Finite element method applied to magnetic flux analysis in large synchronous machines with short circuit faults in the rotor

Método de elementos finitos aplicado al análisis de flujo magnético en máquinas síncronas de gran porte con fallas de corto circuito en el rotor

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Recibido 14 de marzo de 2022, aceptado 07 de diciembre de 2022
Received: March 14, 2022 Accepted: December 07, 2022

ABSTRACT

This paper presents a study of magnetic flux density in a large synchronous large size machine when it is working as a generator. Finite elements software has been used to obtain the same physical and electrical characteristics of the real machine. From the results conveyed from the simulations, it is possible to find the optimal points where the magnetic flux sensors will be placed and to determine short-circuit faults in the rotor coils. The work results are also a reference to evaluate and compare the magnitudes taken by the sensors without creating short-circuits in the actual machine coil. Besides that, the proposed model based on finite elements can be used to make simulation tests of new kinds of sensors.

Keywords: Synchronous machine, finite elements, magnetic flux, short-circuit.

RESUMEN

Este artículo presenta un estudio de la densidad de flujo magnético en una gran máquina síncrona de gran tamaño cuando está funcionando como generador. Se ha utilizado un software de elementos finitos para obtener las mismas características físicas y eléctricas de la máquina real. A partir de los resultados obtenidos por las simulaciones se puede encontrar los puntos óptimos *donde se colocarán los sensores de flujo magnéticos y poder determinar fallas de cortocircuito en las bobinas del rotor. Los resultados del trabajo también son una referencia para evaluar y comparar las magnitudes tomadas por los sensores sin crear cortocircuitos en la bobina de la máquina real. Además, el modelo propuesto basado en elementos finitos puede utilizarse para realizar pruebas de simulación de nuevos tipos de sensores.*

Palabras clave: Máquina síncrona, elementos finitos, flujo magnético, cortocircuito.

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INTRODUCTION

Due to the worldwide need for more efficient and reliable energy management systems, research on synchronous generators has increased to improve their performance and detect faults that can cause unplanned stops, which causes a wide time of unavailability of the machine and high maintenance cost.

The peculiarity of the synchronous machine (SM) is that it rotates at a constant speed in a steady state. Unlike induction machines, the magnetic field and the rotor rotate in the SM at the same speed, called synchronous speed [1]. In addition to being used in large power plants, synchronous generators are also used to generate electricity in small plants, and emergency generators installed in industries, hospitals, airports, and others. In this case, the generator is not connected to an extensive power system but is working in a sunny manner [2]. SMs are used in most electrical power generation systems worldwide, and their operation can affect the reliability and stability of the electrical power system. SMs are considered one of the main elements of the power system, and short-circuit failures in the rotor winding can cause an increase in temperature and vibrations in the rotor, as well as variation in the output voltage. These faults are difficult to detect through simple voltage and current measurements or vibration analysis. Additional SM variables, such as the magnetic flux density inside the machine, must be analyzed to diagnose this type of failure [3].

It is proposed to use the finite element method (FEM) to study the behavior of the magnetic flux inside the large synchronous machine when short-circuit faults occur in the rotor coils; this computational tool can accurately simulate physical problems. The COMSOL Multiphysics software was used to perform the simulations using the finite element method. This software is a multi-purpose platform based on advanced numerical methods, where you can model and simulate a large number of physical systems.

STATE OF ART

Although SM is an integral part of the power system, and FEM is a highly accurate tool that allows studies to be carried out without the need for a real machine, there are few studies dedicated to detecting failures in SM using FEM. As seen in the references [4-6], where we work on the modeling of synchronous machines using analytical methods and validating the results with finite element software, getting results that the calculated data and those obtained through element simulation finite are similar in both cases. In [7-12], the electrical parameters of SMs are determined through methods such as the optimized analysis, domain decomposition method, and simulation of three-phase short circuits. After obtaining the data necessary to determine these parameters from the finite element simulations, the results are compared with values acquired from real tests or provided by the manufacturer, observing good compliance between both values. Only in the studies [13-15] the faults in SMs are analyzed through FEM. In [13], the effects of internal short circuits produced by insulation degradation are studied. A mathematical model is developed by collecting current and voltage samples to monitor and protect synchronous generators against faults and having a database on current and voltage behavior. In [14], short-circuit failures are analyzed at the terminals of the stator winding, with the magnetic data flow obtained from the simulations, a comparison was performed to determine the differences in the SM working under normal operating conditions and with failures, giving as a result that during the short circuit there is demagnetization of the stator and a strong magnetization in the rotor.

The detection of short-circuit faults in the rotor winding of a smooth-pole SM is studied in (15). From the computer simulations of the SM operating with and without faults, magnetic flux density values in the air gap are obtained. These values are analyzed through signal processing techniques to characterize the flow density in the frequency domain. The magnetic flux density signal spectrum pattern was observed to change when short circuits were placed in the windings of the pole coils, which was helpful in identifying this type of fault in the synchronous machine. Neither of the mentioned studies analyzes short-circuit faults in SMs with protruding or large poles, (3) and (15) are the closest studies; however, the synchronous machines studied are dissimilar; the first one is of protruding poles, but it is small and the second one is of smooth poles, while the one used in our study is of large protruding poles. Compared to others, the added value of this work is that there are no previous precedents in this field of research, and it can be helpful in future works where it is necessary to study this type of flaw. It can also be used to compare the results of implementing a device capable of detecting these failures.

METHODOLOGY

Finite elements

The finite element method approximates continuous problems divided into a finite number of parts called finite elements. The behavior of these small parts is specified through a finite number of equations associated with the points (nodes) that connect the elements; thus, a system of linear or non-linear equations conforms the discrete model. The process of dividing the discrete geometric model into small elements is called mottled or "Mesh" [3, 16].

There are Alternative methods to MEF, such as the finite difference method (MDF) and the finite volume method (MVF), but these have certain restrictions. MDF applies simple geometries, and MVF is focused on working with fluids and solids, where it has an excellent performance [17, 18].

COMSOL Multiphysics is a software that facilitates the modeling process through an interface that allows solving using different physical phenomena. That is why it receives the name Multiphysics; this is one of its main advantages over other finite element software, besides having a visual interface that is easier to work with. This software can solve systems with non-linear equations using FEM [19, 20].

Magnetic Phenomena

The magnetic phenomena inside the Synchronous Machine are described using equations derived from Maxwell's equations, which are represented differently. In these equations, the Magnetic flux is described in a closed and limited system with permeable and conductive regions [13]. The FEM, through the magnetic vector potential, calculates the magnetic flux density, which is the quantity of the highest interest in this study. The equations used by COMSOL Multiphysics for magnetic calculations in dynamic analysis obey:

$$\sigma \frac{\partial \vec{A}}{\partial t} + \nabla \times \left(\frac{\vec{B}}{\mu_o \mu_r} \right) - \sigma \vec{v} \times \vec{B} = \vec{J_e} \qquad (1)$$

$$\vec{B} = \nabla \times \vec{A} \qquad (2)$$

Where: σ – Material conductivity, $\vec{A}$ – Magnetic vector potential (Wb/m), $\vec{B}$ – Magnetic flux density (T), μ_o – Permeability of free space, μ_r – Permeability of the material, $\vec{v}$ – Conductor speed, $\vec{J_e}$ – External current density (A/m^2).

Equation (1) is the ampere equation; it is used together with equation (2) to calculate the magnetic vector potential. In equation (1), the displacement current density is neglected due to the low application frequencies and $\left|\vec{J_e}\right| \gg \left|\frac{\partial D}{\partial t}\right|$. However, in this equation, the term $\sigma\vec{v}$ x $\vec{B}$is added to represent the eddy currents generated thanks to the variant magnetic flux within the SM. The external current density $\vec{J_e}$ is constant throughout the conductive area where it is applied. Equation (2) expresses the relationship between magnetic flux density and magnetic vector potential, which is a function of the latter's rotational.

Unlike Ampere's law, Faraday's law and Gauss's law, there are no changes for dynamic analysis (equation (3) -equation (4)).

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad (3)$$

$$\nabla \cdot \vec{B} = 0 \qquad (4)$$

In references (21, 22), equation (3) and equation (4) are described. As the SM has a rotating magnetic field density at a given speed, through equation (5), certain transformations are imposed on the definitions of electric fields in all domains; these transformations are a function of the rotation speed. The electric field is fundamental to calculating the voltage generated by the synchronous machine.

$$\vec{E} = \vec{E}_{material} + \vec{v} \times \vec{B} \qquad (5)$$

In addition to the previous equations, the boundary region equations, must be fulfilled to define the study limits.

$$\vec{n} \times \vec{A} = 0 \qquad (6)$$

$$\vec{n} \cdot \vec{B} = 0 \qquad (7)$$

Equation (6) and equation (7) are applied to the magnetic isolation nodes and establish that the vector product between the normal vector and the magnetic potential in this region is equal to zero, with the same result for the product scaling between the normal and the magnetic flux density.

GENERALITY

In this work, the geometric model of a large machine was used, which has 60 projecting poles and 468 grooves in the stator. Figure 1 shows a cross-section with a detailed view of the geometric model that represents this synchronous machine, and its electrical characteristics under nominal conditions are shown in Table 1.

The stator winding, and the phases are represented by the letters A, B, and C. The type of winding is interwoven and distributed in 468 grooves two layers and with three circuits in parallel per phase.

RESULTS

In the simulations developed in COMSOL Multiphysics, a temporal magnetic flux density analysis is performed. Some results of the simulations are visualized as a thermographic image, where the value of the magnetic flux density is indicated according to the color scale present in the image. It is also possible to observe how the flux density behaves in the MS working under normal operating conditions (without failures) and failure conditions (when there is a short circuit in the rotor coils).

Table 1. SM electrical characteristics.

Number of Phases	**3**
Nominal Apparent Power	200 MVA
Nominal Voltage (phase - phase)	13.8 kV
Current Nominal	8367 [A]
Power factor	Cosø = 0.95
Nominal Speed	120 [rpm]
Operation Frequency	60 [Hz]

Figure 2 shows the image of a small part of the MS, showing that the magnetic flux has constant radial symmetry over time. It is also possible to observe the magnetic paths as they travel through the poles, air gap, teeth, and stator crown. As the MS operates under normal conditions, these behaviors will be repeated throughout the MS. These behaviors are presented in small MSs in the study [3]. The magnetic flux density in the MS reaches its maximum value in the upper corners of the rotor coils; in this area, the flux density has values close to 1.67 [T]. Figure 3 shows in more detail the distribution of flux density in the poles and teeth of the stator.

The points where a sensor can be easily installed in an MS to measure the flux density directly are the air chamber and the ventilation duct, and therefore the focus of the analysis will be on these points. Figure 4 shows how the density of magnetic flux in the air gap behaves when it is analyzed as a function of time. Each of these crests represents the flow density at the poles, and the valleys represent the space between pole and pole.

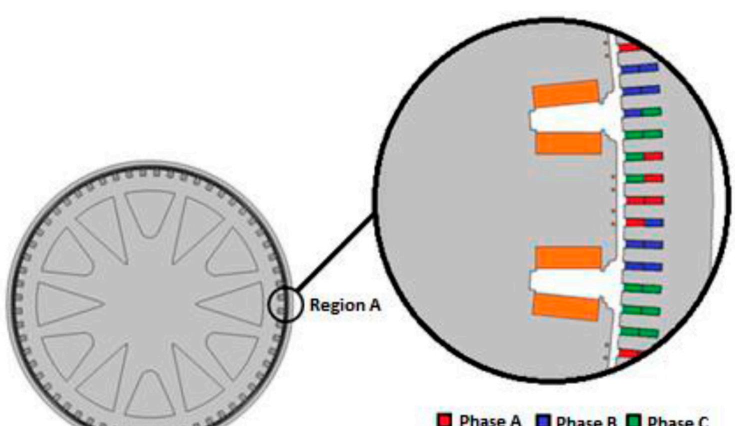

Figure 1. Cross section of SM.

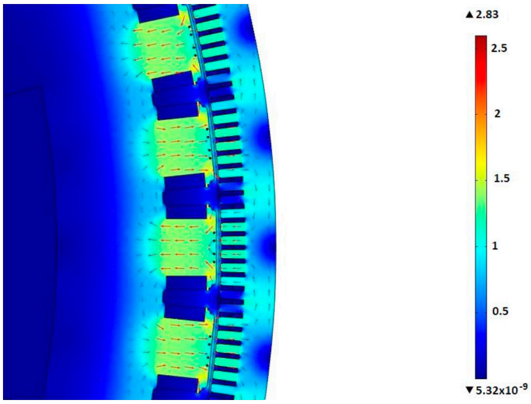

Figure 2. Flow in SM in normal operating condition.

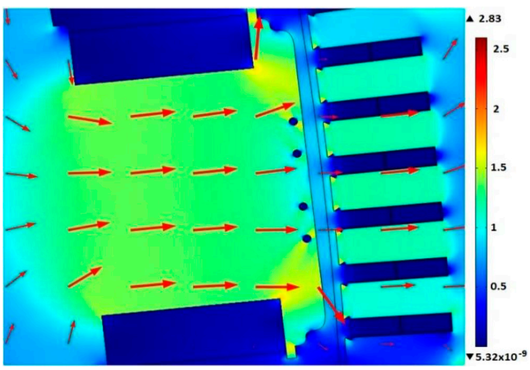

Figure 3. Flow in a pole in normal operating condition.

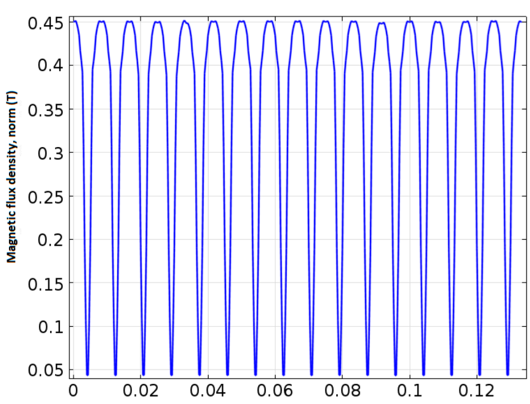

Figure 4. Magnetic flow in the air gap.

The voltages obtained in the stator coils showed a sinusoidal behavior with a 120 ° lag between each of the phases, as seen in the following Figure 5.

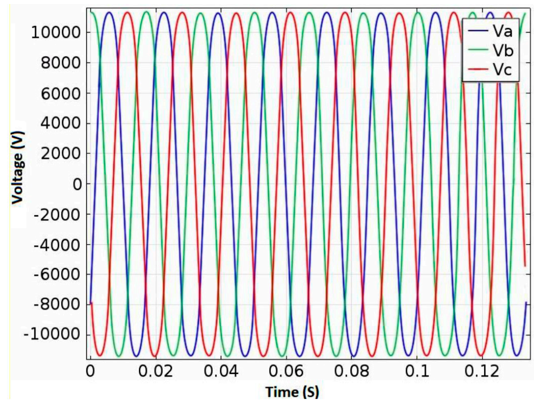

Figure 5. Voltage in the MS stator coils in normal operating condition.

The peak voltage in each phase has a value of 11267 [V]. It can be seen that the waveform is entirely sinusoidal due to the type of winding of the machine, which also attenuates the harmonic components that appear in the MS' small s shown in [3].

When a pole is shorted, the behavior of the magnetic flux density will change. A 5% of the nominal current density of the non-faulted simulations was used to simulate a short circuit in the coil of one of the poles.

Figure 6, shows how the magnetic flux density distribution varied due to the short circuit. The magnetic flux density does not present radial symmetry as it does when the machine operates under normal conditions. The intensity of the magnetic flux density in the short-circuited pole is less than in the neighboring poles to the east. The

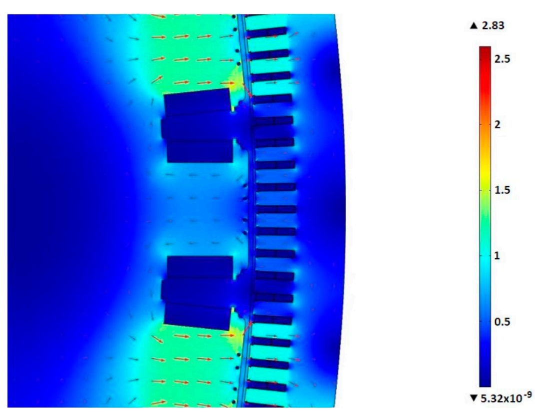

Figure 6. Short-circuit pole flow density.

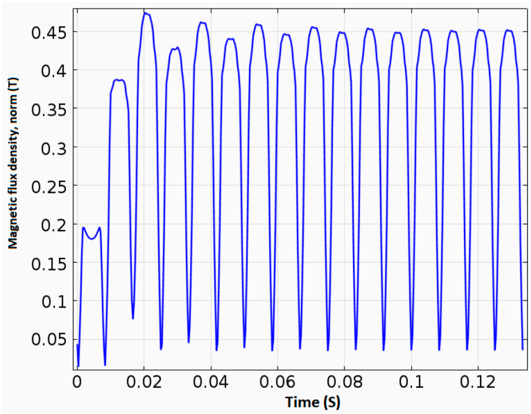

Figure 7. Magnetic flow in the air gap.

magnetic circuit formed by the poles neighboring the short-circuited pole is more intense than the magnetic circuit in the short-circuited pole. The maximum value of the magnetic flux density will be 1.90 [T]. The short circuit will render unstable the behavior of the flux density generated by the poles in the air gap, and it will only stabilize from the poles that are 90º from the short-circuited pole, as shown in Figure 7. This graph also shows that due to the short circuit, the magnetic flux density reaches higher values than when the MS operates under normal conditions.

The small valleys that appear at the tip of some ridges representing the magnetic flux generated by each of the poles in the air gap are caused by the large size of the pole and the small value of the magnetic flux density that is generated by the short circuit; this is shown in Figure 8.

The short circuit in the coil of one of the poles does not affect the waveform of the voltage of the stator coils or their lag, but it reduces the amplitude of the wave. The peak value decreases by approximately 200 [V] due to the short-circuit in the coil of one of the poles.

Another optimum point for the magnetic flux density analysis is the ventilation duct, which runs through the entire stator in a specific area; as shown in Figure 9, the MS has a total of 34 ventilation ducts. In Figure 9, it is also possible to observe how the magnetic flux density in the stator varies due to the air present in the ventilation duct; the flux density is higher in the stator core and lowers in the duct since the air has a high magnetic reluctance.

Figure 10 shows how the magnetic paths in MS are established during their course through two poles, between the ferro, teeth, and crown of the stator. In this case, the non-stator magnetic path will be concentrated before reaching a maximum value in the area that limits the stator core as a ventilation duct. No ventilation duct, it is also possible to observe part of the magnetic path, more than a value much lower than or present no stator core.

Figure 11 shows the behavior of the magnetic flux density as a function of time inside the ventilation duct. The crests represent the magnetic paths of the magnetic flux density as it travels from the north pole to the south pole through the stator. It is noticed that the behavior is entirely different to the behavior of the flow density in the air gap (Figure 4), and the nozzles of the crests are thinner than in the air gap.

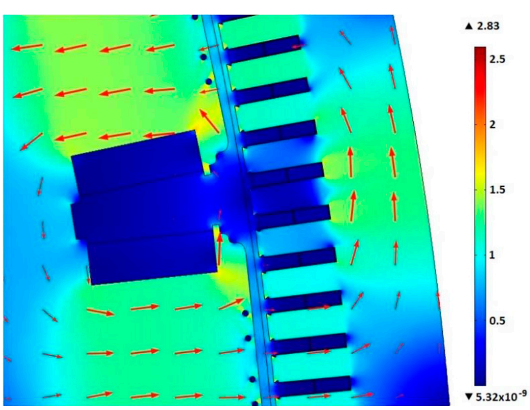

Figure 8. Magnetic flux density at a pole.

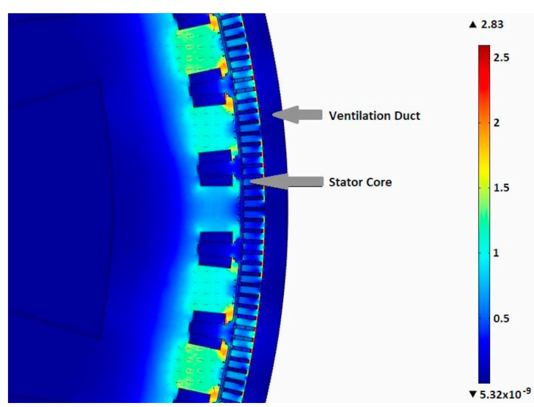

Figure 9. Magnetic flux in MS in normal operating conditions.

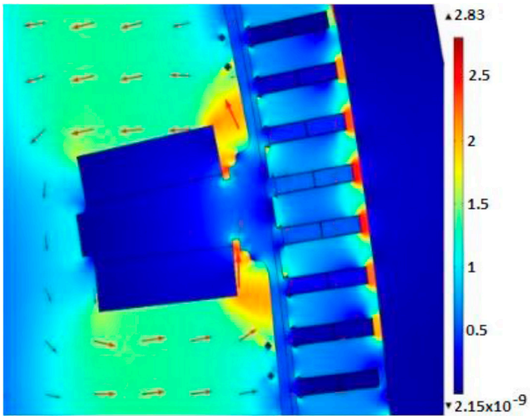

Figure 10. Magnetic circuit in normal operation condition.

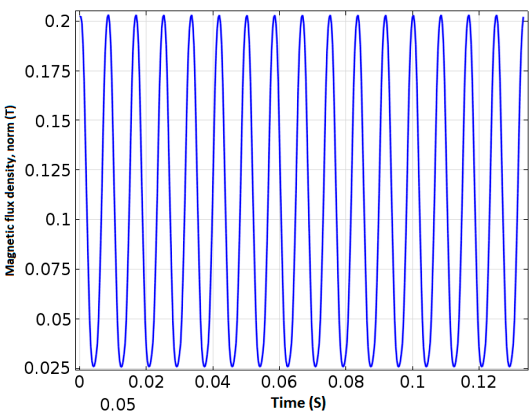

Figure 11. Flow density behavior in the ventilation duct.

When a short circuit occurs in the coil of one of the poles, the behavior of the flow density in the ventilation duct is shown in Figure 12. The two crests of lesser value represent the magnetic paths in the stator between the shorted pole and neighboring poles; in this way, we see that there is a short circuit in one of the poles of the MS.

The distribution of the magnetic flux density in the other areas of the MS is similar to that shown in the previous cases; the intensity of the magnetic flux density in the short-circuited pole will be less than in the neighboring poles, the magnetic circuit formed by the poles neighboring the short-circuited pole becomes more intense than the magnetic circuit in the short-circuited pole, the magnetic path in the stator will be more concentrated in the teeth of the stator since in this area it has a magnetic reluctance less than that of the air present in the ventilation duct. All of these behaviors are described in Figure 13.

CONCLUSIONS

Under normal operating conditions, the magnetic flux density has radial symmetry and is also uniform in some regions of the large MS, a behavior similar to the small machine. Nevertheless, this uniformity and radial symmetry are lost when a short- circuit in the coil of one of the poles decreases the magnetic flux density in the shorted pole and the poles neighboring it and the amplitude of the output voltage but does not change the sine waveform.

The magnetic flux density in the poles adjacent to the faulted pole will also decrease. However, some

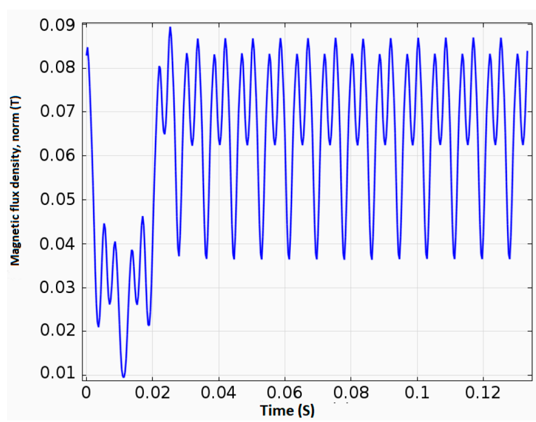

Figure 12. Flow density in the ventilation duct.

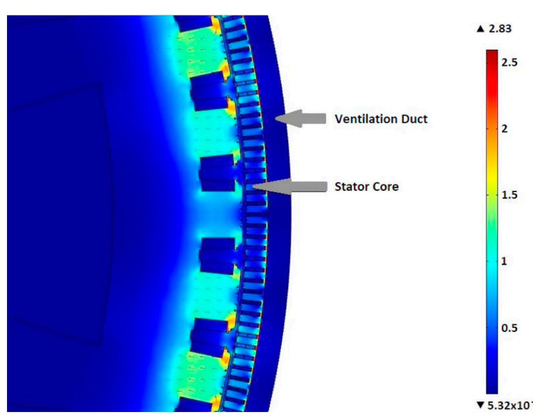

Figure 13. Density of magnetic flow with pole in short circuit.

poles close to the shorted pole show an increase in magnetic flux density, trying to compensate for the magnetic flux not generated by the shorted pole.

When the MS has a large number of poles, the behavior of the magnetic flux density will vary greatly when there is a short circuit in the coil of one of these poles. The behavior of the flux density in the air gap and the ventilation duct is unstable from the short-circuited pole and stabilizes from the poles physically located 90º from the short-circuited pole.

The air gap and the ventilation duct in a large synchronous machine are points where the behavior of the magnetic flux can be easily analyzed for the detection of short-circuit faults in the poles since they are easily accessible points and the flux has a pattern-defined behavior.

The magnetic flux density analysis is an excellent method for detecting short-circuit failures in the pole coils since when this happens, it directly affects the value and the behavior pattern of this magnitude, something that does not happen with the variables monitored by conventional methods. A short circuit in the coil of one of the poles also affects the output voltage, increases the temperature, and causes vibrations. However, these quantities can also be affected by the variation of other types of magnitudes present in the MS.

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