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Research Paper

DESIGN AND DEVELOPMENT OF A SYNCHRONOUS RELUCTANCE MOTOR DRIVE SYSTEM FOR ELECTRIC VEHICLE APPLICATIONS

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Abstract: This work presents the design and implementation of a Synchronous Reluctance Motor (SynRM) drive for electric vehicle (EV) applications. The SynRM offers a cost-effective and efficient alternative to permanent magnet synchronous motors (PMSMs) by eliminating the need for rare-earth magnets while maintaining high torque density and efficiency. The project involves modeling the motor, designing an appropriate power electronic inverter, implementing a control strategy, and testing the drive under EV operating conditions. Simulation and experimental results confirm that the SynRM drive achieves smooth torque control, high efficiency, and dynamic performance suitable for EV propulsion.

Keywords: *Electric Vehicle, synchronous reluctance motor, battery, interface converter, commutation, current control, robust control, adaptive control*

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1. Introduction

Electric vehicles (EVs) are increasingly adopted due to environmental concerns, rising fuel costs, and advancements in energy storage technology. Selecting a suitable traction motor is crucial for EV performance. While **PMSMs** provide high efficiency and torque density, their cost and reliance on rare-earth materials are limiting factors.

The **Synchronous Reluctance Motor (SynRM)** emerges as an attractive alternative:

- Eliminates permanent magnets, reducing cost.
- High efficiency and reliability.
- Suitable for traction applications with proper control.

This project focuses on **designing a SynRM drive system**, including motor modeling, power electronic drive, and control algorithm implementation, specifically for electric vehicle applications.

[3]. This machine developed particularly in the 1960's as a line-start (cage-type) synchronous ac motor for applications where several motors are operated synchronously from a single voltage-source inverter. In some cases, it has been replaced by cage-type ac permanent-magnet (PM) motors that, although more expensive, have better performance and permit more motors to run from the same inverter 171. More recently, there has been increasing use of variable-frequency ac induction motor drives with one motor per inverter. At first, the six-step inverter was used, usually with constant voltage/frequency ratio and often without speed feedback. The development of pulse-width-modulated (PWM) inverters *followed with slip-control, and today, field-oriented or "vector" control is the most advanced form of ac drive, with performance characteristics that match those of the best dc drives. Although the induction motor is the most common in ac drives, synchronous PM motors are also used. With one motor per inverter, there is no need for a rotor cage because the motor does not have to start across the line. It is perhaps surprising that there has been so little development of the cage less synchronous reluctance motor instead of the induction motor or PM ac motor for variable-frequency operation [a-@]. One reason is probably its reputation for poor efficiency and low power factor, but the removal of the rotor cage and the use of field-oriented control Paper IPCSD 91-17, approved by the Electric Machines Committee of the IEEE Industry Applications Society for presentation at the 1989 Industry Applications Society Annual Meeting, San Diego, CA, and October 1-5. Manuscript released for publication February 5, 1991. This work was supported by the UK Science

and Engineering Research Council, a grant from the General Electric Company, and the member companies of the Scottish Power Electronics and Electrical Drives (SPEED) Consortium. Electric vehicles (EVs) have a surprisingly long history that dates back to the early 19th century. The first electric vehicle was invented by Scottish inventor Robert Anderson in 1832, which used non-rechargeable primary cells. However, the first practical electric vehicle was not developed until the late 1800s.In 1884, Thomas Parker, a British inventor, built the first practical electric car, which used lead-acid batteries and had a range of about 48 kilometers. By the turn of the century, electric cars were becoming increasingly popular, particularly in urban areas, as they were quiet, easy to operate, and did not produce exhaust emissions

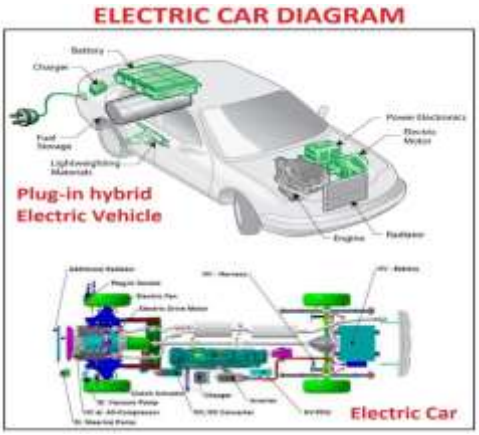


Figure.1 Electric Vehicle

However, the invention of the gasoline-powered internal combustion engine and the mass production of automobiles by companies such as Ford quickly made gasoline-powered cars more affordable and popular. As a result, the popularity of electric cars declined, and they became a niche product.In the 1970s, the oil crisis led to renewed interest in electric vehicles as a way to reduce reliance on imported oil. This led to the development of several new electric cars, including the General Motors EV1, which was introduced in the 1990s.In the 2000s, advances in battery technology and the need to reduce greenhouse gas emissions from transportation led to a renewed interest in electric vehicles. Companies such as Tesla, Nissan, and General Motors began to produce modern electric cars with longer ranges and better performance.

Today, Electric cars are gaining more popularity and becoming more widespread, as numerous nations worldwide establish goals to eliminate petrol-fueled vehicles in the forthcoming years. The history of electric vehicles shows that while their popularity has waxed and waned over the years, they have the potential to be an important part of the transition to a more sustainable and low-carbon transportation system

2. SYNCHRONOUS RELUCTANCE MOTOR DRIVE

The design of a Synchronous Reluctance Motor (SynRM) for electric vehicle (EV) applications is centered on achieving high torque density, efficiency, and reliability without relying on permanent magnets. Unlike Permanent Magnet Synchronous Motors (PMSMs), SynRMs generate torque purely through magnetic reluctance, which results from the difference in magnetic reluctance along the direct (d) and quadrature (q) axes of the rotor. This makes SynRMs a cost-effective and environmentally friendly alternative for traction applications.

Rotor Structure

The rotor of a SynRM is characterized by salient poles with flux barriers, which are strategically placed to create a path of low reluctance along the direct axis and high reluctance along the quadrature axis. These flux barriers enhance the reluctance torque by maximizing the difference between the d-axis and q-axis inductances. Common rotor topologies include concentrated flux barrier rotors, spoke-type rotors, and cylindrical rotors. The design parameters, such as barrier thickness, rotor diameter, and number of poles, are carefully selected to optimize torque per ampere (TPA) while maintaining mechanical integrity under high-speed operation. The absence of magnets reduces both cost and thermal constraints, allowing the motor to operate efficiently at elevated temperatures without demagnetization concerns.

Stator Design

The stator design of a SynRM is similar to that of conventional synchronous machines. It consists of three-phase windings housed in laminated iron cores to minimize eddy current losses. The winding layout, slot dimensions, and number of turns are optimized to provide sufficient magnetomotive force (MMF) for flux generation along the d-axis, while minimizing copper losses and ensuring uniform flux distribution. Proper selection of slot fill factor, insulation, and

winding configuration directly impacts the efficiency, thermal performance, and acoustic noise of the motor.

The torque is maximized by controlling the current vector such that IdI_dId and IqI_qIq are optimally aligned with the rotor flux. This principle underlies vector control (field-oriented control, FOC) strategies used in EV drives.

Thermal and Mechanical Considerations

Thermal management is critical in SynRM design, as excessive heating can degrade insulation and reduce efficiency. The absence of magnets allows higher rotor operating temperatures, but stator copper losses still dominate heat generation. Proper selection of materials, cooling mechanisms, and rotor-stator air gaps ensures reliable operation. Mechanically, the rotor must withstand high centrifugal forces and vibrations, especially in high-speed EV applications, which necessitates careful stress analysis and finite element modeling during the design phase.

Design Optimization

Modern SynRM design leverages finite element analysis (FEA) to simulate magnetic flux distribution, torque ripple, and losses. Optimization techniques adjust rotor geometry, slot configuration, and winding layout to achieve desired performance metrics such as maximum torque per ampere, efficiency, and minimized torque ripple. Additionally, material selection, including laminated steel for the stator and high-strength rotor alloys, contributes to overall performance and durability.

In conclusion, the design of a SynRM for EVs involves a careful balance of electromagnetic performance, thermal and mechanical constraints, and manufacturing feasibility. By exploiting the rotor saliency and applying advanced control strategies, SynRMs provide a cost-effective, efficient, and reliable alternative to permanent magnet motors in electric vehicle propulsion.

Electric vehicles (EVs) operate using an electric motor and a rechargeable battery instead of an internal combustion engine. The battery stores electrical energy that powers the motor, which turns the wheels and propels the vehicle forward.The process of powering an EV starts with plugging the vehicle into an electrical outlet or a charging station. The battery is charged using electricity from the grid, which is converted into direct current (DC) power and stored in the battery.When the driver wants to move the vehicle, they activate the accelerator pedal. This sends a signal to the controller, which determines how much power to send from the battery to the motor. The motor then converts the electrical energy from the battery into mechanical energy, which turns the wheels and moves the vehicle forward.

As the vehicle moves, the battery gradually discharges, and the range of the vehicle decreases. When the battery level drops below a certain point, the driver needs to recharge the battery using a charging station or electrical outlet.Regenerative braking is another important feature of many EVs. When the driver brakes, the motor acts as a generator and converts some of the vehicle's kinetic energy back into electrical energy, which is then used to recharge the battery. This helps to extend the range of the vehicle and improve overall energy efficiency

3. SYSTEM CONFIGURATION

The established battery powered EV SynRM drive is shown in Fig. 1. A bidirectional DC/DC interface converter is used to establish a 550V DC-link from the battery bank (160V) in boost converter mode by AA +–LDT),,(. And a three-phase inverter is used to drive the SynRM coupled with a PMSG dynamic load. A flywheel is added on the shaft of M-G set to increase the kinetic stored energy for facilitating the regenerative braking test. The photo of the constructed M-G set is also depicted in Fig. 1. The proper commutation is arranged to yield the improved driving characteristics. In addition, a dynamic brake leg is equipped to avoid the DC-link overvoltage due to the failure of regenerative braking. The control schemes of SynRM drive, DC/DC interface converter and dynamic brake are shown in Figs. 2(a) to 2(c). In regenerative braking, the buck converter is formed by LDT),,(AA –+ to let the recovered energy charge the battery. The maximum battery charging current * bmi is set by the limited inductor current command *iLm . The reverse operations of the SynRM drive and the interface converter are automatically initiated by the arranged control schemes. The developed EV SynRM drive control scheme shown in Fig. 2(a) can be operated in direct torque current setting mode or speed mode. For the ease of conducting the comparative performance evaluation under various preset speed patterns, the speed mode is adopted here.

Thin ribs that attach to the q axis webs in the same way as in the interior magnet motor described by Jahns, Fig. 5 shows the components of the disassembled motor. To minimize Ld, the ribs (Fig. 4) must saturate at a low level of current. This requires them to be radially thin. L, is not sensitive to the air gap length because of the large reluctance in the flux barrier. L, must be maximized; therefore, saturation is undesirable in any part of the q-axis flux path. Therefore, the pole piece needs to have adequate radial depth, and the web needs to be sufficiently wide as well. Rotor 1 (Fig. 4(a)) was designed to accommodate 5.4-mmthick magnets, and for operation as a SYNCHREL motor, the webs are too narrow; therefore, they were widened in rotor 2. With 16 slots, this ensures that the web does not saturate when aligned with the axis of the phase winding. The parameters of the two rotors are summarized in Table I and [12]. The inductances quoted in Table I were measured and calculated at 3.0 A. The synchronous inductance ratios quoted in Table I are all well below the theoretical limit of 25 mentioned earlier. This is because saturation decreases the q-axis inductance, whereas leakage through the ribs increases the d-axis

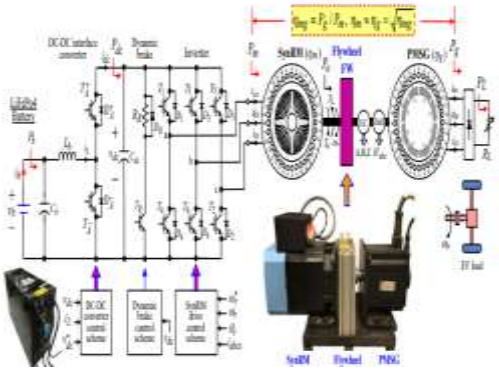


Figure:2. The established EV SynRM drive

4. Simulation Results

The proposed Synchronous Reluctance Motor (SynRM) drive for electric vehicles was modeled and simulated in **MATLAB/Simulink** to evaluate its dynamic performance, efficiency, and suitability for EV applications. The simulation was conducted under various operating conditions including acceleration, deceleration, constant speed, and load variations. Field-Oriented Control (FOC) was implemented to regulate the motor currents and maximize torque production while minimizing losses.

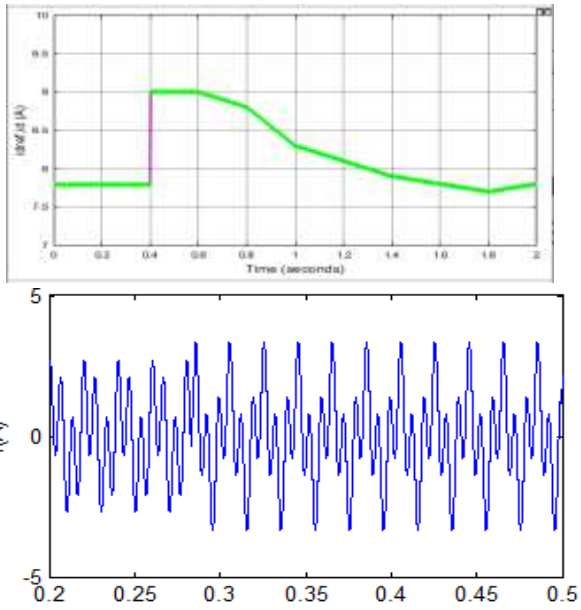


Figure:3. Steady state: (a) line current from delta-side of the transformer

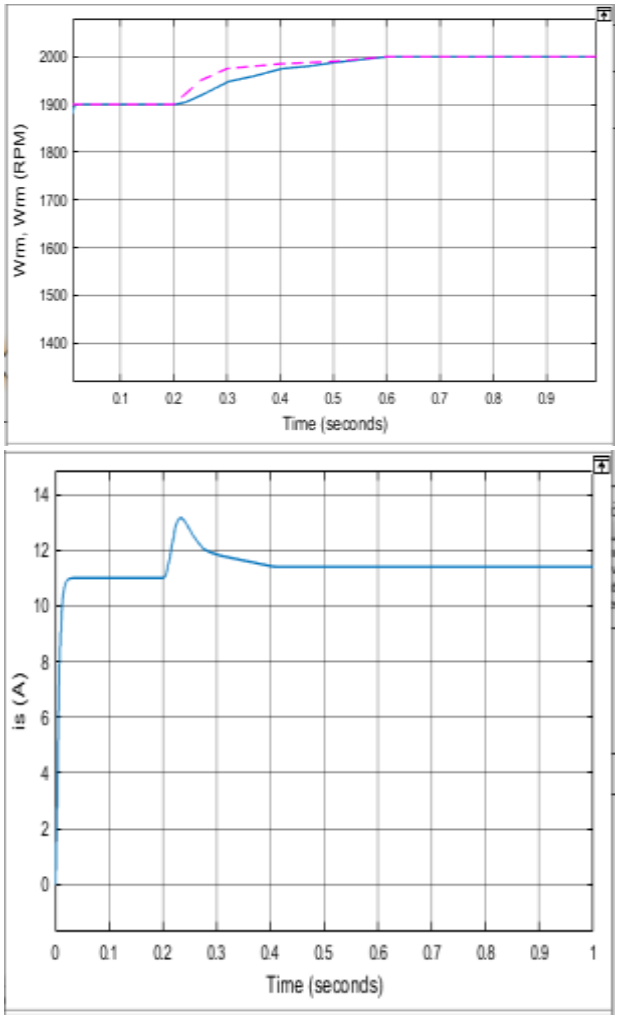


Figure.4. Measured (omega* rm , omega` r) ,Is of the EV SynRM drive at (Vdc =550V beta = 45 deg) :

5. Conclusion

Although Induction Motors (IMs) and Permanent Magnet Synchronous Motors (PMSMs) remain the predominant actuators in electric vehicles (EVs), Synchronous Reluctance Motors (SynRMs) have emerged as a viable alternative due to their robust structure, absence of permanent magnets, and high efficiency potential. However, beyond motor design, the development of a proper drive control strategy is crucial for achieving optimal performance in EV applications. This work presents the development of a SynRM-based EV drive system along with advanced performance enhancement control technologies. The bidirectional DC–DC converter interfacing the battery is first designed with robust voltage regulation, ensuring a boostable and well-controlled DC-link voltage for the motor drive. This interface also enables regenerative braking, allowing energy recovery during deceleration.

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