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A Tubular Hydro-Generator Through-Bolts Failure Troubleshooting

L. JIANFU, Z. GUANGHOU, L. YIGANG, X. JIAN, L. CHUANKUN
DongFang Electrical Machinery Co., Ltd.
China

SUMMARY

After normally running for several years, in the maintenance of a tubular turbine, lots of melted through bolts, fatigue fractures, insulation damages were found. To find out the root failure, firstly a theoretic analysis is done. Followed by finite element electromagnetic and modal analysis to investigate the eddy currents, losses and the electromagnetic force acted on the through-bolts, and their natural frequency. The whole analysis pointed out that after long-term operation, under the action of the electromagnetic force vibration, with fatigue effect and deformation , the insulation of through bolts corrupted gradually, short circuit formed between the through bolts and key bars, which became a current loop together with end plates. This loop circuit links main flux and generates huge eddy current and huge amount heat, and as a result the bolts failure occurred. After the root cause was found, corresponding treatment scheme was proposed and applied. Two years after the treatment, the bolts condition are examined and it shows the condition is still in good state, which proved the measured were effective. This case provides useful information for generator design and relative failure diagnosis.

KEYWORDS

Hydro-generator, Through-bolt, Failure, Fault diagnosis

Ljf365@gmail.com

0 INTRODUCTION

After running for several years, in a maintenance of a tubular turbine hydro generator, melting, fatigue fracture, insulation damage were found in some through bolts.

According to the inspection, 32 bolts with insulation failure; 21bolts with the insulation resistance value zero; eight screws in 132 screw were melted. Phenomena has the following characteristics:

- The melting bolts distribution has obvious pattern as they are opposing the key bars.
- Leaked oil found on bolts.
- Some key bars are over heated.
- Some fracture is transverse fatigue fracture.

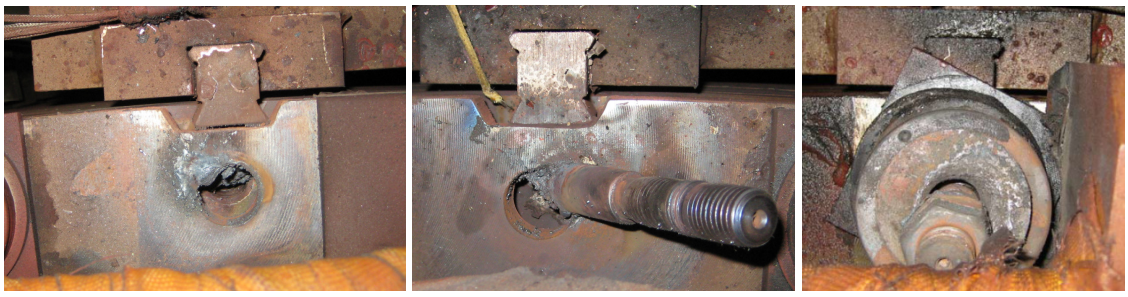

Fig 1. Melted through bolts and heated key bar

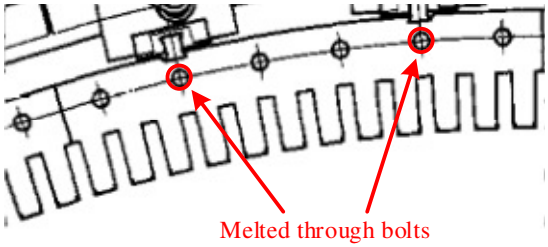

Fig 2. Melted through bolts distribution

1 Basic analysis

According to the investigation, it seems large force was applied to the damaged bolts. After years of operation, the fatigue fracture formed. At the meantime, large loss generated in the bolts and the bolts melted. It was likely that after the through bolt insulation damaged, the through bolts were short circuited with the key bars at the back of stator core.

When short circuit happens, large current and EM force will be generated in the through bolts. If the force frequency is near the natural frequency, it will cause big vibration. A similar mechanism is the stator core frame current, which was generated by the leakage flux linkage both at end part and the central part of the machine. But in that situation the circulating path has less resistance and less flux linkage. [1]

In order to find out the root cause of the failure, the EM force and eddy losses should be analyzed, as well as the modal characteristic.

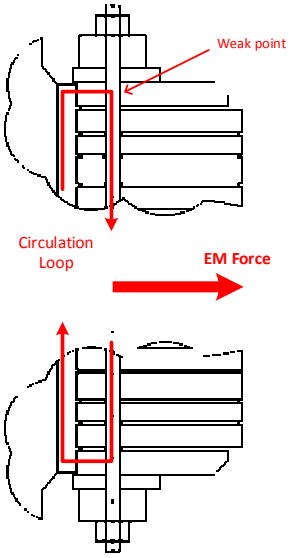

Fig 4. Short circuit path

The Laplace force density can be expressed by the current density and the flux density on a point:

$$d\vec{F_L} = \vec{J} \times \vec{B}$$

The Laplace force acted on a volume region can be expressed by:

$$\vec{F_L} = \int_V (\vec{J} \times \vec{B}) dv$$

After we get the current density distribution, we can get the loss density:

$$p = \left|\vec{J}\right|^2 \times \sigma$$

As the same, integration of the region loss density is the region loss.

The most serious condition is that the through bolts are short-circuited at the end parts with key bars and core [2]. And the Electromagnetic field is analyzed.

2 No load Electromagnetic analysis

Both the normal condition and insulation failure condition are analyzed for no load operation. In most situation, the short circuit position is at end part because the bolt fixation. So the calculation were done in 2D region. It means if the insulation is broken, the key bar and the nearest through bolt will be short circuited together, and the linked flux will be the whole axial direction, which induces significant eddy current and force, and corresponding forces. This is the most severe situation possible.

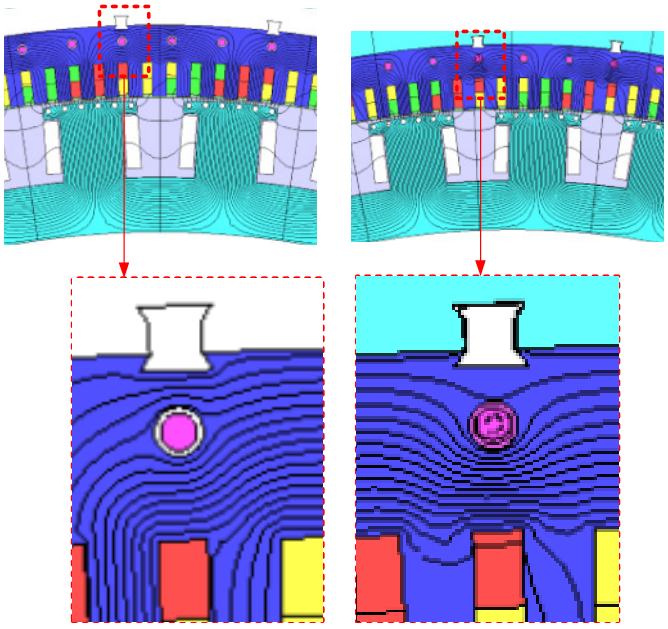

Fig 5. Magnetic flux line distribution at no load condition
with insulation in good condition(left) and in bad condition(right)

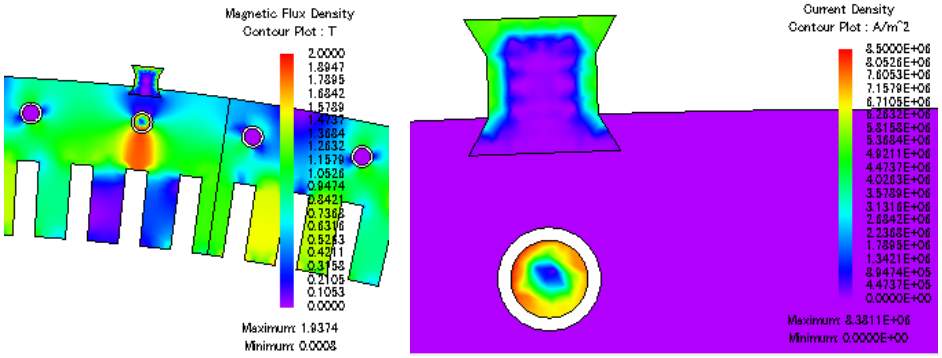

Fig 6. Magnetic flux density and eddy current distribution at no load condition with failure insulation

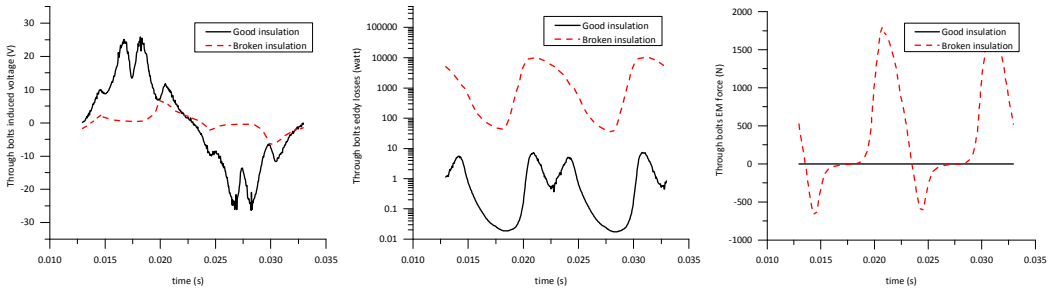

Fig 7. Induced voltage, eddy loss, eletromagnetic force in through bolts

According to the vibration analysis, as the pre-tightening force gradually decaying, the second order natural frequency would be reduced from 138Hz to 97.2Hz. That means, after long term operation, because of the core vibration and hot-cool cycling, the natural frequency will be decreased to 97.2Hz at last.

As the electromagnetic analysis, the EM force acted on the bolts is mainly 100Hz, which will result large vibration in the bolts.

3 Rated load analysis

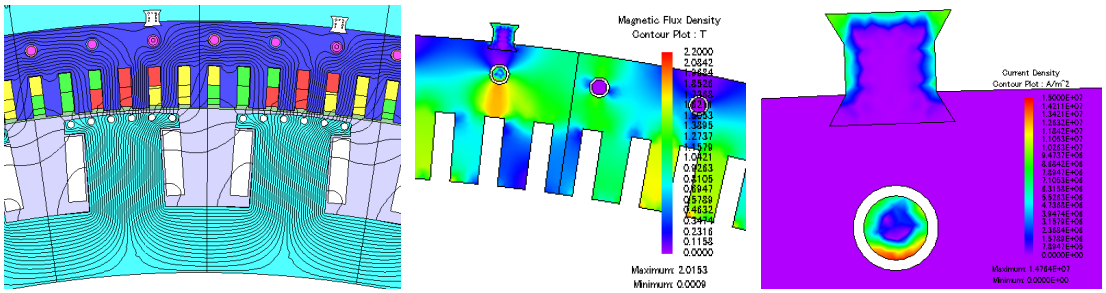

Fig 8. Magnetic flux line, density and eddy current distribution at no load condition with failure insulation

As the result of rated load showing in fig. 8, because of the armature reacting, the flux lines are twisted. And the flux linkage between the key bar and through bolt are also changed compared to no load condition, which also influenced the flux density and eddy current distribution.

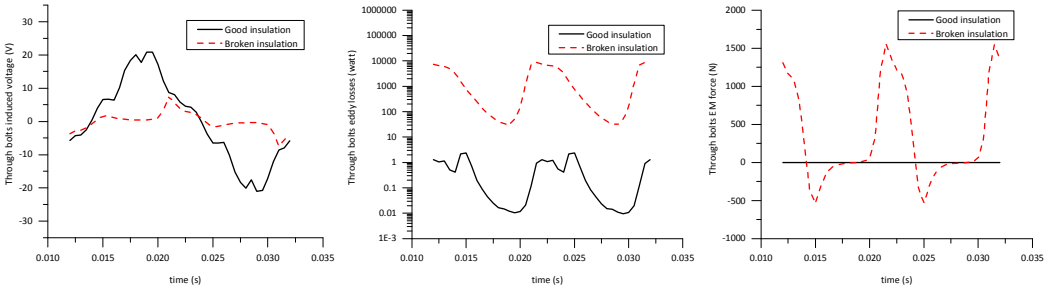

Fig 9. Induced voltage, eddy loss, eletromagnetic force in through bolts at rated load

All mentioned condition simulation results are listed in table 1.

Tab.1 Main Calculation Results of the Through Bolts

Condition	No load		Rated load	
Insulation Condition	Good	Bad	Good	Bad
Voltage /V	13.20	2.71	12.37	2.64
Loss /W	1.43	3097.87	0.58	2457.61
Loss Density/ W/m^3	2.95E+03	6.39E+06	1.19E+03	5.07E+06
Loss Density proportion to coil	0.01	23.39	0.00	18.55
Electromagnetic Force /N	0.67	2514.48	0.24	2099.10

After the results were analyzed, following important conclusions were obtained:

a) When the bolt insulation is good, the eddy current and the electromagnetic force is negligible;
b) When the insulation fails, the eddy loss can be very high. At the most serious condition, the eddy loss is about 3kW per bolt, and the loss density is about 22 times the stator coil value. The loss would make the bolts melt;
c) The electromagnetic force is mainly 100Hz, 2.5kN per bolt.

d) The bolts near the key bars are more easily short circuited which the key bars. So they are more likely to melt and broke.

4 Modal analysis

A modal analysis is carried out to examine the natural frequency.

Firstly, a 2-support schemes is evaluated, which means the bolts are fixed only with the nuts at end part. Results show that the second order natural frequency is 97.2Hz, which is too close to 100Hz, the electromagnetic force frequency. According to the electromagnetic simulation, resonance will happen in the bolt.

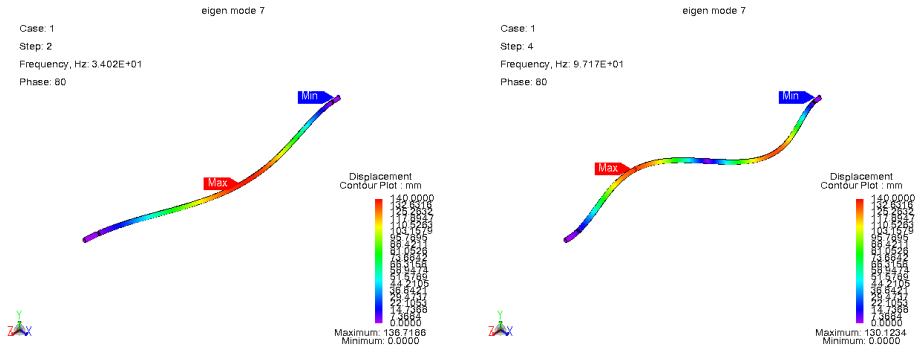

Fig. 10 Modal analysis of 2 supports scheme

Secondly, a 7-support schemes is evaluated, which stands for the situation in which the bolts are also fixed well with the core in active part except the end part fixation. Results show that the natural frequency is higher than 983.5Hz, and it is far away from the 100Hz, the EM force frequency.

By this means, we can take corresponding measures to increase the natural frequency to avoid resonance of the through bolts.

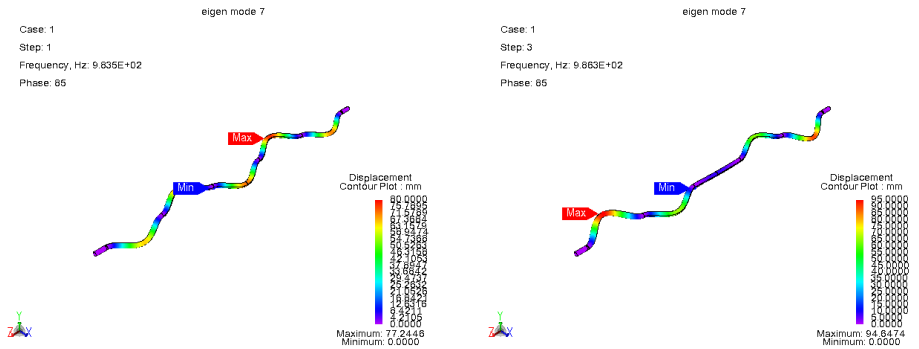

Fig. 11 Modal analysis of 7 supports scheme

Tab.2 Through Bolts modal analysis result

Scheme \ Order	1	2	3	4
2 supports	34.0	97.2	185.1	306.5
7 supports	983.5	986.3	993.5	1001

5 Conclusion

After the electromagnetic and mechanical analysis, the root cause of the failure was found:

After long time of service, the tighten force gradually decreases, and the natural frequency is decreased to near 100Hz, stimulating the resonance and making the mechanical and insulation failure.

Meanwhile, other factor which endanger the insulation also happen. For example, oil mist has not been cleaned for years; As insulation gets worse and worse, the 2-point short circuit happens, then huge force and eddy loss are generated. Vibration and failure insulation reinforce each other. Greater vibration will damage the insulation, and worse insulation will generate greater vibration and heat. At end, the bolts are damaged eventually.

Based on the root causes, several measures were taken to prevent this happening again:

a) Improve the bolt fixation to avoid 100Hz natural frequency.
b) Use thicker bolt insulation.
c) Fill the gap between the core and bolts with flexible material to minimize the vibration.
d) Improve the seal to reduce the oil mist.
e) Clean the oil mist regularly.

Two years operation after the measured were taken to this unit, the through bolts insulation performance was checked again, which was still in good state. This proved the measured were effective. This case provides useful information for generators design and relative failure diagnosis.

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