

# Experimental Model of a Switched Reluctance Machine for Engineering Education

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**Abstract**—This paper presents a physical didactic model of a switched reluctance machine that allows students to modify the number of poles in the rotor and stator. This hands-on approach improves understanding of magnetization, torque behavior, control, and power circuits. Built with simple ferrous materials for low cost and accessibility, the model integrates experimental and active learning techniques. The benefits for learning and its integration with simulation tools for analyzing magnetic fields are also discussed.

**Keywords**— machine models, simulation, engineering teaching

## I. INTRODUCTION

The teaching and learning of electrical machines in engineering courses present significant challenges, as they involve complex concepts of electromagnetism, energy conversion, and more [1]. Many of these concepts are abstract and require a solid theoretical foundation before being applied in practice. Due to the complexity of electrical machines, well-equipped laboratories are essential, allowing students to understand the underlying phenomena and apply appropriate methods and techniques [2]. Hands-on experimentation plays a crucial role in this process, enabling the consolidation of theoretical knowledge and a deeper understanding of the technical characteristics, advantages and limitations of electrical machines [3].

In the specific case of the switched reluctance machine (SRM), its operation is based on complex principles such as the dynamic variation of reluctance, the distribution of magnetic fields, and the generation of electromagnetic torque [4, 5]. These concepts often remain abstract when studied solely from a theoretical perspective. Additionally, the machine requires a control system with sensors and a power converter to operate under different conditions [6], adding another layer of complexity to its understanding. The challenge of integrating all these concepts can create a gap between theory and practice, making essential to develop didactic approaches that enhance accessibility and promote a more interactive learning experience.

To address this educational need, this paper presents the development and application of a didactic physical model of a SRM, aiming to enhance teaching and learning in electrical engineering courses. Section II characterizes the SRM and its nonlinear mathematical model, emphasizing its theoretical complexity and the need for complementary approaches to improve the students' understanding. Section III outlines the objectives of the physical model, describing its modular structure, construction process and assembly, enabling experimentation with different SRM topologies. Section IV explores the educational impact of the model, facilitating its interactivity with computational tools, which enhances the

understanding of electromagnetic principles and machine control, and bridges the gap between theory and practice. Section V presents active learning techniques that integrate the SRM physical model, adaptable to different academic levels. Finally, Section VI summarizes the key conclusions, highlighting the advantages of various SRM configurations, the model's flexibility as a configurable didactic resource, and its role in innovative pedagogical strategies for engineering education.

## II. SRM CHARACTERIZATION

The SRM is a type of synchronous electric motor with a simple construction and robustness make it an efficient alternative for various industrial applications, including electric vehicles [7,8]. The SRM, as shown in Fig. 1, is composed by a rotor and a stator with salient polar regions [9], resulting in a variation of magnetic reluctance depending on the shaft angular position [10]. In Fig. 1, the stator contains concentrated windings on its poles, labeled by a, b, c, while the rotor is made of a ferromagnetic core without windings or conductive bars with poles indicated as a', b', c'. The stator pole arc is denoted by  $B_s$ , the rotor pole arc by  $B_r$ , and  $sp$  represents the overlap angle between pole pairs when there is one pole pair aligned, as set out in poles c and c'.

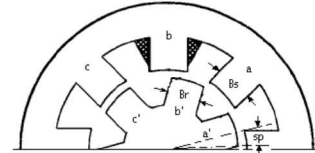


Fig. 1. Cross-section with the detail of SRM's geometry.

The regular geometry of the magnetic circuit in this SRM can have different combinations of stator and rotor pole numbers, resulting in varying performance characteristics.

The SRM electrical circuit is expressed in (1).

$$V_k = Ri_k + \frac{\partial \lambda_k(\theta, i_k)}{\partial i_k} \frac{di_k}{dt} + \frac{\partial \lambda_k(\theta, i_k)}{\partial \theta} \frac{d\theta}{dt} \quad (1)$$

where  $V_k$  is the phase voltage,  $i_k$  the phase current,  $R$  the resistance per phase,  $k$  the active phase,  $\lambda_k$  the phase linkage flux,  $\theta$  the shaft position and  $t$  the time.

Due to the salient poles of both rotor and stator, the variation in magnetic reluctance affects directly the self-inductance coefficient ( $L$ ), which also depends on both the rotor position ( $\theta$ ) and the phase winding current ( $i$ ), as expressed in (2). This variation in  $L$  is highly nonlinear.

$$L_k(\theta, i_k) = \frac{\lambda_k(\theta, i_k)}{i_k} \quad (2)$$

The torque developed in the active phase  $k$  also depends on both the rotor position ( $\theta$ ) and the phase winding current ( $i$ ), as expressed in (3). This means the torque depends on the current value and the  $L_k$  variation with the  $\theta$  variation.

$$T_k(\theta, i_k) = \frac{1}{2} i_k^2 \frac{\partial L_k(\theta, i_k)}{\partial \theta} \quad (3)$$

where  $T_k$  is the phase torque,  $i_k$  the phase current,  $L_k$  the self-inductance coefficient in the active phase  $k$ , and  $\theta$  the rotor position. All these variations are nonlinear, making it challenging for students to grasp due to the complex interdependence of multiple variables [11,12]. To simplify the initial analysis of a SRM, a linear variation of  $L$  with rotor position ( $\theta$ ) is considered for the machine's nominal current ( $i$ ) value. Although this approach reduces complexity, when combined with hands-on observation of a physical SRM model, it significantly enhances the understanding of magnetic phenomena. So, a physical model serves as a valuable didactic tool for studying the SRM.

### III. SRM PHYSICAL MODEL

The main objective in designing and constructing a didactic physical model of the SRM is to provide students with an interactive platform to explore its operating principles across various topologies. The key goal is to allow physical modifications to the rotor and stator pole structures, enabling a deeper understanding of how geometry affects magnetic field distribution, torque production, and overall machine performance. This hands-on approach aims to facilitate the assimilation of abstract concepts, making learning more intuitive and seamlessly integrating with students' background knowledge. Furthermore, the model is designed to promote interactivity by allowing students to perform key measurements, analyze real-time and simulations machine behavior, and validate some theoretical predictions. By bridging the gap between theory and practical application, it fosters creativity in designing alternative SRM configurations, enhances problem-solving skills, and strengthens the foundational knowledge essential for modern engineering education.

#### A. SRM Model Construction

The model was initially developed by designing and calculating the dimensions of all the machine components, which were then detailed and drafted, as exemplified by the 8/6 SRM shown in Fig. 2. All structural parts of the machine were made from soft iron, with some components machined on a lathe and others fabricated using a CNC machine.

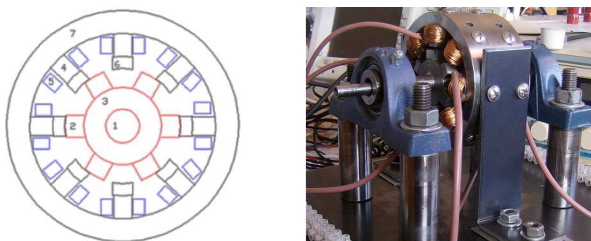


Fig. 2. Cross-section of the 8/6 SRM project model and assembled SRM.

In Fig. 2, the frame (7) is a 100 mm diameter and 50 mm depth ring, defining the machine's external dimensions. It features regularly spaced drilled holes to secure the stator poles. A set of 16 threaded holes allows for the mounting of 1 to 4 pole pairs with their respective windings, enabling the

construction of various SRM topologies. The stator poles are composed of two parts: the winding core (4) and the pole head (6). The winding core remains the same across all machine topologies, and the windings (5) are also identical, each consisting of 100 turns of 0.5 mm<sup>2</sup> copper wire. Two diametrically opposed windings are connected in series, forming an electrical circuit of one phase. The pole head varies in size depending on the SRM topology. For the shaft (1) and rotor base ring (3), a 33 mm diameter was defined, along with 12 threaded holes to mount the rotor poles, allowing for the installation of 1 to 3 pole pairs. The rotor poles (2) also vary in dimensions depending on the desired topology.

#### B. SRM Model Assembly

The components designed in the previous section were produced using low-cost materials and assembled in a way that allows for the configuration of various standard SRM topologies, one at a time. Additionally, this approach enables the exploration of less conventional topologies for analysis, as well as the investigation of structures with shorter magnetic flux paths, based on the available polar components. The most used configurations with the fabricated components are now presented.

##### a) Biphasic Configuration (4/2 SRM)

This is one of the simplest SRM topology, consisting of a stator with 4 poles, each with a 40° polar arc ( $B_s$ ), and a rotor with 2 salient poles, each with a 42° polar arc ( $B_r$ ). Fig. 3 illustrates both the project design and the assembled 4/2 SRM with its mounted poles. This machine requires a power electronics circuit with only two semiconductor switches, making it suitable for low-power applications and simplified control systems.

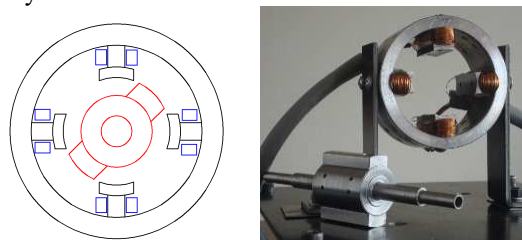


Fig. 3. 4/2 SRM topology project and assembled machine.

##### b) Three-Phase Configuration (6/4 SRM)

This configuration features a stator with 6 poles and 30° polar arcs ( $B_s$ ), along with a rotor comprising 4 salient poles with 32° polar arcs ( $B_r$ ), as shown in Fig. 4. The 6/4 SRM is the most widely used due to its balance between performance and control simplicity, offering lower torque ripple and higher efficiency compared to the biphasic version for the same power rating. This machine is commonly applied in industrial drives, electric vehicle traction systems and power generation applications.

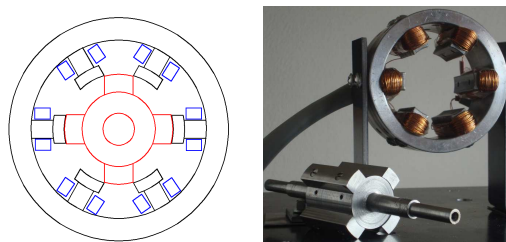


Fig. 4. 6/4 SRM topology projected and assembled machine.

### c) Four-Phase Configuration (8/6 SRM)

In this setup, the stator consists of 8 poles with  $20^\circ$  polar arcs ( $B_s$ ), while the rotor has 6 salient poles with  $22^\circ$  polar arcs ( $B_r$ ), as shown in Fig. 5. The 8/6 SRM delivers higher torque with reduced ripple compared to the previous configurations, along with improved dynamic performance. However, it also introduces greater complexity in the control system, requiring more advanced power electronics and signal processing.

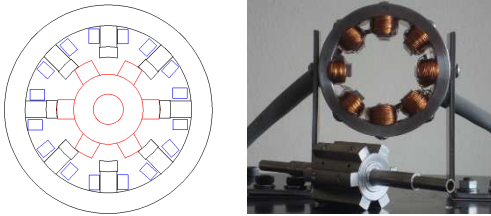


Fig. 5. 8/6 SRM topology projected and assembled machine.

This modular approach for assembling different SRM topologies not only facilitates experimental analysis but also enhances the understanding of how machine geometry influences its performance, making it a valuable tool for both research and training in electrical engineering.

#### IV. EDUCATIONAL IMPACT OF SRM MODEL

The use of this physical SRM model, combined with the theoretical concepts that define the machine, provides students with an engaging, intuitive and interactive learning experience, contributing to a meaningful knowledge acquisition. Its pedagogical significance extends beyond mere visualization, offering an enriched hands-on experience through integration with various measurement, analysis and control tools. Depending on the intended learning objectives, this physical model can foster the students' understanding in different ways and levels of expertise, including:

- *Structural visualization and comprehension.* Direct manipulation of SRM components allows students to observe the geometry of the stator and rotor, as presented in sub-topic B of section III, understand the angular arrangement of poles and winding connections, and recognize how pole positioning influences magnetic reluctance variation, affecting the machine's performance. This approach reduces the abstraction of theoretical concepts and creates a clear bridge between theoretical models and real-world applications.
- *Interactivity and experimentation with different topologies.* This model enables students to physically modify the machine's pole configuration by changing the number of rotor and stator poles, allowing for direct testing and comparison of two-phase, three-phase and four-phase configurations, as presented in sub-topic B of section III. This hands-on experimentation facilitates the study of how structural variations have direct impact in the distribution of magnetic fields, electromagnetic torque production, and energy conversion efficiency.
- *Integration of measurements and static tests.* By incorporating an angular position sensor, students can perform direct measurements and track inductance and torque variations as a function of rotor position. These experimental tests provide real data that can be compared with results obtained from mathematical and

computational simulations, as shown in Fig. 6, reinforcing the connection between theory and practice.

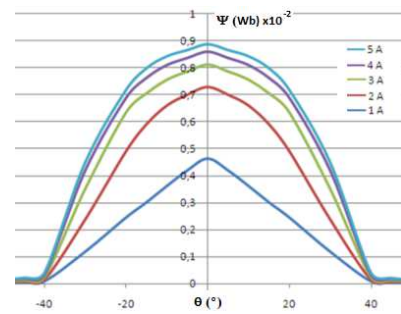


Fig. 6. 4/2 SRM electromagnetic characteristics.

- *Integration with mathematical models and computational simulations.* The physical model structure can be used in finite element simulations to validate concepts, allowing students to visualize and analyze the distribution of magnetic fields, as presented in Fig. 7 for a 6/4 topology, and the effects of reluctance variation based on rotor position. In addition, students can experiment with different ferromagnetic materials, adjust pole dimensions, and modify pole spacing. Also, they can apply the machine's mathematical equations to numerical methods to correlate experimental and simulated results.

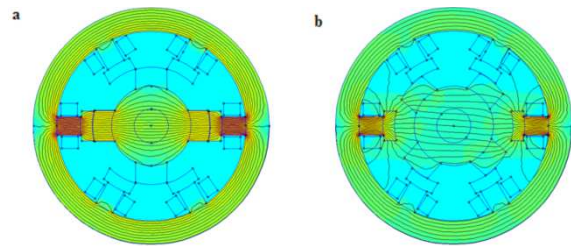


Fig. 7. Flux distribution in FEMM software of a 6/4 SRM topology with aligned poles (a) and unaligned poles (b).

- *Interaction with control systems.* The model can be integrated with a power converter and a digital control system, enabling students to experiment with various drive strategies, such as hysteresis control, as shown in Fig. 8, PWM techniques and advanced control methods. This allows students to analyze machine efficiency, torque oscillations, and response under different control conditions.

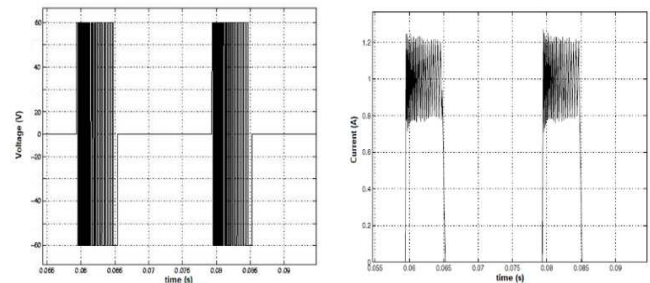


Fig. 8. One phase 8/6 SRM hysteresis drive control simulation of voltage and current.

- *Stimulation of creativity.* The SRM physical model provides a foundational experience that stimulates hypothesis formulation, exploration of alternative structural designs, as 4/4 SRM and 2/2 SRM presented in Fig. 9, testing of different configurations, and critical

analysis of the results obtained. This approach enhances creative thinking, problem-solving abilities, and prototype development, preparing students for the challenges in the electric drive industry.



Fig. 9. 4/4 SRM and 2/2 SRM new topology.

## V. ACTIVE LEARNING TECHNIQUES APPLIED

The application of the didactic SRM model enables the integration of various active learning techniques [13], fostering a more effective theoretical and practical understanding through an engaging hands-on experience. This approach allows students to connect different areas of knowledge.

Concerning undergraduate courses, depending on its learning objectives, the pedagogical approach used for SRM model was project-based learning and problem-based learning [14]. Students worked in teams of four members, assembling the machine topology and tackling practical challenges related to its operating principles. This approach stimulates critical thinking and collaborative problem-solving.

For a deeper technical understanding, an experience-based learning approach can be applied, where small student groups perform electrical, structural and mechanical measurements. These experimental results can then use in computational simulations to predict dynamic operating conditions and analyze the distribution of magnetic fields.

At a more advanced level, inquiry-based learning encourages students to formulate hypotheses and autonomously explore the model. This approach enhances creativity in designing new SRM topologies and fosters critical analysis of their performance, preparing students for innovative problem-solving in engineering.

## VI. CONCLUSIONS

Each SRM topology presents specific advantages and challenges. While the biphasic version is simpler and more economical, the three-phase version offers a better balance between control and performance. The four-phase version provides more uniform torque and is ideal for applications that require higher efficiency and lower noise.

The didactic physical model of the SRM presented is a teaching resource that enhances students' ability to understand and apply electromagnetic, mechanical and electronic concepts. The opportunity to interact with the machine's structure, conduct experimental tests, integrate computational simulations and develop electronic control systems, reduces the gap between theoretical concepts and practical implementation. Moreover, this approach fosters a more dynamic and engaging learning experience, closely aligned with real-world challenges in electrical engineering, better preparing students for innovative projects and industrial applications. This experimental model has been tested and integrated with other technological resources for the past three

years. Currently, additional identical units are needed to accommodate multiple student work groups across different academic levels and areas of knowledge.

The use of a didactic SRM model enables the application of active learning techniques in teaching, enhancing the effectiveness of the learning process through interactive and practical experiences, and allowing students to connect theoretical knowledge, test hypotheses, simulate different topologies and analyze the machine's operation in a practical and integrated way. In the part of the course where this integrated physical model was applied, a 20% improvement in students' evaluations was verified.

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