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# Design Comparison of Dual Axial Flux Rotor and Stator Structure for Electric Vehicle Applications

**H. Abdullah*, G. Ramasamy**, K. Ramar** and C.V. Aravind*****

**ABSTRACT**

Vehicle dynamic depends on the power rating as it tallies the required initial acceleration and overall performance. If the vehicle motor operational characteristics provides high torque at constant power, the power rating of the machine can be reduced. Besides, extended constant power range can also recover more kinetic energy during regenerative braking. Therefore, a motor with extended constant power and torque is advantageous for EV and HEV traction application [1]. In order to obtain high torque at constant power range, Axial Flux Permanent Magnet (AFPM) with dual magnetic circuit is much preferred compared to conventional radial motors as high torque is easily achieved through large placement of permanent magnet on its axial platform. Besides, by achieving slim design, AFPM motors can be much efficient on torque production due to weight reduction. This paper compares AFPM motor characteristics based on Double Stator (DSAFPM) and Double Rotor (DRAFPM) structures with same rated power and design elements. Finite element analysis are carried out for both modeled structure base on designed value of 1 kW machine simulated on 132V-3phase DC supply.

***Keywords:*** Axial flux permanent magnet (AFPM), double stator AFPM (DSAFPM), double rotor AFPM (DRAFPM)

## 1. INTRODUCTION

For the past few decades, greenhouse gas emission has been the most crucial problem as they lead to many unpredictable disasters. In the next 50 years, it is expected that the global population will increase from 6 billion to 10 billion and the vehicles they own will increase form 700 million to 2.5 billion [2-3]. One of the most vibrant issues on greenhouse gas emissions reflects directly on emission gases produced by gasoline vehicles. Besides, the ever rising concerns on natural resources has also accelerated the development of automobile which saves fuel by maximizing energy conservation such as Electric-Gasoline Hybrid [4]. However the future of automotive industry are seriously looking towards development of vehicles that produces zero emission such as battery or fuel cell powered vehicles [5]. For both systems, high efficiency electric motor with high *torque at constant power* is much needed to produce the vehicle dynamics, driving range and performance [1]. A large number of motor types and technologies were considered, developed and employed in the past decades. However the choice are limited by the availability of motor, the electronic control technologies together with the traction requirements. [1-5]. Currently, Interior Permanent Magnet (IPM) – Permanent Magnet Synchronous Motors (PMSM) have been widely selected by international automakers such as Toyota, Nissan and Tesla which they believe the best motor to satisfy BEV characteristic. Besides, IPM-PMSM have also gained fame through reliability based on market test for the past few years. However, IPM-PMSM motors are much expensive, difficult to maintain and often demands high energy source to produce the desired output which limits the driving range [1-6].

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* Research Scholar, Faculty of Engineering, Multimedia University, Cyberjaya, Selangor, Malaysia, *Email: gobbi@ieee.org*

** Research Supervisor, Faculty of Engineering, Multimedia University, Cyberjaya, Selangor, Malaysia, *Email: gobbi@ieee.org*

*** Research Co-Supervisor, Faculty of Engineering, Taylor's University, Subang Jaya, Selangor, Malaysia, *Email: aravindcv@ieee.org*

Recently, Axial flux Machine (AFM) are being considered for EV propulsion system as they are capable of producing much higher torque compared to Radial Flux machines in the same volume. It is also noted that AFM usually are being developed in less complicated coil design which makes them easy to maintain and reliable which indirectly promotes towards a cheaper alternative to automakers. Likewise radial system, to maximize the flux density, AFM is also widely considered to be designed and developed with dual flux system.

To examine the characteristics of Dual Axial Flux Permanent Magnet Motor, both combination of Double Stator – Single Rotor Axial Flux Permanent Magnet (DSAFPM) and Double Rotor Single Stator Axial Permanent Magnet (DRAFPM) have been simulated and the results were been discussed. Since the design consideration are mainly focused on prototype design for Electric Vehicle propulsion system, below are the expectation and simulation parameter have been set accordingly.

1. High torque density and power density
2. Extended constant power range
3. Fast response torque
4. Low noise and high reliability

Typical torque power speed characteristics required for traction motor is as shown in Figure.1.

## 2. AXIAL MAGNETIC DESIGN CONSIDERATIONS

### 2.1. Design Concepts

Basic principle of axial magnetic circuit are shown in Figure 2. Torque production occurs with an air-gap between the surface of the permanent magnet and the electro-magnetic coil which turn into opposing magnet when there is a flow of current. The torque density depends on the magnetic force available in the airgap.

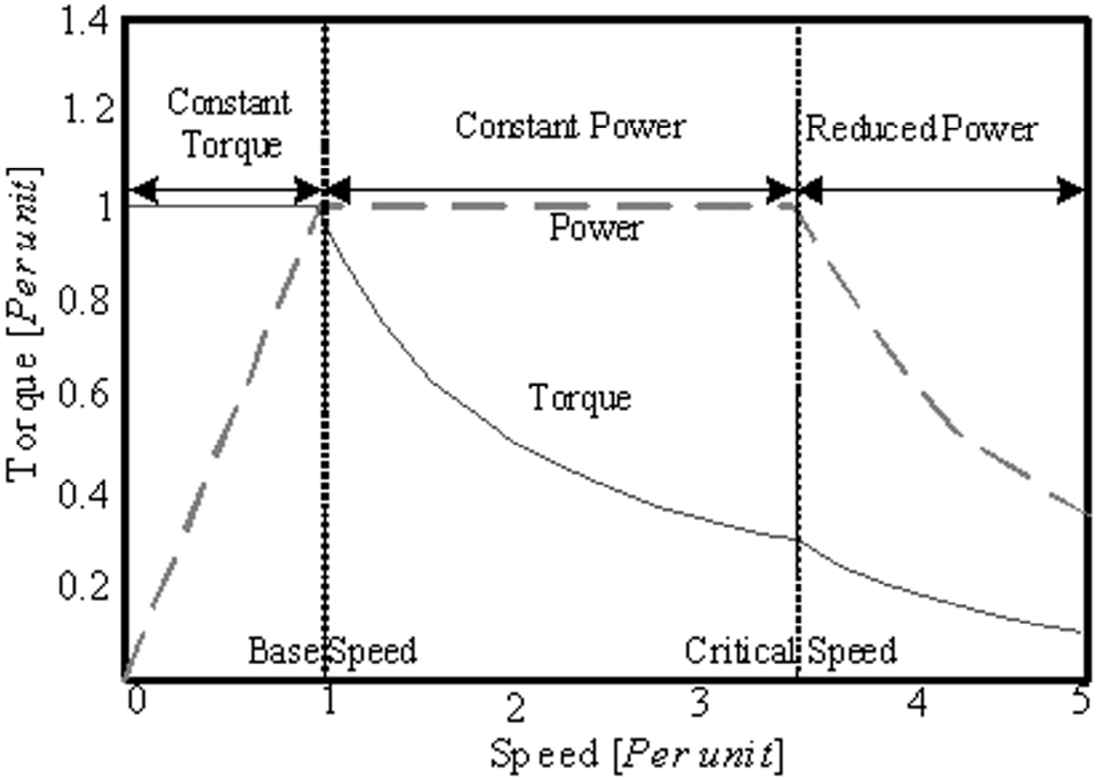

Figure 1: Torque Power Characteristics of EV [1]

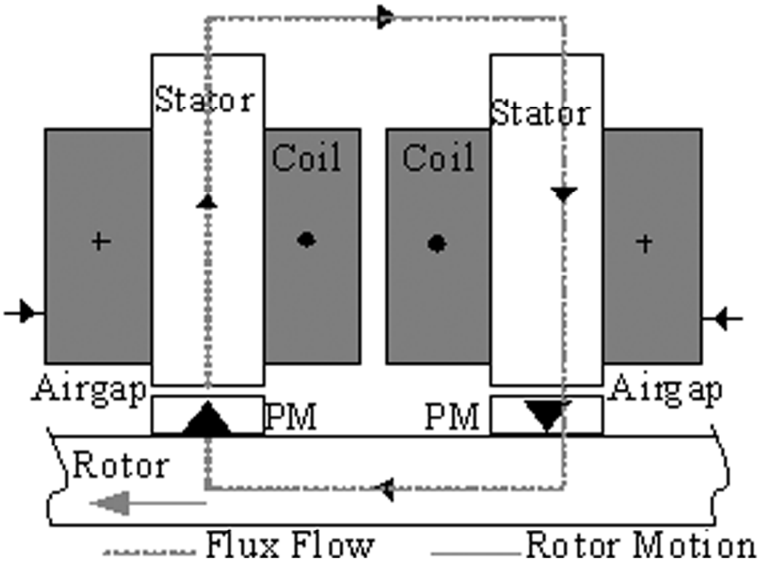

**Figure 2: Magnetic Flow Concept [1]**

This is influenced by the way the magnetic circuit is established. This concept of magnetic flux flow can be done through the radial flux or axial flux to create a rotational motion. The choice of axial or radial type of flux flow depends on the applications requirement. For instance in case of electric vehicle the diameter of the machine could be bigger as there are not much constrain of space as such Axial motor will be ideal as they are capable of producing high torque to supply the demand of the vehicle dynamics [7]. However if there is a space constrain, then radial motor will be preferred as the stack length of motor can be compensated for the loss of diameter is the size reduction. Due to flywheel effect, motor diameter is something that can't be avoided if high torque production is expected [1].

## 2.2. Tradeoff between Radial and Axial Flux flow

Figure. 3 and Figure 4 shows the radial and the axial configurations topology.

The output power (P) for any electrical machine is expressed as in Eq. (1).

$$P = \eta \frac{m}{T} \int_0^{\tau} e(t) i(t) dt = \eta m k_p E_{pk} I_{pk} \tag{1}$$

where η: efficiency, *m*: number of phases *T*: Torque exerted by the machine $k_p$ is the torque constant.

The peak value of the air gap phase EMF for the axial flux machine is as in Eq. (2).

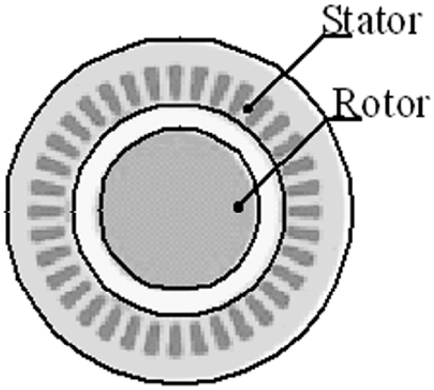

**Figure 3: Slotted Radial Configuration [1]**

**Figure 4: Slotted Axial Configuration – external rotor [1]**

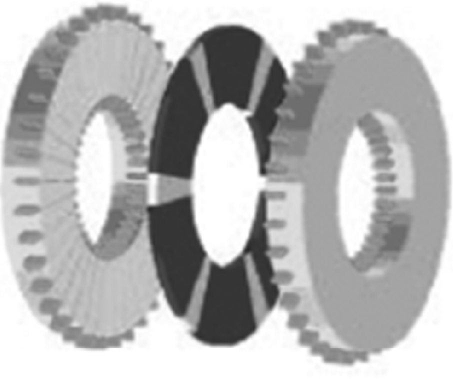

**Figure 5: Slotted Axial Configuration – internal rotor [1]**

$$E_{pk} = K_e N_t B_g \frac{f}{p} \lambda_{0r} D_0 L_e \tag{2}$$

where $L_e$ effective stack length, $\lambda_{or}$: is the ratio of air-gap diameter $D_g$ to the outer diameter $D_0$, $f$: frequency of rotation, $N_t$: *number of turns*, $K_e$: *material constanton winding*, *factor* = 0.955, $p$ is the number of magnetic poles.

The peak value of the air gap phase EMF for the axial flux machine is as in Eq. (3).

$$E_{pk} = K_e N_t B_g \frac{f}{p} \left(1 - \lambda_{0a}{}^{2}\right) D_0^2 \tag{3}$$

where $K_e$ is the EMF factor that includes the distribution and winding factor, $\lambda_{oa}$ is the ratio of inner diameter $D_i$ to that of the outer diameter $D_0$. The peak phase current for the radial flux machine is as in Eq. (4).

$$I_{pk} = \frac{1}{1 + K\phi} k_i A \pi \lambda_{0r} \frac{D_0}{2mN_t} \tag{4}$$

With reference to the above equations, it is notable that the stack length of Radial Flux machine is relatively silent on the motor torque performance. However the stack length is difficult to reduce as practically it is needed to accommodate the coils of the stator. This entire situation has promoted axial motor design as better alternative as the stack length can be reduced which will promote better efficiency with its reduced volume [8-9].

### 2.3. Axial Flux Flow Configurations

In the axial machines, the concept of dual axis flow or the double rotor and double stator concept brings challenging aspects in the fabrication though at the simulation these machines perform very well [6]. It derives drawback in the unbalancing of the flux flow and also invokes much of vibration and noise. In the radial topology this is not challenged as the flux flow is in radial direction and also the diameter of the stator rotors involved in the torque production of the same surface level. However in the need of high efficiency with regards to the power to weight ratio and high torque capabilities, a fine tune axial motor will be the best candidate [13-15].

## 3. DESIGN METHODOLGY & RESULTS

### 3.1. Sizing of Machine

Ideally both design of single stator double coil and double stator single rotor Axial motors are to be design in very similar sizing to have the best comparison on the simulation level. As a target, both motors are to be designed to have 1kW of rated power, 2 × 3-phase coils and 2 × 2-poles of permanent magnets.

$$T = 2N_m K B_g N_t i \int_{D_i/2}^{D_o/2} r dr \tag{5}$$

**Table 1**
**Requirement Specification of Motor**

| *Parameter* | *Requirement* |
|---|---|
| Type | Dual Axial Flux Topology |
| Motor volume | Do 129mm × Di 50.8mm × L 43mm |
| Cogging torque | < 2 % of Peak torque |
| Operational temperature | 80° C |
| Drive electronics | Six pulse PWM drives |

$$T = 0.5\ N_m K B_g N_t i (D_0^2 - D_i^2) \tag{6}$$

The torque output of the motor which is the product of electrical loading and magnetic loading. The maximum electromagnetic force is given as in Eq. (7)

$$e_{\max} = \frac{T\omega_m}{i} = 0.5 N_m K B_g N_t i (D_0^2 - D_i^2)\omega_m \tag{7}$$

From the above the number of turns per slot required to produce the $e_{max}$ can be calculated as in Eq. (8).

$$n_s = \frac{e_{\max}}{i} = \frac{e_{\max}}{0.5\ N_m K B_g N_t i (D_0^2 - D_i^2)\omega_m} \tag{8}$$

The slot current is calculated using the Eq. (9)

$$I_s = \frac{T}{0.5\ N_m K B_g N_t i (D_0^2 - D_i^2)} \tag{9}$$

The phase current is given as in Eq. (10).

$$I_{ph} = \frac{I_s}{N_t} \tag{10}$$

The current density is given as in Eq. (11)

$$J_c = \frac{I_s}{A_c} \tag{11}$$

From the above the turns per slot and the maximum current density of the machine designed is computed for the specified sizing of the machine based on the initial design on capability of the machine which is later used in the simulation study of the machine using the FEA tool [10-12].

### 3.2. Design Parameter

Figure 6 projects both design ideas which should be accurately compared as both of them may sound identical in the theoretical however in terms of practical performances, both motor seem to have their unique characteristic which could be advantages for selected application. However, typically for Electric Vehicle application, besides torque production as main design concern, the reliability of the motor need to be considered as well as only then the vehicle dynamics can sustain throughout the entire speed curve.

**Table 2**
**Design Parameters**

| *Parameters* | *Term/Values* |
|---|---|
| Rated Speed | 150 rpm |
| Rated Power | 1 kW |
| Number of phases | 3 |
| Number of magnets | 12 × 4 sets |
| Number of armature core | 9 |
| Magnet type | N40 |
| Motor overall diameter | 500 mm |
| Motor axial diameter | 50 mm |
| Number of turns/ phase | 1000 |
| Type of winding | Concentrated |
| Total amp-turns | 12000 A-t |
| Conductor Material | Copper alloy |
| Core Material | M22 Steel |

**Figure 6: Design Concept on Double Rotor Single Stator & Double Stator Single Rotor**

## 3.3. Simulation parameters

**Table 3**
**Design Parameter used**

| *Parameters* | *Term/Values* |
|---|---|
| Rated Speed | 200 rpm |
| Rated Power | 1 kW |
| Number of phases | 3 |
| Number of magnets | 12 × 4 sets |
| Number of armature core | 6 |
| Magnet type | NEOMAX-28EH |
| Motor overall diameter | 500 mm |
| Motor axial diameter | 50 mm |
| Number of turns/ phase | 1000 |
| Type of winding | Concentrated |
| Total amp-turns | 12000 A-t |
| Conductor Material | Copper alloy |
| Core Material | M22 Steel |

### 3.4. Finite element design and analysis

Both Axial motors as shown on figure 5 was drawn in 3D mode using Jmag Designer simulation software. Upon design completion each and every component on the motor were carefully define based on available list as close as possible to obtain a genuine result. The design parameter were set on the simulation software based on table 3 above. Since both are 3-phase motor, the circuit was set with a PWM DC source of 132V.

### 3.5. Results and Discussions

Figure 8 proves that the simulated design is acceptable as the static analysis produced a smooth waveform with no short circuit in between phases. Flux linkage obtained is proportional to the torque produced which

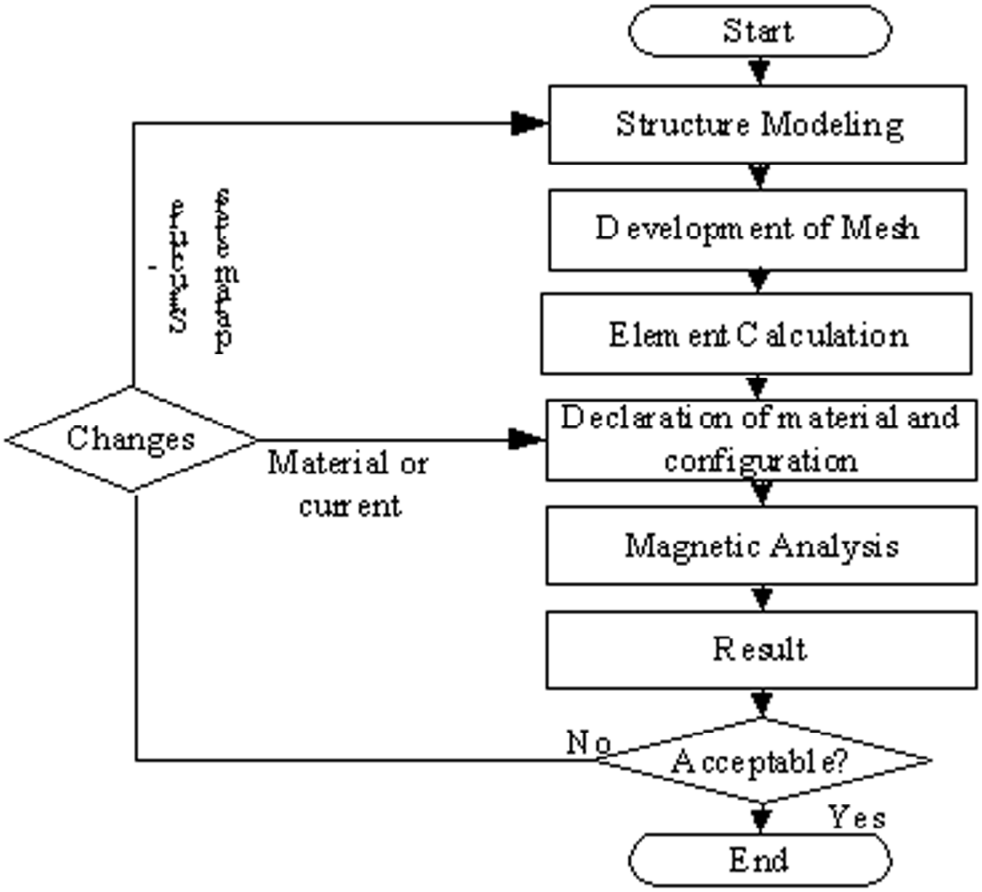

Figure 7: Flow chart used in FEA

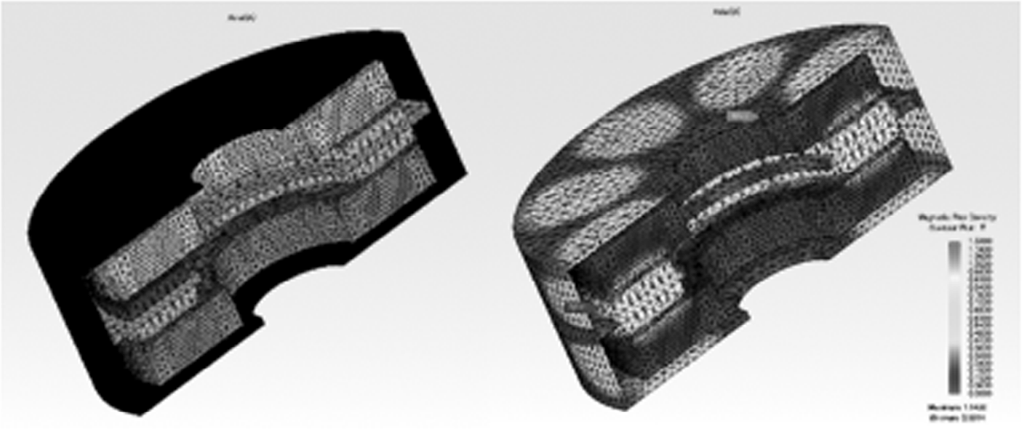

Figure 8: Finite Element Analysis – Double Stator

was further analyzed in the graph below. Since this motor is targeted for a specific application of electric vehicle, a dynamic analysis on 3D modelling was done as below

- No of steps: 36 steps
- Interval: 100

The simulated model achieve its highest torque at 1000 rpm which is approximately 4.5Nm of torque, as the speed increase the torque drops relatively. However the torque maintains its value up to 2000rpm, in order to achieve good dynamics the vehicle driven by this Axial Motor need to be further optimized to achieve constant torque up to 2500 rpm,

Figure 13 above was captured with simulations on dynamic condition to evaluate the regenerative properties. Phase A was plotted with different rpm speed and in order to achieve the desired voltage a minimum speed of 200 rpm is needed, as such on the application of EV together with the mechanical assistance, the low speed regeneration is highly achievable which can be considered as serious parameter for vehicle range extension.

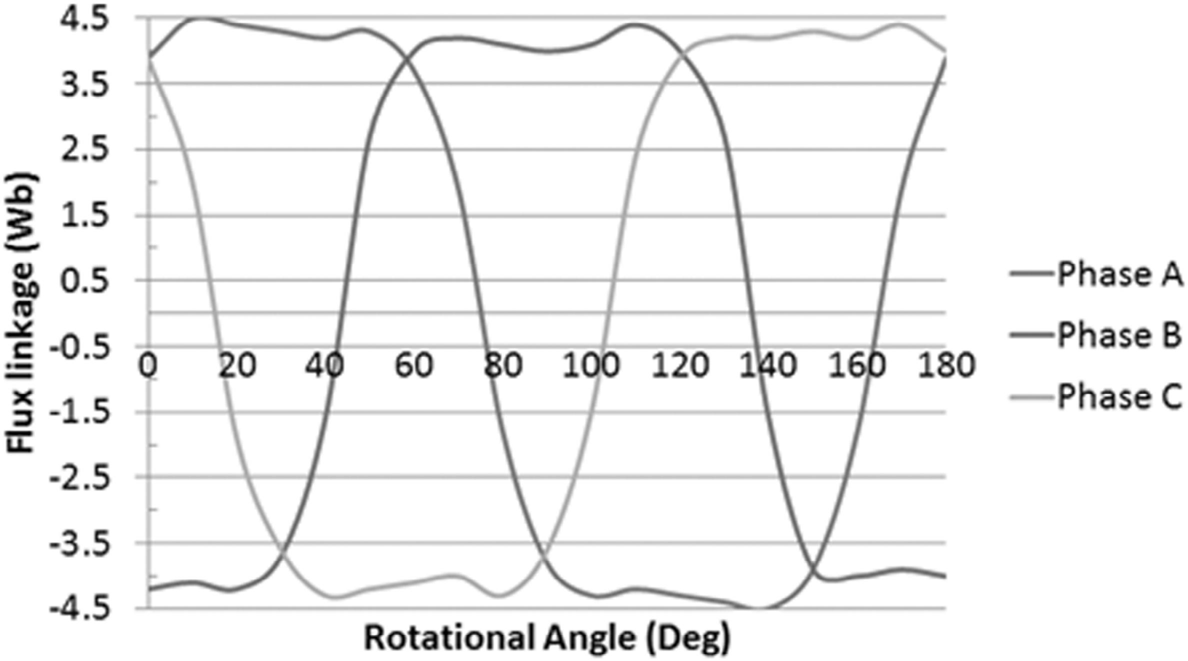

**Figure 9: Flux Linkage in the coils**

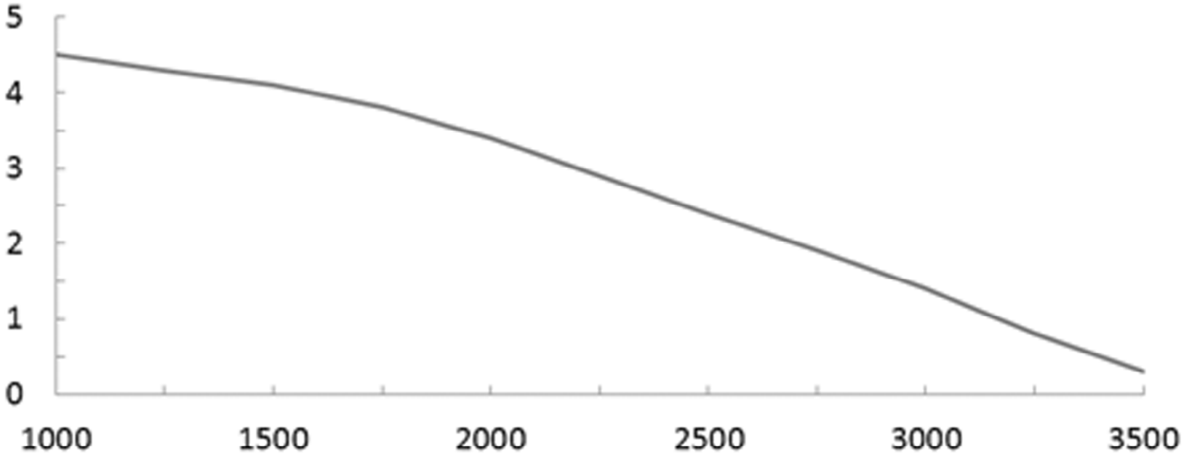

**Figure 10: Torque vs Speed**

For comparison the above design was simulated, all the parameter with the earlier design are exactly the same, however this second simulation has an invert design of the previous whereby the stator coil has been placed on the innersection and the rotor at the outer section matching sandwiched stator concept. In terms of magnetic flux, the above simulation shows a better density compared to the earlier model, as such a slight improvement on the overall readings has been captured as figure 11 below:

With the increase in flux linkage the torque has a little improvement as well with maximum value of 4.65Nm.

However this does not change the regeneration capabilities as to achieve the desired voltage a minimum 200 rpm is still needed as shown in figure 12 above.

With Sandwiched design, it is notable that the torque production is much more constant, this is mainly due to the flywheel effect of the external rotors which is more stable compared to the internal structure whereby the balancinghas an effect due to inconsistency of the added permanent magnet weights.

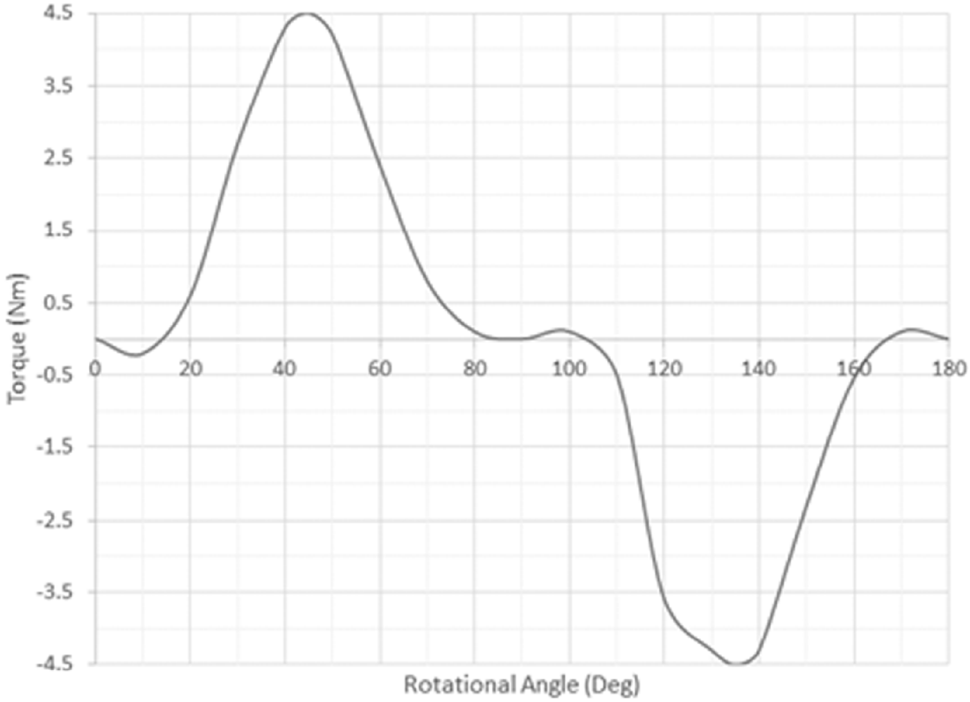

**Figure 11: Regenerative voltage capability of the simulated**

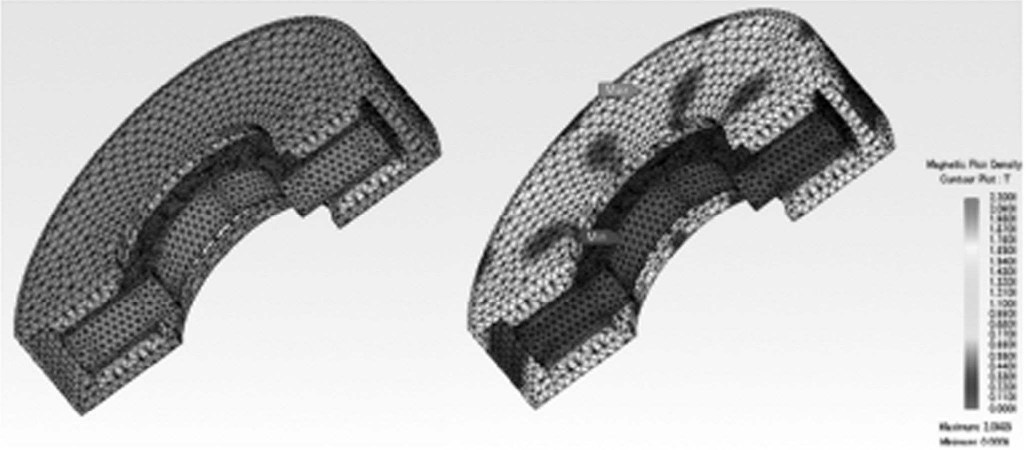

**Figure 12: Finite Element Analysis – Sandwich design**

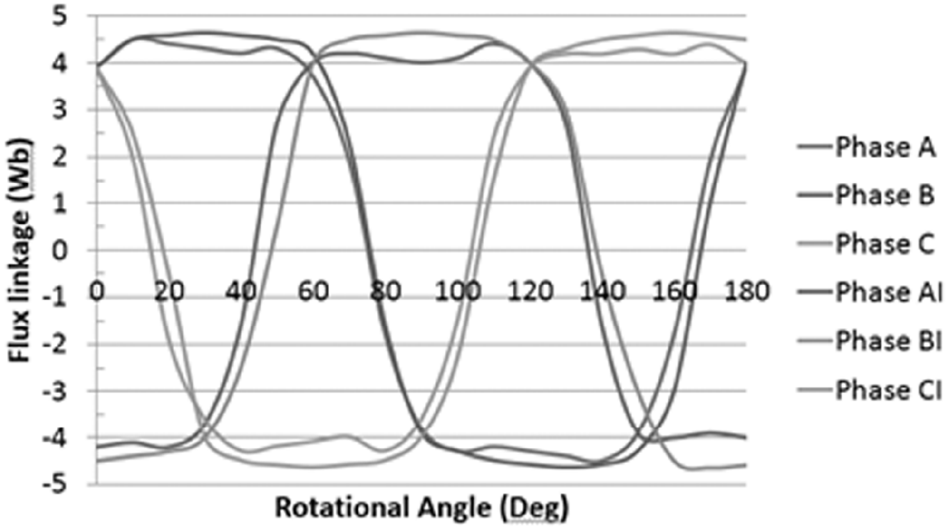

Figure 13. Flux linkage on the coil – Sandwich design vs Double Rotor Design

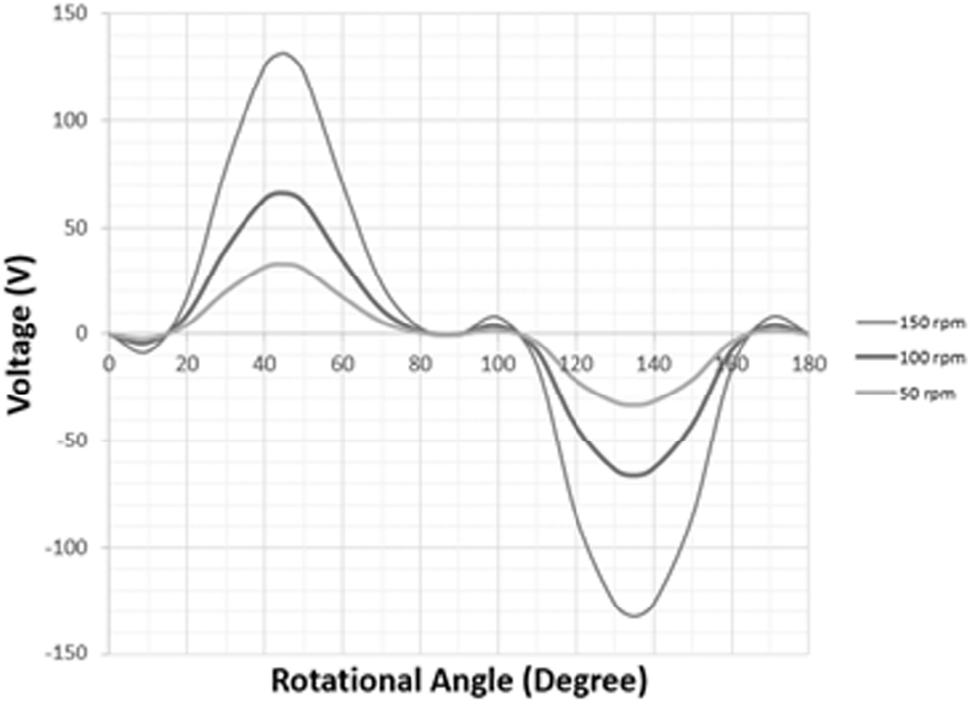

Figure 14: Flux linkage on the coil – Sandwich design

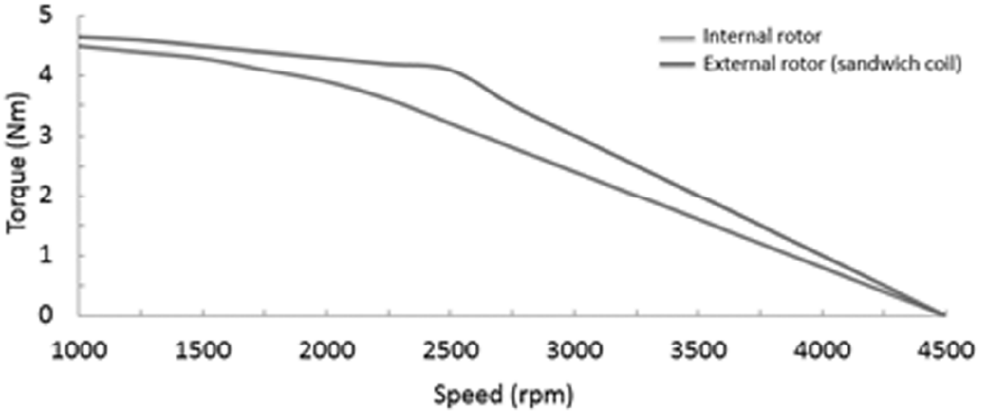

Figure 15: Torque vs Speed for both simulated model

## 4. CONCLUSION

The design variations in the axial flux flow pertaining to the use in EV is presented. A dual axial flux flow through double rotor (exterior rotor) and sandwiched stator is presented. The magnetic circuit analysis is done and the designed machine is modelled, designed and simulated using the standard FEA tool and the preliminary result on the torque is presented. As a result, it is noted that external rotor concept does provide an added advantage by better torque production due to a more balanced mechanical structure. Besides, external rotor concept is also much more feasible as practically it is easier to fabricate. With above consideration, Axial motor can be concluded as a good candidate for Battery Operated Electric Vehicle as it is able to produce the needed dynamics and reliable for robust application due to simple structure compared to radial machines. With reduced stack length and weight proportion to it, high efficiency is able to achieve. Besides, by placing permanent magnets on the Axial path, it allows the motor to have bigger airgaps which promotes towards less cogging and better cooling which translates towards better reliability.

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