ARTICLE INFO
Article ID: 05-17-01-0005

doi:10.4271/05-17-01-0005

Peculiarities of the Design of Housing Parts of Large Direct Current Machines

Oleksii Tretiak,[1] Serhii Serhiienko,[1,2] Anton Zhukov,[1,2] Pavlo Gakal,[3] Yevhen Don,[4] Mariia Arefieva,[1] Iryna Tretiak,[3] Stanislav Kravchenko,[1] and Oleg Bohozhavets[1]

[1]*National Aerospace University Kharkiv Aviation Institute, Faculty of Aircraft Engineering, Department of Aerohydrodynamics, Ukraine*
[2]*Limited Liability Company "Kharkov Electric Machine-Building Plant," Ukraine*
[3]*National Aerospace University Kharkiv Aviation Institute, Department of Aerospace Thermal Engineering, Ukraine*
[4]*Kharkiv National Automobile and Highway University, Department of Automobiles named after A.B. Gredeskul, Ukraine*

Abstract

In this work the design and stress–strain calculation of housing parts of large machines during operation are considered. At the same time, both classical electromagnetic forces and technological operations necessary for mechanical processing and assembly of such objects as well as transportation processes are taken into account for the first time. The task of analyzing of the stress–strain state of the framework was solved in the three-dimensional setting using the finite element method by the SolidWorks software complex.

The three-dimensional analysis of the stress–strain state of the structure for technological operations, namely tilting, lifting, and moving the large DC machines frame without poles and with poles, showed that the values of mechanical stresses that arise in the connections of the frame exceed the permissible limits, resulting in significant deformation of the structure. The work proposed the modernized frame design with additional stiffeners and re-calculated the stress–strain state of the unit. The analysis, that was carried out, showed that when performing technological operations, the mechanical stresses that arise do not exceed the permissible ones, and all deformations are in the elastic zone for the given metal.

History

Received: 25 Jun 2023
Revised: 25 Sep 2023
Accepted: 07 Dec 2023
e-Available: 23 Dec 2023

Keywords

Direct Current (DC) machines, Electromagnetic forces, Three-dimensional modeling, Stress–strain state

Citation

Tretiak, O., Serhiienko, S., Zhukov, A., Gakal, P. et al., "Peculiarities of the Design of Housing Parts of Large Direct Current Machines," *SAE Int. J. Mater. Manuf.* 17(1):59-72, 2024, doi:10.4271/05-17-01-0005.

ISSN: 1946-3979
e-ISSN: 1946-3987

1. Introduction

Direct current (DC) machine is electrical–mechanical device for power conversion. There are two types of DC machines: the first one is DC generator, which converts mechanical power into direct current electrical power, and the other one is known as a DC motor that converts DC electrical power into mechanical power. The main advantages of DC electric motors are the ability to gradually adjust the speed of rotation of the shaft by electrical methods, a wide range of speeds, and a significant starting torque. These advantages determine the field of use of DC electric motors namely electric drive. The main disadvantages of DC generators are unsatisfactory mass and dimensional indicators (large dimensions and weight), compared to alternating current generators, and the presence of a sparking collector. It is these disadvantages that determine limitation of the use of DC generators [1].

In recent decades, there has been a trend to optimize the design of electric machines in order to ensure minimum mass with maximum power. However, the main efforts were aimed at reducing the weight of hydrogenerators and turbogenerators as the heaviest machines [2, 3]. Most of the studies for DC machines are dedicated to optimizing the modeling of units depending on their direction of use, namely, choosing the type of DC machine, choosing the optimal length of the active part [4]. Particular attention is paid to the three-dimensional modeling of transient processes, the study of the operating characteristics of units and the improvement of reliability indicators during operation [5, 6].

Malfunctions of DC machines attract great attention of researchers. Therefore, most of the work in this direction is devoted to malfunctions during the operation of DC machines, namely sparking, overheating, low/high rotation frequencies, which are mostly caused by electromagnetic reasons [7]. As a rule, one of the most critical components is the brush-collector apparatus. Both the brushes and the commutator are used as the switching system that allows the DC machine to operate, and both require special attention such as monitoring sparking, temperature, and special preventative maintenance processes. Currently, active work is being carried out toward the creation of monitoring systems based on artificial intelligence for the purpose of effective maintenance of DC machines [8]. Despite the large number of works devoted to DC machines, the problems of mechanical engineering of large machines, namely housing parts, are almost not considered. But there are works [9, 10] devoted to methods of modeling and optimization of production in order to increase their reliability and reduce equipment downtime.

Considering the fact that a wide demand for large DC machines for mining equipment and metallurgical mills is expected, it is necessary to create methods that will allow to calculate a new designed structures taking into account their manufacture, transportation, assembly, and operation. Nowadays, there are very few works devoted to this topic. Therefore, the analysis of the stress–strain state of housing parts of large DC machines is relevant.

2. Large DC Machines

The principle of operation of DC machines (generators and motors) is based on the phenomenon of electromagnetic induction and the phenomenon of interaction of a conductor, through which a current passes, with a magnetic field. At the same time, DC machines also have the property of reversibility, that is, each machine can work both in generator mode and in engine mode. The detailed principle of operation and construction was considered by the author Gerling, D. [11].

In this article, the DC machines are considered, the design of which is presented in Figures 1 and 2. It consists of two main parts: a stationary part namely the stator and a rotating part namely the armature. The stator is a frame, on the inner surface of which the cores of the main poles with pole coils and additional poles are fixed.

The most massive part of the large DC machines design is the framework. It is made of steel or cast iron. The stand is part of the magnetic circuit of the machine, to which the main and additional poles are attached. The frameworks of the stators of electrical machines are made solid casted, welded, or made from pipes.

In order to reduce the size of the bearing shields and increase their rigidity, the length of the framework is sometimes increased. The side of the bearing shields developed part of the framework may have less thickness. The thickness of the framework is determined from the electromagnetic calculation. The obtained dimensions of the framework ensure its sufficient strength and rigidity.

It is necessary to pay special attention that the parameters got for the framework, which are determined to be sufficient for mechanical calculation, do not always satisfy the mechanical requirements of the structure.

In fact, two types of loads act on the framework construction at different stages of the service life cycle:

1. Technological namely turning over and transfer;
2. Workloads, caused by electromagnetic forces.

FIGURE 1 DC machine.

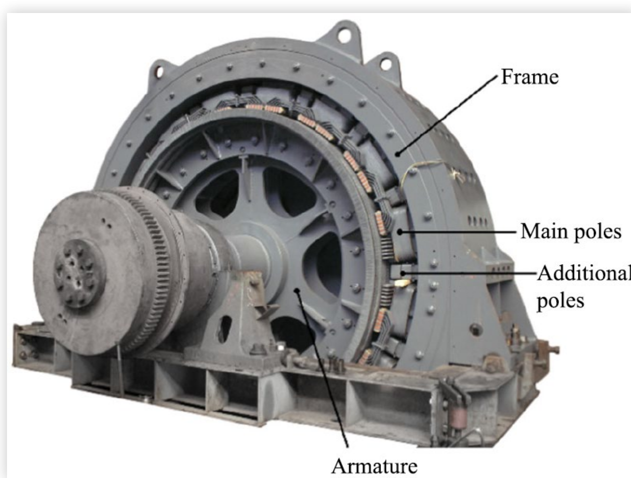
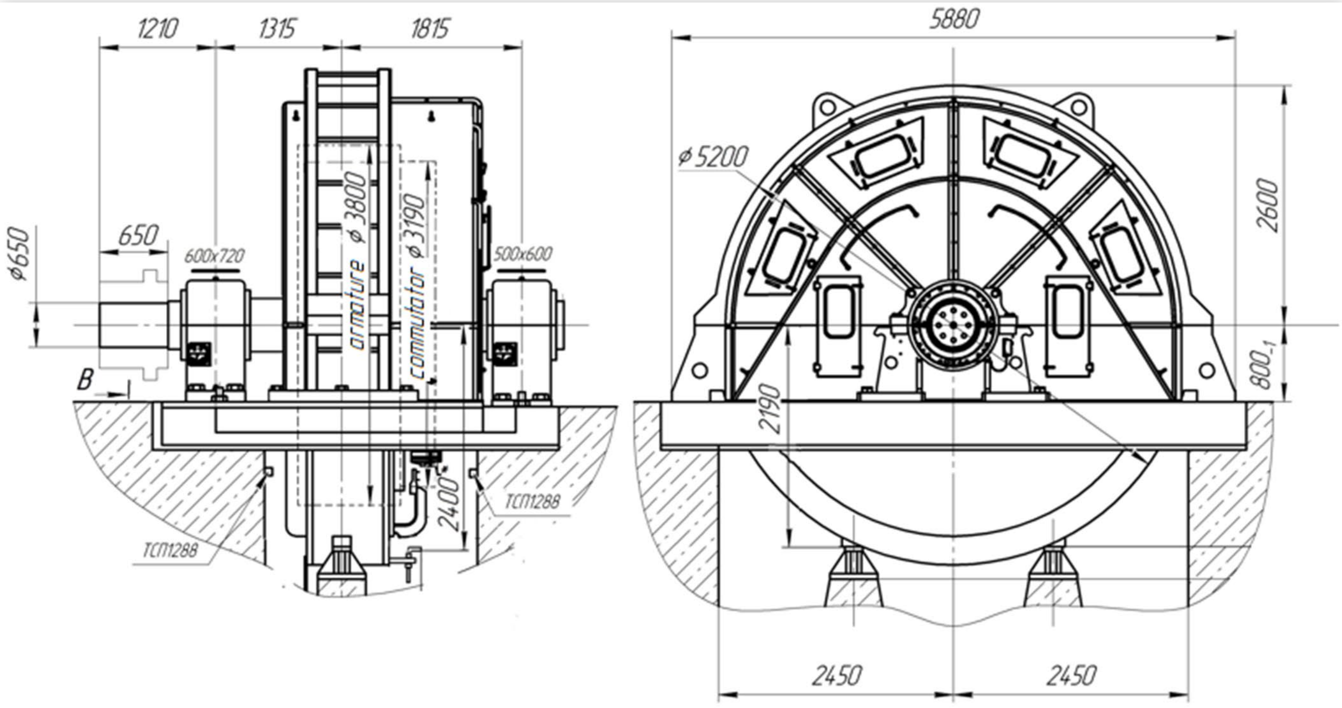


FIGURE 2 General view drawing of the DC machine design under study.



Weight, t			
Magnetic system	Armature	Bearing units	Total (without base plate)
49	44	18	109

3. Operational Electromagnetic Loads

In DC machines, the framework, in addition to the fact that the main and additional poles are attached to it, is part of the magnetic circuit. At the same time, all dynamic mechanical loads are perceived by the framework both through the fastening elements from the poles and their own along the diameter of the case.

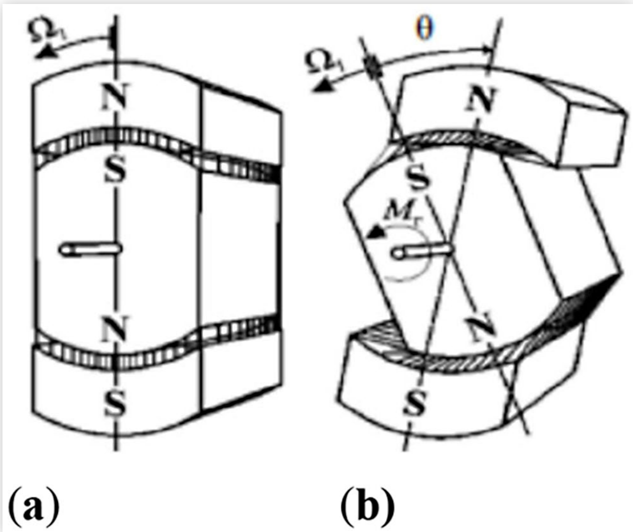
When electric current flows around the armature winding the load of the generator, its own magnetic field is created, which affects the excitation windings. The effect of the armature magnetic flux on the field of the excitation winding is the armature reaction. When these two fluxes rotate at the same frequency, a resultant rotating magnetic flux is created. Under the action of the armature flow, this resulting flow is shifted relative to the flow by the misalignment angle θ in the direction of the lag (see Figure 3). The leading link in electromagnetic conversion is the rotor, i.e., the pole of the rotor is ahead of the pole of the resulting magnetic flux of the synchronous generator. This final magnetic flux creates significant forces on the housing (framework). The most complete calculation of efforts in statics and dynamics is given in the literature [12].

4. Electromagnetic Characteristics of the DC Machine under Study

Basic parameters of the electric motors shall correspond to the indicated ones in Table 1 and should be suitable for long-term operation (S1) as per DSTU IEC 60034-1:2019.

Rated operational mode should be as per S8 as per DSTU IEC 60034-1:2019. The electric motor should admit operation in modes S1 and S8 as per DSTU IEC 60034-1:2019. The basic calculation mode is mode S1, according to which the electric motor is marked and tested.

FIGURE 3 Interaction of the magnetic fluxes of the armature and the excitation winding: (a) idle; (b) under load.



The overload capacity of the electric motor in p.u. (per units) to the rated current should correspond to the following values:

- Maximum operational –2.5;
- Switching off –2.75.

The duration of the specified operating overload shall not exceed 15 sec. In this case, sparking on the collector should not have any impact in the future on long-term and safe operation. The duration of overloads, the value of which is lower than the maximum operating one, is not limited, provided that the r.m.s. (root mean square) current for 10 min of work should not exceed the rated value.

Sparkling degree on the collector of the electric motor should not be higher 1½ as per DSTU IEC 60034-1:2019.

The rotation of the electric motor should be reverse.

The electric motor should allow acceleration and deceleration as many times per shift as required by the mode of operation of the mechanism, provided that the r.m.s. (root mean square) current for 10 min of work should not exceed the rated value.

TABLE 1 Basic technical parameters.

Parameter description	Value
Rated power, kW	2200
Rated voltage, V	900
Rated current, A	2690
Excitation voltage, B	220
Excitation current, A	129 + 20%
Rated speed, rpm	38
Rated torque, kNm	553
Efficiency, %	91%

The electric motor should admit regulation of speed from zero up to the rated one by changing of voltage at the armature terminal clamps.

At power supply of the armature circuit of the electric motor from thyristor converters, the amplitude value of the variable component of the armature current should not exceed 4% of the rated armature current at rated voltage. When the armature voltage drops to 25% of the rated voltage, an increase in the amplitude value of the variable component of the armature current is allowed up to 7%.

The excitation current of the electric motor is specified based on the results of bench tests.

The case insulation of the field winding is designed for maximum voltage of 1000 V.

The insulation of the motor armature windings should be of heat resistance class "H," the excitation windings of heat resistance class "F" in accordance with GOST 8865-93.

The dielectric strength of the insulation of all windings of the armature circuit of the electric motor is designed for a maximum voltage of 1500 V relatively to the housing (the value 1500 V is the test voltage for checking the insulation for electrical strength; serviceable insulation should not be damaged at this value). The insulation resistance of all motor windings relative to the housing and between the windings at operating temperature should be not less than 10^6 Omh.

4.1. Requirements for Resistance to External Influences

Climatic version is UHL. Placement category is 4 in accordance with DSTU EN 60529:2018. The rated value of climatic factors in accordance with DSTU 8280:2015 and DSTU EN 60529:2018, while the ambient temperature is from +1 to +40°C.

The environment should be non-explosive, not containing conductive dust in concentrations that reduce the parameters of the electric motor to unacceptable limits.

The air entering the electric motor should be clean, not containing conductive dust, caustic vapors that reduce the strength and durability of the electric motor insulation, the dust content in the air cooling the electric motor shall not exceed 0.2 mg/m^3.

Cooling air temperature should be from +5 up to 40°C.

Radial and axial loads from the mechanism of the lifting machine on the end of the motor shaft should be absent.

4.2. Requirements to Reliability

The established trouble-free operating time should be not less 24,000 hours (subject to the completion by the customer of all inspections and repairs within the time specified in the operational documentation). The established resource before overhaul should be not less than 8 years. Complete operational service life should be not less than 25 years. Readiness factor should be not less than 0.995. Indicators of durability and reliability of electric motor components should comply with the standards or specifications for these items.

4.3. Requirements to Design

The electric motor should be installed on the existing foundation and foundation plates of the existing motor PBK 380/65, serial number 421849, manufactured in 1952, outline drawing TB200170. All installation and connection dimensions should be saved.

Conventional designation of the design version of the electric motor as per the assembly method shall be IM 7321 as per DSTU 2365-94.

The electric motor shall be manufactured with one working end of the shaft for connection with the lifting machine mechanism. On the opposite end of the working shaft, it must be adapted for attaching a pulse speed control pulse sensor to it (the type of sensor is agreed with the customer).

The noise level (average sound level), measured at a distance of 1 m from the motor housing, in the idle mode of the motor should not exceed 92 dBA according to DSTU EN 60034-9:2014.

The design of the electric motor should be closed with forced ventilation in a closed cycle according to the scheme: fan—electric motor. Cooling air supply from below from the foundation pit through the shield on the drive end, heated air outlet through the foundation pit from the collector side. Ventilation equipment and air-separating partitions in the foundation pit are not included in the scope of supply of the enterprise-manufacturer of the electric motor.

The motor framework should be steel and have a connector in a horizontal plane.

The compensation winding in the places of the connector should have bolted connections. The common point of the anchor and compensation windings should be terminated to the terminals with a wire with a cross section of 16 mm^2, the end of the wire should be marked “O”.

Permissible current for the control circuit, taken from the compensation winding and winding of additional poles, should be not over than 5 A.

The armature should rotate in sliding bearings. The bearing on the collector end should be isolated from the foundation plate. The resistance of the bearing insulation from the foundation plate should be not less than 10^6 Omh.

Temperature control of the bearings should be carried out by manometric thermometers of the TKP-160 SG type and by resistance temperature detectors TSP-1088.

To control the temperature of the incoming and outgoing cooling air, the customer should install resistance temperature detectors of TSP-1288 type with fittings for fastening to the foundation in the foundation pit. The mentioned resistance temperature detectors with fittings should be included in the supply of the electric motor manufacturer.

Temperature control of the motor windings should be carried out according to the resistance method (measurements after stop of the armature) in accordance with DSTU EN 60034-2:2014.

Protection degree by the shell of the electric motor should be:

- Higher foundation plate is IP 22 as per DSTU EN 60034-5:2014;
- Lower of the level of the foundation plate is IP 00 as per DSTU EN 60034-5:2014.

The appearance of coatings should comply with the requirements of DSTU B B.2.6-76:2008 for the sixth class of coating. Protective, decorative, and paint coatings are in accordance with DSTU GOST 9.101:2004 and design documentation.

Provide manufacturing of coils of the main pole according to the characteristics and geometric dimensions of the windings of the operating electric motor PBK 380/65. Material is copper.

The electric motor shall be manufactured with one working end of the shaft for connection with the BBM (ball bearing mechanism) mechanism, for which it is necessary to provide for the manufacture of a coupling between the motor and the root part of the lifting installation, complete with hardware. On the side opposite to the working end of the shaft, it is necessary to adapt to attach a pulse sensor for pulse speed control to it.

4.4. Requirements for Operation, Convenience of Maintenance, and Repair

Group of conditions for the operation of the electric motor in terms of the action of external mechanical factors should be M1 as per DSTU 7308:2013.

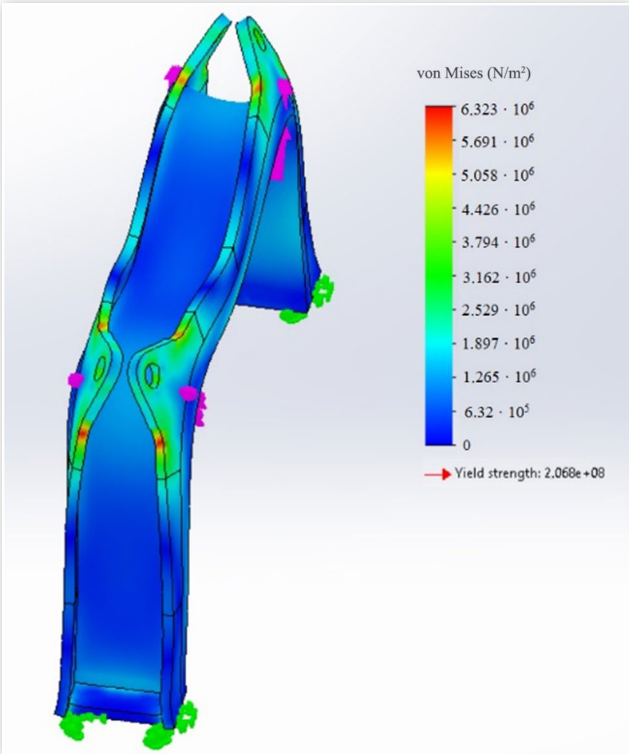
In order to develop and manufacture a lifting cross-piece for lifting of the armature of the electric motor during installation and disassembly, the manufacturer of the electric motor should indicate the required dimensions and weight of the armature on the outline drawing.

On the electric motor housing, provide a ladder and points for the motor maintenance. On the motor housing, provide a ladder and places for motor maintenance.

5. Slinging and Turning over of Heavy Parts for Technological Processing

At turning over of heavy large-sized parts the free-fall amplitude can be high, so the jerks can be strong. It is almost

FIGURE 4 Diagram of stress during lifting of the classic basic structure of the framework.



impossible to eliminate them, since the speed of the fall of the load is much higher than the speed of movement of the mechanisms of any crane.

Choice of the turning over way depends upon the mass and overall dimensions of the load, its shape, the availability of gripping points, and the possibility of attaching to slings. The most common methods are turning over on a weight, on a stop, and on a throw.

In this work, smooth turning over of the load on a scale was used for the technological processing of the framework, i.e., turning over. In this, the load is turned over by coordinated movements of the crane: raising or lowering the hook, moving the bridge or trolley. The overturning is done directly by the movement of the bridge or cart. At the same time, the part will stop simply with a grip or a hook.

The following is the result of the calculation of the technological process of moving the framework of the classic basic design. The stresses during lifting of this structure are presented in Figure 4, with turning over in Figure 5. Figure 6 shows the stress during turning over. With the installed poles, the deformation during lifting of the framework and the stress during its turning over are presented in Figures 7 and 8.

The pink arrows show the direction of the specified loads on the structure. The value of effort was assumed to be equal to the mass of the structure. To analyze the stresses and deformations of the structure, when building the model, the grid described in the article was used [13].

The results of calculations of stresses and deformations of the frame showed that the deformations go beyond the elastic zone of the structure. The voltage for the welds exceeds the allowable ones, and the deformations in the future can affect the change of the air gaps. Based on the results of these results, a decision was made to create one belt of the framework fasteners, the design is presented in Figure 9.

The results of calculations of stresses and deformations of the framework with one belt of fastenings (Figures 10 and 11) showed that such modernization did not solve the problem with deformations that go beyond the elastic zone of the structure. The stress for the welds exceeds the allowable ones, and the deformations in the future can affect the change of the air gaps.

When installing one central belt of fasteners, the stresses correspond to the maximum allowable in relation to the yield strength for welded joints, but further movements change the central axis of rotation. Therefore, further strengthening of the structure is required.

FIGURE 5 Diagram of stress during turning over of classic basic structure of the framework.

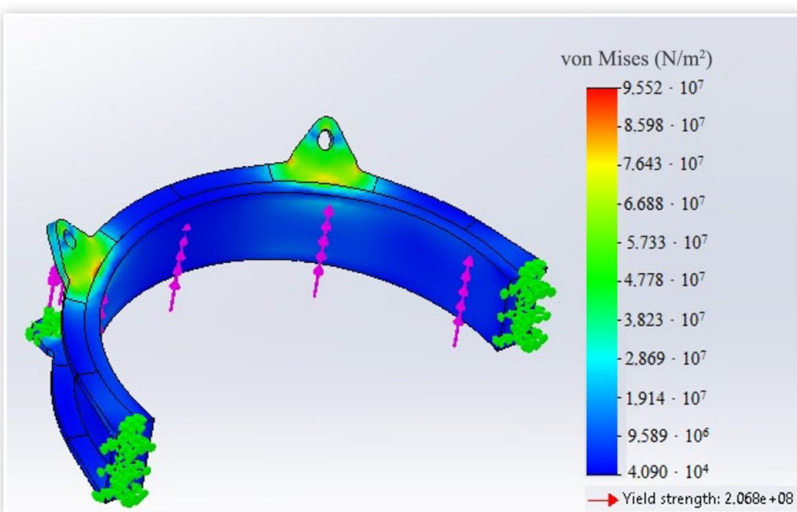
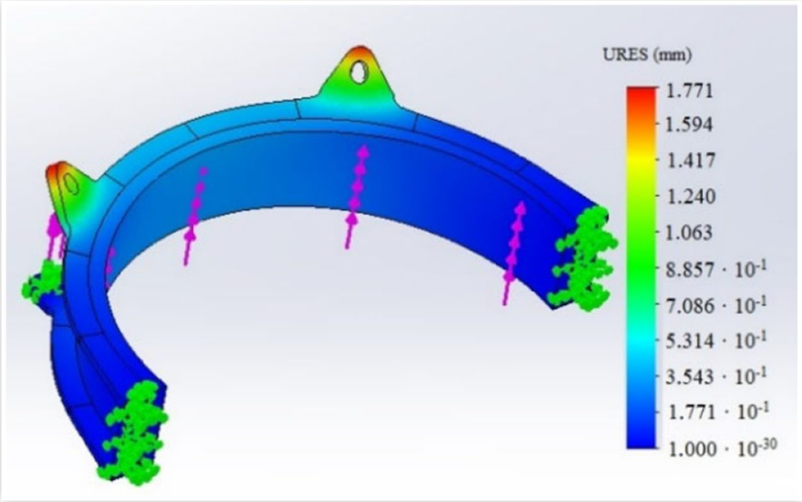


FIGURE 6 Deformations during turning over of classic basic structure of the framework.



6. Deep Modernization of the Structure and Calculation of Its Stress–Strain State

After a more detailed analysis of the structure of the framework under the conditions of technological and working loads, it was decided to add additional transverse and longitudinal ribs, as well as round plates in the area of the ears (all elements are of 40 mm thick) to strengthen the structure of the framework. The appearance of the modernized framework with additional ribs is shown in Figure 12.

The results of the calculations of the stress–strain state of the final structure are shown in in Figures 13-21.

This modernization made it possible to reduce deformations and stresses, meeting all the requirements of technology and operation. Mechanical stresses during lifting and working conditions do not exceed 25 MPa (60 MPa is permissible for welding), movements during lifting and working conditions do not exceed 0.2 mm. Stresses during turning over achieve up to 130 MPa on the base metal, and displacements do not exceed 2 mm. However, all deformations are in the elastic zone.

7. Discussion

This scientific work presents the results of the modernization of the structure of the framework of a large direct current (DC) machine, which made it possible to reduce deformations and leave them in the zone of elastic deformations. At the same time, both classical electromagnetic forces and technological operations necessary for mechanical processing and assembly of such objects, as well as their transportation processes are taken into account for the first time.

For the first time, a regularity of the need to increase the strength of the structure caused by the technological features of assembly and turning over of a large-sized part was obtained.

According to the submitted result, the subsequent installation of the ribs does not make changes to the stress–strain state of the structure at saving of the overall dimensions.

FIGURE 7 Deformations during lifting of the framework with installed poles.

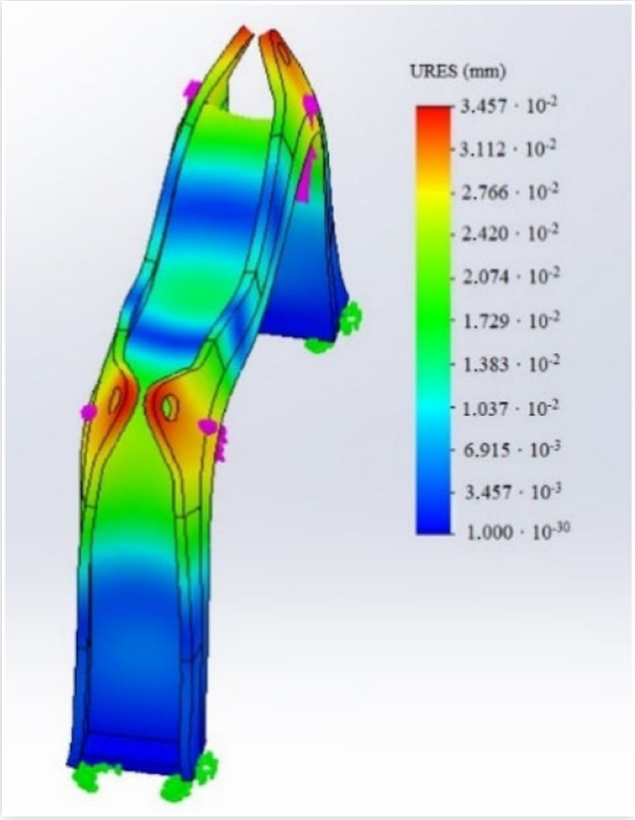


FIGURE 8 Diagram of stress during turning over of the framework with installed poles.

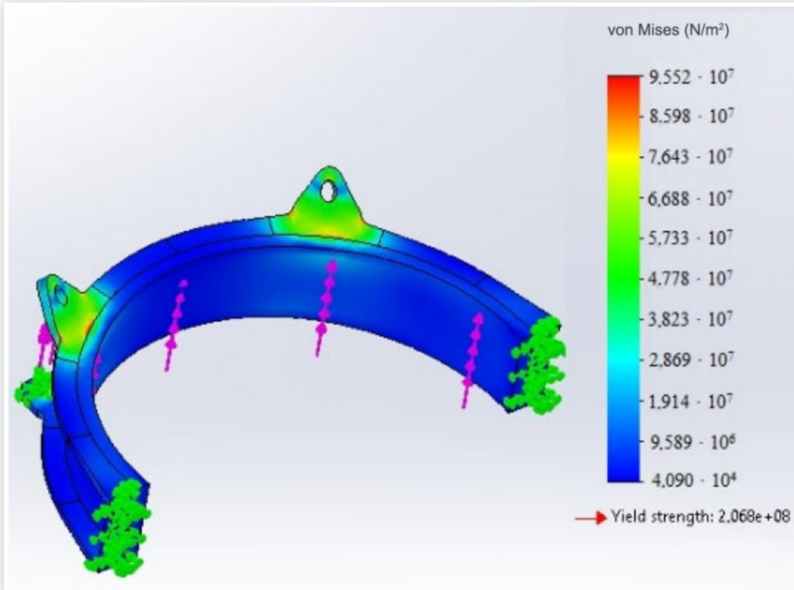


FIGURE 9 Design of the framework with one fastening belt.

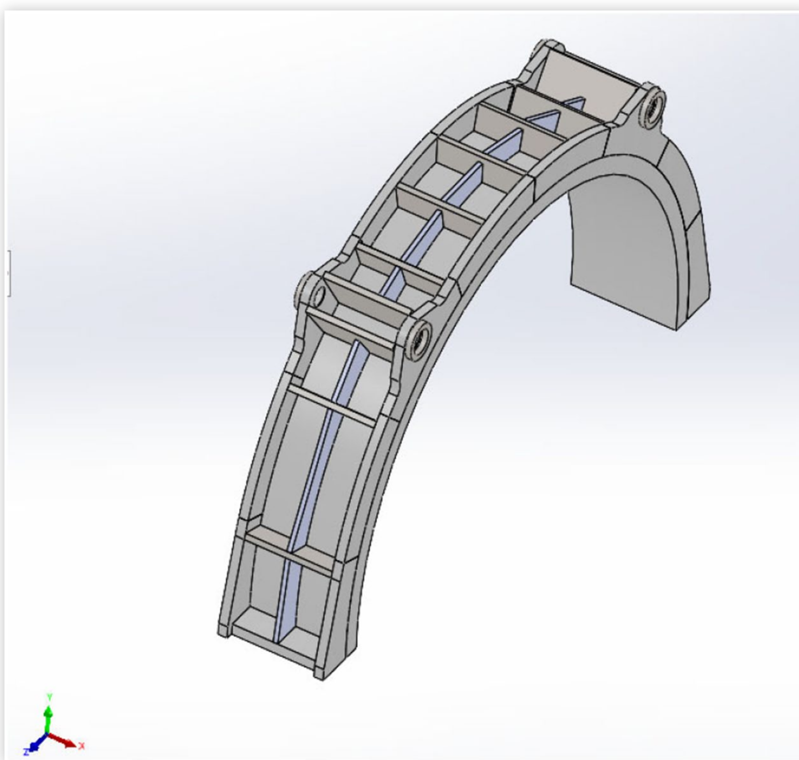


FIGURE 10 Diagram of stress during lifting of the framework with one belt of fasteners.

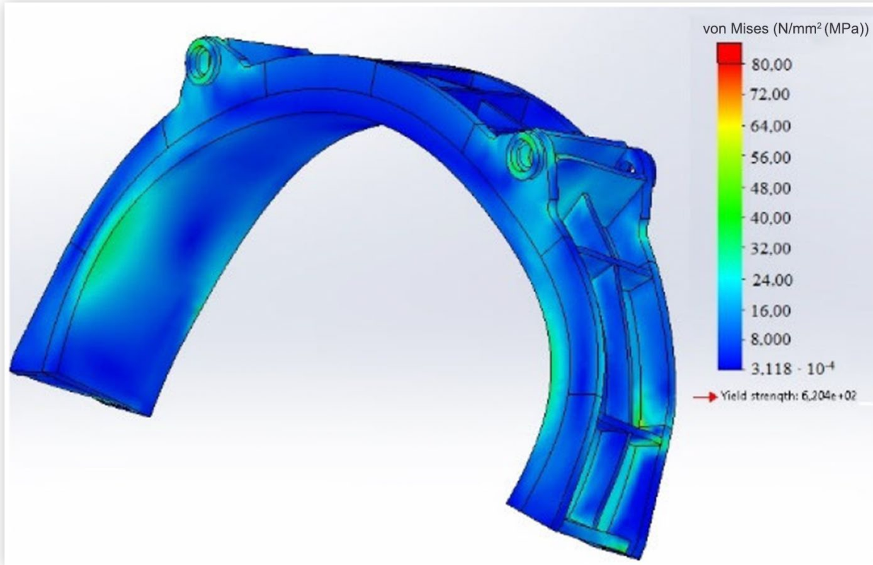


FIGURE 11 Deformations during lifting of the framework with one belt of fasteners.

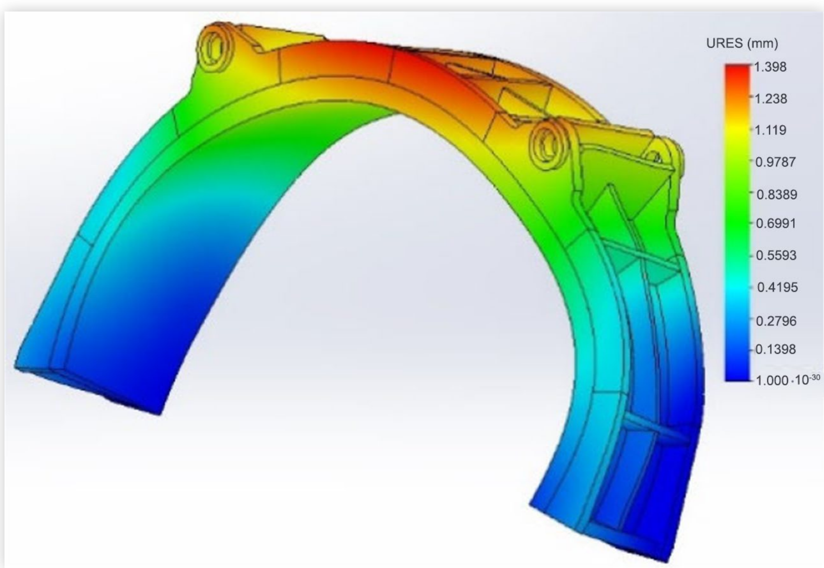


FIGURE 12 The appearance of modernized framework with additional ribs.

FIGURE 13 Loads during lifting of the modernized framework with additional ribs.

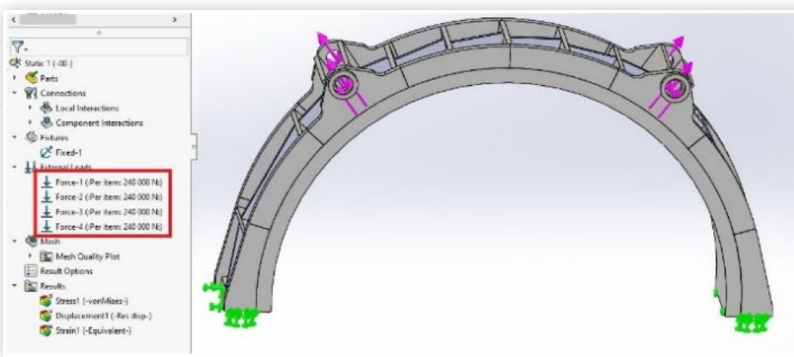


FIGURE 14 Diagram of stress during lifting of the modernized framework with additional ribs.

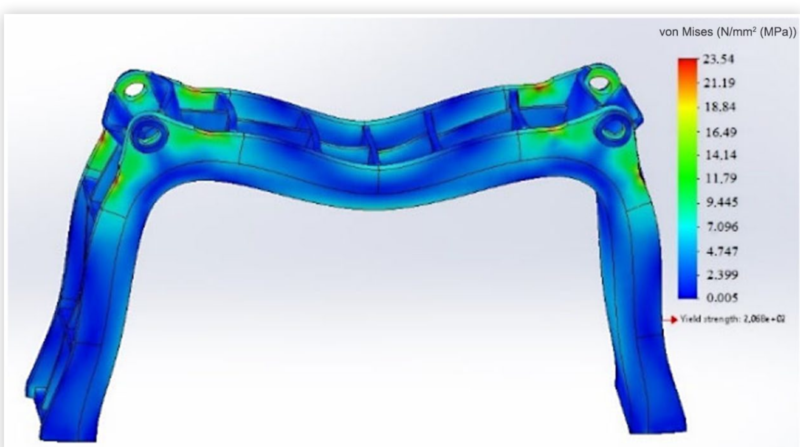


FIGURE 15 Deformations during lifting of the modernized framework with additional ribs.

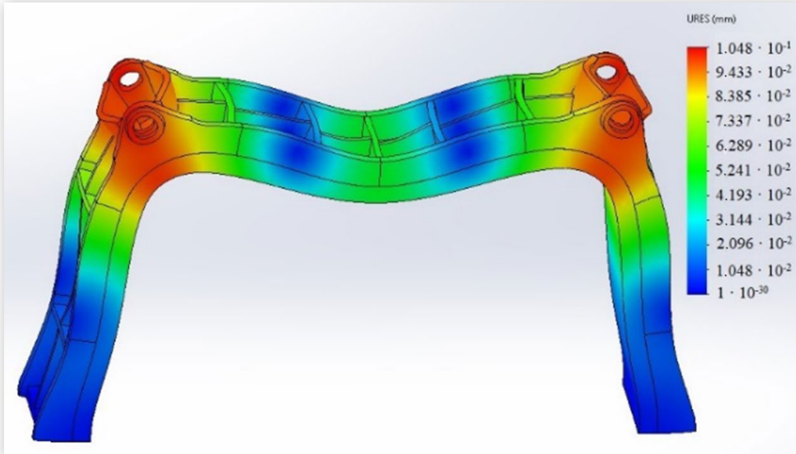


FIGURE 16 Loads during operational state of the modernized framework with additional ribs.

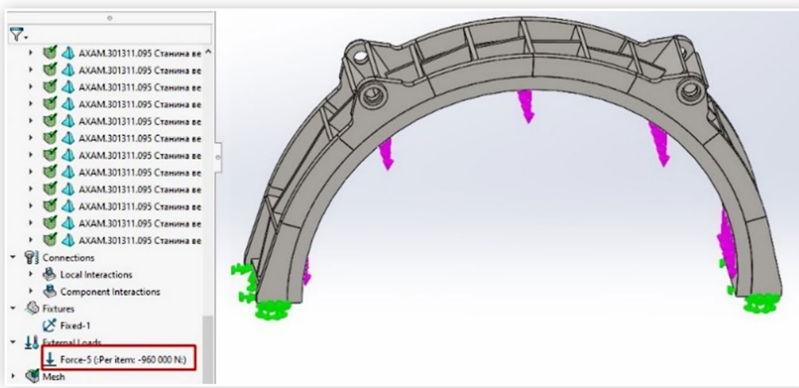


FIGURE 17 Diagram of stress during operational state of the modernized framework with additional ribs.

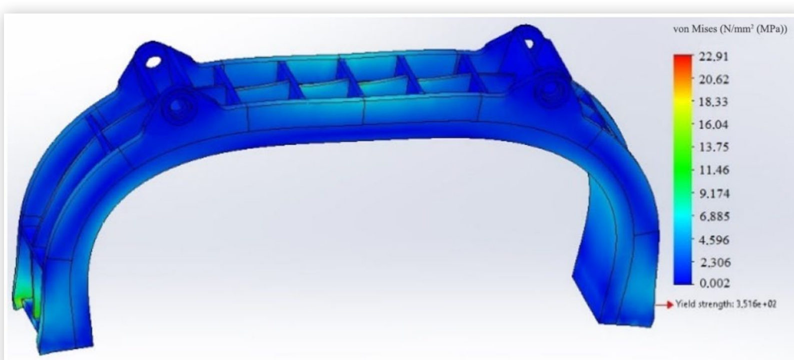


FIGURE 18 Deformations during operational state of the modernized framework with additional ribs.

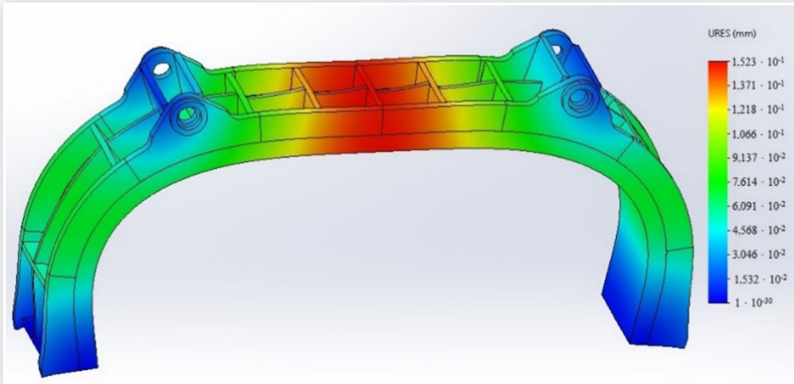


FIGURE 19 Loads during turning over of the modernized framework with additional ribs.

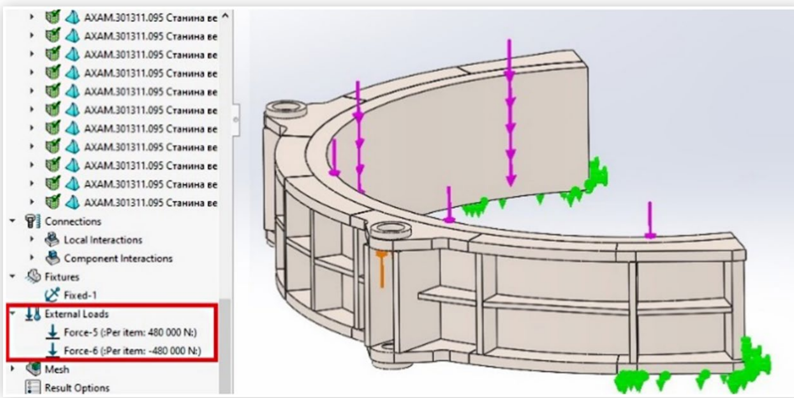


FIGURE 20 Diagram of stress during turning over of the modernized framework with additional ribs.

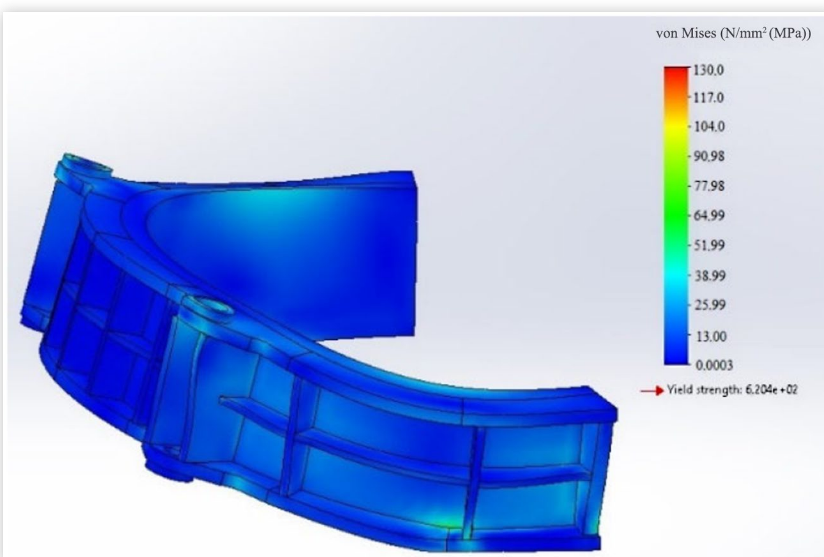
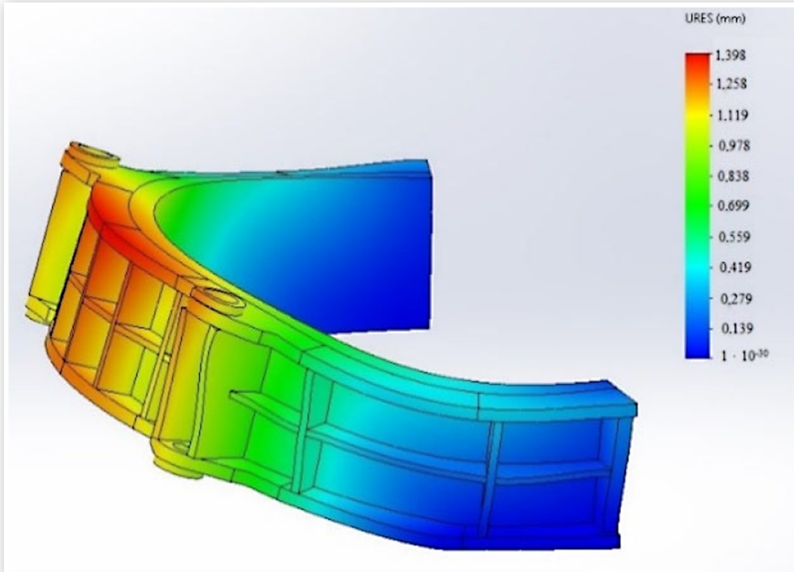


FIGURE 21 Deformations during turning over of the modernized framework with additional ribs.



The presented design was created at limited liability company "Kharkov electric machine-building plant" and passed all bench tests at our own test station. The parameters shown in Table 1 have been verified in full on the running engine.

Funding

This research received no external funding.

Institutional Review Board Statement

"Not applicable" for studies not involving humans or animals.

Conflicts of Interest

The authors declare no conflict of interest.

Contact Information

Dr. Oleksii Tretiak
alex3tretjak@ukr.net

Mariia Arefieva
marii.arefieva@gmail.com

References

1. Warnes, L.A.A., "DC Machines," in: Lynn, P.A. (ed.), *Electronic and Electrical Engineering*, Macmillan New Electronics Series (London: Palgrave, 1994), doi:https://doi.org/10.1007/978-1-349-13012-2_13.
2. Simond, J.-J., Ramirez, C., Xuan, M., and Stephan, C.-E., "A Numerical Test Platform for Large Synchronous Machines Also Useful as a Design Optimization Tool," in *2006 IEEE Power Engineering Society General Meeting*, Montreal, QC, Canada, 2006, 7, doi:10.1109/PES.2006.1709207.
3. Gruboy, O.P. Kuzmin, V.V., Cheremisov, I.Ya., Kobzar, K.O. et al., "Problems and Prospects for the Development of Turbo-Generator Construction in Ukraine Hydropower of Ukraine," 2006, no. 2, 27-35.
4. Melfi, M.J. and Umans, S.D., "DC Machines," in: García, J. (ed.), *Encyclopedia of Electrical and Electronic Power Engineering* (Elsevier, 2023), 264-279, https://doi.org/10.1016/B978-0-12-821204-2.00005-2.
5. Boucht, R.J., Filippini, D., and Lupi, D.O., "Novel Characterization to DC Machines and Their Loads," *IFAC Proceedings Volumes* 28, no. 19 (1995): 255-261, doi:https://doi.org/10.1016/S1474-6670(17)45089-0.
6. Brandisky, K., Pahner, U., and Belmans, R., "Comparative Analysis of Three Classes of Experiment Design Applied to Optimization of PM DC Machines," in: Nicolet, A. and Belmans, R. (eds), *Electric and Magnetic Fields* (Boston, MA: Springer, 1995), doi:https://doi.org/10.1007/978-1-4615-1961-4_15.
7. Sindhu, A., "A Review on Maintenance and Troubleshooting of DC Machines," 2016, doi:10.13140/RG.2.2.36091.67365, https://www.researchgate.net/publication/334783780_A_Review_on_Maintenance_and_Troubleshooting_of_DC_Machines

8. Gosavi, P.R. and Wadhekar, A.R., "DC Motor Condition Monitoring Using Artificial Neural Network," *International Journal of Innovations in Engineering Research and Technology* 5, no. 4 (2018): 105-109.
9. Bahootoroody, F., Khalaj, S., Leoni, L., De Carlo, F. et al., "Reliability Estimation of Reinforced Slopes to Prioritize Maintenance Actions," *International Journal of Environmental Research and Public Health* 18, no. 2 (2021): 373.
10. Di Bona, G., Falcone, D., and Forcina, A., "AHP-TOPSIS Model to Evaluate Maintenance Strategy Using RAMS and Production Parameters," *International Journal of Operations and Quantitative Management* 25, no. 3 (2019): 175-201.
11. Gerling, D., "DC-Machines," in: Lynn, P.A. (ed.), *Electrical Machines. Mathematical Engineering*, vol. 4 (Berlin, Heidelberg: Springer, 2015), doi:https://doi.org/10.1007/978-3-642-17584-8_2.
12. Mollet, Y., Barbierato, G., and Gyselinck, J., "Finite-Element and Magnetic-Equivalent-Circuit Modelling of Brushed Wound-Field DC Machines with Cross-Saturation," in *2016 XXII International Conference on Electrical Machines (ICEM)*, Lausanne, Switzerland, 2016, 350-356, doi:10.1109/ICELMACH.2016.7732550.
13. Tretiak, O., Kritskiy, D., Kobzar, I., Arefieva, M. et al., "Stress-Strained State of the Thrust Bearing Disc of Hydrogenerator-Motor," *Computation* 11 (2023): 60, doi:https://doi.org/10.3390/computation11030060.