# Design, simulation and performance analysis of a hybrid dual rotor motor for electric scooter

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Abstract—The increase in pollution created by Internal Combustion(IC) engine vehicles and the increased consumption of fossil fuels has led to the development of an Electric Vehicle(EV) era.Reduction in weight and space are main constraints of an EV which are also the major challenges during its development. In this paper a Hybrid Dual Rotor Motor (H-DRM) with improved torque density and reduced space is designed for an electric scooter. A 750W H-DRM is designed and analyzed using Finite Element Method (FEM) in Ansys Maxwell 2D. FEM simulation is made on the conventionally used induction motor (IM) and permanent magnet synchronous motor (PMSM) with same main dimensions for comparison.It is observed that the H-DRM gives higher torque as compared to the IM and PMSM of the same main dimensions.

Index Terms—Hybrid Dual Rotor Motor,Finite Element Method,Electric Vehicle

## I. INTRODUCTION

EV industry is advancing day by day in terms of the technology used in EVs .Developments and researches continue in the area of electric motor topologies,their control and batteries used in EVs. One among the critical subsystem of EV drive train is the Electric Motor(EM).The EM used in EVs should have high torque density and power density.The other major constraints for EM used in an EV are weight, space,efficiency and cost.

Different types of motors like PMSMs,IMs,Switched Reluctance Motors(SRM),Brushless DC(BLDC) motors are being used in EVs[11]-[13].But not a single motor can meet all the desired factors of an EV.A multi-motor drive train configura-tion improves the performance of EV,but complexity of the power converter circuit increases.So a hybrid combination of the conventional motors, to exploit the advantages of conven-tional motors at the same time to overcome their disadvantages is presented. A DRM results in increased torque density,as a given power output can be achieved with smaller motor size [3].

In [1] a proof of concept prototype is made by selecting outer rotor as PM and inner squirrel cage rotor.Different possible configurations, design and testing for DRM are also presented.An analytical model for DRM is developed in 2-D polar coordinates using sub-domain model approach and has been validated using FEM[2].In [3] a dual-rotor PMSM-based plug in EV propulsion system with four-axis vector-control is proposed.In [4] an electrical equivalent circuit for a hybrid PMSM-IM motor is being developed.Also the torque equation for the motor is derived from the equivalent circuit.A double rotor PMSM,used as a four-quadrant drive system in hybrid electric vehicles (HEVs) is presented in [5].DRMs for air conditioners for using in compressors and evaporators are also developed [6].From the literature,it is inferred that DRM is a suitable choice for EV applications due to its high torque density.

The objective of this paper is to design and analyze an H-DRM for an electric scooter,Hero Optima E5.The H-DRM has a PM outer rotor(OR) and a squirrel cage inner rotor(IR) with three phase distributed winding on the stator.The OR runs at synchronous speed and the IR runs at sub-synchronous speed depending on the slip.Torque produced by the two rotors can be coupled using a mechanical coupler,usually planetary gear-boxes to use in EVs.The machine is modelled and analysed using Ansys Maxwell 2D.To bring out the advantage of H-DRM,a PMSM and an IM with the same main dimensions for the same electric scooter is also analysed.

Section II of the paper explains the configuration and working principle of DRM.The choice and design of H-DRM is discussed in section III and its FEA simulation is discussed in and IV.Section V includes the comparison of H-DRM with PMSM and IM of same dimensions and its FEA simulation results and section VI is the conclusion part.

## II. H-DRM CONFIGURATION AND WORKING PRINCIPLE

### A. DRM - POSSIBLE CONFIGURATIONS

AC motors can be classified as interaction type and reluc-tance type based on the torque production.Interaction type motors can be classified as asynchronous and synchronous type motors.Switched Reluctance motor(SRM),synchronous reluctance motors are reluctance type motors[1]. All the AC motors available in the literature either fall in any of the above classification or is an advanced version of these basic types or their combination.The DRM presented in this paper is a hybrid combination of PMSM and IM.

At-most one mechanical port(rotor) and two electrical ports are generally present in motors. In a DRM, three electrical ports and two mechanical ports are possible atmost.Increase in mechanical ports leads to increase in possible configurations.A

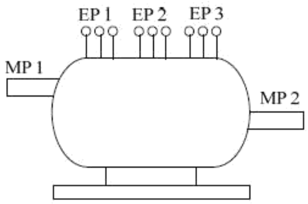


Fig. 1. Schematic of motor having 3 electric port and 2 mechanical port[3]

schematic of a three electric port two mechanical port machine and a DRM schematic are shown in Fig 1 and 2 respectively.

## B. H-DRM CONFIGURATION

Generally electrical winding is preferred to be on the stationary part to reduce maintenance.The objective of DRM is to improve the torque density.So one rotor is chosen as PM rotor.But choosing two rotors as PM rotors would not be cost effective.Squirrel cage rotor is preferred as the IR due to its well known advantages over wound rotor like ease of manufacture,less maintenance and ruggedness[1]. Thereby the H-DRM chosen for EV application has a three phase distributed winding on the stator,PM OR and a squirrel cage IR as shown in Fig 3 .

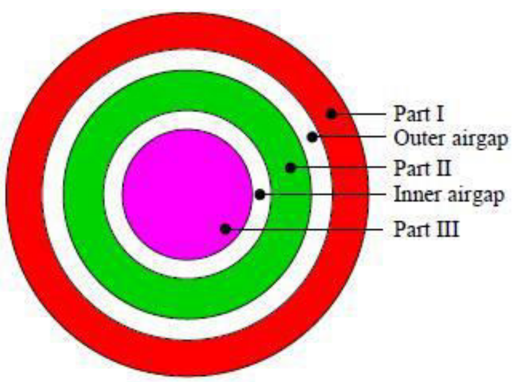


Fig. 2. DRM schematic[1]

## C. WORKING PRINCIPLE

The H-DRM can be analysed as a combination of two concentric motors.The stator and the outer rotor can be viewed as a PMSM and the stator and inner rotor constitute a squirrel cage IM. When the stator is energised from a three phase supply,the outer PM rotor rotates at synchronous speed depending on the number of poles and the frequency of supply.A rotating magnetic field is created in the inner air gap due to this rotating OR.This causes the inner rotor to rotate inorder to minimize the electromagnetic induction.Thus the inner rotor starts rotating at a sub synchronous speed depending on the operating slip.The two rotors can be couples using a mechanical coupled usually a planetary gearbox[4]

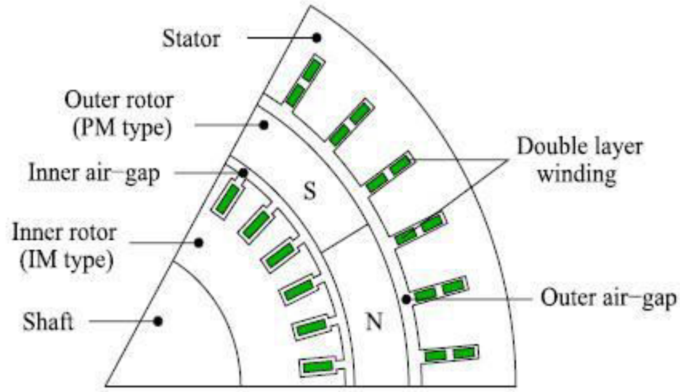


Fig. 3. H-DRM schematic[2]

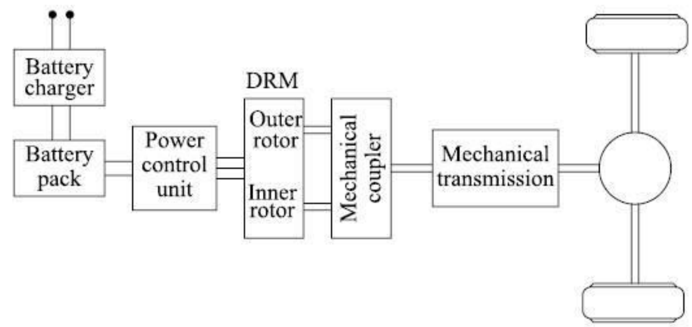


Fig. 4. Drive train configuration[3]

## D. DRIVE TRAIN CONFIGURATION

The arrangement of H-DRM in an EV is shown in Fig.4. A planetary gear set is a three port carrier which has a sun gear at the centre,planetary carrier and a ring gear.The front view and cut section view of a planetary gear set is shown in Fig.5.a and fig 5.b respectively.The OR is connected to the sun gear, IR to the planetary carrier and drive shaft connected to the ring gear[4].

# III. H-DRM DESIGN

## A. Power rating based on vehicle dynamics

An electric scooter Hero Optima E5 is chosen which has the specifications as shown in Table I.Various forces acting on the electric scooter is shown in Fig.6

TABLE I
VEHICLE SPECIFICATIONS

| Specification | VALUE | UNIT |
|---|---|---|
| Gross weight (P) | 175 | kg |
| Maximum speed | 35 | kmph |
| Tire diameter | 0.18 | mm |
| Dimensions | 1725*750*1080 | mm |

Force required for driving a vehicle is,

$$F_{total} = F_{rolling} + F_{aerodrag} + F_{acceleration} \quad (1)$$

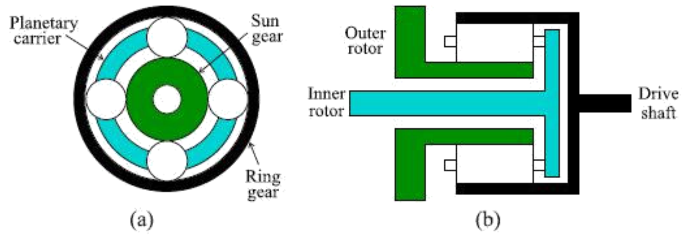


Fig. 5. Planetary gear arrangement[3]

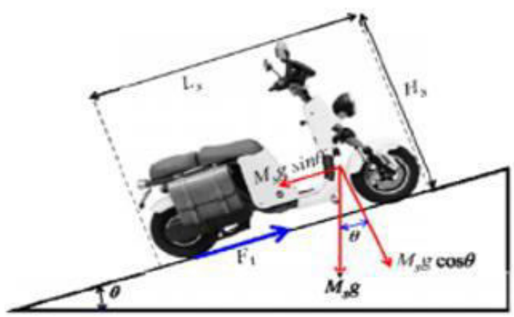

Fig. 6. Forces acting on a vehicle

Rolling resistance,

$$F_{rolling} = C_{rr} M g cos \qquad (2)$$

Gradient resistance,

$$F_{gradient} = M gsin \qquad (3)$$

Aero dynamic drag,

$$F_{aerodrag} = 0{:}5 C_d A_f \; v^2 \qquad (4)$$

Acceleration resistance,

$$F_a = M + \quad J_r ot = r_{dyn}^2 \qquad (5)$$

Total power,

$$P = F \; v = 3600 \qquad (6)$$

TABLE II
CALCULATED VALUES

| Parameter | Value | Unit |
|---|---|---|
| $F_{rolling}$ | 21.61 | N |
| $F_{aerodrag}$ | 12.143 | N |
| $F_{acceleration}$ | 106.1 | N |
| $F_{gradient}$ | 101.69 | N |
| Ftot | 248.5 | N |
| P | 670 | W |
| Motor rating chosen | 750 | W |

By using the above equations opposing forces are calculated and listed in Table II.The total power demand calculated is 670W.So 750W is the chosen power rating for motor.

B. Design of H-DRM

The design of H-DRM needs special attention due to its complex structure.Some of the electrical and mechanical considerations for the design of are

In literature many Interior PM (IPM)configurations are reported [8].So IPM is chosen for outer rotor such that flux links with both the stator and IR.

Inorder to minimize cogging torque, a non integer slot per pole ratio is chosen.So the number of stator slots is selected as 36 which also make it possible for a 3-phase winding.[9]

IM rotor is designed based on standard design principles[9].Unlike most of the IMs the number of rotor bar is selected less than number of stator slots due to space limit as the IM rotor is placed inside the PM rotor.

The design parameters are shown in table I.

TABLE III
MACHINE SPECIFICATIONS

| PARAMETER | VALUE | UNIT |
|---|---|---|
| Power | 0.75 | kW |
| Voltage | 380 | V |
| Frequency | 50 | Hz |
| Number of phase | 3 | |
| Poles | 8 | |
| Speed ($N_{OR}$) | 750 | rpm |
| Speed($N_{IR}$) | 650 | rpm |
| Outer diameter(OD) of stator | 150 | mm |
| Inner diameter(ID) of stator | 103 | mm |
| PM rotor OD | 102 | mm |
| PM rotor ID | 85 | mm |
| Cage rotor OD | 84 | mm |
| Shaft diameter | 28 | mm |
| Motor stack length | 50 | mm |
| Stator slots | 36 | |
| IR slots | 34 | |
| Magnet width | 20 | mm |
| Magnet height | 4 | mm |

Using the parameters in Table III H-DRM is modelled and analysed using FEM in Ansys Maxwell 2D.The machine is designed for two wheeler EV applications and the power rating chosen is 750W.

## IV. FEM 2D ANALYSIS OF H-DRM

The 2D model of H-DRM created in Ansys Maxwell 2D is shown in Fig.7.The total torque produced by the H-DRM is found to be 12.8Nm as shown in Fig.8.Fig 9 and fig 10 shows the torques produced by outer rotor and inner rotor respectively.The flux density plot of the machine is shown in fig.11.

## V. COMPARISON WITH PMSM AND IM

In order to validate the torque density improvement in H-DRM, it is compared with conventional PMSM and IM of the same main dimensions,ie,same outer diameter and length and the results are presented in this section.

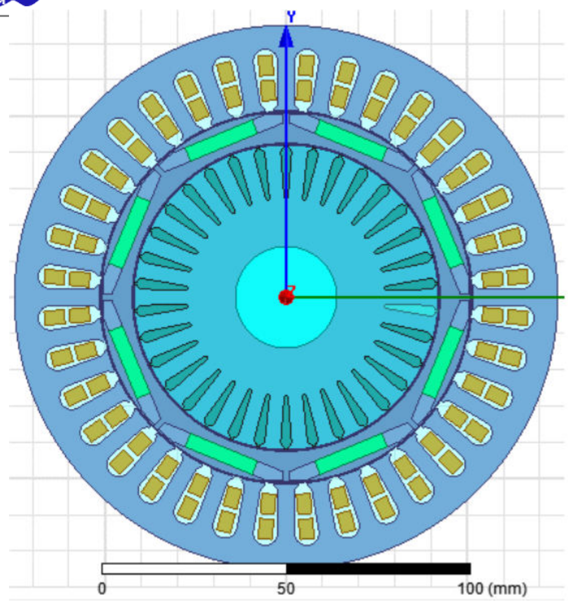


Fig. 7. H-DRM Ansys model

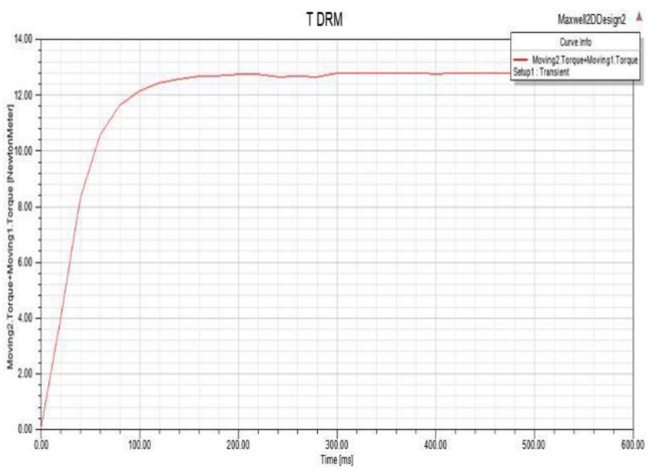


Fig. 8. H-DRM total torque

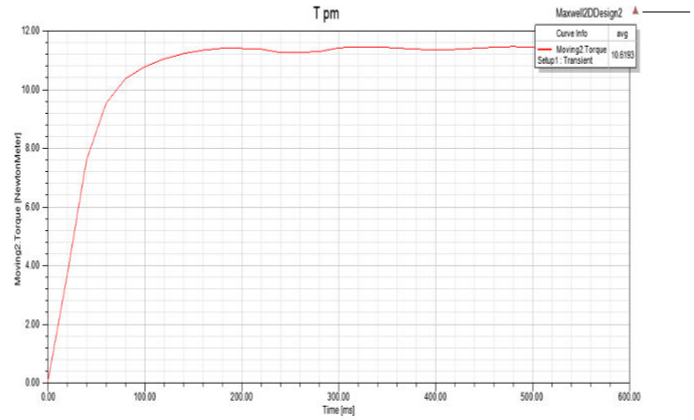


Fig. 9. Outer rotor torque

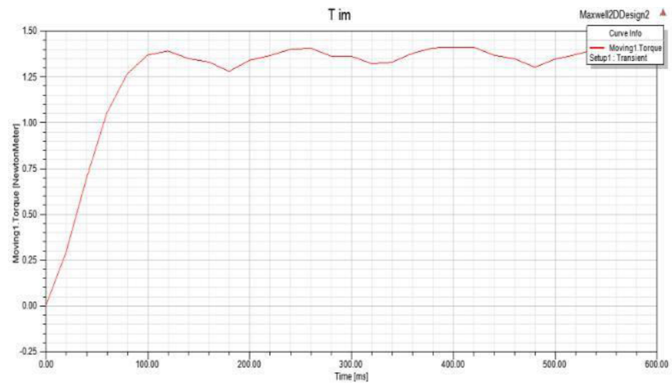


Fig. 10. Inner rotor torque

TABLE IV
PMSM DESIGN DETAILS

| PARAMETER | VALUE | UNIT |
|---|---|---|
| Voltage | 380 | V |
| Frequency | 50 | Hz |
| Number of phase | 3 | |
| Poles | 8 | |
| Speed | 750 | rpm |
| Stator OD | 150 | mm |
| Stator ID | 103 | mm |
| PM rotor OD | 102 | mm |
| PM rotor ID | 85 | mm |
| Motor stack length | 50 | mm |
| Stator slots | 36 | |
| Magnet width | 20 | mm |
| Magnet height | 4 | mm |

## A. FEM 2D analysis of PMSM

The important design parameters for PMSM are listed in Table IV.Using these parameters PMSM is modelled in Ansys Maxwell 2D and its cut section view is shown in Fig.12.

The PMSM torque is found to be 7.5Nm,shown in Fig 13.

## B. FEM 2D analysis of IM

The important design parameters for IM are listed in Table V.The cut section view of the modelled IM is shown in Fig 14.

The IM torque is found to be 3.6Nm ,shown in Fig.15

## VI. CONCLUSION

A new type of motor which is a hybrid combination of a synchronous and an asynchronous rotor for application in electric scooter is presented in this paper.The machine is modelled and analysed in Ansys Maxwell 2D platform.To bring out the advantage of the H-DRM,its performance is compared with conventional PMSM and IM of same outer diameter and length.From comparison, it is observed that the torque developed by H-DRM is higher than that of the PMSM and IM .So H-DRM is a better choice for electric scooter in terms of torque density.

The designed H-DRM is not an optimized one.Design

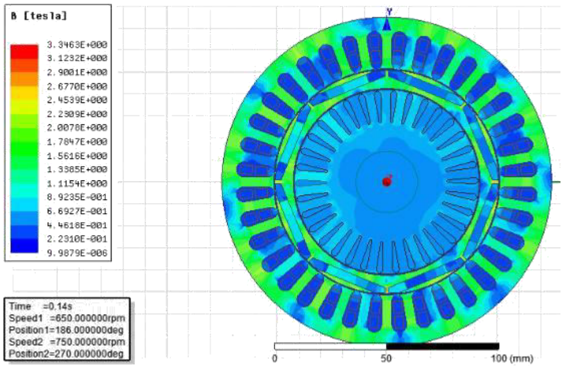

Fig. 11. Flux distribution plot-H-DRM

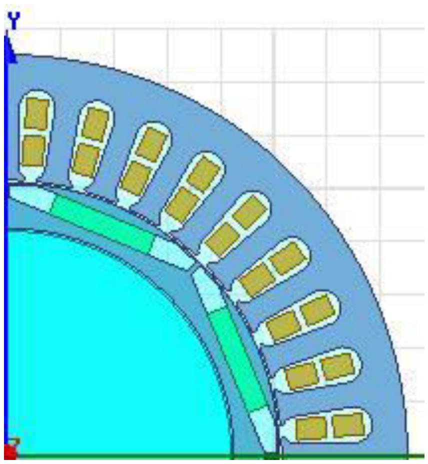

Fig. 12. PMSM Ansys model

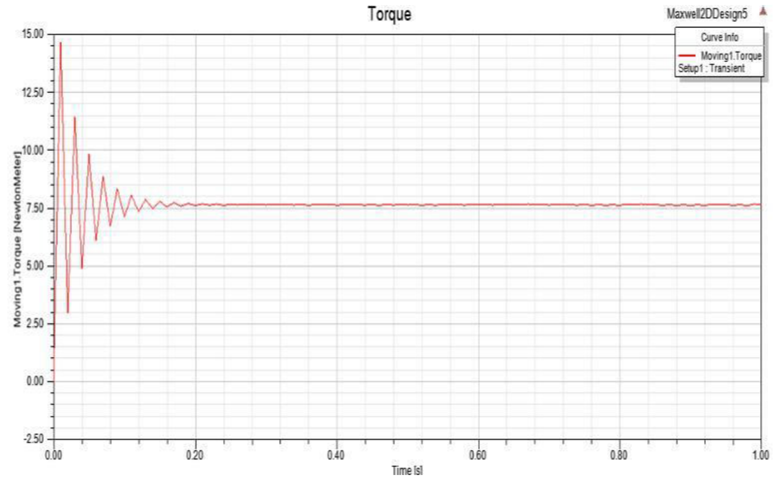


Fig. 13. PMSM torque

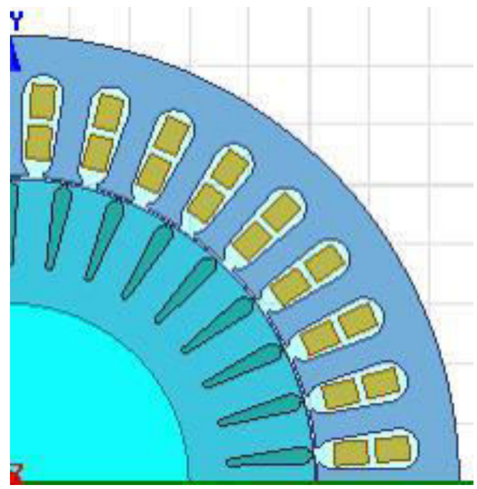

Fig. 14. Cut section of IM Ansys model

TABLE V
IM DESIGN DETAILS

| PARAMETER | VALUE | UNIT |
|---|---|---|
| Voltage | 380 | V |
| Frequency | 50 | Hz |
| Number of phase | 3 | |
| Poles | 8 | |
| Speed | 650 | rpm |
| Stator OD | 150 | mm |
| Stator ID | 103 | mm |
| Rotor OD | 102 | mm |
| Rotor ID | 85 | mm |
| Motor stack length | 50 | mm |
| Stator slots | 36 | |
| Rotor slots | 34 | |

optimization of H-DRM is a scope for future work.

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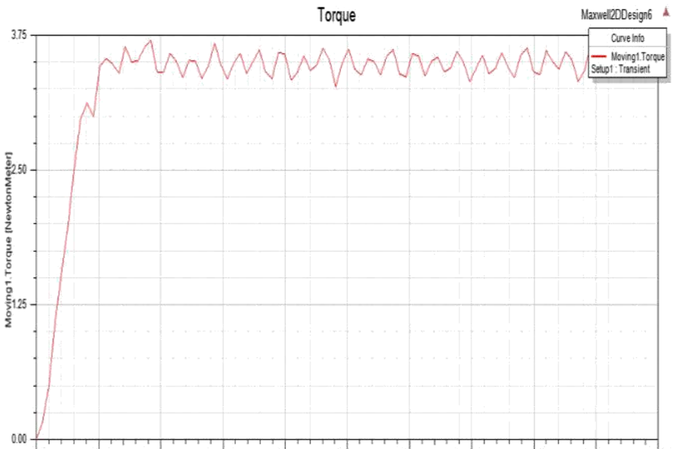


Fig. 15. IM torque

experimental validation of a double rotor synchronous PM machine used for HEV," IEEE Trans. on Magn., vol. 49, no. 1, pp. 152–155, 2013.