Detection of humidity ingress using online common-mode insulation impedance-monitoring system

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Abstract: Enhanced machine reliability through monitoring of its state of health is an emerging field of research. Ingress of contaminants such as moisture can affect electrical machine state of health and contribute to failure in winding insulation. This paper demonstrates the application of an online insulation health monitoring method to study the effect of moisture ingress on ground-wall insulation through practical experiment. The method, based on real-time high-frequency leakage current measurement, is implemented on a 2.83 kW machine during operation in open-loop configuration. The results are presented and discussed, demonstrating the feasibility of diagnosis of moisture ingress.

1 Introduction

Electrical machine reliability and availability is becoming increasingly important, with ever-growing numbers of machines in important roles in high reliability applications. In response to these requirements, there has been a recent increase of interest in machine health monitoring. Successful diagnosis of incipient faults allows planned stoppage and maintenance, thereby reducing the impact on the system functionality.

Literature review shows consistently that the second-most prevalent mode of electrical machine failure is through the winding [1]. The winding is the hardest component in a machine to replace, and it is vital to prevent serious damage before it occurs. Moisture ingress can initiate faults and exacerbate existing flaws in the winding, and has been identified as a significant contributor to failure in transformers [2] and motors [3]. The use of offline tests, such as the measurement of insulation resistance, have been successfully used to diagnose moisture ingress [4]; however, these may not be applicable where regular maintenance cannot be implemented.

Here, the insulation capacitance and dissipation behaviour is monitored online in real time, using leakage current due to inverter switching. An experiment is carried out to introduce a low-voltage random wound machine to different levels of humidity and observe parameter change in real-time. The monitoring method and experiment methodology are described, followed by a discussion of the online monitored parameter results. A strategy to diagnose moisture ingress based on observed results is presented.

2 Ground-wall insulation

The machine investigated here is a low-voltage (<1 kV) random wound servo motor, class H rated insulation to survive the equivalent of 20,000 h at 180°C. The insulation system consists of the ground-wall paper, the individual wire turn insulation, and the impregnation material. Typically this class of machines uses organic insulation material throughout [5], consisting of long polymer chains. Typical materials include aromatic aramids, polyester, polyimide, and polyurethane. The insulation layers are considered together as a bulk for the purposes of monitoring the state of health of machine, allowing the measurement of the dielectric characteristic of the system to be used for diagnosis.

2.1 Insulation model

The conventional model used in the diagnosis of insulation state of health considers the winding copper and stator lamination iron as two plates of a parallel capacitor, with the insulating dielectric material in between. An additional resistor is placed in parallel with the capacitance to represent the losses in the dielectric material as shown in Fig. 1. Monitoring the value of capacitance and dissipation allows diagnosis of various aging and fault mechanisms that are present during machine lifetime [6, 7]. The loss current is also commonly expressed as a fraction of the capacitive current.

It was found in [8], however, that this model is only valid for single frequency measurement. Dielectric loss is present in organic insulating materials because polymer molecules have a polar dipole moment; therefore, when the molecules are subject to a time-varying electric field, they will be forced to vibrate [9]. The implied result of the root cause of dielectric loss is that at higher frequencies there should be more loss, due to a faster movement of molecules. The implications for monitoring are further discussed.

3 Ground-wall insulation impedance monitoring

Insulation capacitance and dissipation are measured typically using offline methods, e.g. using impedance analysers. A method proposed by the authors in [8] for online measurement is briefly summarised here with the preceding literature review. In an ideal machine, current leaving a winding should be equal to the current entering. This is not the case, however, as the ground-wall insulation provides an additional path to ground, where leakage current flows through the insulation material. Measuring the residual current on individual coils was used in [10] to measure insulation impedance to ground for line-driven machines, illustrating the possibility of using exiting winding-ground voltage as the source for inducing insulation current. The advantage of this
method over using an impedance analyser is also that the measurement can be taken in real time during machine operation.

In inverter-driven machines, there are other voltage sources present in addition to the normal line voltage. Common mode voltage exists because of the diode rectification ripple, the instantaneous switching voltage and implicit addition of common mode harmonics during space vector modulation.

Measuring the common mode voltage and resulting leakage current through the insulation allows measurement of the common mode impedance and, therefore, the overall status of the ground-wall insulation system. The novelty of the method developed by the University of Sheffield comes from both the utilisation of high-frequency inverter harmonics and the data processing methods used to interpret the data.

### 3.1 Monitoring equipment

Common mode voltage and current is measured at frequencies between 6 and 1 MHz. The requirements and equipment used are specified here.

Common mode voltage is measured by creating an artificial neutral network using three resistors as is shown in Fig. 2. The centre of the resistor network presents the sum of phase voltages and is measured by a DP-25 differential probe.

The definition of common mode current is the residual remaining after summation of the three-phase currents. The summation is performed here through magnetic cancellation using a single current sensor. The sensor required for this must have a large aperture and high bandwidth. To achieve these contradictory objectives, an ACCT-S-055-MSH closed-loop current transformer from Bergoz was selected. The sensor has excellent long-term stability and noise characteristics and experience with the sensor has shown the feasibility of measuring impedance magnitude to within 0.1% precision.

The acquisition is performed by a Red Pitaya 14 bit 125 MS/s Zynq 7010-base system. This unit was selected because of its acquisition capabilities, its flexibility and its computing power. The data are filtered and down-sampled inside the Zynq FPGA, and are then processed by the on-board ARM A9 CPU in real time. The data processing chain consists of transforming the time domain data to the frequency domain using the FFTW library, compensating the frequency response of the current sensor and the calculation and storage of the impedance at the first 40 odd inverter switching harmonics. For the acquisition, 20 ms of data were acquired at 125 MS/s, resulting in 1,000,001 data points for both current and voltage, after being down sampled to 25 MS/s. The data acquisition and processing executes once every 2 min for the duration of the experiment.

### 3.2 Common-mode impedance

For comparison, experimental measurement of the common-mode impedance, obtained using a Hioki 3750 impedance analyser on the test motor is presented here.

The measured equivalent parallel resistance is shown in Fig. 3. Clear agreement is visible between the offline and online measurement. Resistance decreases steadily up to 50 kHz, showing the polar dissipation dependency with frequency. At frequencies above this, other effects influence the impedance of the insulation, better observed in the measured capacitance result.

The measured equivalent capacitance result is shown in Fig. 4. The capacitance value is a constant until it nears an abrupt change at 200 kHz. The cause of this change is the interaction between the parasitic ground-wall capacitance and the winding inductance.

Further information can be obtained about the state of the machine by tracking the resonance frequency and parameters measured above and below this frequency. The full model and use of these is outlined in [8]. To present the data in this experiment, only the data below 50 kHz is used. At frequencies below the resonance, the assumptions about steady capacitance and decreasing Req with frequencies hold to the predictions from theory. This allows the extrapolation of capacitance, Req and dissipation to values at 50 Hz, to be comparable to results from offline testing methods [6].

\[
R_{\text{offHz}} = 10^{-5m} \times 50^c
\]
\[ \tan \delta_{50} = 100 \times \frac{1}{2\pi \times 50 \times C_{50} \times R_{50}} \]  

(2)

3.3 Expected effect of moisture ingress

Capacitance is determined by the dielectric constant of the insulation material used, once the physical machine parameters are set. Typically, the relative dielectric constant is between 3 and 5 [11], an increase of which corresponds to increased capacitance. The dielectric constant of water at temperatures and frequencies tested is around 80 [12]; therefore, a small ingress of water is expected to cause a significant increase in capacitance. Water is also a polar molecule; therefore, an increase in water content is also expected to increase the measured dissipation factor.

Literature reports increases of \( C_{eq} \) between 5% [7] and 20% [13]. Dissipation reported in [13] almost doubled from 6% up to 10% during spraying of end-windings. It is expected that data measured during the online experiment will reflect similar magnitudes to the literature.

4 Methodology

The machine tested in the experiment is a Unimotor 142L2B300VBCAA165240 three-phase 2.83 kW servo motor. This is driven by an M700 drive, with a 600 V DC link. The purpose of the setup was to recreate as close as possible the conditions as would be seen in a typical industrial setting.

During the experiment, the motor is placed inside an SH-662 humidity chamber as shown in Fig. 5. For safety reasons, the rotor has been removed from the machine. The stator is operated in open-loop configuration to produce a rotating magnetic field as would normal during operation.

For operation, 40 V line voltage was commanded at 200 Hz. The frequency and voltage were selected to enable significant modulation index (greater than 0.1) without dissipating >20 W in the windings, to subject the machine to a typical common mode waveform and to decouple temperature effects, respectively. The environmental chamber itself was set to 80°C, as almost no aging should result for a Class H rated machine at this temperature.

The equipment was connected as shown in Fig. 2, where the insulation monitoring setup was placed in series with the drive and motor. The ground-wall of the cable connecting the monitoring system to the machine is measured in parallel with the stator. As the machine only is subject to the moisture, the cable impedance was measured offline prior to the experiment and its influence has been subtracted from the results.

At the start of the experiment, the temperature was raised to 80°C and humidity set to the minimum value of 10% in order to dry out the stator. The humidity was then increased in steps of 20% up to 90% and held for 2 h at a time. The moisture was then set to 30% and left overnight. A repeat of the experiment set the moisture command to maximum 100% for 6 h to observe the effects of extreme moisture ingress.

5 Results

In the first 5 h, the measured low-frequency capacitance in Fig. 6 rises to 1.25 nF and stabilises. This is taken as the nominal value of capacitance with minimal moisture. It was expected that as humidity increased from 10 to 70%, clear step increases in \( C_{eq} \) would be observed. This was not the case, however, as the increases of \( C_{eq} \) at humidity values between 10 and 70% were almost equalled when the command was increased to 90%.

Significant changes in capacitance occur at the time of maximum humidity. The capacitance increases 6.1% on the nominal value at 90% humidity and 9.3% during the 100% humidity command. The change is highly non-linear, as the increase of capacitance is only 3.5% between 10 and 70% humidity steps. During the overnight experiment pause, a significant fluctuation occurs at hour 20. It is possible this occurs due to an overshoot of the on-off humidity controller.

The abrupt change is more visible in the Req results in Fig. 7. At humidity values 10 to 50%, the change is comparable to the normal variation at nominal value. After 1 h at 70% humidity, it can be seen that the Req value starts decreasing and accelerates as the command is switched to 90%. The value of Req drops from a nominal 230 MΩhm down to 140 MΩhm for 90% moisture, and 110 MΩhm for 100%.

6 Discussion

Relatively small change was observed across all monitored parameters, until the humidity was increased to values above 90%. During the experiment, condensation was observed during periods of high humidity on the chamber walls, machine cable, and the machine itself. It is not unreasonable to speculate that liquid water was also present in the windings themselves. The disproportionate
change of parameters during high humidity may be due to direct water exposure on the windings.

Moisture is ever-present in the surrounding air and machines are, therefore, designed to accept a normal operating environment. For the purpose of monitoring, little change of the parameters over 10~70% humidity range is conducive to tracking high level of humidity during normal operation. Based on the experimental results, it is proposed that an online measurement of dissipation be used as the primary method for tracking moisture ingress, as little change has been measured until an extreme scenario is reached.

Despite the condensation, the test machine continued to operate normally at full voltage. This shows that the monitoring system has enough time to reliably detect the problem, without the need to stop the drive instantly to prevent damage.

7 Conclusion

The impedance of a low-voltage random wound machine ground-wall insulation has been monitored online successfully during a humidity exposure experiment. The equivalent measured insulation capacitance, resistance, and dissipation at 50 Hz have been presented.

It was shown that the capacitance and dissipation factor increase in response to humidity. Magnitudes of +9.3% for capacitance and +200% for dissipation have been observed at maximum humidity. The magnitude of change and the directions match the theoretical prediction and what has been stated by literature, allowing distinct diagnosis of moisture ingress.

It was also shown that normal amounts of humidity do not greatly change the measured parameters. Using insulation dissipation value, it is possible to discriminate between normal operation and abnormal, problematic moisture ingress. The cause of non-linear change of parameters has been discussed.

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9 References

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