDDSHDV     | Consumption       | Wh/km | 760.3  | 716.6         | 714.0         |
|             | Range             | km    | 89.8   | 95.3          | 95.7          |
|             | Acceleration time | s     | 15.79  | 16.07         | 15.11         |
|             | Max. speed        | km/h  | 136.77 | 136.77        | 136.78        |

Table 6: Class IV electric vehicle parameters for drive cycle simulation

| Parameter           | Unit           | Value |
|---------------------|----------------|-------|
| Vehicle mass        | kg             | 6373  |
| Final drive ratio   |                | 6.5:1 |
| Coefficient of drag |                | 0.7   |
| Frontal area        | m <sup>2</sup> | 7.02  |
| Tire rolling radius | m              | 0.393 |

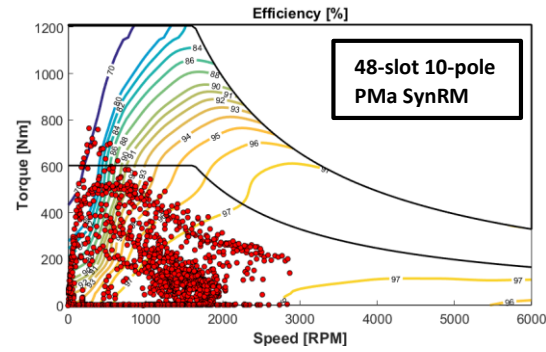


Figure 6: Time distribution map for OCC simulation

## 4. Conclusion

The design and optimization of a 10/12 FSCW, a 10/48 PMa SynRM and an 8/33 PMa SynRM has been presented for a Class IV electric step van application. The electromagnetic, thermal, NVH and vehicle dynamics results have been shown. Several conclusions can be drawn from this comparative study. First, viable design solutions from both motor topologies can be obtained. Second, the volume or mass of the PMa SynRM is significantly lower than the FSCW machine. Despite its high power density, the larger size of the FSCW machine cannot be avoided, because of the necessity to meet the cooling requirement for its magnets and windings. On the other hand, the power factor of the FSCW machine is better which has a positive impact on the inverter size and system cost. From a vehicle dynamics perspective, all three motors perform reasonably well. The FSCW motor's consumption for the NYCC drive cycle, which relies on regularly starting and stopping in urban scenarios, is better than the PMa SynRMs' because of the FSCW's high efficient region at low speeds. Conversely, the PMa SynRMs consume less energy for other drive cycles due to their improved efficiencies near high speeds. Lastly, the 33-slot 8-pole machine is suggested to its 48-slot 8-pole counterpart due to its lower torque ripple, higher efficiency, better vehicle performance and lower material cost.

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