Rotating Electrical Machines: Types, Applications and Recent Advances

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Abstract:
The Rotating Electrical Machines (REMs) are classified into Motors and Generators. They powered the industrial, domestic and commercial loads. Because of their importance. This paper discussed different types of REMs, their applications and recent advances. REMs are applied in Teaching, Domestic, Mechatronics, Motorcycle, Three-wheelers, Electric Vehicle, Healthcare, Flywheel Energy Storage and Wind Energy Conversion Systems. It periscopes the advances of REMs in design, Fault diagnostic, control and condition monitoring. Its significance is to shed light on some advances made in REM.

Keywords: Rotating Electrical Machines, Applications, Recent Advances in design, Fault diagnostic, control and condition monitoring.

Introduction
Electrical Rotating Machines are the driven horses in power plants, construction, transportation, agriculture and automation sectors (Dineva, et al., 2019). REMs are the sources of mechanical power in industries because of their robustness and reliability (Martinez-Roman, et al., 2021). Electrical Machines can be broadly classified into Stationery and Rotational Electric Machines. The stationary Electrical Machines are the Transformers (Figure 1) their operation is not based on motional-Electro-Motive-Force (EMF). The Rotating Electrical Machines are AC and DC Generators and Motors which operate based on motional EMF (Figures 2, 3, 4 and 5). The main components of REM that can fail are the rotor and stator windings, rotor and stator laminated core, bearings, magnets, airgap, load and auxiliaries (Frosini, 2020).
The Generators convert the input Mechanical Energy to output Electrical Energy while the Motors convert the input Electrical Energy to output Mechanical Energy (Amodeo, Chiacchiarini, & Oliva, 2012). The motors run our Freezer, Fan, Air conditioner, Refrigerator, Vacuum Cleaner Washing Machine. The single-phase AC and DC Generators can be found in residential and administrative areas, for the generation of electrical energy for lighting, and heating. The three-phase AC and DC Generators and Motors can be found in commercial and industrial areas for powering three-phase loads. Both the single and three phase Generators and Motors are based on Faraday’s Law of Electro-Magnetic induction presented in Equation (1).

\[ E_{emf} = \frac{dN\Phi}{dt} \]  

(1)

Where \( E \) is the induced emf, \( \frac{dN\Phi}{dt} \) is the rate of change of magnetic flux in the coil. \( N \) is the number of turns in the coil.

Related studies

There is new research and development on REM which makes them more and more relevant to our lives. The diagnostic methods for REM were classified and reviewed in Djagarov, et al., (2020). Frosini, (2020) reviewed the current methods of diagnosis of Electrical Machines. The techniques of condition monitoring of Electrical Machines were reviewed by Kande, et al., (2017). The magnetic flux analysis for condition monitoring of Electrical Machines was reviewed by Zamudio-Ramirez, et al., (2022). The different technologies of high-speed Electrical Machines were presented by Gerada,
et al., (2014). The different models and measurements of core losses of soft Magnetic Materials for Electrical Machines were discussed by Guo, et al., (2008). This paper presents the types of REM, their Applications and Recent Advances and it ends with a conclusion.

Types of Rotating Electrical Machines

The different types of REM are the Brushless DC Machines (BLDCM) (Kethiri, & Charrouf, 2023; Akar, Eker, & Akin, 2021), Induction Machines, Synchronous Machines, and Switched Reluctance Machines (SRM) (Akar, Eker, & Akin, 2021). Others are the Doubly Fed Induction Machine and the Brushless Doubly Fed Induction Machine (Frosini, 2020). There are also Synchronous Reluctance Machines (SynRM), AC Homopolar Machines (ACHM) and Bearing-less Machines (Cristea, 2023). The Induction Motor is a very popular REM because it is cheap and rugged (Dineva, et al., 2019). The electric traction machines consisting of Voltage Source Inviters driving electric machines are REM (Dineva, et al., 2019). Other types of electric traction machines in electric vehicles are the permanent magnet and variable reluctance machines which possess high power density and simple control methods (Kethiri, & Charrouf, 2023). Section 3.0 discusses the applications of REM.

Applications of Rotating Electrical Machines

The REMs find applications as generators in power generation, in gas compressors for oil, chemical and gas industries, in industrial Air Compressors, in Air Blowers in the pharmaceutical industry and in turbomolecular pumps (Gerada, et al., 2014). This section briefly discussed the applications of REM.

Application in Teaching, Domestic and Mechatronics

The DC Motor was applied in a closed-loop control system to teach students the function of the PID Controller (Dume, & Metalla, 2023). The REMs are applied in hardware in the loop to teach students the virtual instrument measurements in electrical laboratories (Dume, & Metalla, 2023). The Rotating Electrical Machines are applied in teaching the characterization of the three-phase-induction motor (Torrent, Martinez, & Perat, 2020). The Induction Motors are applied in vacuum cleaners, and ceiling Fans (Vishwakarma, & Keshri, 2023). The small-sized rotating electric machines are applied in the actuation of mechatronic systems (Akawung, Ebot, & Fujimoto, 2023).

Application in three-wheelers and Scooters.

The small-size Rotating Electrical Motors are used in in-wheel systems like Moto/Scooters, because of improved torque which increases acceleration in slope conditions (Gong, et al., 2022). The switched Reluctant Motors are widely used in three-wheelers because they are efficient in reducing windage loss of the wheelers(Seshadri, & Natesan, 2023).

Application in Electric Vehicles and Healthcare

The induction motor based on Direct Torque Control is applied in Electric Vehicle (EV) propulsion systems due to its simplicity in construction and rapid response (Singh, et al., 2006). The Brushless Direct Current (BLDC) Motors are applied in Light Electric Vehicle (Akar, Eker, & Akin, 2021). The Permanent Magnet Synchronous Motor(PMSM) finds application in Electric Vehicles because of its high efficiency (Keshari, & Jarariya, 2023). The DC Motor is applied in the crank-shaft to turn the arm of a ventilator system while delivering oxygen to patients (Raffik, et al., 2023).
**Application in Flywheel Energy Storage and Wind Energy Conversion Systems**

The electrical Rotating machines are applied in the Flywheel Energy Storage System (FESS) which has advantages such as high efficiency, long lifetime, scalability, high power density, and fast dynamic, over other energy storage systems (Takarli, et al., 2023). The DC Electric Machine driven by a traction Motor was applied in the Flywheel Energy Storage System to increase the efficiency of mining and lifting machines (Barbashov, Polyantseva, & Smirnov, 2023).

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Type of Rotating Electrical Machine</th>
<th>Field of Application</th>
<th>Derived Benefits</th>
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</thead>
<tbody>
<tr>
<td>Dume, &amp; Metalla, 2023</td>
<td>DC Motor</td>
<td>Teaching PID Controller</td>
<td>Not specified</td>
</tr>
<tr>
<td>Torrent, Martinez, &amp; Perat, 2020</td>
<td>Rotating Electrical Machines</td>
<td>Teaching three-phase-Induction Motor</td>
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<tr>
<td>Vishwakarma, &amp; Keshri, 2023</td>
<td>Induction Motors</td>
<td>Domestic appliances</td>
<td>Not specified</td>
</tr>
<tr>
<td>Akawung, Ebot, &amp; Fujimoto, 2023</td>
<td>Rotating Electric Machines</td>
<td>Actuation of Mechatronic Systems</td>
<td>Not specified</td>
</tr>
<tr>
<td>Singh, et al., 2006</td>
<td>small-size Rotating Electrical Motors</td>
<td>In-wheel Systems</td>
<td>Increases acceleration</td>
</tr>
<tr>
<td>Seshadri, &amp; Natesan, 2023</td>
<td>Switched Reluctant Motors</td>
<td>Three-wheelers for transportation</td>
<td>Reducing windage loss in wheelers</td>
</tr>
<tr>
<td>Akar, Eker, &amp; Akin, 2021</td>
<td>BLDC Motor</td>
<td>Light Electric Vehicle</td>
<td>Not specified</td>
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<tr>
<td>Singh, et al., 2006</td>
<td>PMSM</td>
<td>Electric Vehicles</td>
<td>High efficiency</td>
</tr>
<tr>
<td>Raffik, et al., 2023</td>
<td>DC Motor</td>
<td>Ventilator System</td>
<td>Not specified</td>
</tr>
<tr>
<td>Takarli, et al., 2023</td>
<td>Electrical Rotating Machines</td>
<td>Flywheel Energy Storage System</td>
<td>High efficiency, long lifetime, scalability</td>
</tr>
<tr>
<td>Barbashov, Polyantseva, &amp; Smirnov, 2023</td>
<td>DC Electric Machine</td>
<td>Flywheel Energy Storage System</td>
<td>Increase the efficiency.</td>
</tr>
<tr>
<td>Fager, &amp; Kosanlioglu, 2023</td>
<td>Synchronous Machines</td>
<td>Wind Energy Conversion Systems</td>
<td>Not specified</td>
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The Synchronous Machines have been very efficient and are applied in the Wind Energy Conversion Systems which are environment friendly (Fager, & Kosanlioglu, 2023).

**Recent Advances in Rotating Electrical Machines**

This paper briefly discussed the recent trends in the Fault Diagnosis of REMs, control and condition monitoring of REM, and Design of REM.

**Trend in Fault Diagnosis**

Fault Diagnosis consists of filtering, preprocessing, feature extraction and pattern recognition (Djagarov, et al., 2020). Protecting critical Machines against failure is vital for improved availability of Machines in industrial settings leading to reduced maintenance costs (Alshorman, et al., 2020). Consequently, there are advances in Fault detection and diagnosis of REM reported in the literature. The vibration monitoring was applied by Dragnev, (2023) to diagnose bearing faults caused by bearing currents introduced by Power Electronic Converters in electric machines. The Infrared camera was applied by Kalyan, & Syal, (2023) to capture thermal images for detecting early failure...
in electrical machines, which can lead to lower maintenance costs. Another recent method is Electromagnetic Measurement reported by Frosini, (2020) for separating the fault signature from the electrical signal introduced by Power Electronic Converters that control REM. A new technique for the diagnosis of faults in the cores of Induction Machines(IM) based on tensor algebra was reported by Martinez-Roman, et al., (2021). The technique overcomes the luck of accurate IM models. Image Processing Technique was proposed by Alshorman, et al., (2020) for Fault Diagnosis and detection in REM.

Siddique, Yadava, & Singh, (2003) stated that the Expert System, Fuzzy Logic System, Artificial Neural Networks, and Genetic Algorithm are applied for fault diagnostics of Induction Machines. The multi-label classification method was proposed by Dineva, et al., (2019) for detecting and diagnosing Motor Faults under severe noise conditions. The Radial Basis Function Neural Network is applied to detect bearing faults from current samples (Gs, et al., 2011). The combined variation mode, Convolution Neural Network, and Hilbert-Huang Transform were applied by El-Dalahmeh, et al., (2023) to detect inter-turn short circuit, static eccentricity and partial demagnetization faults in Permanent Magnet Synchronous Motors. The Shallow and Deep Neural Networks were reported by (Orlowska-Kowalska, et al., 2022) as one of the recent trends in fault detection and classifications in Permanent Magnet Synchronous Motors. A model-based Neural Network was proposed by Anbalagan, et al., (2023) for fault diagnosis of Electrical Motors which overcomes the assumption made in training and testing data that limits the practical implementation of fault diagnosis of Electrical Motors.

The daisy-chain digital bus architecture data acquisition System was proposed by Toscani, et al., (2023) for monitoring complex machinery in industries. The Machine Learning and Data Acquisition System were reported by Gonzalez-Jimenez, et al., (2021) for Fault Detection and Diagnosis in Electric Drives.

**Trends in control and condition monitoring**

The Adaptive Neural Fuzzy Inference System (ANFIS) was reported by Djagarov, et al., (2020) as a new method for monitoring faults in electric machine bearings. A new trend in the estimation of the operating temperature of the Stator, Rotor, Winding and Yoke of Permanent Magnet Synchronous Motors is by applying the deep recurrent convolution Neural Networks (Kirchgässner, Wallscheid, & Böcker, 2021). The hardware platform of Electric Motors finds application in the emulation system to collect enough data to train Machine Learning Models (Zhang, Wallscheid, & Porrmann, 2023) for control and monitoring of electrical machine drives. The search-coil and hall sensors are applied to monitor the condition of electrical machines based on internal magnetic flux measurement, while ferromagnetic core and fluxgate sensors are better options for external flux sensing (Gurusamy, et al., 2022).

**Trends in the Design of Rotating Electrical Machines**

The recent improvement of Permanent Magnet materials, microelectronics and solid-state devices has increased the efficiency of brushless Motors (Dineva, et al., 2019). The present trend in selecting material for laminated rotors is the utilization of high-strength electrical steel grades to fabricate high-speed Induction Motors (Gerada, et al., 2014). Another trend is the replacement of laminated steel sheets with soft Magnetic Composite Materials for the fabrication of rotor and stator cores of rotating electrical generators for high-frequency operation (Dias, et al., 2020). In Ajamloo, Ibrahim, & Sergeant, (2023) the rotor T-shape of a Permanent Magnet Electric Machine was modified, leading to reduced harmonics in the air-gap, and reduced torque ripples in the machine. A cost-effective prototype slot-less toroidal stator wind machine was fabricated in Garrido, & Silveyra, (2023). The wiring stages consist, of the winding of a primary copper spool, the transfer of the primary copper spool
onto the secondary spool, and it is unwinding onto the toroidal core. In Ashouri-Zadeh, & Nasiri-Gheidari, (2023) the Global search, additional stator and stator teeth shifting methods were applied to reduce force ripples in the Tubular Permanent Magnet Linear Machines (TPPLM).

The low magnetization rate of narrow space in designing of spoke-type Permanent Magnet Synchronous Motors (PMSMs) using post-assembly method was solved using a novel yoke structure that reduced the gap between the coil and magnet (Jeong, et al., 2023). Besides the eddy current loss model, Pyrhönen, et al., (2015) added the hysteresis loss model in calculating the losses in the Permanent Magnetic Core of REM. Tombul, Tillmann, & Andert, (2023) estimate the bearing currents generated by the Pulse Width Modulation (PWM) Inverter that caused failure in electric traction machines and proposed reduction of parasitic capacitance between the windings and the stator core, increased the stator end winding leakage inductance as remedies the failure in the machines. The Artificial Neural Network was applied in modelling the Permanent Magnet Synchronous Machine for Electric Vehicle application to solve the nonlinearity in the machines (Fujimoto, Senington, & Holmberg, 2023).

Conclusion

The single-phase Generators and Motors are applied in lightening, heating and cooling appliances, while the three-phase Generators are applied to power three-phase loads. The switched Reluctant Motors are applied in three-wheelers because of their efficiency in reducing windage loss in the wheelers while the PMSMs are applied in Electric Vehicles due to efficiency. The recent types of Rotating Electrical Machines are AC Homopolar Machines (ACHM) and Bearing-less Machines.

Electromagnetic measurement, machine vibration monitoring, Image Processing, Machine Learning Data Acquisition, multi-level classification and Artificial Intelligence are the recent techniques for detecting faults in Rotating Electrical Machines. Machine Learning, ANFIS, Deep Recurrent Convolution Neural Networks, search-coil and hall sensors, are new methods for monitoring faults in Rotating Electrical Machines. The recent trend in materials for fabricating rotor and stator cores of high-speed rotating electrical generators is the use of high-strength electrical steel grades and soft Magnetic Composite Materials. A new design method for calculating the losses in the Permanent Magnetic Core of Rotating Electrical Machines is the addition of a hysteresis loss model with an eddy current loss model.

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