Book Chapter

Stray Flux Sensors Core Impact on the Condition Monitoring of Electrical Machines

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Abstract

The analysis of the stray flux for electrical machine condition monitoring is a very modern and active research topic. Thanks to this technique, it is possible to detect several types of failures, as stator and rotor inter-turn faults, broken rotor bars and mechanical faults among others. The main advantages are that is a non-invasive technique applied with low-cost monitoring equipment. The standard practice is to use coreless flux sensors, with which the stray flux of the machine is not perturbed and there are no problems due to saturation or nonlinear behavior of the iron. However, the induced voltage in the coreless coil sensor may be very low and even, in some cases, with similar amplitude than the noise floor. This paper studies the use of iron core stray flux sensors for condition monitoring of electrical machines. The main advantage of iron core flux sensor is that the measured electromotive force is stronger, and in the case of large machines in noisy environments this can be crucial. Two different types of iron core stray flux sensors and a coreless flux sensor are tested. A comparison of the three sensor is presented. Extensive experimental testing with all sensors shows the superiority and greater sensitivity of sensors with core versus the coreless ones.

Keywords

Electrical Machines Condition Monitoring, Field Winding Inter-Turn Fault, Stray Flux, Stray Flux Sensor, Stator Inter-Turn Fault

Introduction

Detection of electrical machines faults via the stray flux has become a very modern and active research topic, as many early faults that create a magnetic asymmetry in the machines, have become possible to detect [1].

In the case of induction machines, many different cases such as; broken rotor bars [2], inter-turn faults [3] problems in the bearings [4] or even the insulation health and ageing can be detected [5]. For these purposes, several techniques have been applied to analyze the stray flux such as; the bispectrum and covariance [6], the correlation coefficients [7] or the frequency extraction [8]. In some cases, two or more flux sensors are used [3] [7-8]. The mechanical speed frequency has also an important role in the rotor electrical and eccentricity faults detection [9]. Also, Finite Element Method (FEM) studies have been performed studying the impact of different faults on the stray flux in induction machines [10-11].

In case of permanent magnet synchronous machines, the stray flux has been used not only for faults detections [12] but also for metering the rotation speed [13].

Conventional, rotor-wounded, synchronous machines are the most important machines in power generation. The stray flux analysis may be a reliable method to detect early faults in such electrical machines. Past works suggest that inter-turn faults in both the rotor and the stator can be detected reliably [14-15].

Throughout the literature, the most frequently met flux sensors to measure the stray flux in electrical machines are coreless coils, normally know as research coils [1-2] [4-9] some of the authors use rectangular shapes coils [14-15]. Only few authors use other

type of sensors as Giant magneto resistive GMR [11] or Tunneling Magneto resistive Sensors TMR [12-13].

The general operation principle dictates that, the sensors supply an induced voltage, which is proportional to the derivative of the flux. The induced voltage is then recorded and analyzed with appropriate signal processing methods. The positioning of the sensor on the machine is also important as it can lead to the measurement of either the axial or the radial component of the stray flux.

Other industrial sensors, not often used for electrical machine monitoring, are the flux gate sensors or the hall effect sensor [16]. But many researchers design the own sensors adapted to the size of the machine.

In other industrial applications the development of new magnetic field sensors is an ongoing research field. The use of microwires [17], the delta-E effect [18] or the magnetic flux leakage sensor [19] are some of the recent novelties in the area.

The most widespread sensor for electrical machines monitoring is the air core type, mainly for two reasons. This sensor type does not modify the stray flux of the machine and the measurements are not influenced by the nonlinear behavior of the iron core due to the permeability, saturation, hysteresis or eddy currents. On the other hand, as the stray flux may have a low amplitude, the voltage induced in the sensor may be also small, therefore a large number of turns is required.

In this paper two different topologies of iron core stray flux sensors are presented and tested in the laboratory with a special synchronous machine. The magnetic core of the machine is modified by the iron of the sensor and consequently the stray flux changes. The main advantage of the iron core sensors is that the induced voltage is significantly higher than in an air core sensor.

After a thorough experimental investigation, the conclusion is that, the operation of the iron core stray flux sensor is

appropriate and the faults are detected more accurately than with conventional sensors.

Materials and Methods

Air and Iron Core Stray Flux Sensors

The sensors used in this work are manufactured with rectangular shape and are composed by 200 turns of copper wire. The coils are placed in similar dielectric supports. Then at a second stage, the three individual coils are further discriminated by the use or not of iron core. The first coil forms a coreless flux sensor. For the other two sensors, the coils are mounted on iron cores, with U and E shapes respectively. The iron cores have been built by standard magnetic steel laminations used in small transformers. The sensor coil supports are shown in the Figure 1. The dimensions of the sensors are presented in the Figure 2. The dimensions of the laminations are displayed in the Figure 3. All the geometrical data of the sensors are presented in the Table 1. The measurement system is just an oscilloscope which records the induced voltage in the sensors. Afterwards the records are analyzed with Matlab software in a computer.

Figure 1: Flux sensors: Air, Iron core U and Iron core E.

Figure 2: Side and Top views of the coils support.

Figure 3: Dimension of magnetic steel lamination shape U and E.

Table 1: Sensor Data.

Type of Sensor	Iron E		Iron U	Air
Copper Turns numbers	200	200		200
Box Length [mm]	45	45		45
Box Width [mm]	40	40		40
Box High [mm]	25	25		25
Hollow Length [mm]	26	26		26
Hollow Width [mm]	20	20		20
Iron U Length [mm]		40		
Iron U Width [mm]		30		
Iron U one Foot Width [mm]		10		
Iron E Length [mm]	40			

Iron E Width [mm]	60		
Iron E Right &Left Foot Width [mm]	10		
Iron E Middle Foot Width [mm]	20		

The stray fluxes in the three sensors are different. In the case of the air core sensor, the stray flux is not distorted in any way. On the other hand, the iron cores increase the magnetic flux density due to the low permeability of the new flux path. Consequently, the sensors output voltage amplitude will be significantly greater with iron core sensors.

Laboratory Experimental Setup

This section describes the experimental setup for testing the three stray flux sensors. The tests have been performed in a specially reconfigured synchronous machine where is possible to carry out different electrical faults in the rotor and the stator. In Figure 4 and Figure 5, the electric connections schemes of the stator and rotor are shown respectively. The stator phase C has partial windings taps which allow to perform inter-turn faults of variable severity in the stator (Figure 4). Additionally, the salient poles connections are reachable through a hole in the shaft, so inter-turn rotor faults of varied severity can be emulated by the use of the variable fault resistance R_F (Figure 5).

Figure 4: Synchronous machine stator connections.

The complete experimental test bed is shown in Figure 6. The synchronous machine (1) is driven by an induction motor (2) fed by a frequency converter (3). The excitation of the machine is connected to an adjustable DC voltage source (4). The machine is connected to the power system by a panel (5) comprising of a synchronizer. In this particular test an iron core stray flux sensor with E shape is placed in the upside part of the machine (6). Other tests have been performed with the sensor placed in the right side of the machine. The induced voltage in the sensor is recorded in an oscilloscope (7).

Figure 5: Synchronous machine rotor connections.

As explained before, the pole connections are accessible in the shaft (8). In the connections different resistances R_F can be connected to emulate inter-turn faults. On the other hand, there are additional terminals with the taps of the stator phase C (9). The rated parameters of the special synchronous machine are shown in the Appendix.

Figure 6: Experimental setup. (1) Synchronous machine, (2) Asynchronous motor, (3) Frequency converter (4) DC adjustable voltage source for excitation, (5) Connection panel with synchronizer, (6) Iron core E type Flux sensor, (7) Oscilloscope, (8) Poles connections and (9) stator taps terminals.

The synchronous machine is synchronized and connected to the grid. The active and reactive powers are controlled by the frequency converter (3) and the DC adjustable voltage source (4) respectively.

Results

In this section, the results of the different tests under different conditions are presented. The first set of tests has been performed with the healthy machine. The second set of tests corresponds to the machine with rotor inter-turn fault with different fault severities. This fault produces an unbalance related to the mechanical frequency, which for this case is 25 Hz. Finally, the third set of tests corresponds to inter-turn fault in the

stator. This fault normally produces a signature at 850 Hz and 950 Hz. Because these frequencies (f_{SISC}) are related to the electrical frequency (f_1) multiplied by number of stator slots (k) divided by the pair poles (p), according to the equation (1). In this case the stator slots are 36 and the pole pairs are 2, while the electrical frequency is 50 Hz.

$$f_{SISC} = \left[\frac{k}{p} \pm 1 \right] f_1 \quad (1)$$

Healthy Condition

This section presents the results of the three sensors metering stray flux in a laboratory synchronous machine in healthy conditions in two different positions, one in the upper part of the machine and the other in one side, as explained in the previous section.

Figure 7: Induced voltage measurement in healthy conditions right side position.

In the Figure 7 the induced voltage in the three flux sensors are presented. In case of healthy machine, the main component of the voltage corresponds to the 50 Hz frequency harmonic, as it can be shown in the Figure 8. As it can be clearly observed in the Figures 7 and 8, the signals and their respective harmonic components are similar. However, the voltage amplitudes offered by the iron core sensors are between four and seven times greater than those by the air-cored sensor.

Figure 8: Frequency analysis of the induced voltage measurement in healthy conditions right side position

The measurements have been taken in a laboratory where there are some electronic power converters in operation. Consequently, the three sensors have a high noise floor. However, the noise influences the case of the air-cored sensor the most (Fig. 10).

In Figures 9 and 10 the induced voltages and their harmonics' analysis are presented respectively for the case of the healthy machine with the flux sensors placed in the upside position.

Figure 9: Induced voltage measurement in healthy conditions upside position.

Figure 10: Frequency analysis of the induced voltage measurement in healthy conditions upside position.

Table 2 shows the results obtained by the three sensors under healthy condition at different positions. A comparison between the 50 Hz, the 25 Hz and the 850 Hz components are presented, as these frequencies are typical in the rotor and stator inter-turn faults respectively.

Table 2: Results of Healthy Condition.

Condition	Healthy Upside			Healthy Right side		
Type of Sensor	Iron E	Iron U	Air	Iron E	Iron U	Air
Max Voltage [V] (Abs value)	3.6	3.12	0.824	3.52	2.88	0.888
Amplitude at 50Hz [dB]	0	0	0	0	0	0
Amplitude at 25Hz [dB]	-26	-26	-24	-25	-26	-23
Amplitude at 850Hz [dB]	-46	-44	-32	-40	-44	-33

Rotor Inter-Turn Faulty Conditions

This subsection presents the results of the three stray flux sensors metering in the laboratory in case of synchronous machine rotor inter-turn faults with 5 % and 15 % of fault severity.

In the case of an inter-turn fault, one of the poles of the machine has a lower number of winding turns in operation. Consequently, a magnetic unbalance is created, as one of the poles produces a lower magnetomotive force than the others. Under such conditions, a harmonic correspondent to the rotating frequency is expected to appear in the stray flux of the stator [14-15].

Figure 11: Induced voltage measurement with a 5% inter-turn rotor fault severity. Upside position.

Figure 12: Frequency analysis of the induced voltage measurement with a 5% inter-turn rotor fault severity. Upside position.

In Figure 11 the induced voltages recorded by the three sensors are presented for operation under 5% rotor inter-turn fault. While the machine has four poles, the rotating mechanical frequency is 25 Hz. The corresponding harmonic analysis are displayed in Fig. 12 for all sensor cases.

The induced voltage amplitude is greater in case of iron core sensors than air, especially in the E shape type. Moreover, the calculated spectra are similar, while it can be clearly seen that the 25 Hz harmonic, correspondent to the inter-turn fault in the field winding, presents an increased amplitude compared to the healthy machine.

In Figures 13 and 14, the induced voltage and the harmonics analysis in the three sensors are presented respectively for a 15% rotor inter-turn fault. The results are close to those presented above, but the amplitudes of the 25 Hz components are greater than in previously studied cases as expected.

Figure 13: Induced voltage measurement with a 15% inter-turn rotor fault severity. Upside position.

Figure 14: Frequency analysis of the induced voltage measurement with a 15% inter-turn rotor fault severity. Upside position.

From Table 3, it can be clearly seen that the 25 Hz component can be detected by the three sensors. Furthermore, the amplitude differences between the fundamentals at 50 Hz and the 25 Hz signatures are similar. However, the induced voltage amplitude in the iron core E shape is eight time greater than in the case of air core.

Table 3: Results of Rotor Inter-Turn fault.

Condition	Rotor Inter-Turn 5%			Rotor Inter-Turn 15%		
Type of Sensor	Iron E	Iron U	Air	Iron E	Iron U	Air
Max Voltage [V] (Abs value)	4.08	2.64	0.56	5.68	3.76	0.72
Amplitude at 50Hz [dB]	0	0	0	0	0	0
Amplitude at 25Hz [dB]	-17	-17	-17	-7	-9	-10

Stator Inter-Turn Fault Conditions

This section presents the results from the three sensors metering stray flux analysis in a laboratory synchronous machine in case of stator inter-turn faults. The severity level of the fault has been set to 2 % and 4 % of the winding. In both cases a 3 Ω limiting resistor is connected with the shorted loop in order to limit the developed short current of high amplitude, so that the machine is kept safe from overheating and catastrophic damage.

Figure 15: Induced voltage measurement with a 2% inter-turn stator fault severity. Upside position.

Figure 16: Frequency analysis of the induced voltage measurement with a 2% inter-turn stator fault severity. Upside position.

Figures 15 and 16 present the induced voltage waveforms in both the time domain and frequency domain under operation with 2% stator inter-turn fault. The synchronous machine tested has 36 stator slots and 2 pole pairs. Therefore, the 17th and the 19th harmonics raise in case of an inter-turn fault in the stator. In the case of iron core sensors these harmonics are quite clear. However, the same harmonics are hidden in the noise floor for the case of the coreless sensor.

In Figures 17 and 18 the induced voltage waveforms and the respective harmonics analysis for the three sensors are presented respectively for machine operation under 4% stator inter-turn fault. The results are close to those presented above, the amplitudes of the 17th and 19th harmonics components are similar than those obtained for 2% fault severity, the non-monotonous behavior is similar as in the case of induction machines [20].

The results analysis for machine operation under stator inter-turn faults are summarized in Table 4 for all used sensors and fault severity levels.

Figure 17: Induced voltage measurement with a 4% inter-turn stator fault severity.

Figure 18: Frequency analysis of the induced voltage measurement with a 4% inter-turn stator fault severity.

Table 4: Results of Stator Inter-Turn Fault.

Condition	Stator Inter-Turn 2%			Stator Inter-Turn 4%		
Type of Sensor	Iron E	Iron U	Air	Iron E	Iron U	Air
Max Voltage [V] (Abs value)	3.8	2.4	0.84	4.32	3.56	0.664
Amplitude at 50Hz [dB]	0	0	0	0	0	0
Amplitude at 850Hz [dB]	-25	-29	-21	-36	-35	-25

Discussion

Air-cored sensors has been the usual solution met in past works. The sensors consist of rigid coils with different shapes, either round or rectangular. The coils should have a high number of turns to increase the sensors sensitivity, because the stray flux amplitude is very low due to the high magnetic reluctance between the stator iron core and the exterior of the machine. As a result, only a small fraction of the flux radiates outside the machine.

In this paper, two different iron core stray flux sensors are presented and compared to an air-cored flux sensor with similar turns number. The iron core shapes used are U and E, typically found in small transformers. At the beginning of this research, two different problems were expected. On one hand the iron core of the sensor will modify the magnetic circuit when placed close to the machine. Consequently, the stray flux in this part of the machine is different than in the rest. It was not sure that the assessment of the flux under such conditions can identify the faults. After the tests we can conclude that the iron core stray flux sensor can identify the faults in exactly the same way as the conventional coreless one

On the other hand, the saturation, and the nonlinear behavior of the iron can modify the induced voltage in the sensor coil. According the performed tests, the waveform in the iron core sensor and in the air-cored sensor are similar for frequencies up to 300 Hz. For frequencies above 300 Hz the iron core sensors have lower gains. But in the case of stator inter-turn faults the 17th and 19th harmonics are better detected than in the case of air core sensor.

The use of iron presents an important advantage, the induced voltages in the coil are greater than in the case of the air-cored sensor. In the executed tests, the obtained amplitudes are between 4 and 7 times higher.

In Table 5 a summary of the results is presented. To evaluate the sensibility of the sensors, the amplitude differences of the

various harmonics from their respective fundamentals are compared.

Table 5: Summary of the Results.

Type of Sensor	Iron E	Iron U	Air
Healthy			
Amplitude [dB] (25 Hz)	-26	-26	-24
Rotor Interturn 5%			
Amplitude [dB] (25 Hz)	-17	-17	-17
Rotor Interturn 15%			
Amplitude [dB] (25 Hz)	-7	-9	-10
Healthy			
Amplitude [dB] (850 Hz)	-46	-44	-32
Stator interturn 2%			
Amplitude [dB] (850 Hz)	-25	-29	-21
Stator interturn 4%			
Amplitude [dB] (850 Hz)	-36	-35	-25

In the case of the E shape sensor, if an inter-turn fault happens in the rotor, the amplitude of the 25 Hz harmonic increases by 9dB (from -26 dB to -17 dB) for 5% and 19 dB (from -26 dB to -7dB) for 15 % fault severity respectively. The obtained results by using the U shape are similar, increasing by 9 dB and 17 dB for 5% and 15% inter-turn rotor faults respectively. For the air-cored sensor the increases are 7 dB and 14 dB respectively.

The inter-turns stator faults are undoubtedly better observed by using the iron core sensors. The amplitudes increase of the 17th and 19th harmonics are remarkable when compared to the adjacent harmonics. This can be clearly seen in Fig 16 and Fig. 18. On the other hand, these harmonics are not so easily detected when the air-cored sensor is applied.

Conclusions

The normal practice in electrical machine monitoring is the use of air-cored flux sensors. After mounted outside of the monitored machine, the induced voltage is recorded and analyzed. In this way the stray flux of the machine is not perturbed and there are no problems due to saturation or nonlinear behavior of the iron.

However, the induced voltage may be weak, mainly due to the high reluctance between the actual stator iron core and the sensors.

Instead, this paper proposes iron core stray flux sensors with E and U shapes for the same task. These sensors have been built with standard iron lamination used for small transformers. Although the magnetic circuit of the machine is slightly modified and consequently the stray flux, the faults can be easily detected. The characteristic frequencies of the rotor and stator interturn fault can be clearly observed in the performed tests. On the other hand, the non-linear behavior of the iron due to the permeability, saturation, hysteresis or eddy currents does not affect to the fault detection.

Two different types of iron core stray flux sensors and an air-cored flux sensor have been tested and compared. All sensors have the same geometry and number of turns in the rigid coil. The correct operation of the iron core stray flux sensors has been validated by experimental results in a specially reconfigured synchronous machine where inter-turn faults are performed in the rotor and in the stator windings.

The analysis results suggest that the use of iron core flux sensors is advantageous. The main advantage is significantly greater amplitude of the induced voltage for the same stray flux. This feature can be crucial for the case of large machines in noisy environments. Furthermore, the sensitivity of the iron core flux sensors to the signatures related with stator inter-turn faults was significantly greater than that of air-cored ones. Finally, in case of rotor inter-turn faults, the use of the iron core sensor with E shape offered slightly better results.

Appendix A

Table 6: Rating of the synchronous machine.

Machine Type	3 Phase Synchronous Machine	10LCE-132ME1.4
Rated Power	3.4	kVA
Rated Voltage	400	V
Rated power factor	0.8	
Rated Frequency	50	Hz
Speed	1500	Rpm
Rated Field Voltage/ Current	32/2.9	V /A
Stator slot	36	
Pole pairs	2	

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