Theory and Experiment for Electromagnetic Shaft Current in Rotating Machinery

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ABSTRACT

Electrical damages to critical parts in rotating machinery have caused many machinery failures and hours of costly downtime. The problem of shaft currents generated in non-electrical machines has puzzled both users and manufacturers of these machines. The main solution for preventing electromagnetic type damage is to demagnetize all of the machinery parts, however this is costly and time consuming. Therefore a thorough investigation into the causes and physical characteristics of electromagnetic shaft currents is needed. In this paper, the self excitation theory was developed for a simple model, an axial flux Faraday disk machine surrounded by a long solenoid. Experimental tests were conducted to investigate the physical characteristics on an electromagnetic self excitation rig. The theory showed that the directions of both the shaft rotation and the coil turns should be identical if self excitation is to occur. From the tests, the electromagnetic type shaft current had both AC and DC components occurred at all vibration frequencies. This could point to a way to detect small instabilities or natural frequency locations by monitoring shaft currents.

Key Words : Self-Excitation, Shaft Current, Rotating Machinery

1. Introduction

Electrical damages to bearings, and other critical parts in rotating machinery by shaft current have caused many machinery failures and hours of costly down time. The problems of shaft current generated in non-electrical machines have puzzled both users and manufacturers of these machines. A number of efforts to identify the causes of shaft current damage in non-electrical machinery and to eliminate its sources, whether electrostatic or electromagnetic in nature have been made. A special shaft brush has been developed by Sohre(9) and used in industry to prevent shaft current damage. Although the shaft brush is useful to prevent the electrostatic type of shaft current, it is not effective for preventing electro-magnetic type shaft currents because there is no effective way to ground some types of electromagnetically induced currents. The main solution for preventing electromagnetic type damage is to demagnetize all of the machinery part, however this is costly and time consuming. Therefore, a thorough investigation into the causes and prevention of shaft currents is needed.

This article investigates several aspects of the electromagnetic shaft current problem from theoretical and experimental perspectives.

2. Theoretic Model of electromagnetic type shaft current

The axial flux faraday disk machine surrounded by a long solenoid in Fig. 1 is utilized as an analytical model for electromagnetic type shaft current, a self excitation model.[11]

Only uniform permeability of the disk is considered because the analysis for a nonlinear magnetic material with field-dependent permeability is highly complicated.

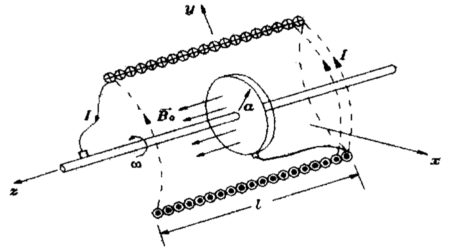

Fig. 1 Model for self excitation analysis

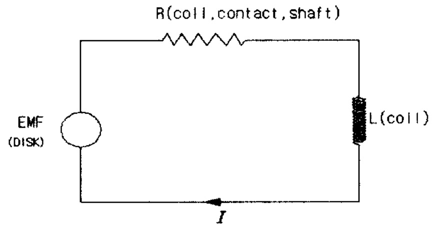

Fig. 2 Equivalent diagram for the model

Figure 2 shows an ideal circuit repre- sentation of the self excitation machine. The circuit contains the electromotive force(EMF), ε(if it circulates clockwise about the $+\hat{z}$ $\varepsilon>0$) of the rotating disk. From kirchhoff law,

$$IR + L\frac{dI}{dt} = \varepsilon \qquad (1)$$

where

I : Current flow in the circuit ($I>0$ if it circulates clockwise about the $+\hat{z}$)

R : Total noninductive resistance

L : Self-inductance of solenoid

From the magnetostatics, the magnetic flux density is defined as

$$\vec{B} = \vec{B_0} + \mu(\vec{H_s} + \vec{H_m}) \qquad (2)$$

where $\vec{B_0}$ $(= B_0\hat{z})$ represents the intial mag-netic flux density and the source field, $\vec{H_s}$ by the solenoid becomes

$$\vec{H_s} = \alpha NI\hat{z} \qquad (3)$$

where $\hat{z}$ is the unit vector in the axial direction and α is +1(-1) if the direction of coil turns is clockwise(counterclockwise) about the $+\hat{z}$ axis. The magnetic field intensity due to the magnetization induced in the disk, $\vec{H_m}$ defined as

$$\vec{H_m} = -\nabla\phi \qquad (4)$$

where ϕ is scalar potential.

Substitution of Eqs. (3) and (4) into the maxwell's equation($\nabla\cdot\vec{B}=0$)

$$\nabla\cdot\vec{B_0} - \nabla\cdot(\mu\nabla\Phi) + \nabla\cdot(\mu\vec{H_s}) = 0 \qquad (5)$$

In a uniform, linear medium Eq. (5) becomes

$$\nabla^2\Phi = 0 \qquad (6)$$

since $\nabla\cdot\vec{H_s}=0$ always and $\vec{B_0}$ is constant.

If the disk fills the solenoid cross-section, the field within it must be axially uniform, so that Eq. (6) has a solution :

$$\Phi = cz \qquad (7)$$

therefore

$$\vec{H_m} = \begin{cases} -c\,\hat{z} & \textit{inside the disk} \\ 0 & \textit{within the solenoid} \end{cases} \qquad (8)$$

where $\hat{z}$ is the unit vector along the z axis. The constant c is determined by requiring that the solution (8) satisfy the boundary condition that the normal component of $\vec{B}$ be continuous at a discontinuity in permeability. Therefore on either face of the disk

$$\mu_0\vec{H_s} = \mu(\vec{H_s} + \vec{H_m}) \qquad (9)$$

Substituting Eqs. (3) and (8) into Eq. (9) yields:

$$c = \alpha NI(1 - \frac{\mu_0}{\mu}) \qquad (10)$$

Substituting of Eqs. (3), (8) and (10) into Eq. (2) provides the magnetic flux density $\vec{B}$ in the disk as

$$\vec{B} = a\mu NI\hat{z} - a\mu NI(1-\frac{\mu_0}{\mu})\hat{z} + B_0\hat{z} = (B_0 + a\mu_0 NI)\hat{z} \tag{11}$$

The electric field $\vec{E}$ in the disk is

$$\vec{E} = \vec{V}\times\vec{B} = \vec{\omega}\times\vec{r}\times\vec{B} \tag{12}$$

The EMF between the shaft's center and the disk's edge is

$$\varepsilon = \oint \vec{E}\cdot d\vec{s} = \int_0^a \vec{E}\cdot d\vec{r} = \int_0^a \omega Br dr = \frac{1}{2}\omega Ba^2 \tag{13}$$

where ω is positive (negative) if the rotation is clockwise(counterclockwise) about the +z axis. Substituting Eq. (11) into Eq. (13) yields

$$\varepsilon = \frac{1}{2}\omega a^2(B_0 + a\mu_0 NI) \tag{14}$$

Finally, substituting Eq. (14) into Eq. (1), the closed loop circuit analog equation becomes

$$IR + L\frac{dI}{dt} = \frac{1}{2}\omega a^2(B_0 + a\mu_0 NI) \tag{15}$$

The solution of the first order differential equation in Eq. (15) with the initial condition (at $t=0$, $I=0$) is

$$I(t) = -\frac{B_0\omega a^2}{2L\lambda}(1 - e^{\lambda t}) \tag{16}$$

where

$$\lambda = (-2R + a\mu_0 Na^2|\omega|)/2L \tag{17}$$

Theoretically, self excitation will occur if λ is greater than 0. Since the values of R, N, a, μ_0 and L is positive, the condition that $\lambda > 0$ can be satisfied only if the directions of both shaft rotation and coil turns are identical.

Therefore, if the direction of both ω and the coil turns are identical,

$$R < \frac{\mu_0 Na^2|\omega|}{2} \tag{18}$$

In summary:

(1) Directions of both the shaft rotation and the coil turns should be identical if self excitation is to occur.

(2) Likelihood of of self excitation increas -es with increasing disk radius(a), shaft speed(ω) or number of coil turns(N), or with decreasing resistance(R).

The second type of instability or resonance may occur when the denominator in Eq. (16) equals zero ($\lambda = 0$.

which implies

$$\omega = \frac{2R}{a\mu_0 Na^2} \tag{19}$$

which from Eq. (17) is the speed at the threshold of instability.

The steady state ($t\to\infty$) current for the stable system is given by Eqs. (16) and (17) as

$$I_{t\to\infty} = \frac{-B_0\omega a^2}{-2R + a\mu_0 Na^2\omega} \tag{20}$$

A plot of this quantity(I) versus the shaft speed(ω) is shown in Fig 3. for two cases of spin and coil direction the same and opposite. The values used in this plot are $R=0.01\Omega$, $B_0=50$ gauss, $a=0.1m$ and $N=1{,}000$ turns per meter.

This condition may occur if the coil windings and shaft rotation are in the same direction. Equation (19) implies that as the rotor speed increase, the shaft currents become very large and exponentially go to infinity.

If the initial magnetic density $\vec{B_0}$ is sinusoidally distributed as show in Fig. 4, the magnetic density $\vec{B_0}$ becomes

$$\vec{B} = (B_0 \sin\omega t + a\mu_0 NI)\hat{z} \tag{21}$$

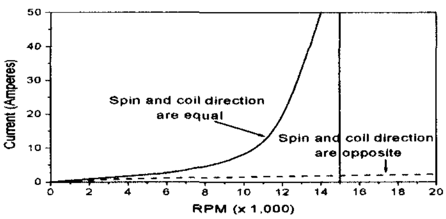

Fig. 3 Steady state current $I_{t\to\infty}$ versus shaft speed ω

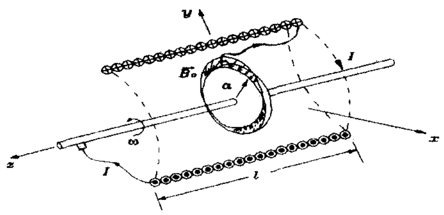

Fig. 4 Disk in the sinusoidally distributed $\overrightarrow{B_0}$

Substituting Eq. (21) into Eq (11), the EMF is

$$\varepsilon = \frac{1}{2}\omega a^2 (B_0 \sin\omega t + \alpha\mu_0 NI) \qquad (22)$$

And then substitution of Eq. (22) into Eq. (1) yields

$$IR + L\frac{dI}{dt} = \frac{1}{2}\omega a^2 (B_0 \sin\omega t + \alpha\mu_0 NI) \quad (23)$$

The solution of Eq. (23) with the initial condition (at $t=0$, $I=0$) is

$$I(t) = \frac{B_0 \omega a^2}{2L\sqrt{\lambda^2+\omega^2}} \left\{ \frac{\omega}{\sqrt{\lambda^2+\omega^2}} e^{\lambda t} + \sin(\omega t - \delta) \right\} \qquad (24)$$

Where

$$\lambda = \frac{-2R + \alpha\mu_0 N a^2 \omega}{2L} \qquad (25)$$

$$\delta = \tan^{-1}(\omega/\lambda) \qquad (26)$$

Therefore from Eq. (24) if $\overrightarrow{B_0}$ is sinusoidally distributed, the current I has both a decaying DC and AC component. Since $\overrightarrow{B_0}$ is distributed in a complex way, the shaft currents may have many harmonics.

3. Experiment for electromagnetic shaft current

An electromagnetic shaft current test rig was assembled in order to investigate the presence of electromagnetic shaft currents in rotating machinery and the relationship between shaft current and vibration, by the experiments with magnetization effects of shaft and the magnetic return path and the electric return path, as shown in Fig.5.

The test rig rotor is slightly magnetized(up to 45 gauss) and consists of a steel shaft with three solid disks mounted on it.

The currents sensor used in this rig is a Model No. S273-50 bidirectional current sensor(current to voltage transducer) made by American Aerospace Controls, Inc., with $0.1\ volt/ampere$ sensitivity. Eddy current displacement probes ($0.2\ V/mil$) are used to obtain vibration signal and shaft speed. These probes are mounted at both ends of the shaft and at disk #1 and are connected to proximities which covert the distance between the probe tip and the shaft surface to voltage output. A SD380 spectrum analyzer by Scientific Atlanta was also used.

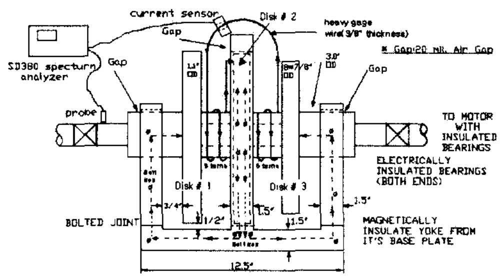

Fig. 5 Concept of the electromagnetic shaft current test rig

4. Results

Figures 6 and Figures 7 show frequency domain data from the current to voltage transducer and an eddy current displacement probe when both of the contact points of the electrical return path are at the center disk, and one contact point moves to the end of the rotor, respectively. The lower and upper traces represent frequency spectra of the vibration and the current sensor's output.

A comparison of Fig. 6 and 7 shows that current through the coil may change significantly depending on the locations of the contact points and rotor speed. Note that the current amplitude is 0.02 Amps in Fig. 6 yet that is 0.15 Amps in Fig. 7. The cause of this may be that the electromotive force produced by rotating shaft is dependent on the locations of the contact point. In addition, these figures show that the shaft current has both DC and AC components. The AC components occur at frequencies of rotation. This is clearly shown by comparing the upper and lower traces in Fig. 8. The lower trace is a frequency spectrum of the shaft vibration which has components at the shaft's speed ($39.1\,Hz$) and at the driving motor's speed ($19.5\,Hz$). The currents sensor's output voltage in the upper trace has frequency components at both frequency encountered in the vibration spectrum. The vibration component is very small(0.024 mils), yet the current signal is significant (0.213 amps). This may point to a way to detect small instabilities or natural frequency locations by monitoring shaft currents.

Figures 9 and 10 show frequency cascade plots of the shaft vibration and the current sensor's output voltage from 400rpm to 3100rpm when one contact point is at the center disk and the other is at the end of the rotor, respectively.

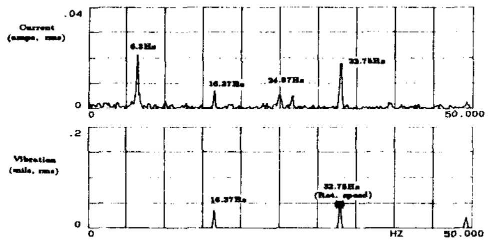

Fig. 6 Frequency spectra with both contact points at the center disk

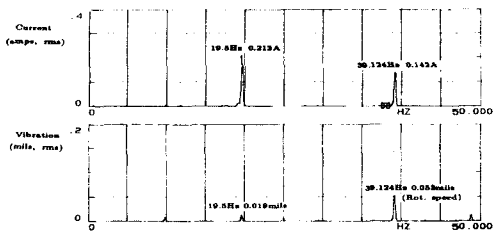

Fig. 7 Frequency spectra with contact points at the center disk and at the end of shaft

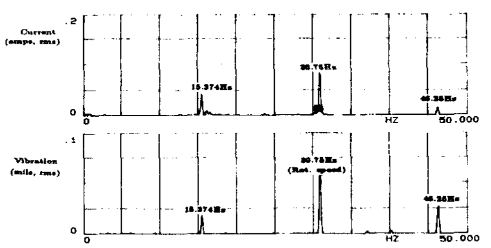

Fig. 8 Vibration and current with contact points at the center disk and at the end of shaft

Although the vibration cascade plot shows only the components of the shaft rotation speed and motor's speed, the current signal includes those of vibration and two more unknown components.

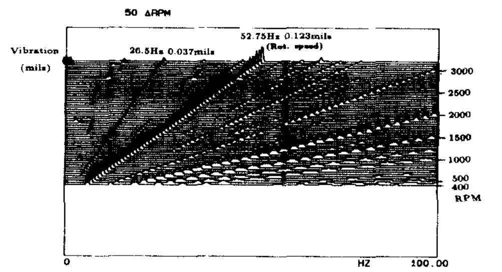

Fig. 9 Cascade plot of the vibration of rotor

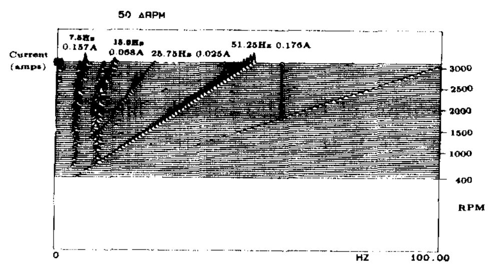

Fig. 10 Cascade plot of current sensor's output

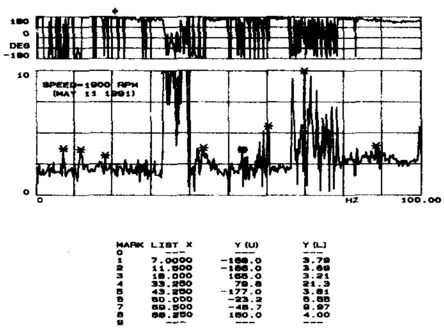

Fig. 11 Vibration/force for the impact test at 1900rpm

Figure 11 shows the result of the impact test at 1900rpm. The unknown components in the current signal may be the natural frequencies of the system as compared with Fig. 10.

5. conclusions

1. A simple self excitation model, an axial flux Faraday disk machine surrounded by a long solenoid, was developed in order to explain the principle of buildup and self excitation phenomenon.

2. The theory showed that the directions of both the shaft rotation and coil turns should be identical if self excitation increases with increasing disk radius, shaft speed or number of coil turns, or with decreasing electrical return path resistance.

3. When the rotating machineries are set up in industries, the sources of magnetic fields around the machineries must be previously checked in order to prevent the electromagnetic shaft currents. In the case that the machineries are, unavoidably, set up under the magnetic field sources, the directions of magnetic flux densities generating by the field source and by the shaft rotation must be considered.

4. From experimental test performed to know physical characteristics of electromagnetic shaft current, the electromagnetic type shaft current had both AC and DC components and the AC components occurred at all vibration frequencies.

5. The theory for self excitation phenomenon developed in this article may be used to develop new test devices which can make sure the prevention of the electromagnetic shaft current generated in non-electrical machines.

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