IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)
An International Open Access, Peer-reviewed, Refereed Journal

A OVERVIEW & ANALYSIS OF SWITCHED RELUCTANCE MOTOR

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Abstract: The Paper presents study of the design & analysis of switched reluctance motor. In this paper Switched Reluctance Motor is at firstly briefly described and subsequently followed by design of simple SRM and benefits of SRM system. The design includes Design steps, Input requirements, working principle & design considerations. This Motor works on principle producing torque through the attraction of its rotor poles to stator poles. As name suggest this motor rely on the Magnetic reluctance effect. In this effect, rotor force itself to align with the stator poles that created minimum reluctance path.

Index Terms **– SRM, ZEV, Stator, Rotor, Pole arc, BLDC, PMSM, Torque, Flux Linkages, and Efficiency.**

I. INTRODUCTION

In High Efficiency motors era, Induction motor despite having several advantages fails when high efficiency required for specific application. To overcome this BLDC motor or PMAC (Permanent Magnet AC) Motor and PMSM (Permanent Magnet Synchronous Motor) get highlighted & both are popularly used now at several applications specifically Electric Vehicle segments.

In Vehicle segment, IC engine have very low efficiency 20-30 %, having major contribution to overall environmental pollution in urban centers. Also, energy contingency & environmental pollution emergency all over world forced to all peoples on earth to pay attention in the research & development of any alternative especially in vehicle segment which can save energy sources & minimize the pollution. As stated above, the present situation ICE is major contributor of urban pollution. As per reports ICE produces 45-50% Ozone, 85-90% carbon dioxide & 55-60 % of air Toxin which are found in city areas.

To overcome this, past 20 years many developed Countries are into research for the alternatives. In some countries Government requires LEV (Low Emission Vehicles) , ZEV (Zero Emission Vehicles). As far as all concerns only reliable known option which meets above requirements are Electric Vehicles. Electric vehicles gives more suitable solution for ZEV, having zero emission, Energy saving, environment eco-friendly. One of the components of electric vehicles is electric motor which produces mechanical torque. Several researchers compared & evaluated various electric motors, in which BLDC (PMAC), PMSM & SRM are preferred. Despite having advantages, BLDC & PMSM depends upon the permanent magnets causing several issues like cost, availability & monopoly. Therefore later researchers went for SRM because of permanent Magnet free, simple construction structure, high efficiency, low cost & flexibility in control.

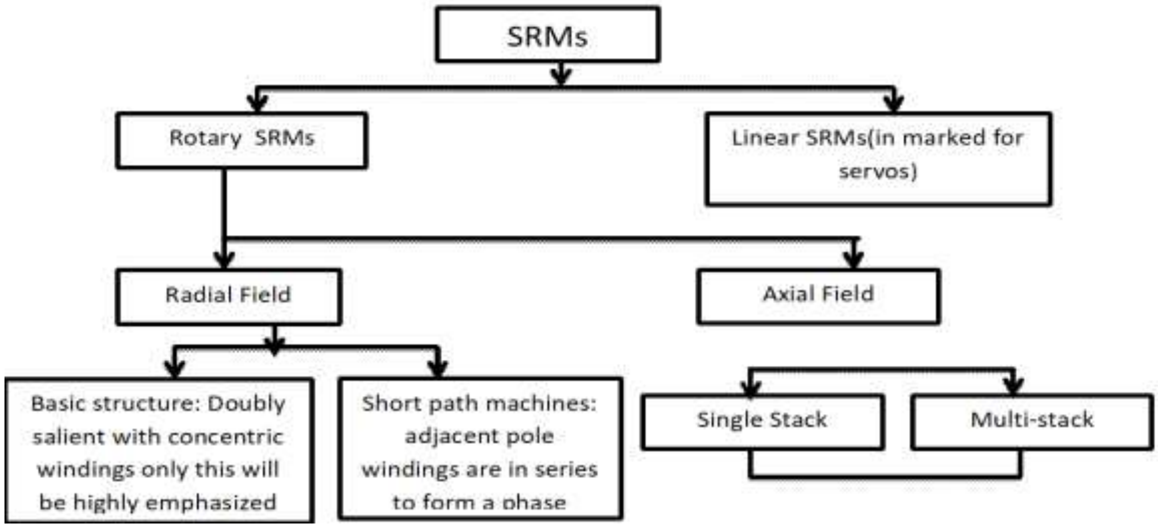
Below is the difference table showing all motors which are popularly used in E-vehicle segments

E-Vehicles Motors	BLDC	IPMSM	AC-IM	SRM
Advantages	Torque Density very high Rotor Copper loss is zero Smaller size & Light in weight Better heat dissipation High Reliability	Very High Efficiency Specific Torque High Power Density	Ruggedness Maximum Peak torque Dynamic response is good Less Maintenance	Power density very high Robust & Simple in construction Fault Tolerant Cost effective than other High Speed Very efficient
Disadvantages	Permanent Magnet Raw material cost is very high so motor cost is high Constant Power range less High Cogging & Reluctance torque ripple decreased with increase in speed	Iron loss maximizes at high speed High cost due to Permanent magnet material	Lower Efficiency Copper Loss is more.	Low Torque density High Torque ripple

From Above table, it is clear that SRM having advantages on other motors when cost is the main consideration

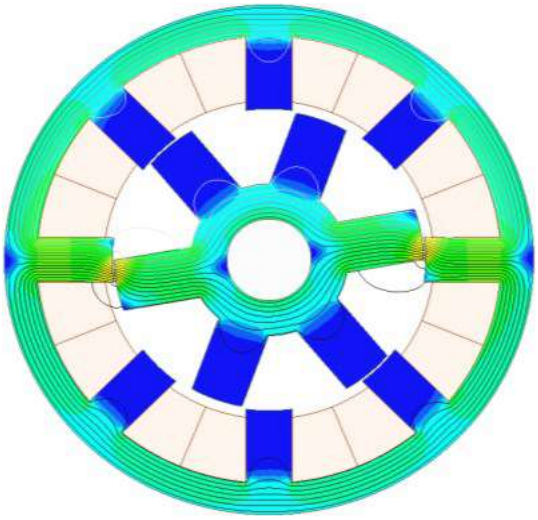
1.1.Classification of SRM's

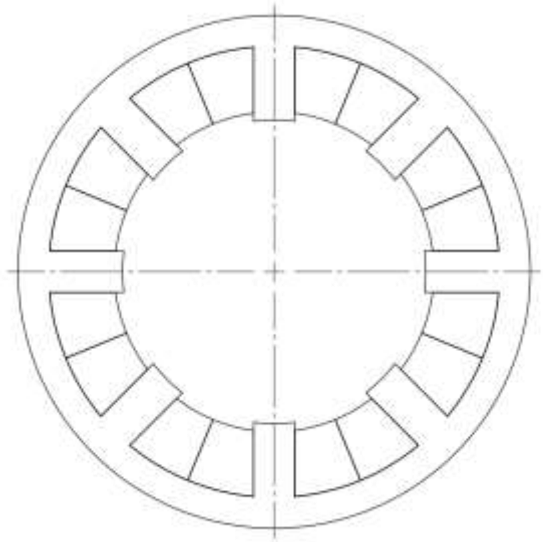
Switch Reluctance Motors are classified as shown in Fig.1.1 SRM majorly classified on the basis of motion of the rotors such as rotating & liner. The linear SRMs largely used for conveyor systems.



1.2 Switched Reluctance Motor

The working principle of an SRM involves exploiting the tendency of a magnetic circuit to align itself in a way that minimizes reluctance. SRMs have rotor and stator poles without windings, and they rely on the magnetic reluctance of their structure to create torque. By controlling the current in the stator windings, the rotor's position can be controlled, allowing for precise control of the motor's operation. SRMs are known for their robustness, simple construction, and suitability for high-speed and high-temperature applications.





1.3 **Switched reluctance motor Construction** (SRMs): This motor have a relatively simpler construction compared to other motor types, which influences the materials used and their corresponding parts. Here are the typical materials and components found in a switched reluctance motor:

1. **Stator**: Made of magnetic steel laminations to reduce eddy current losses and improve magnetic properties. Also stator have salient pole. While stator making, consists parameters such as stator back iron thickness, stator coil dimensions, stator pole height, outer diameter of stator lamination etc.
2. **Rotor**: Rotor made of ferromagnetic material, such as laminated steel or iron, to create the magnetic flux linkage with the stator. The rotor typically has salient poles. While stator making, consists parameters such as rotor back iron thickness, rotor pole height etc.
3. **Windings**: Copper or aluminium wires wound around the stator poles to produce the electromagnetic fields required for motor operation. In SRMs salient pole with structures with concentrated windings is used. Windings are designed to create a sequence of magnetic events that drive to rotor towards alignment with stator poles.
4. **Bearings:** These can be made of various materials, including steel, ceramic, or polymers. The choice of bearing depends on factors such as load, speed & environmental condition. Bearing available such as ball bearing, roller bearing, magnetic bearing, plain bearings etc. In SRMs ball bearings is suitable for application where moderate to high speeds are required.
5. **Control Electronics**: The control system comprises semiconductor devices (like power transistors, diodes, or switches), microcontrollers, and sensors to manage the motor's operation.
6. **Shaft and Housing:** The shaft, usually made of steel, connects the rotor to external loads, while the motor housing protects the internal components and provides structural support.
7. **Insulation**: Some parts may be coated or encapsulated with insulating materials to protect against environmental factors and ensure electrical isolation.
8. **Magnets**: The choice of materials for SRM parts aims to optimize magnetic properties, minimize losses, enhance durability, and improve overall motor efficiency. Advances in material science continually influence the design and manufacturing of these motors, aiming to achieve better performance and reliability.

Diagram of Switch Reluctance Motor:

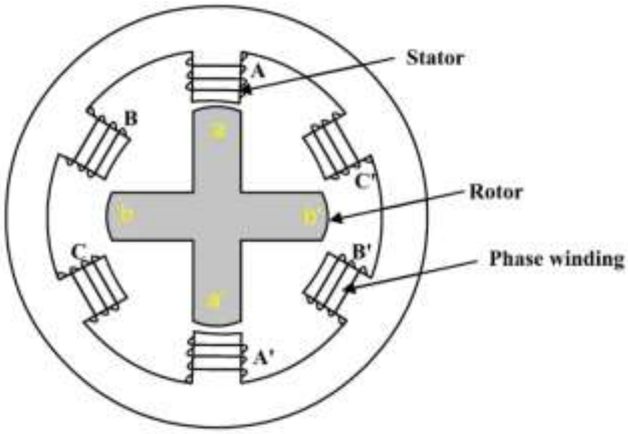


Fig1.4. Constructional Diagram of Switch Reluctance Motor of 6/4 Pole

Consider an SRM with a stator and rotor having alternating poles:
Stator (S): Rotor (R):

S1	R1
S2	*R2*
S3	*R3*
S4	*R4*
...	...

The control system switches the current through the stator windings in a sequence. For instance:-
1. Energize S1, S2, S3 -> Rotor aligns with these poles.
2. Turn off S1, energize S4 -> Rotor follows the change in the magnetic field, aligning with S4.
3. Repeat this sequence in a controlled manner, causing continuous rotation of the rotor.

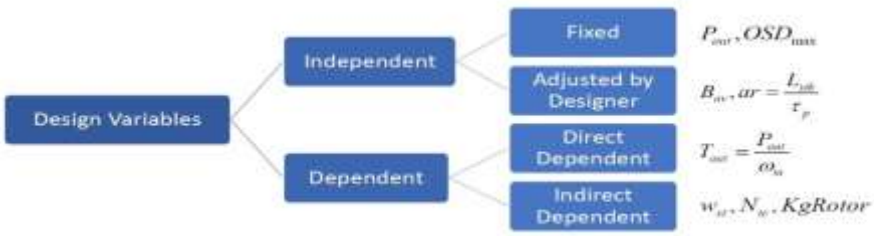
This rotating sequence of energizing stator poles generates motion in the rotor, resulting in the motor's operation without the need for permanent magnets in the rotor or brushes for commutation, making SRMs potentially simpler and more robust.

i. **Structure**: An SRM typically consists of a stator with multiple salient poles and a rotor with corresponding salient poles. The stator poles are encircled by coils of wire.
ii. **Pole Phases**: The stator and rotor have an uneven number of poles to create alternating phases. When the stator poles are energized sequentially, they attract the rotor poles to align with them.
iii. **Rotor Movement**: The rotor aligns itself with the stator poles due to magnetic reluctance, seeking the path of least reluctance. As one set of stator poles is energized, the rotor moves to align itself with the magnetic field.
iv. **Controlled Switching**: The key to SRM operation is the controlled switching of the current through the stator windings. By s witching the phases in a synchronized manner, the rotor rotates to follow the changing magnetic field, generating torque.

2. Design of Switch Reluctance Motor

- **Motor Specification:** - Gather requirements such as power rating, speed range, operating conditions (temperature, environment), efficiency targets, and duty cycle.
- **Output Torque**: - Calculate the required output torque based on the application's load requirements, acceleration, and speed specifications. For calculating torque formula should be
  $T_{shaft} = (P_{out} X\ 2\ X\ \pi\ X\ N)/60$ (Nm)
  Rated Output Torque = Rated Output power / Rated Mechanical speed
- **Dimensions:** - Determine the overall size constraints for the motor, considering factors like available space, mounting requirements, and integration with other components in the system. For finalising the frame size for the motor body we have to determine Stator outer diameter (D)
  For this D = $\sqrt[3]{((D2L)}/ar$; where D – Bore diameter , L- Stack Length , ar - Aspect Ratio
  $D^2L = P_{out} / G\ X\ rps$ ar = L / D ; L = ar / D

- **Defining Pole Numbers**: - Select the number of rotor and stator poles based on the desired speed-torque characteristics and operating frequency. Higher pole numbers typically lead to smoother torque output but may require more complex control algorithms.
  Some popular poles ratio is like 6/4, 6/8 for 3 phases or 8/6 & 8/10 for four phases.
- **Determining Stator & Rotor Pole Angles**: - Calculate the optimal pole angles for both the stator and rotor to maximize torque production and minimize torque ripple. This may involve trade-offs between torque output, cogging torque, and electromagnetic losses. Typically rotor pole angle should be larger than Stator pole angle.
- **Determining Air Gap Lengths**: - Determine the air gap lengths between the rotor and stator poles. Optimize the air gap to ensure sufficient magnetic flux density for torque generation while minimizing losses due to magnetic saturation and reluctance.
- **Stack Length Ratio**: - Determine the ratio of the stack length to the pole pitch. This ratio affects the motor's performance and efficiency. Optimal stack length ratio is typically chosen based on factors such as magnetic saturation, torque ripple, and mechanical stability.
  Typically ratio of stack height / Rotor outer diameter is in between 0.4 to 3.0
- **Rotor Ratio**: - Calculate the rotor ratio, which is the ratio of the rotor pole arc to the pole pitch. This parameter influences the motor's torque-speed characteristics and efficiency. Higher rotor ratios generally result in higher torque density but may also increase torque ripple.
  The ratio of Rotor outer radius to stator outer radius should be generally lies in between 0.50 to 0.55



Design variables should be summarised as per above

2.1 Design Problem

For 6/4 Switch reluctance motor we have considered following dimensions & specifications

- Stator Outer Diameter :- 125 mm
- Rotor Outer diameter :- 70.8 mm
- Stack Core Length:- 70 mm
- Stator Stack slot height:- 16.3 mm
- Air Gap:- 0.5 mm
- Rotor stack Slot Height :- 16.25 mm
- Stator core thickness :- 13 mm
- Rotor core thickness :- 18 mm
- Steel Material :- CRNGO 35C350 Grade
- Stator Pole Arc :- 23 ^{o}
- Rotor Pole Arc :- 29 ^{o}

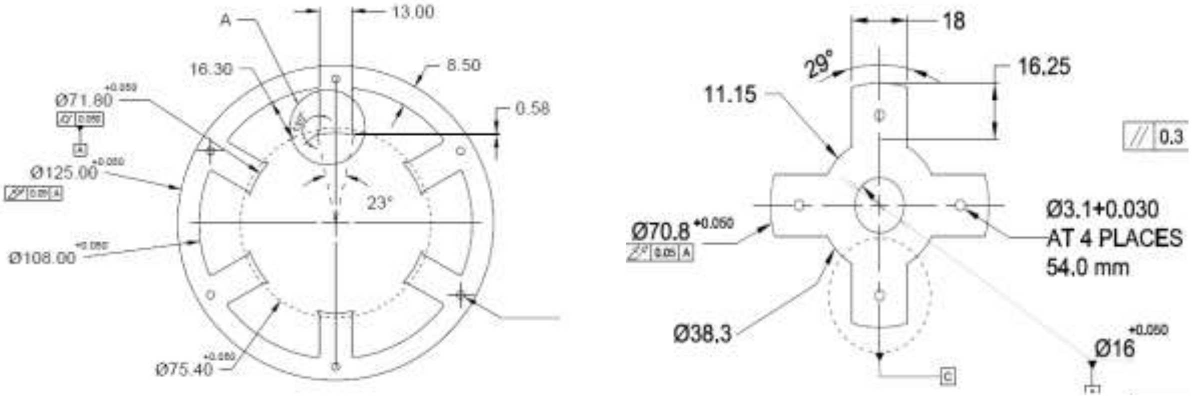


Fig.2.1 CAD Model for designed Stack core & Rotor core

Fig.2.3 Actual Rotor & Stator with winding during assembly

Dynamic Simulation of the Motor using Transient FEA & analytical method

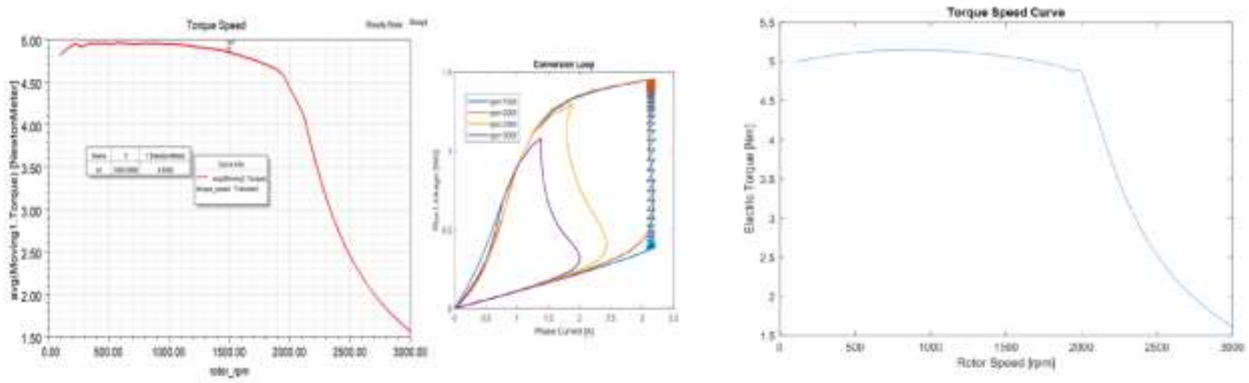
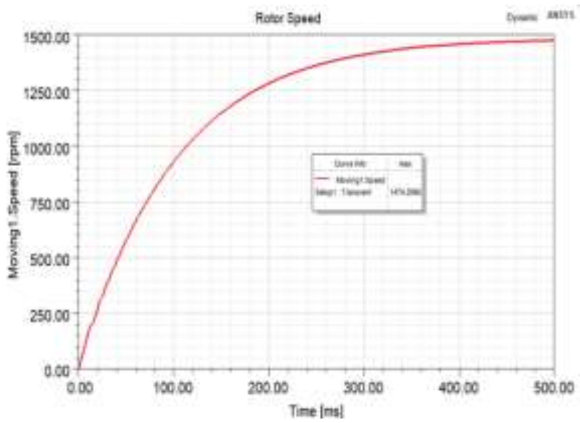


Fig.3.Torque Speed Curves with constant on & Off angles



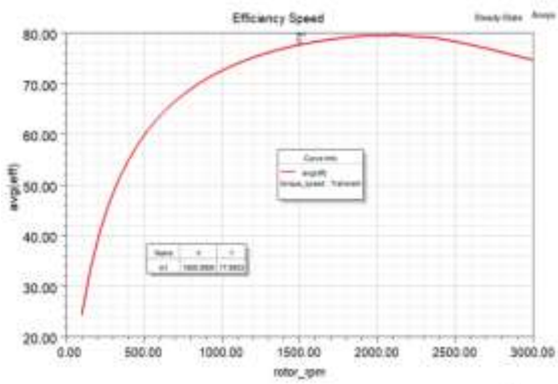


Fig.4 Rotor Speed curve Fig.5 Efficiency vs Rotor Speed curve

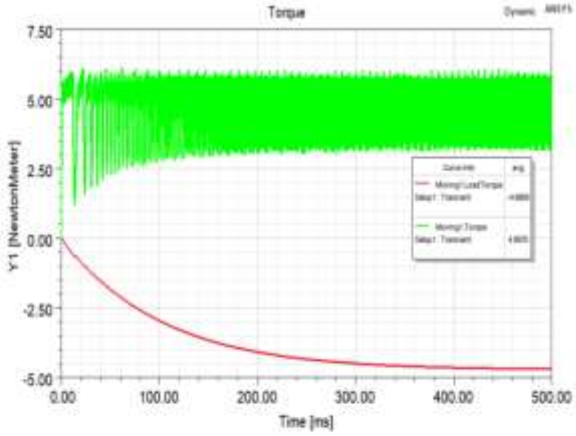


Fig.6 Electrical Torque

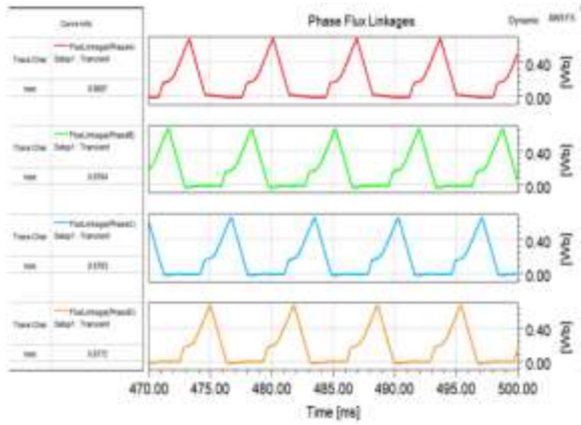


Fig.7 Phase Flux Linkages

3. Switch Reluctance Motor benefits

i. **High Reliability:** SRMs have a simple and robust construction with no brushes or commutators, resulting in fewer parts prone to wear and failure, thus enhancing reliability.

ii. **High Power Density**: SRMs can achieve high power density due to their simple design and high torque-to-inertia ratio, making them suitable for applications requiring high torque in a compact size.

iii. **Wide Speed Range**: SRMs can operate over a wide speed range without the need for complex control schemes, making them suitable for variable-speed applications.

iv. **Efficiency:** SRMs can achieve high efficiency over a wide operating range, especially at low speeds and under dynamic loading conditions, leading to energy savings.

v. **Robustness in Harsh Environments**: SRMs are less sensitive to temperature variations, dust, moisture, and vibrations compared to other motor types, making them suitable for use in harsh operating environments.

vi. **Ease of Control:** SRMs have a simple control scheme compared to other motor types, requiring fewer sensors and less complex control algorithms, which reduce system complexity and cost.

vii. **Cost-Effectiveness:** SRMs often have lower manufacturing costs compared to other motor types due to their simpler design and fewer components.

viii. **Regenerative Braking:** SRMs can perform regenerative braking efficiently, converting kinetic energy into electrical energy during deceleration, which improves overall energy efficiency. Overall, SRMs offer a compelling combination of reliability, efficiency, and simplicity, making them attractive for a wide range of industrial and automotive applications.

ix. **Balancing Application:** An SRMs can be controlled to adjust the speed & position of a rotating mass, such as a flywheel or a rotor, to maintain stability. The motor's ability to respond quickly to changes in load & tasks like stabilizing rotating systems.

x. **Magnet Cost:** SRMs may have lower magnet costs, they may require more complex control systems to achieve desired performance characteristics which could affect the overall system cost.

xi. **Cost controller:** The cost of the controller for an SRM application depends on a variety of factors related to hardware, software, and compliance, manufacturing & supply chain decision. Balancing performance requirements with cost consideration is essential in selecting an appropriate controller solution.

4. Applications for SRM (Popular sectors)

Switched Reluctance Motors (SRMs) find applications across various industries due to their unique advantages. Some popular applications include:

i. Industrial Automation: SRMs are commonly used in industrial automation systems for tasks such as conveyor belt drives, robotic actuators, and pump and compressor drives due to their high reliability and efficiency.

ii. Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs): SRMs are increasingly being used in EVs and HEVs for propulsion systems due to their high torque density, wide speed range, and efficiency, contributing to improved vehicle performance and range.

iii. HVAC Systems: SRMs are utilized in heating, ventilation, and air conditioning (HVAC) systems for fan and pump drives, where their high efficiency and ability to operate over a wide speed range contribute to energy savings. **iv. Home Appliances:** SRMs are found in various home appliances such as washing machines, vacuum cleaners, and kitchen appliances for tasks requiring variable-speed operation, where their simplicity, reliability, and cost-effectiveness are advantageous.

v. Renewable Energy: SRMs are used in wind turbine generators and solar tracking systems due to their ability to operate efficiently under variable load conditions and withstand harsh environmental conditions, contributing to increased renewable energy production.

vi. Aerospace and Defence: SRMs are employed in aerospace and defence applications such as actuators for aircraft control surfaces, missile fin control systems, and turret positioning systems, where their reliability, high power density, and robustness are critical.

vii. Medical Devices: SRMs are used in medical devices such as surgical tools, medical pumps, and imaging equipment, where their compact size, high efficiency, and precise control are essential for performance and reliability.

viii. Consumer Electronics: SRMs are increasingly being used in consumer electronics such as electric power tools, electric bicycles, and personal mobility devices due to their lightweight, compact size, and high efficiency.

These applications highlight the versatility and suitability of SRMs across a wide range of industries, where their unique characteristics fulfill specific performance and operational requirements.

5. Conclusion

For Energy contingency issue along with environmental pollution hazards, the era in the motor & motor control is low cost systems & energy efficient. SRM will be more prominent in applications of energy efficiency when improvements in the converter technologies happen. In this paper design steps are reviewed. Different specifications are reviewed to observe machine performance.

Without changing motor basic size with using the better raw material to improve output torque effectively.

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