ISSN (Online) 2456-1290
International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)
Vol 9, Issue 6, June 2022

Overview of Electric Scooter operating on Synchronous Reluctance Motor (SynRM)

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***Abstract*— this paper deals in research and review of a 3-phase motor inverter to run a designed synchronous reluctance motor which would be used in electric scooters. The synchronous reluctance motor falls in the category of rare earth free magnet motors, yet provides better efficiency and gives straight competition to other AC and DC motors. It also includes designing of swappable battery packs for mobility purposes which offers easy removal and installation of batteries. All the major components which are to be use in electric scooter powertrain have been discussed here..**

***Index Terms*— 3 Phase Inverter Board, Battery Management System (BMS), Energy Management system (EMS), Pulse Width Modulation (PWM), Synchronous Reluctance motor (SynRM)**

I. INTRODUCTION

Due to increasing population, the need for consumption of fossil fuels for day-to-day work, commercial and industrial applications have been increasing at an alarming rate. Due to which catastrophic problems occur nowadays like alarming issues of increasing pollution which has adverse effects on all living forms. The increasing population is actively contributing to increasing demand for mobility and transportation for both personal and commercial applications. The current mode for mobility and transportation mainly depends on IC engine vehicles. This class of vehicle majorly depends on diesel and petrol which actively contributes to increasing pollution. The increasing imports of crude fuels and utter demand have caused fuel prices to skyrocket. All these factors combined have played a major effect on a person's daily life. As fuel prices increase the transportation cost also increases which lead to increase in prices of daily day to day needs. The recent mode of transportation which depends entirely on fossil [1] fuels must be shifted towards the use of alternate fuel which is eco-friendly or change the mode of transportation to electric mobility. The Indian Government has issued various policies and subsidies for new EV owners in order to increase awareness towards living a sustainable mode of life and not depending on fossil fuels for transportation. The new policies and regulations aim for converting the current mode of transportation to electric by 2030. The electrification of the Indian automobile industry will lead to less or mere no pollution and would litigate the dependence of importing crude fuels and ultimately lead to economic and social development. This paper describes the research and designing of an electric scooter which will be fed on an AC motor. All major parts and their working principle are described. SynRM is designed on ANSYS MOTORCAD, and 3 phase motor inverter is simulated on Matlab.

The main objectives of designing an electric scooter are as follows

1. To design a swappable battery pack for easily removable and installation of batteries.
2. Rare earth permanent magnet free Synchronous Reluctance Motor (SynRM) is designed which gives direct competition to AC motors.
3. Micro-controller fed 3 phases inverted and motor controller is designed to run the designed SynRM.

II. OVERVIEW OF ELECTRIC SCOOTER

The designed electric scooter consists of following major parts as

A. Swappable battery pack
B. Synchronous reluctance motor
C. Motor Controller
D. Dc-Dc Converter
E. Energy Management System
F. Other accessories.

The electric scooter's main components and their respective positions are shown below.

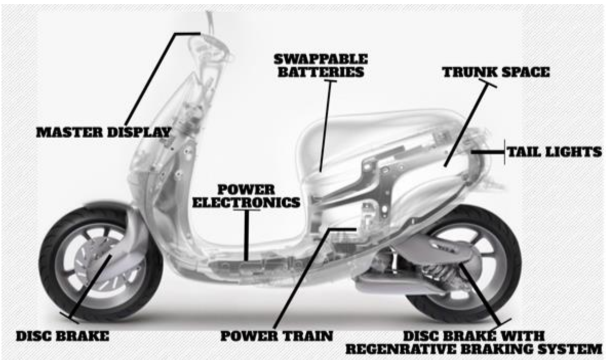

Figure 2.1- Main components of Electric Scooter

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ISSN (Online) 2456-1290
International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)
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The power electronics consists of all major electronics components like DC-DC converter, 3 Phase Inverter board, EMS and other slave micro-controllers. The EMS is connected to cloud via 4G connectivity and all scooter parameters which include battery condition, motor health and any fault detection can viewed on cloud. The powertrain consists of 3 phase[2] SynRM which delivers the instant torque to rear wheels via belt drive system. There are two swappable battery packs which can be accommodated under the seats and half trunk space is kept free for keeping belongings or full size helmets. The electric scooter doesn't have any on-board charger, since depleted batteries can be hot swapped by charged batteries. The whole electric scooter is designed to keep ergonomic features feasible for the rider. The other accessories include a master display which features all the information from the EMS in a clean user interface which can be read by the rider. The master display consist of raspberry pi 4 board and 7 inch capacitive touch screen, the raspberry pi 4 runs on android as operating system which enables the rider to easily access the pre-installed apps. The master display offers Android-Auto, through which rider can easily navigate from one location to another without accessing their cell phone. The electric scooter is fitted with GPS which offers onboard navigation and live location tracking on rider's cell phone. All other accessories run on 12 VDC supplied by DC-DC converter.

The dimensions of the electric scooter are illustrated with the help of given table

Table 2.1- dimensions of designed electric scooter

Parameter	Value
Length	1800 mm
Width	700 mm
Height	1300 mm
Wheel base	1250 mm
Ground clearance	165 mm
Seat height	770 mm
Kerb weight	115 kg
F:R Weight ratio	51:49

III. OPERATION OF ELECTRIC SCOOTER

The user operates the throttle which acts as a potentiometer. The throttle provides a voltage feedback signal (0-5V) to the Energy management system. The energy management system consists of a master micro-controller which in turn controls other slave micro-controllers. Each slave micro controller which operates in a separate domain of electric scooter is controlled by EMS. Based on the voltage feedback signal the master micro controller directs the amount of current to be required to run the motor from battery pack to inverter unit. The battery pack provides 2880 wH of electrical energy in the form of 48V 60Ah.The 48VDC supply from the battery pack is converted to 12VDC with the help of a DC-DC converter. The other 12VDC supply is fed to auxiliary circuits. Then 12VDC supply is fed to a single-phase inverter board which converts the 12VDC to 220VAC supply. Then 220VAC is fed to 3 phase inverter boards which convert to 3 phase AC supply to run 3 phase SynRM. The SynRM converts the electrical energy into mechanical energy which drives the vehicle forward, reverse depending upon the polarity of current fed to SynRM.

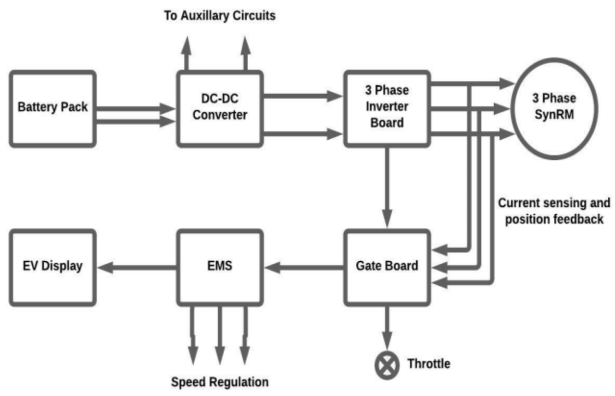
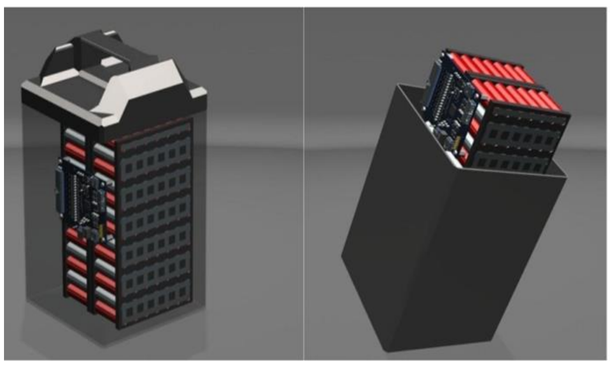


Figure 3.1- Block diagram for Electric Scooter

IV. SWAPPABLE BATTERY PACK

The designed electric scooter consists of 2 swappable battery packs which are supposed to be located under the seats. The capacity of each battery pack is 48V 30Ah. Total capacity of swappable battery packs is 48V 60Ah which delivers 2880wH of electrical energy to the powertrain. The cells used in battery packs [3] are SAMSUNG 35E. Each battery pack consists of 130 cells which are arranged in the order of 13 rows and 10 columns. The structure of the battery pack is 13S10P which denotes 13 cells are in series and 10 cells are in parallel combinations. The 13S provides 48v as each cell has nominal voltage of 3.7v, thus 13 cells in series each having nominal voltage of 3.7v delivers 48v DC supply. Whereas 10P provides 30Ah of current as cell capacity of each cell is 3Ah. Each battery pack weighs around 7.5 kg.



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International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)

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Figure 4.1 -Swappable battery pack with BMS

The BMS is the most important part of the battery pack as it protects the battery from cases of thermal runaway and maintains the condition of battery life consequently by actively balancing. The BMS accounts for safety of cells by cell balancing, charge control, state of heath count, state of charge as all these data is controlled by bms which accounts for proper balancing of cell packs. During charging the cells are having different voltages due to internal resistance being different in each case. The nominal capacity of the cell is 4.1v and during charging [4] the voltage of each cell keeps on increasing till their nominal value after which the current is stopped in that series connection of the cell. The role of BMS is to ensure that each cell in the series connection is charged at uniform rate thereby actively balancing the current to be sent to each cell. In case of abrupt voltage difference among cells or abrupt rise in temperature, the BMS shuts off the supply thereby protecting the battery pack. For keeping the swappable nature of the battery pack the common port is used from battery end terminals, this common port is common for both motor controller and charger. In such a mechanism the rider has not to connect and disconnect wires of batteries, rather just push and pull the batteries in case of swapping.

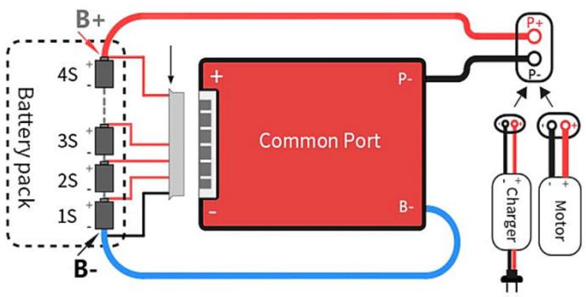

Figure 4.2- 13S 100 AMPS Common port BMS.

V. MOTOR

The motor converts the electrical energy from battery to mechanical energy and drives the rear wheel. The DC supply from the battery pack is converted to 3 phase AC supply by a 3-phase inverter board which in turn runs the 3 phase AC motor. The ac motor which is designed is synchronous reluctance motor falls in the category of rare earth permanent magnet free motor. The construction of the induction motor and SynRM is almost the same, only the rotor is different.

I. Working of Synchronous Reluctance Motor (SynRM)

SynRM produces reluctance torque resulting from changing magnetic reluctance. The geometry of rotors offers freedom to design the barriers and ribs in such a fashion that there are maximum and minimum areas for magnetic flux to pass. The magnetic flux produced by the stator flows into the rotor via the lowest magnetic flux path. This flow of magnetic flux to the lowest magnetic flux path in the rotor geometry produces rotational force due to reluctance torque which in turn rotates the rotor at synchronous speed.

The synchronous speed of SynRM is given by

$N_s = 120\ f/P$

where N_s = synchronous speed, F = frequency, P = no of poles of stator

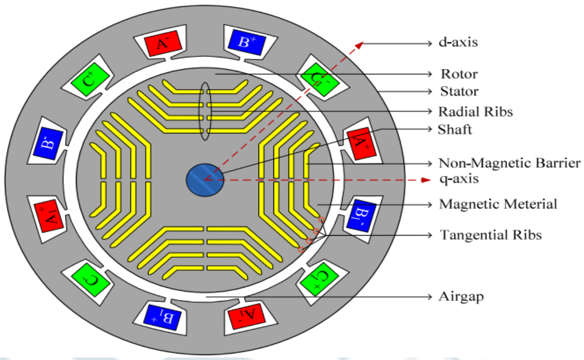

Figure 5.1 - General representation of 4 pole SynRM

II. Designed SynRM

The 3 phase SynRM of given specifications have been designed on ANSYS MOTOR CAD software. The designed motor is having 4 barriers which have been designed keeping mechanical, electromagnetic and thermal effects altogether balanced. The main objective of designing the motor is to –

1. Increase the saliency ratio
2. Introduce high anisotropy to rotor design
3. Acceptable insulation ratio
4. Improved power factor
5. Low torque ripple
6. Mechanically robust
7. Adequate thermal response
8. Allow maximum flow of magnetic flux from stator to rotor.

The electromagnetic torque developed by SynRM is given by the following equation

$T= 1.5\ P.L_d(1\text{-}1/\dot{\varepsilon})I_d.I_q,$

Where P= no of poles, L_d =inductance along d axis , I_d and I_q are current component along d and q axis respectively. The saliency ratio ($\dot{\varepsilon}$) is defined as the ratio of L_d and L_q i.e. ratio of inductance along d and q axis respectively. While designing SynRM the value [5] of saliency ratio is kept as high as possible, this can be achieved by improving the rotor design. The rotor is designed in such a way that it offers-

i. low reluctance path parallel to barriers
ii. high reluctance path parallel to barriers.

If the structure is similar from all view it is called isotropic structure, whereas if the structure is having dissimilarities in the view it is called anisotropic structure. The rotor must have high anisotropy which can be achieved by introducing more flux barriers, i.e. decreasing the material from rotor. This will also increase the saliency ratio, but there must be appropriate balance between all the parameters because if material is decreased it can hinder the mechanical integrity of the rotor.

The designed SynRM on ANSYS Motor Cad is shown below

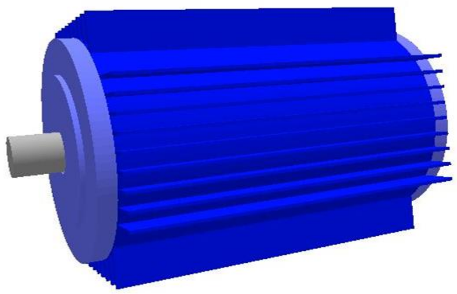

Figure 5.2- 2D view of designed SynRM

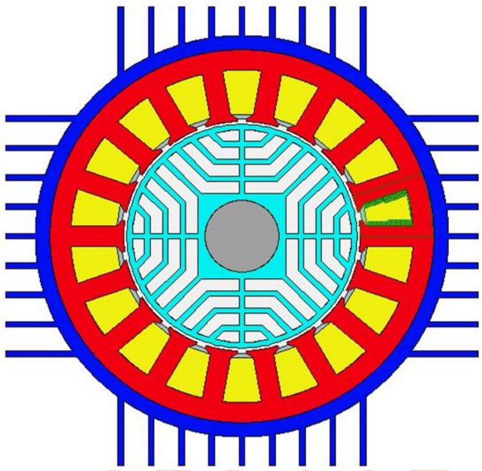

Figure 5.3- Cross sectional view of designed 4 poles SynRM

Based on the critical factors the motor is designed by balancing all mechanical , electromagnetic and thermal effects, the specifications of final motor are discussed below.

Table 5.1 specifications of 3 Phase SynRM

Parameters	**Value**
Rated Power	3 kW
Rated Torque	9 N-m
Maximum Torque	24 N-m
Rated Speed	1800 rpm
Rated Frequency	50 Hz
Voltage	220 VAC
Rated Current	10 A
Weight	11 Kg

III. Motor Winding

To increase the torque density, a combined star-delta winding is used as it offers 10% higher torque density over conventional winding. The winding of designed SynRM is shown below

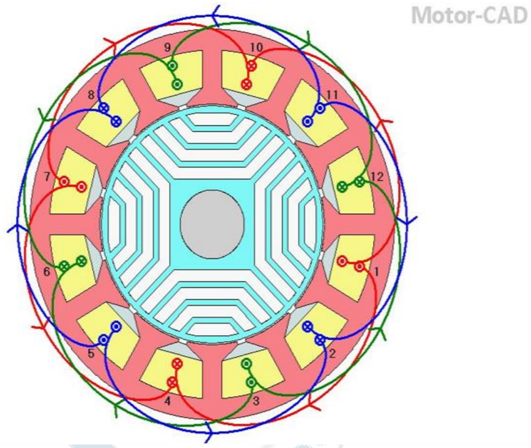

Figure 5.4- Combined star-delta winding of SynRM.

VI. MOTOR CONTROLLER

Motor controller is known as a device which is used to control the speed of AC MOTORS. An AC motor controller can also be referred as variable frequency drive. The main objective of the AC motor control is to supply 3 phase AC supply at adjustable frequency as directed by EMS. Based on voltage feedback signal from the throttle, the motor controller feeds the motor with required current at required conditions. The main objectives of designing AC motor control are

1. Develop control architecture with a PI controller
2. Turn the gain of PI controller to meet performance requirements
3. Design PWM control
4. Design fault detection and protection logic
5. Verify and validate controller performance across different operating conditions

I. 3 Phase Inverter Board

The motor controller consists of

1. Rectifier
2. DC filter
3. 3 phase inverter board
4. Gate board

The rectifier rectifies the ac supply to dc supply with the help of a full bridge rectifier. The DC filter consists of a capacitor which absorbs the ac ripple and delivers a smooth dc voltage. At the end the smooth dc voltage is converted to 3 phase AC supply by 3 phase inverter board. The inverter board consists of six switching components. These switching

ISSN (Online) 2456-1290

International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)

Vol 9, Issue 6, June 2022

components can be MOSFETS or Insulated-Gate Bipolar Transistor (IGBTs), depending upon load and power rating of inverter. The timing of switching of these components is controlled by MCU. The rectifier and inverter are controlled by gate board. The gate board consists of microcontroller and driver circuits. [6] The speed and direction of the motor is controlled by the gate board depending upon PWM signals. The switching rate is controlled to vary the frequency of the simulated AC that is fed to motor. The timing of switching mosfets is controlled by MCU. The switching is made in such a fashion that current fed to motor is sinusoidal in nature. As more degree of sinusoidoiuness of AC supply, signifies less harmonics and torque ripples, which will ultimately increase the efficiency of motor and controller.

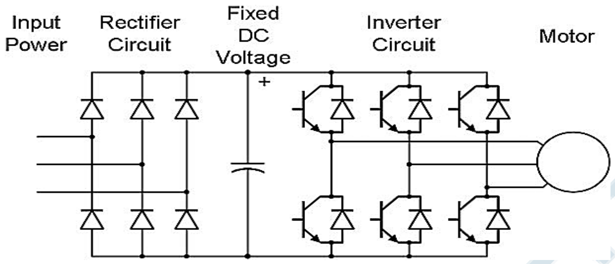

Figure 6.1- Block diagram of 3 Phase Inverter

II. Open Loop V/f Theory

The open loop voltage/frequency control is used by the inverter in order to run the motor with no velocity and position feedback. The V/f ratio is maintained constant to provide constant (maximum) torque over the operating range. This form is relatively inexpensive and easy to implement. The most common method for adjusting the motor voltage is called pulse width modulation (PWM).

The operation of a 3 phase SynRM is governed by two principles:

1. Base speed is directly proportional to the frequency of the alternating current applied to the stator and the number of poles of the motor.
2. Torque is directly proportional to the ratio of applied voltage and the frequency of the applied AC current. Therefore, speed can be controlled by varying the input frequency of the applied alternating current and torque can be maintained constant by varying the amplitude in direct proportion to the frequency. These are the two basic aims of open-loop V/f control.

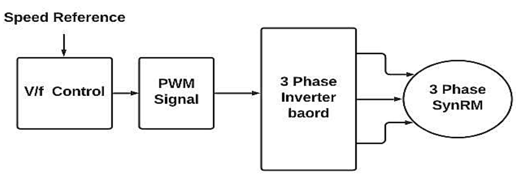

Figure 6.2- open loop v/f control system

VII. CONCLUSION

In this paper the electric scooter powertrain including rare earth permanent magnet free SynRM and 3 phase inverter motor controller has been presented. The SynRM provides better torque response and efficiency when compared to other AC machine of same specifications. The SynRM provides a better replacement for other AC and DC machines, as it doesn't include any permanent magnets for its operation and deliver more promising results. Although the permanent magnet can be fitted in the gaps of carriers to increase the average torque output. The principle of magnetic reluctance is perfectly used in the operation of SynRM. With the advancement in semiconductors, more advanced power electronic components can be designed which will help in reducing the size of powertrain and increase the efficiency of the system. A new concept of swappable battery pack have been designed which offers great mobility. The swappable battery back features a common port for charging and discharging, which means the rider has not to connect any wires.

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