Extended Summary

Insulation Deterioration Detection System using Zero-Sequence Current Analysis for Induction Motors

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Keywords: induction motors, insulation deterioration, fault diagnosis

1. Introduction

Generally, the insulation breakdown of motors, the main fault associated with motors, is caused by the compound factor of thermal, electrical, mechanical, and environment deterioration. For preventive maintenance for insulation breakdown, the insulation test of a stator coil is performed for motors in the power and industry plant once in several years, periodically. Insulation failure expensively deteriorates the plant operation. Therefore, for the maintenance of these motors, various tests such as an insulation test and research and development of insulation deterioration diagnosis, on-line PD (partial discharge) monitoring, etc. have been actively carried out. On the other hand, the maintenance of LV (low voltage) motors has stayed in BDM (Break Down Maintenance) because many and many LV motors are running in plant and the maintenance of LV motors should consider cost-effectiveness from HV motors.

2. Detection of Insulation Deterioration by Analyzing Deferential Waveform of Zero-sequence Current

Our simulation and experiment using a real motor have confirmed the following.

(1) The zero-sequence current and voltage waveforms differ between the normal conditions and the fault (earth fault and layer-short) conditions.

(2) The fault symptom can be detected in the first (power source frequency), third, and fifth frequencies of the deferential current waveform, which are generated by the zero-sequence current of the normal condition and the fault condition.

3. Life Assessment by Changing the Ratio of the PSD of the Deferential Waveform

In the insulation tests, the insulation resistance has the highest correlation with the breakdown voltage of the coil insulation. Fig. 1 shows the correlation between the breakdown voltage of the stator coil and the insulation resistance, which is the field data of LV motors. In the field, the life management of most LV motors is carried out by trend management of the insulation resistance and the correlation between the breakdown voltage and the insulation resistance.

The deference in the PSD (power spectrum density) between the normal condition and the deterioration condition, which is measured from the zero-sequence current waveform (normal condition) and the deferential current waveform FFT (fast Fourier transform) analysis, is monitored so as to detect the symptom of insulation deterioration. The monitoring PSD values are the first (power source frequency), third, and fifth frequencies, fault symptom can be detected. The deference in the PSD values between the normal condition and the deterioration condition is defined using formula (1).

\[
\Delta \text{PSD}_n = \frac{p_n}{P_1} \quad (n = 1, 2, 3, \ldots)
\]

Fig. 2 shows the interrelation between \(\Delta \text{PSD}_n\) and the insulation resistance, which has high interrelation with the breakdown voltage of insulation and the insulation life expectancy. The insulation resistance decreases as the \(\Delta \text{PSD}_n\) increase, therefore, \(\Delta \text{PSD}_n\) indicates the progress of insulation deterioration.

4. Conclusions

Below are the results of this study obtained by simulation and by performing tests on a real motor;

(1) The coil insulation fault symptom can be accurately detected by FFT of the deferential current wave between the normal and the fault conditions of the zero-sequence current.

(2) The ratio of high-frequency current \(\Delta \text{PSD}_n\), calculated by the PSD (power spectrum density) value of the first frequencies (power source frequency) and third and fifth frequencies of the deference zero-sequence current wave, indicates the insulation deterioration progress.

(3) Monitoring of the zero-sequence current, which is applied the ratio of high-frequency current \(\Delta \text{PSD}_n\), analyzed by FFT of the deference zero-sequence wave, is effective for detecting the insulation deterioration progress and the insulation life assessment.

Fig. 1. Insulation resistance versus breakdown voltage

Fig. 2. Insulation resistance versus ratio of high-frequency current \(\Delta \text{PSD}\) (Earth fault condition)
Performance Evaluation of Linear Oscillatory Actuator for Active Control Engine Mount

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Keywords: linear oscillatory actuator, active control engine mount, 3-D finite element method, vibration control

1. Introduction
At present, we are studying active control engine mounts (ACMs) with linear oscillatory actuators (LOAs) mounted on automobiles to reduce frame vibration and noise. The structure of the ACM is shown in Fig. 1. The basic construction of our ACM consists of two main parts: a hydraulic mount for passive vibration damping and an LOA for active vibration damping.

The basic structure of the LOA is shown in Fig. 2. It has good linearity characteristics and high thrust. It consists of a light mover that is made of iron and an aluminum alloy, a stator that is composed of two magnets, some yokes and a coil, and some springs. When the coil is excited, the flux in the air gaps becomes asymmetrical, resulting in the generation of a net force. The LOA characteristics are determined through analysis by the 3-D FEM.

Further, we determined the active control performance of the ACM by a dynamic vibration simulation combined with the vibration model of the ACM, with the LOA characteristics obtained from the 3-D FEM analysis. We used a sinusoidal wave output and an LMS adaptive feed forward control as the active control methods.

The simulation results are shown in Figs. 3 and 4. Through the simulations, we determined that an ACM system using a sinusoidal wave output is capable of reducing over 90% of the vibration in the chassis in almost the 20–200 Hz frequency range. In addition, we found that the active control performance of an ACM system using a sinusoidal wave output is higher than the performance of an ACM system using an LMS adaptive feed forward control. Finally, we clearly identified the relationship between the resonances of the LOA and the active control performance of an ACM.
Basic Study on Construction of Analysis Model for Brush Wear in Sliding Electric Contacts

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Keywords: brush, sliding electric contact, wear, bridge rupture, arc discharge evaporation

Sliding electric contact technologies play a very important role in the manufacture of various electrical components such as brushes and slip rings of turbine generators, including variable-speed hydraulic turbine generators and wind turbine generators, and elucidating electric wear phenomena of the brush is important for improving the technologies. We classified these phenomena into two modes: bridge rupture and arc discharge evaporation. The modes are based on existing theories in the field of switching the contacts, and they were used to construct an analysis model for elucidating electric brush wear volume. After a theoretical analysis, we examined the accuracy of brush wear prediction on the basis of comparisons between calculated results and experimental results.

For the bridge rupture mode, we calculated the temperature of the molten metal (called “bridge”), which contained copper and carbon as the main elements, and by using an unsteady heat conduction equation that considers dynamic changes in the bridge dimensions, we derived the “scattered bridge volume” when the bridge reached boiling point. Using both the obtained scattered volume and the re-contact time calculated by the “smallest gap search method”, we examined the variation of the electric wear volume in the case of bridge rupture with the sliding distance (Fig. 1). At a given sliding distance, the volume of copper \( W_b(Cu) \) was more than that of carbon \( W_b(C) \) by a factor of several hundred, which is a result of the difference in specific electric resistance.

For the arc discharge evaporation mode, we calculated the evaporated copper volume for steady arc discharge and measured the arc discharge voltage and the arc duration time while the slip ring slid under the brush. Then, using these calculated and measured values, we estimated the electric wear volume for arc discharge evaporation (Fig. 2). The volume was approximately one-tenth of that in the case of bridge rupture for the same copper material, \( W_a(Cu) \) and \( W_b(Cu) \), and it was approximately equal to that in the case of bridge rupture for the alloy consisting of copper and carbon, \( W_b(Cu/C) \). Therefore, we found that it was necessary to calculate the electric wear volume by considering both modes.

We measured the electric wear volume in the brush using brush/ring experimental equipment and compared the theoretically and experimentally determined dependence of the electric wear volume on the sliding distance (Fig. 3). Almost all the experimental values (plots) were between the calculated lines of the bridge rupture and the combination of bridge rupture and arc discharge evaporation. Furthermore, the experimental values and the calculated values showed good agreement. Thus, the analysis model was found to be useful for predicting the electric wear volume in the brush associated with sliding electric contact.
Robust Controller Design for Sinusoidal PWM Inverters

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Keywords: PWM inverter, robust control, linear matrix inequality, internal model principle

Pulse width modulation (PWM) control for inverters is widely used, and many controller design methods for PWM inverters have been proposed. The output voltage frequency is usually 50 Hz or 60 Hz for the constant-voltage constant-frequency applications. This recognized information has been utilized to develop some control system configuration methods for PWM inverters on the basis of the so-called internal model principle.

This paper proposes a robust controller for sinusoidal PWM inverters, which can track a sinusoidal reference with zero steady-state error. A closed-loop system for single-phase full-bridge inverters is constructed on the basis of the internal model principle. The main feature of the proposed controller is that it is designed so that the control performance is robust against uncertainties and variations in circuit constants such as resistance, inductance, and capacitance. It is also shown that the pole-placement constraints and control performance indexes based on the $H^2$ and $H^\infty$ norms as well as a standard quadric performance index in optimal control can be applied to the proposed robust controller. Therefore, the proposed robust controller is suitable for various control specifications.

In this paper, we deal with the sinusoidal PWM inverter as shown in Fig. 1. Let the capacitor voltage $v_C$ and current $i_C$ be the state variable $x = [v_C, i_C]^T$. Then, we consider the system configuration as shown in Fig. 2. The signals $u$, $y$, and $r$ are the input of the inverter, the capacitor voltage, and the sinusoidal reference input, respectively. We adopt the structure of the controller S as shown in Fig. 3 in order to take into account not only the fundamental angular frequency $\omega_1$ but also the harmonic frequencies $\omega_3, \omega_5, \ldots$. The proposed controller consists of the state-feedback controller of the inverter and the controller S, and it is designed by finding the appropriate control gains $k_P$ and $k_S$ in this setting. The resulting design problem is reduced to a state-feedback control problem with uncertain parameters, which can be solved using linear matrix inequality approaches. As a result, the proposed controller can achieve not only zero steady-state error tracking but also robust stability and robust transient response.

Digital computer simulation is implemented to confirm the validity of the proposed robust controller with the internal model principle. Moreover, a prototype experimental model is constructed and tested. Some examples of experimental results are shown in Fig. 4. It is seen from the figure that the output can track the reference input precisely and can maintain the tracking performance regardless of the abrupt change in the reference input and the capacitance variations of $C = 60 \mu F$ and $C = 10 \mu F$. 

![Fig. 1. Sinusoidal PWM inverter circuit](image1)

![Fig. 2. Closed-loop system for controller design](image2)

![Fig. 3. Structure of controller S](image3)

![Fig. 4. Experimental results](image4)
Suspension Characteristics of Multi-Consequent-Pole Bearingless Motor with Toroidal Windings

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Keywords: bearingless motor, magnetic bearing, two-axis actively control, multi-pole, low speed, toroidal winding

A multi-pole bearingless motor for low-speed applications such as rotating and swinging stages or platforms have been previously proposed. The proposed multi-pole bearingless motor has 40 rotor poles and 48 stator slots. This bearingless motor arrangement has the advantages of a low cogging torque, low pulsation in the torque and suspension force, and a small force angular error. Moreover, the bearingless motor is inexpensive and small in size because only two degrees of freedom are actively regulated in the $x$-$y$ directions.

However, there exists a problem with respect to the windings. If a conventional 4-pole and 2-pole windings structure is employed, then the axial length of the coil end-windings of the suspension and drive windings tends to be large as compared to the lamination stack length of the bearingless motor.

In this study, toroidal coil windings are used for the suspension winding in order to make the coil end-windings compact. A test machine is built so that successful operation is confirmed by experimental verification.

Fig. 1(a) shows the prototype machine and the controller. The rotor diameter is 150 mm, with a lamination stack length of 10 mm. To realize a compact suspension winding, a toroidal winding structure for the suspension winding is proposed. The coils are wound around the stator yoke. There are 40 turns per one slot. Fig. 1(b) shows the side view of the stator with toroidal windings. The coil end-winding protrudes by 3.75 mm so that the axial length, including the end-windings, is about 17.5 mm.

Figs. 2(a) and 2(b) show the conventional and proposed experimental methods for the measurement of the radial suspension force, respectively. Fig. 3 shows a plot of current $i_y$ versus the radial suspension force $f_y$. The experimental results of the radial suspension force measured by the proposed method are corresponding to the 3D-FEM analysis results.
Tracking Control System with Equivalent Perfect Tracking Control for Optical Disks

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Keywords: optical disk, tracking control, feedforward control, perfect tracking control, equivalent perfect tracking control

In recent years, the capacity and transfer rate of optical disk and hard disk recording systems have been greatly improved through the expansion of digital video and computers. However, the video archive at a television (TV) station is stored on magnetic tape. Because of their random access functionality and long-term data storage, optical disks are expected to be an alternative to magnetic tape for video archive media. Therefore, optical disks require increased storage density and data transfer rate. Near-field recording (NFR), which provides large storage capacity, has been proposed. Increased data transfer rate is also required for video archive media. Hence, it is necessary to increase the disk rotation speed. Consequently, a flexible optical disk with a rotation speed of over 10000 rpm has been developed. As stated above, a high-precision tracking control system is required in order to increase the storage capacity and data transfer rate.

For this purpose, we have already proposed a tracking control system composed of a high gain servo controller (HGSC) and perfect tracking control (PTC). The conventional feedforward tracking control system well suppresses the tracking error caused by track eccentricity. However, this system is complicated. The PTC uses an inverse plant system in multi-rate sampling. The multi-rate sampling is suited to hard disk drive systems that have a limitation of output timing. The PTC system has speed-up limitation in the optical disk tracking control system. Hence, this paper proposes a new high-speed and high-precision tracking control system with equivalent-perfect tracking control (E-PTC).

Fig. 1 shows the proposed E-PTC system. The proposed system is constructed in single-rate sampling, and it realizes a quick executing servo system. The proposed system reduces the processing time to 45% of that of the conventional system. The experimental results confirm that the proposed system well suppresses the tracking error at a DVD+R disk rotation speed of 7200 rpm. Fast operation at a sampling frequency of 300 kHz is realized by reducing the processing time in the proposed system. The experimental results of the proposed E-PTC system operating at 300 kHz are shown in Fig. 2. The residual tracking error is 4.35 nm $\pm 0.98$ nm. Therefore, the proposed tracking method is suitable for a high-speed, high-precision tracking control system.
Frequency Domain Analysis of Magnetic Bearings and Its Application to the Design of Controllers

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Keywords: magnetic bearing, frequency response, distributed system, delay time, finite element analysis

1. Purpose
This paper proposes a method to derive the frequency response of an actuator with a solid iron core. This actuator is designed for a thrust magnet bearing of a high-speed motor, as illustrated in Fig. 1. The objective of this study is to estimate the frequency response of the actuator before prototyping.

2. Analytical Formulations
The actuator is treated as a distributed system with eddy currents in the solid iron core. A model of the actuator is formulated by using complex permeability as given in (1) and by using a simple magnetic circuit model as shown in Fig. 2. Finite element analysis (FEA) as shown in Fig. 3, and actual measurements are also performed. The obtained results are compared with the analytical results.

\[ \mu_s(j\omega) = \frac{\Phi}{2\pi x_0 H_0} = \frac{\mu}{2\pi x_0 T} (1 - \exp(-2T x_0)) \]  

(1)

3. Approximation for the Transfer Function by Rational Expressions
In order to approximate the frequency response, a method for obtaining the rational expression of the frequency response is derived. This method is essentially based on a least-square method. However, it is modified to some extent in order to obtain a rational expression. By using this method, the transfer function can be well approximated, as shown in Fig. 4. A method to improve the frequency response is also presented. Slits at the yoke of the magnetic bearing are introduced in order to reduce the eddy current at the yoke. The results are illustrated in Fig. 4.

4. Experimental Results
The experimental results were obtained by using an actual machine. The frequency response of the actuator was measured using a servo analyzer. As shown in Fig. 5, the actual sensitive function of feedback control is well predicted by the FEA and the approximation by the rational expression mentioned above. It was shown that the controller for the magnetic bearings can be designed with usable accuracy, before prototyping.
Proposal and Verification of a Technique for Reducing Leakage Current Using Zero-Sequence Voltage

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Keywords: leakage current, zero-sequence voltage, common-mode, common-mode choke, EMI

This paper proposes a technique for reducing the leakage current that flows into a power source as conductive noise. Fig. 1 shows the system configuration of the proposed method. In the system, the common-mode choke is connected between the power supply and the diode rectifier. Grounding capacitors are connected between power lines, which are placed between the common-mode choke and the diode rectifier, and a ground point. The inverter switching frequency is 10 kHz.

High-speed switching produces a zero-sequence current that flows into the ground via parasitic stray capacitors in the motor. The zero-sequence current divides into a leakage current $i_c$ that flows through the power supply via peripheral equipment and a current that flows through the grounding capacitors. The leakage current $i_c$ may have an adverse effect on the peripheral equipment; that is, it could cause malfunctions. The proposed method applies a zero-sequence voltage $v^*_z$ to the output voltage references. As a result, the fundamental frequency component of the zero-sequence voltage produced by the inverter decreases and the leakage current $i_c$ reduces. In the experiment, the output voltage references are 0 V because $i_c$ becomes maximum. This condition occurs frequently in an elevator system and a servo system.

Fig. 2 shows the peak values of $i_c$ when $v^*_z$ is applied. The calculated results agree well with the experimental results. The leakage current can be reduced further by increasing the additional zero-sequence voltage reference. Fig. 3 shows the experimental results of the inverter output voltage $v_{un}$ and the leakage current $i_c$ under the conventional conditions. The shape of $v_{un}$ is identical to the shape of the zero-sequence voltage because the output voltage references are 0 V. $v_{un}$ is a square wave whose duty ratio is 50%, and the peak value of $i_c$ is 150 mA. Fig. 4 shows the experimental results of $v_{un}$ and $i_c$ when the zero-sequence voltage of $50 \sqrt{2} V$ is applied. $v_{un}$ becomes a square wave whose duty ratio is 75%, and the peak value of $i_c$ decreases to 120 mA. In this study, the proposed method could reduce the leakage current by 20%.
Compensation for Disk-Flutter Vibrations of Head-Positioning Control Systems in Hard Disk Drives

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Keywords: hard disk drives, positioning control, vibration control, residual response, disk flutter

In a head-positioning control system of a hard disk drive (HDD), the positioning error includes repeatable runout (RRO) and non-repeatable runout (NRRO). One cause of NRROs is the airflow-induced vibration of disks (called “disk flutter”). Therefore, the control system must compensate for the disk-flutter-induced positioning error. Fig. 1 shows modal shapes of disk-flutter-induced vibrations, and Fig. 2 shows the time-response of a disk-flutter-induced disturbance in the head-positioning control system.

We have developed a control design method using a resonant filter. By using this method, control engineers can easily design and implement a controller that can suppress the NRRO caused by the mechanical vibrations. However, the resonant filter is kept inactive during track-seeking control because the transient response of the resonant filter may worsen the positioning accuracy after the track-seeking control.

To overcome this issue, we propose a new framework of the head-positioning control system using a resonant filter to suppress the disk-flutter-induced positioning error. The control system uses resonant filters with variable gains that depend on the cylinder number of the head position and the modal shape of the flow-induced vibrations of disks.

Fig. 3 shows a block diagram of the proposed control system. The variable gains are optimized depending on the cylinder number of the head position. As a result, the resonant filter is able to improve the transient response after the track-seeking control.

To demonstrate the validity of the proposed method, we conducted simulations of track-seeking controls in an HDD benchmark problem that has been widely used for HDD researches. Fig. 4 shows the simulation results of position error signals. The dashed line represents the result with the conventional method, and the solid line represents that with the proposed method. The results of the track-seeking simulations showed that the proposed method was effective in decreasing the positioning error caused by the disk-flutter-induced vibration and improving the seek time of the HDD.

Fig. 1. Modal shapes of disk-flutter-induced vibration
(a) (0, 1) mode. (b) (0, 2) mode.

Fig. 2. Time response of disk-flutter-induced vibration

Fig. 3. Block diagram of control system

Fig. 4. Simulation results of position error signal
A Method of Voltage Unbalance Compensation on Y-connection Modular Multilevel Converter

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Keywords: STATCOM, unbalance compensation, transient simulation, multilevel converter

A STATCOM is expected to be suitable for use as voltage control equipment for a distribution system that needs to be controlled to suppress the voltage deviation caused by an increase in the number of photovoltaic energy sources. A Y-connection MMC is a promising alternative for the STATCOM circuit topology. However, it has been known that the Y-connection MMC cannot achieve capacitor voltage balance between phases with unbalance current output for compensating system voltage unbalance. To solve this problem, we propose a novel method to control the capacitor voltage in the case of an unbalance current output.

Fig. 1 shows a control block diagram of the proposed control. The proposed control involves feedforward and feedback zero sequence voltage control. The feedforward control prevents capacitor voltage unbalance between phases, which is caused by the unbalance current which Y-connection MMC outputs. The feedback control cancels the remaining error of the feedforward control.

We verified the performance of the control through transient simulation. Fig. 2 shows simulation waveforms of the Y-connection MMC STATCOM with and without feedforward control. The Y-connection MMC with feedforward control can achieve capacitor voltage balance between phases even when the Y-connection MMC outputs an unbalance current. However, the Y-connection MMC without feedforward control cannot achieve capacitor voltage balance between phases.

Additionally, we determined the maximum unbalance current output produced by the Y-connection MMC in relation to the rated capacitor voltage.