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Rotating Electrical Machines: Types, Applications and Recent Advances

Aliyu Hamza Sule
Department of Electrical Engineering, Hassan Usman Katsina Polytechnic, P.M.B. 2052, Katsina, Katsina State, Nigeria

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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).

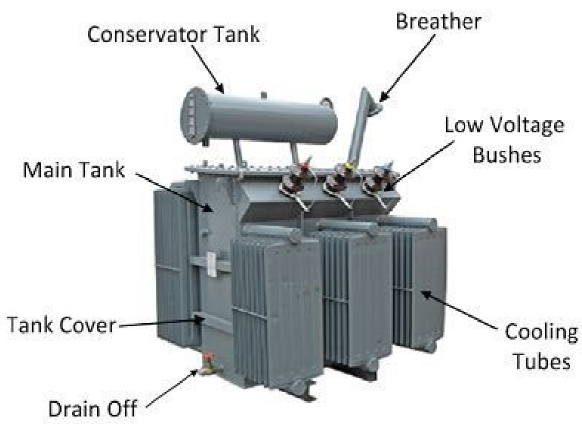

Figure 1. Transformer

Figure 2. A.C. Generator

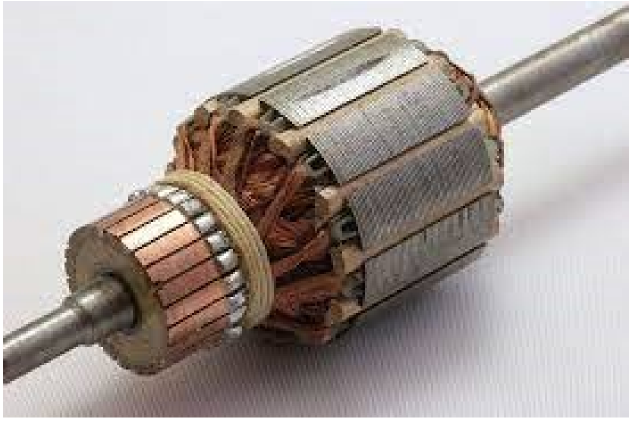

Figure 3. D.C. Generator

Figure 4. AC Motor

Figure 5. DC Motor

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).

$$E_{emf} = \frac{dN\Phi}{dt} \qquad (1)$$

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 1. Summary of Applications of Rotating Electrical Machines

Ref.	Type of Rotating Electrical Machine	Field of Application	Derived Benefits
Dume, & Metalla, 2023	DC Motor	Teaching PID Controller	Not specified
Torrent, Martinez, & Perat, 2020	Rotating Electrical Machines	Teaching three-phase-Induction Motor	Not specified
Vishwakarma, & Keshri, 2023	Induction Motors	Domestic appliances	Not specified
Akawung, Ebot, & Fujimoto, 2023	Rotating Electric Machines	Actuation of Mechatronic Systems	Not specified
Singh, et al., 2006	small-size Rotating Electrical Motors	In-wheel Systems	Increases acceleration
Seshadri, & Natesan, 2023	Switched Reluctant Motors	Three-wheelers for transportation	Reducing windage loss in wheelers
Singh, et al., 2006	Induction motor	Electric Vehicle	Simplicity in construction.
Akar, Eker, & Akin, 2021	BLDC Motor	Light Electric Vehicle	Not specified
Singh, et al., 2006	PMSM	Electric Vehicles	High efficiency
Raffik, et al., 2023	DC Motor	Ventilator System	Not specified
Takarli, et al., 2023	Electrical Rotating Machines	Flywheel Energy Storage System	High efficiency, long lifetime, scalability
Barbashov, Polyantseva, & Smirnov, 2023	DC Electric Machine	Flywheel Energy Storage System	Increase the efficiency.
Fager, & Kosanlioglu, 2023	Synchronous Machines	Wind Energy Conversion Systems	Not specified

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, pre-processing, 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(TPMLM).

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.

References

Ajamloo, A.M., Ibrahim, M.N., & Sergeant, P. (2023). Design, Modelling and Optimization of a High Power Density Axial Flux SRM with Reduced Torque Ripple for Electric Vehicles. *Machines*, *11*, 759. https://doi.org/10.3390/machines11070759

Akar, M., Eker, M., & Akin, F. (2021). BLDC Motor Design and Application for Light Electric Vehicle. *Afyon Kocatepe University Journal of Sciences and Engineering*, *21*, 326–336, 2021, https://doi.org/10.35414/akufemubid.889877

Akawung, A.F., Ebot, B.J. & Fujimoto, Y. (2023). Airflow Cooling Mechanism for High-Power-Density Surface Mounted Permanent Magnet Motor. *Power and Energy,* 1–10, 2023, https://doi.org/10.1109/OJIM.2022.1234567

Alshorman, O., Masadeh, M., Alkahtani, F., & Alshorman, A. (2020). *A Review of Condition Monitoring and Fault Diagnosis and Detection of Rotating Machinery Based on Image Aspects.* In 2020 International Conference on Data Analytics for Business and Industry: Way Towards a Sustainable Economy, ICDABI. https://doi.org/10.1109/ICDABI51230.2020.9325635

Amodeo, S.J., Chiacchiarini, H.G. & Oliva, A.R. (2012). High-performance control of a DC-DC Z-source converter used for an excitation field driver. IEEE Transaction on Power Electronics, 27(6), 2947–2957. https://doi.org/10.1109/TPEL.2011.2176751

Anbalagan, S., Agarwal, D., Natarajan, B., & Srinivasan, B. (2023). *Foundational Models for Fault Diagnosis of Electrical Motors.* NY, USA: Ithaca.

Ashouri-Zadeh, A., & Nasiri-Gheidari, Z. (2023). Force Ripple Reduction Methods for Tubular Permanent Magnet Linear Machines. *Scientia Iranica.* https://doi.org/10.24200/sci.2023.61143.7165

Barbashov, N., Polyantseva, A., & Smirnov, V. (2023). *Energy recovery device for mining and lifting machines.* In 3rd International Conference on Geotechnology, Mining and Rational Use of Natural Resources (GEOTECH-2023). https://doi.org/10.1051/e3sconf/202341701002

Cristea, C.F. (2023). *Theoretical and experimental research regarding the dynamic behaviour of the mechanical system relation to electrical system of the synchronous machine in wind turbine applications.* Universitatea Transilvania din Brașov, Romania.

Dias, M.D.M., Bittencourt, S.D., Fritsch, A.R., Niada, R.F., Borba, M.G., Aquim, P.M., Schneider, E.L., Cezar, J.L., Verney, J.C.K., Gertz, L.C. & Schaeffer, L. (2020). *Application of Soft Magnetic Composite Materials in Rotating Electrical Machines Synchronous.* Stockport UK: Bramhall.

Dineva, A., Mosavi, A., Faizollahzadeh Ardabili, S., Vajda, I., Shamshirband, S., Rabczuk, T., & Chau, K.-W. (2019). Review of soft computing models in design and control of rotating electrical machines. *Energies, 12*(6), 1049. https://doi.org/10.3390/en12061049

Dineva, A., Mosavi, A., Gyimesi, M., Vajda, I., Nabipour, N., & Rabczuk, T. (2019). Fault Diagnosis of Rotating Electrical Machines Using Multi-Label Classification. *Applied Sciences*, *9*(23), 5086. https://doi.org/10.3390/app9235086

Djagarov, N., Enchev, G., Grozdev, Z. & Djagarova, J. (2020). *Overview of Diagnostic Methods for Rotating Electrical Machines.* Proceedings from 7th International Conference on Energy Efficiency and Agricultural Engineering. https://doi.org/10.1109/EEAE49144.2020.9279018

Dragnev, D. (2023). *Application of Vibrodiagnostics for Diagnosis and Analysis of Defects Caused by the Flow of Bearing Currents in Electrical Drives.* In 18th Conference on Electrical Machines, Drives and Power Systems (ELMA). https://doi.org/10.1109/ELMA58392.2023.10202381

Dume, G. & Metalla, J. (2023). *Hardware in the loop technique for real-time control of electrical machines using LabVIEW software for laboratory works in electrical engineering faculties.* In 7th Advanced Engineering Days (AED).

El-Dalahmeh, M., Al-Greer, M., Bashir, I., El-Dalahmeh, M., Demirel, A., & Keysan, O. (2023). Autonomous fault detection and diagnosis for permanent magnet synchronous motors using combined variational mode decomposition, the Hilbert-Huang transform, and a convolutional neural network. *Computers and Electrical Engineering, 110,* 108894. https://doi.org/10.1016/j.compeleceng.2023.108894

Fager, F. & Kosanlioglu, J. (2023). *Competitor Analysis of the Synchronous Machines Market.* KTH Industrial Engineering and Management Industrial Economics and Management Retrieved from https://kth.diva-portal.org/smash/get/diva2:1785559/FULLTEXT01.pdf

Frosini, L. (2020). Novel Diagnostic Techniques for Rotating Electrical Machines—A Review. *Energies*, *13*(19), 5066. https://doi.org/10.3390/en13195066

Fujimoto, Y., Senington, R., & Holmberg, K. (2023). *Neural Networks for Modelling of Electrical Parameters and Losses in Electric Vehicle.* University of Skovde.

Garrido, J.M.C. & Silveyra, J.M. (2023). *Design and fabrication of a cost-effective coil winding machine for slotless toroidal stators Design and fabrication of a cost-effective coil winding machine for slotless toroidal stators.* In 21st LACCEI International Multi-Conference for Engineering, Education, and Technology.

Gerada, D., Mebarki, A., Brown, N., Gerada, C., Cavagnino, A., & Boglietti, A. (2014). High-speed electrical machines: technologies, trends and developments. *IEEE Transactions on Industrial Electronics, 61*(6), https://doi.org/10.1109/TIE.2013.2286777

Gong, J., Zhao, B., Huang, Y., Semail, E., & Nguyen, N. K. (2022). Quantitative Comparisons of Outer-Rotor Permanent Magnet Machines of Different Structures/Phases for In-Wheel Electrical Vehicle Application. *Energies*, *15*(18), 6688. http://dx.doi.org/10.3390/en15186688

Gonzalez-Jimenez, D., Del-Olmo, J., Poza, J., Garramiola, F., & Madina, P. (2021). Data-Driven Fault Diagnosis for Electric Drives: A Review. *Sensors (Basel, Switzerland)*, *21*(12), 4024. https://doi.org/10.3390/s21124024

Gs, V., Pai, S.P., Sriram, N.S. & Rao, P.B.K.N. (2011). Bearing Diagnostics Â A Radial Basis Function Neural Network Approach. In 24th International Congress on Condition Monitoring and Diagnostics Engineering Management, Advances in Industrial Asset Integrity Management. Retrieved from https://www.researchgate.net/publication/263172843_Bearing_Diagnostics_-_A_Radial_Basis_Function_Neural_Network_Approach

Guo, Y., Zhu, J.G., Zhong, J., Lu, H. & Jin, J.X. (2008). Measurement and modelling of rotational core losses of soft magnetic materials used in electrical machines: A review. *IEEE Transitions on. Magnetics, 44*(2), 279–291. https://doi.org/10.1109/TMAG.2007.911250

Gurusamy, V.V., Capolino, G.-A., Akin, B., Henao, H., & Romary, R. (2022). Recent Trends in Magnetic Sensors and Flux-Based Condition Monitoring of Electromagnetic Devices. *IEEE Transactions on Industry Applications, 58*(4), 4668-4684. https://doi.org/10.1109/TIA.2022.3174804

Istenes, G. & Horvath, K. (2023). *Control Algorithm Development of Electrical Drives by Using Finite Element Model in Connected MATLAB / Simulink and JMAG Framework*. In 2023 18th Conference on Electrical Machines, Drives and Power Systems (ELMA). https://doi.org/10.1109/ELMA58392.2023.10202412

Jeong, M.-J., Lee, K.-B., Song, S.-W., Lee, S.-H. & Kim, W.-H. (2023). A Study on Magnetization Yoke Design for Post-Assembly Magnetization Performance Improvement of a Spoke-Type Permanent Magnet Synchronous Motor. *Machines*, *11*, 850. https://doi.org/10.3390/machines11090850

Kalyan, G.S. & Syal, P. (2023). *Recent Advancements of Thermal Imaging in Induction Motor: A Review*. In 5th International Conference on Energy, Power, and Environment: Towards Flexible Green Energy Technologies. https://doi.org/10.1109/ICEPE57949.2023.10201583

Kande, M., Isaksson, A., Thottappillil, R., & Taylor, N. (2017). Rotating Electrical Machine Condition Monitoring Automation—A Review. *Machines*, *5*(4), 24. https://doi.org/10.3390/machines5040024

Keshari, R. & Jarariya, S. (2023). Performance Analysis of PMSM-Electric Vehicle with Fuzzy Logic Controller. *International Journal of Progressive Research in Engineering Management and Science (IJPREMS), 3*(6), 562–570.

Kethiri, M.F. & Charrouf, O. (2023). *Engineering Sciences in a Globalization World*. Turkey: Duvar Publishing.

Kirchgässner, W., Wallscheid, O., & Böcker, J. (2021). Estimating Electric Motor Temperatures With Deep Residual Machine Learning. *IEEE Transactions on Power Electronics, 36*, 7480-7488. https://doi.org/10.1109/TPEL.2020. 3045596

Martinez-Roman, J., Puche-Panadero, R., Sapena-Bano, A., Terron-Santiago, C., Burriel-Valencia, J., (2021). Pineda-Sanchez. M. Analytical Model of Induction Machines with Multiple Cage Faults Using the Winding Tensor Approach. *Sensors*, *21*(15), 5076. https://doi.org/10.3390/s21155076

Orlowska-Kowalska, T., Wolkiewicz, M., Pietrzak, P., Skowron, M., Ewert, P., Tarchała, G., Krzysztofiak, M. & Kowalski, C.T. (2022).

Fault Diagnosis and Fault-Tolerant Control of PMSM Drives–State of the Art and Future Challenges. *IEEE Access, 10*, 59979–60024. https://doi.org/10.1109/ACCESS.2022.3180153

Pyrhönen, J.J., Ruoho, S., Nerg, J., Paju, M., Tuominen, S., Kankaanpaa, H., Stern, R., Boglietti, A., & Uzhegov, N. (2015). Hysteresis Losses in Sintered NdFeB Permanent Magnets in Rotating Electrical Machines. *IEEE Transactions on Industrial Electronics, 62*, 857-865. https://doi.org/10.1109/TIE.2014.2354597

Raffik, R., Ramaswamy, A.K., Aatheshvar, P., Logesh, R.R. & Nair, A. (2023). *Design and Control of Portable Ventilator Machine using Mechatronics Principles*. In 2nd International Conference on Advancements in Electrical, Electronics, Communication, Computing and Automation. https://doi.org/10.1109/ICAECA56562.2023.10200884

Seshadri, A. & Natesan, L. (2023). Influence of rotor slot profile on the windage loss in a Switched Reluctance Motor for an electric autorickshaw. *Engineering Science and Technology, an International Journal, 46*, 1–28, 2023. https://doi.org/10.1016/j.jestch. 2023.101493

Siddique, A., Yadava, G.S. & Singh, B. (2003). *Applications of artificial intelligence techniques for induction machine stator fault diagnostics: Review*. In IEEE International Symposium on Diagnostics for Electric Machines, Power Electronics and Drives, SDEMPED 2003 – Proceedings. https://doi.org/10.1109/DEMPED.2003.1234543

Singh, B., Jain, P.K., Mittal, A.P., & Gupta, J.R. (2006). Direct torque control: a practical approach to electric vehicle. *2006 IEEE Power India Conference, 4*, 842–845. https://doi.org/10.1109/POWERI.2006.1632617

Takarli, R., Amini, A., Khajueezadeh, M., Zarbil, M. S., Vahedi, A., Kiyoumarsi, A., Tarzamni, H., & Kyyra, J. (2023). A Comprehensive Review on Flywheel Energy Storage Systems: Survey on Electrical Machines, Power Electronics Converters, and Control Systems. *IEEE Access, 11*, 81224-81255. https://doi.org/10.1109/ACCESS.2023.3301148

Tombul, Y., Tillmann, P., & Andert, J. (2023). Simulation of the Circulating Bearing Currents for Different Stator Designs of Electric Traction Machines. *Machines, 11*(8), 811. https://doi.org/10.3390/machines11080811

Torrent, M., Martinez, E. & Perat, J.I. (2020). Application work using software tools and didactic equipment of electrical machines in electrical engineering studies. Computer Applications in Engineering Education, 28(2), 435–443. https://doi.org/10.1002/cae.22205

Toscani, A., Immovilli, F., Member, S., Pinardi, D., & Cattani, L. (2023). A Novel Scalable Digital Data Acquisition System for Industrial Condition Monitoring. *IEEE Transactions on Industrial Electronics,* 1–11. https://doi.org/10.1109/TIE.2023.3301521

Vishwakarma, S.K. & Keshri, V. (2023). Study of Optimization of Squirrel Cage Induction Motor. *International Research Journal of Modernization in Engineering Technology and Science, 5*(08), 211–215.

Zamudio-Ramirez, I., Osornio-Rios, R.A., Antonino-Daviu, J.A., Razik, H. & Romero-Troncoso, R. (2022). Magnetic Flux Analysis for the Condition Monitoring of Electric Machines: A Review. *IEEE Transactions on Industrial Informatics, 18*(5), 2895–2908. https://doi.org/10.1109/TII.2021.3070581

Zhang, S., Wallscheid, O. & Porrmann, M. (2023). Machine Learning for the Control and Monitoring of Electric Machine Drives: Advances and Trends. IEEE *Open Journal of Industry Applications, 4*, 188–214. https://doi.org/10.1109/ojia.2023.3284717