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# Axial Flux Permanent Magnet Motor Integrated Differential Unit (Electric Differential)

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## 1.INTRODUCTION

Since the invention of steam engines in 1698, which was first used to pump water out of the mines, human beings have used prime movers like steam engines and internal combustion engines in automotive applications. We have come a long way, ever since the steam engines kick started the industrial revolution a few centuries back. The technology that we have today has improved by leaps and bounds in comparison to the initial days of the automotive industry. Over the course of time, many new technologies have caught on with multiple iterations, while others have faded either due to strict government/environment norms or because of the failure to prove itself in the market. Globally, we are now at a tipping point where the automotive industry is making a switch from internal combustion powered engines to electric motors. This switch over is not easy and is met with a lot of technical challenges along the way. The concept discussed in this paper would address a few of those problems, that might solve some of the problems faced by the automotive industry.

## 1.1 TECHNICAL BACKROUND

The major problem that plagues battery powered vehicles is the range anxiety, and that is caused by the low energy density of the battery pack when compared to fossil fuel powered vehicles. When it comes to quantifying the energy that can be harnessed from an energy source like fossil fuels or batteries, they are usually represented by energy/unit volume or energy/unit mass of the energy source. The following chart (***Figure 1***) shows the energy densities of some common materials and fuels that are in use today, *y-axis* represents energy density as *Energy/unit volume* and *x-axis* represents energy density as *Energy/unit mass*. No matter how the energy density is measured, whether it is *energy/unit volume* or *energy/unit mass*, we can clearly see that the modern day Lithium ion batteries sit at the bottom of the chart and have one of the worst energy densities of any energy source.

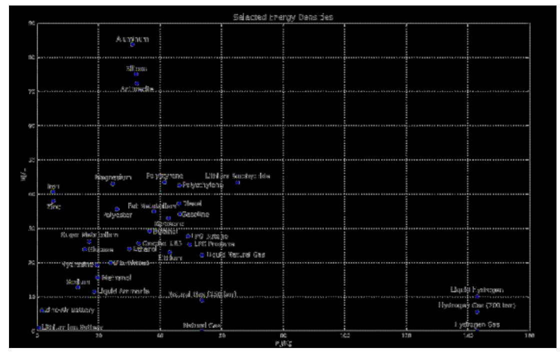


**Fig-1**:Energy Density plot of some common materials and fuels [1],[2],[3],[4],[5],[6],[7]

The implications of having a low energy density in automotive applications are huge. As we know, automotive applications and solutions are all about mobility which makes it necessary for the vehicles to carry its own energy source without taking up much space or making the vehicle heavy which otherwise would reduce the payload capacity making it less efficient. With each new generation of automotive technology manufacturers spend millions of dollars into research to make the vehicles lighter and more efficient. The reason weight becomes critical in automotive applications is because it affects everything from vehicle dynamics to fuel efficiency and payload capacity. However, an automotive manufacturer could make the battery pack very large to increase the energy storage capacity, but doing so would significantly increase the kerb weight of the vehicle because the battery pack already makes up half the total weight of an electric vehicle, along with the added requirement for a large amount of space for the battery pack, thus increasing the battery capacity beyond a certain limit makes it counterproductive. This calls for components which are light weight and compact, thereby offsetting the disadvantages of having a heavy battery pack.

### 1.2 AXIAL FLUX MOTORS

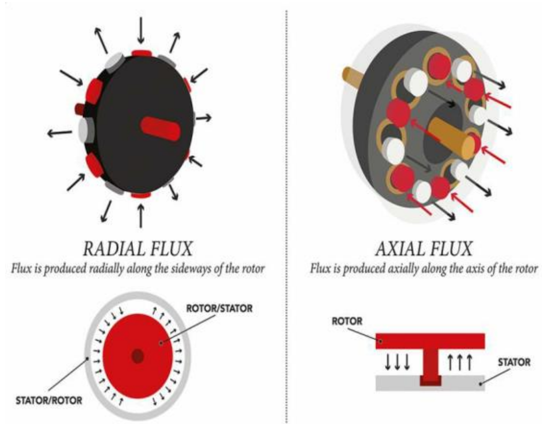


**Fig-2**

An axial flux motor (also known as an axial gap motor, or disc motor) is a type of motor construction where the air gap between the rotor and stator is perpendicular to the face of the rotor, and therefore the direction of magnetic flux between the two, is parallel with the axis of rotation, rather than radially as with the concentric cylindrical geometry of the more common radial flux motor[9]. Although these type of motors have been used since the first electric motors were developed, its usage was not common until the widespread availability of strong permanent magnets like Neodymium, and the development of electronic drives which makes brush less DC motor operation possible. The axial construction in theory can be applied to almost any operating principle (e.g. brushed DC motors, induction motors, stepper motors, switched reluctance motors) that could possibly be used in a radial motor. Additionally it can allow some topologies that would not be practical in a radial geometry[9]. Axial flux permanent magnet motors typically provide more torque per unit volume of motor than a radial motor, since the active magnetic surface area is the face of the rotor rather than the outside diameter in radial flux motors. This makes axial flux motors much more compact and the axial length of the motor is much smaller compared to radial motors, a factor that is often crucial for an application such as a hub motor or direct drive wheel motor[10]. The slender and lightweight structure results in motors with higher power and torque density than a comparable radial machine, without the need to employ very high speed operation to get the same amount of power because we know ***Power = Torque* rpm.***

Axial flux machines can be highly efficient, with efficiency above 96%. That is because of the shorter, one-dimensional flux path, which is comparable to or better than the very best two-dimensional radial flux machines on the market. The axial flux machines are shorter, typically by five to eight times, and can be two to five times lighter than an equivalent radial flux machine[10].

## 2. CONSTRUCTION AND OPERATION OF E-DIFFERENTIAL

The Electric Differential would typically consist of two major components, i.e the stator which has the field windings, and rotors mounted on independent shafts which are connected to each wheels on either side of the stator. The stator itself forms the main housing of the motor since it is a unibody design and because of the unibody design majority of the housing can be milled from a single aluminum billet block with radially cut slots in the stator for accommodating the coils. However in this design we are going with a two stator and four rotor arrangement, i.e a single wheel is connected to and powered by two rotors on a single shaft with a stator in between the rotors and the same applies for the other wheel. In simple words, each wheel is powered by two independent motors operating in the same axis. ***Figure 3*** shows the stator housing without the coils and the exploded view of the rotor and shaft sub assembly and the other two bearings are mounted on the stator housing is a needle roller bearing with cage.

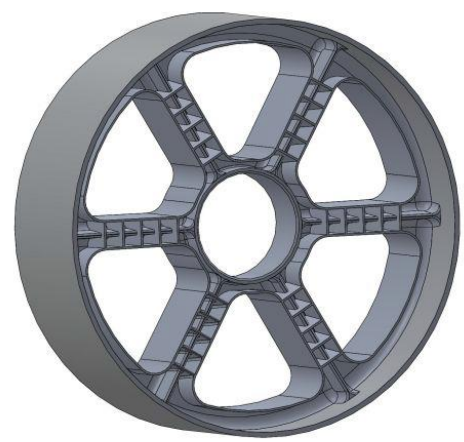

**Fig-3: Stator**

Needle roller with cage type bearing was selected over a regular ball bearing to maximize the area available to the coils thereby The outer bearing races are the inner surface of the stator itself, due to the aluminum construction of the stator, the outer bearing races are electroplated with *Nikasil* which is a nickel matrix silicon carbide coating.

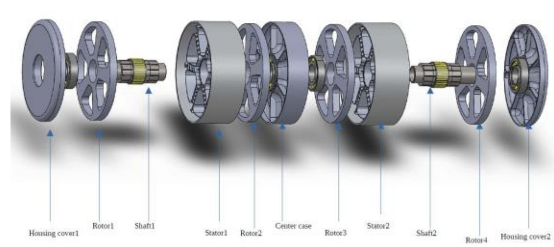


**Fig-4*:*** Exploded view of the full differential structure

This is done to improve the hardness and durability of the bearing race. There are four modes of operation that are possible with this setup, the first mode of improving the volume to power ratio, because a needle roller bearing takes less radial space when compared to a regular single row ball bearing for the same load. operation is under normal operating conditions when the vehicle is traveling on a straight road; under this scenario both the wheels will be supplied with power. Second mode of operation takes over when the vehicle is executing a turn, under this scenario the inner wheels of the vehicle turns slower than the outer wheels, under these circumstances based on the data from wheel speed sensors, only the outer wheels will be supplied with power (or the path of least resistance); this mode is analogous to a regular open mechanical differential. The third mode of operation is analogous to a locking mechanical differential, where power is supplied to the path of most resistance, this happens when the vehicle is stuck in slippery conditions like snow, loose sand, mud, etc; under these circumstances an open mechanical differential would keep supplying power to the path of least resistance which would be the wheel with the least amount of traction, ideally in such cases the power should be supplied to the wheels with the most traction to move the vehicle forward but mechanical differentials are not capable of such an operation unless equipped with differential locks. The fourth mode of operation takes over when the vehicle wants to slow down, in this scenario the motors act like a generator converting the kinetic energy of the vehicle to electrical energy and storing it in a capacitor bank or the battery pack for later use, this is called regenerative braking or kinetic energy recovery system.

## 3. DESIGN GOALS AND THE ADVANTAGES

In traditional electric vehicle applications the Electric motor is coupled with the mechanical differential to propel the vehicle. In this design we improvised the idea one step further by integrating the motors into the differential unit. This would keep the motors in the same axis of rotation as the wheels, this can give significant reduction in weight when compared to traditional electric vehicles. Since the form factor of the complete axle is compact and small, it can save significant space, thereby giving more room for larger battery packs. The biggest

advantage of this design is owed to its modular design, it can be easily scaled up or scaled down depending on the application without any radical changes to the assembly line or tooling for mass manufacturing. For example if an application requires more power, extra rotors and stators can be bolted onto the existing assembly to meet the power requirement without too much of a redesign to the components, this makes it very production line friendly in a mass manufacturing environment. Compared to a traditional mechanical differential, this design has 60% less moving parts thereby improving the mechanical efficiency along with reliability and simplicity, without compromising the functionalities of a mechanical unit.

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