ISSN (Online) : 2348 - 2001

International Refereed Journal of Reviews and Research

Volume 6 Issue 2 March - April 2018

International Manuscript ID : 23482001V6I2032018-05

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Detection of Stator Winding Faults Using Finite Element Analysis (FEA) in BLDC Motors

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Abstract: - Detection of eccentricity faults has been feasible using physical and vibrational parameters. The Brushless DC motor is undergoes various kinds of stresses including mechanical, electrical, thermal, and environmental. These stresses increase the probability of occurrences of stator faults with various severity levels. The well maintained BLDC motor and correct operations decrease the probability of occurrences of faults. These faults are of three types as damage in laminations, damage in frame of stator and faults in stator winding. As per study of IEEE and EPRI, most frequent fault is stator fault, which is approximately 28–36 % of overall faults [1, 2]. Majority of these faults are due to a combination of above stresses.

It is essential to detect and diagnose such faults at the early stage through measurement and monitoring of changes in the magnetic flux of the BLDC motor in the motor windings and stator slots. In this paper, brushless dc motor and its stator, rotor and windings are designed using FEA method .Changes in magnetic flux of each of the element in the motor are monitored in case of the change in the air gap between rotor and stator .Changes in the magnetic flux ,current are analysed using model of healthy and faulty motors with static and dynamic eccentricity faults. The results indicate detection of faults at the early stages of operation of BLDC motor. This early detection and correction of faults will be useful in avoiding wear and tear .

Key Words: Brushless DC motor, Air Gap Eccentricity Faults, FEA Magnetic Flux

1. Introduction

Brushless DC motors are primarily used in industries, automobiles, refrigeration industries and home appliance industries. Industry Assessment Study (IAS) was conducted by Electric Power Research Institute, IEEE working group and Generic Electric (GE) to evaluate the reliability of DC motors and various types of faults were studied [1]. The faults were of broadly of four types as Bearing faults (41%), Stator Faults (36%), Rotor Faults (9%) and other types of faults (14%). The stator faults were further categorized into following categories:

Root Causes for Stator Faults	Percentage (%)
Ground Insulation	22%
Turn Insulation	4%
Bracing	3%
Wedges	1%
Frame	1%
Cable	1%
Other	3%

The insulation windings contribute to 26% with ground insulation (22%) and Turn insulation (4%). As per study of stator faults by Siddique A, Yadava GS, Singh B [2], the stator faults were categorized into following four categories:

Types of BLDC motor Faults	
Laminations	• Core hot spot • Core slackening
Frame	• Vibration • Circulating currents • Loss of coolants • Earth faults
Stator Windings Defects/Faults : End-winding portion	• Local damage to insulation • Fretting of insulation • Contamination of insulation by moisture • Oil or dirt • Damage to connectors • Cracking of insulation • Discharge erosion of insulation
	• Displacement of conductors • Turn-to-turn faults
Stator Windings Defects/Faults : Slot portion	• Fretting of insulation • Displacement of conductors

2. **Root Causes of Stator Winding Fault Failures**

The various causes of Stator Winding Fault Failures stator failures have been identified [2-5] and has been attributed to various kinds of stresses thermal, electrical, mechanical, and environmental.

2. Root Causes of Stator Winding Fault Failures

The various causes of stator winding fault failures have been identified [2-5]. These faults been attributed to various kinds of stresses included (limited to) thermal, electrical, mechanical, and environmental.

A. Thermal Stresses:

The overloading and aging of windings, attributed to continuous operations of motor results in thermal faults. As per study by P. J. Tanver and J. Penman [3], it is observed that the life of insulation is directly proportional to the rise of temperature, which further leads to the vulnerability of overall windings.

L= Loss of Insulation
T = Rise in Temperature

$$L\ \alpha\ \Delta T$$

The loss of insulation results in increase of dielectric, mechanical, and environmental stresses.

D = Dielectric Losses
M= Mechanical Stresses
E= Environmental Stresses

$$L\ \alpha\ \ D\ or\ M\ Or\ E$$

The winding failure will occur irrespective of the degree of thermal aging, if any of the above mentioned stresses becomes severe. The effect of temperature on thermal aging can be minimized by using any of two approaches to ensure longer thermal life either by reducing the operating temperature or by increasing the class of insulation materials used.

B. Electrical Stresses:

The stress due to electrical voltages can be classified into four categories of root causes as dielectric, tracking, corona, and transient voltage conditions [3-4]:

i. **Tracking: It** occurs when windings leads to ground failures. This failure occurs if insulation system is not completely protected from the environment. In case of lack of protection of environment, motors with operating voltages over 600 V results in phenomenon known as tracking. [3]

ii. **Corona :** It is a severe phenomenon on the winding operating above the 5-kV range. [5] Corona is a localized discharge resulting from transient gaseous ionization in insulation system where the voltage stress exceeds a critical value. The root cause of this failure mechanism is due to heating, eroding, or a chemical reaction, resulting in a deterioration of winding insulation.

iii. **Transient voltage conditions** results in reduced winding life or premature failure (either turn-to-turn or turn-to-ground). These conditions can be caused by line-to-line, line-to-ground, multiphase line-to-ground, and three-phase faults, repetitive restriking, current-limiting fuses, rapid bus transfers, opening and closing of circuit breakers, capacitor switching, insulation failure, lightning, and variable frequency drives [6].

C. Mechanical Stresses:

These types of stresses are generated due to coil movement as well as rotor striking the stator[7].

i. Coil Movement: This coil movement results in either of following:

- Damage to the coil insulation
- Loosen the top sticks
- Cause damage to the copper conductors.

The rotor can hit the stator in case of bearing failures, shaft deflection, rotor-to-stator misalignment, etc. [8] In critical cases, force of the rotor can cause the stator laminations to puncture the coil insulation, resulting in grounding the coil. If the rotor strikes the stator when the motor is running at full speed, then the result is very premature grounding of the coil in the stator slot caused by excessive heat generated at the point of contact.

ii. Forces on the coil: The force on the coils due to the stator winding current is maximum during the starting cycle, causing the coils to vibrate at twice the line frequency with movement both in the radial and tangential directions [9].

D. Environmental Stresses/Contamination:

[10] The environmental stresses or contamination results in presence of foreign material which further causes various ill effects on the functioning of the motor-like reduction in heat dissipation, premature bearing failure due to high-localized stresses, and breakdown of the insulation system. This error can be prevented by drying the winding out by use of space heaters or trickle heating during the off cycle [11].

3. Types of Stator Winding Faults:

There are five types of faults in stator windings. The first type of fault is coil to coil fault which occurs due to short circuit between two coils of same phase [12]. The second type of fault is coil to coil fault in case two coils of different phases gets shorted [13]. The third type of faults is Short circuit between turns of two phases—called phase to phase fault, (iv) short circuit between turns of all three phases, (v) short circuit between winding conductors and the stator core— called coil to ground fault, and (vi) open-circuit fault when winding gets break [13].

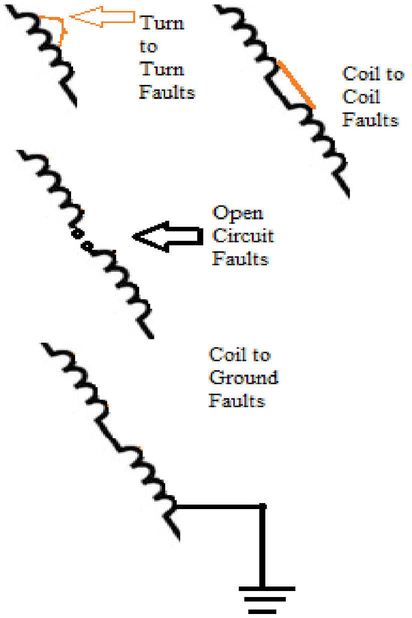

Figure 1: Type of Faults

The earlier diagnosis and detection of faults in brushless dc motors results in drastic reduction of breakdown time. In 2000, W. le Roux et al [1] worked on detection of rotor faults in induction motors using Finite Element Analysis, resulted as expedited detection of faults. Satish Rajagopalan [2] implemented techniques for detection of faults in BLDC motors. The paper includes, the analytical design of motor is created using FEA and 2D model is further designed using RMxprt. This model is analyzed for diagnosis of early symptoms of faults. The FEA analysis is implemented using MAXWELL 2D.The most frequent reason of eccentricity faults is reduction in air gap and changes in magnetic flux. In this paper, static air gap eccentricity fault and dynamic eccentricity faults are simulated using designing of various components and analysis of parameters including Flux density, Radial Air gap flux and Torque plots. These parameters are analyzed relative to the respective parameters of healthy motor.

4. Modelling of Stator Winding Faults in BLDC Motor:

For modeling of stator winding fault, BLDC motor is simulated of 12W, 24 slots, four poles, Inner rotor and 1500 rpm [16]. In this paper, ANSYS Maxwell-2D and RMxprt software tools is used to create a Brushless DC motor's design and to analyze the effects of some specified faulty conditions [15]. The analyses are performed with a computer which the specifications are below:

Computer Platform	Processor	Core i3-3227U CPU 1.90 GHx
	RAM	4 GB
	OS	64 Bit OS X 64 based Processor

BLDC motor specification is used. BLDC motor is simulated using AnSys Maxwell 14.0.

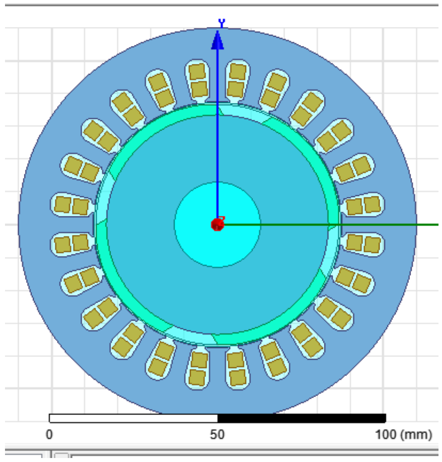

Figure 2: Simulation of Healthy BLDC motor

4.1. Simulation of Slot

The slot configuration is mentioned as in following table [14]:

Parameter	Value
Hs0	2 MM
Hs1	1 mm
Hs2	8.2 mm
Bs0	2.5 mm
Bs1	5.6 mm
Bs2	7.6 mm

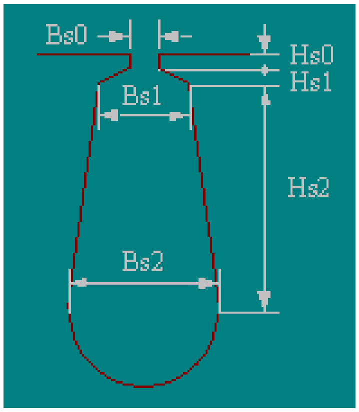

Figure 3: Slot

4.2. Simulation of Stator Winding

The stator winding properties are shown in table below lists the inputs relating to the winding of the machine [17].

Winding Specifications in Healthy Motor	
Parameter	**Value**
Winding Layers	2
Winding Type	Whole-Coiled
Parallel Branches	1
Conductors per Slot	56
Coil Pitch	5
Number of Strands	1
Wire Wrap	0
Wire Size	0 mm

4.3. Simulation of Insulation Specifications

The following simulation depicts the insulation specifications [18] :

Winding Specifications in Faulty Motor		
Parameter	**Value**	Description
Input Half-turn Length	FALSE	
End Extension	7 mm	Distance between the end of stator and one end of a conductor.
Base Inner Radius	0.3 mm	Radius of the base inner corner
Tip Inner Diameter	1 mm	Inner diameter of the coil tip.
End Clearance	4 mm	Distance between two stator coils.
Slot Liner	0.2 mm	Measure of thickness of the slot liner insulation
Wedge Thickness	0.6 mm	Measure of thickness of the wedge insulation in the stator slot.
Layer Insulation	0.5 mm	Thickness of the insulation layer.
Limited Fill Factor	0.75	Ratio between cross-sectional areas of all conductors in one slot to the whole area of the slot.

4.4. Simulation of Stator Winding

The following simulation depicts the flow of magnetic flux between two phases :

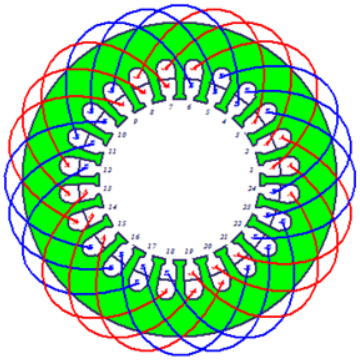

Figure 4: BLDC motor simulation

Coil	**Phase**	**Turns**	**In Slot**	**Out Slot**
Coil_1	A	28	1T	6B
Coil_2	A	28	2T	7B
Coil_3	A	28	3T	8B
Coil_4	B	28	4T	9B
Coil_5	B	28	5T	10B
Coil_6	B	28	6T	11B

4.5. Simulation of Phase A of Stator Winding

The following simulation depicts the flow of magnetic flux between two phases [19]:

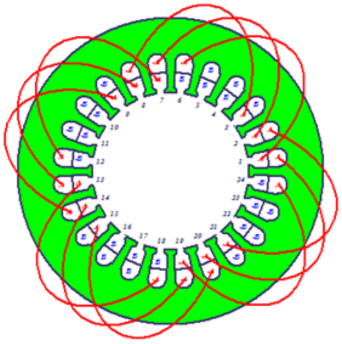

Figure 5: Simulation of Phase A

Coil	Phase	Turns	In Slot	Out Slot
Coil_1	A	28	1T	6B
Coil_2	A	28	2T	7B
Coil_3	A	28	3T	8B

4.6. Analysis Set up

Parameter	Value
Load type	Cont Power
Rated Output Power	550 W
Rate Voltage	220 V
Rated Speed	1500rpm
Operating Temperature	75 Cel

5. Output of Simulation of Stator winding Fault Phase A of Stator Winding

A. Temperature Stress:

Increase in the Operating Temperature from 75 deg Celsius to 150 Degree Celsius

B. Short circuit :

Creation of short by reducing the Hs0 as distance between slot and winding from 2mm to 0.00001mm

Results:

On changing the insulation properties as Limit fill factor from 0.4 (healthy Motor) to 0.0001 (Faulty Motor), following results have been observed

Technique used: Finite Element Analysis and Signal Analysis

A. Impact on Winding Currents

The phase current A and B significantly reduced, as indicated the comparative analysis of healthy (above) and faulty motor (lower with highlights), below:

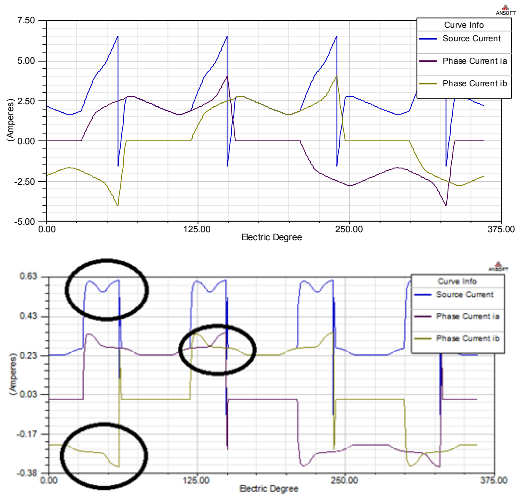

Figure 6: Impact on Phase Current

B. Impact on Phased voltage

The phased voltage is significantly reduced, as indicated the comparative analysis of healthy (above) and faulty motor (lower with highlights), below:

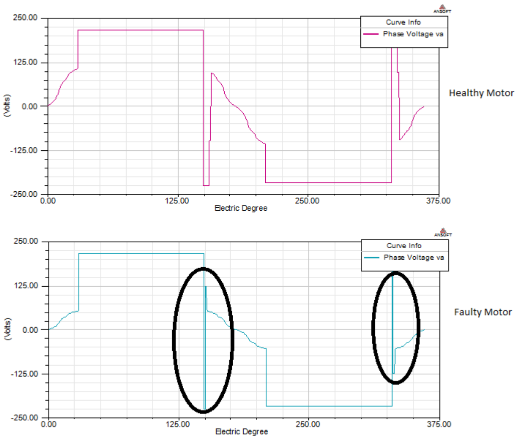

Figure 7: Impact on Phased Voltage

C. Impact on Efficiency Level

The efficiency level is significantly reduced, as indicated the comparative analysis of healthy (above) and faulty motor (lower with highlights), below:

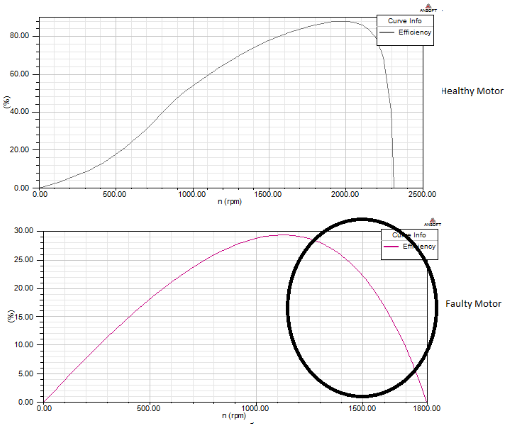

Figure 8: Impact on Efficiency Level

D. Impact on Energy Level

The Energy level between slots is significantly increased near to winding due to reduced insulation thickness, as indicated the comparative analysis of healthy (above) and faulty motor (lower with highlights), below:

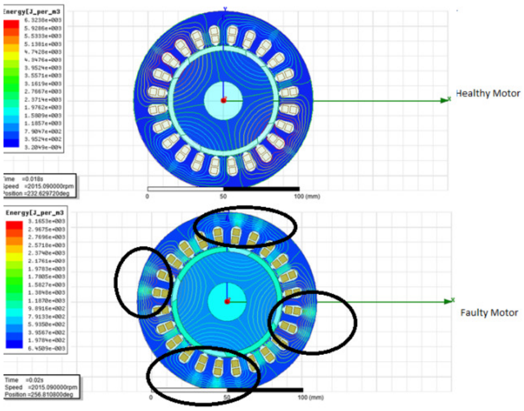

Figure 9: Impact on Energy and Flux Lines

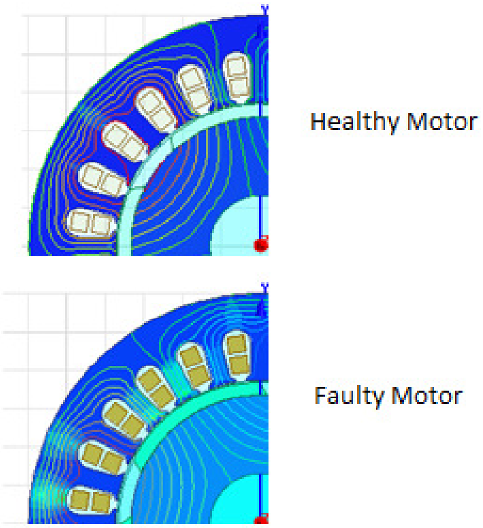

Figure 10: Impact on Energy and Flux Lines

6. Conclusion and Future Scope of Work

In this paper, the fault of Stator winding is simulated and identified the variation of energy levels. As the next step, a theoretical model will be developed with data patterns for prediction of Stator winding faults with desirably high accuracy levels.

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