On-Line Motor Insulation Capacitance Monitoring Using Low-Cost Sensors

Igor Tsyokhla
Sphere Fluidics
Cambridge, UK
igttgit@gmail.com

Antonio Griffo
Dept.Electronic and Electrical Engineering
The University of Sheffield
Sheffield, UK
A.Griffo@sheffield.ac.uk

Jiabin Wang
Dept.Electronic and Electrical Engineering
The University of Sheffield
Sheffield, UK
J.B.Wang@sheffield.ac.uk

***Abstract*—Insulation degradation in electrical machines is a significant factor that leads to machines failure. It has been demonstrated that the state of health of insulation can be evaluated on-line during machine operation with measurement of equivalent ground-wall capacitance, by measuring the common-mode leakage current generated by common mode voltage of standard two-level PWM converters. Low cost implementation of the monitoring system is key to wide adoption in industry. In this paper, inexpensive off-the shelf current sensors are evaluated for use in leakage current monitoring. A full low cost system is designed, built and tested. The testing emphasis the both the short term precision and long term accuracy of the measurement. It is shown that it is possible to use low-cost sensors for long term monitoring, with acceptable compromises**

Keywords—Insulation, Condition monitoring, Electrical machines, sensors, reliability

I. INTRODUCTION

Motors and generators are ubiquitous in industry and their failure can lead to undesirable outcomes [1]. While periodic inspection and maintenance is common in industry, due to cost considerations, it has only been viable to periodically measure the state of health of only high value machines. In order to increase the reliability of large industrial plants with large numbers of relatively low cost machines, or in cost sensitive applications, e.g. automotive, low cost solutions for condition monitoring are desirable. Multiple surveys indicate that stator insulation is the second most likely component to fail after the bearings [2]. It is necessary therefore to monitor the health of the stator winding over the machine lifetime to provide meaningful machine prognosis. The monitoring system must operate on-line during machine operation as continuous measurement is required and the machine operation must not be halted. Stator lifetime is primarily determined by the insulation system used in the winding. The system would typically have three components: the wire turn insulation, ground-wall insulator separator and the impregnation material. As the materials are typically of the same class, they should degrade at similar rates and the entire system can be treated as a single unit. The ground-wall can be represented by a parallel RC model as in Fig. 1, where the capacitance is formed by the winding copper and stator iron with the insulation material is the dielectric. The dissipative term R represents losses inside the dielectric. In [3] it is shown that monitoring the capacitance of insulation ground-wall could be used to predict the lifetime of the machine by measuring its variation during progressive ageing. The challenge is therefore to measure this during the operation of the machine when it is driven by a PWM-controlled inverter.

It can be shown that leakage current inside a three phase stator, resulting from common mode voltage (CMV), flows from the winding copper to the stator through the insulation material. Measurement of ground-wall capacitance has been proposed in [3] [4] by measuring the leakage current and common mode voltage. The leakage current is measured in [4] by magnetic cancellation of the current inside a special sensor. Multiple attempts have been made to use low-cost solutions to measure leakage current for insulation monitoring. In [5] the time domain current waveform subject to voltage steps is studied. The high frequency components of this waveform are resultant from leakage current and using learning algorithms the authors are able to detect large (10%) change of ground-wall capacitance. In [6] the authors use resistive shunts on each phase to measure the residual current. The accuracy of this method however greatly depends on the Kalman filtering algorithm as the measured current contains large amount of noise. In both of these, sophisticated data processing has been used to remedy the drawback of the sensing system.

In this paper, the current cancellation method is used as in [3],[4],[5]. In [3] a high-accuracy (0.1% Full-scale), high-bandwidth (1MHz) sensor was used. This paper investigates alternative low-cost sensing solutions with the aim to assess the minimum requirements of the sensors required to achieve successful insulation health monitoring.

I. GROUND-WALL IMPEDANCE

In low voltage random wound machines, insulation is commonly made of organic insulating material that degrades over time. The voltage withstand capabilities and mechanical strength decrease over time, accelerated primarily by heat induced thermal degradation. Organic insulation consists of long polymer chains of the polymer element. Common polymers used in insulation are polyester, polyurethane, polyimide and others. Over time, the chains break up and

This work was supported by Engineering and Physical Sciences Research Council-EPSRC under Grant EP/S00081X/1, Grant EP/P010350/1, and Grant EP/K034987/1. (Corresponding author: Antonio Griffo.).

reform, exhibiting changed properties depending on the mechanism of degradation.

Off-line testing used in capacitance and dissipation factor testing consider the ground wall as a parallel plate capacitor, with the insulating dielectric between the plates formed by the winding copper and stator iron as in Fig. 1. An online method for measuring the ground wall capacitance in inverter driven machines was presented in [7]. The method is briefly summarized in the following section, while the reminder of the paper will discuss the feasibility of the method with lower cost sensing methods.

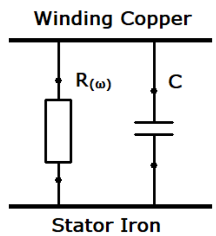


Fig. 1. Ground-wall insulation model

II. Ground-Wall Insulation Health Monitoring

In order to diagnose insulation problems, a number of methods for on-line insulation health monitoring have been proposed using the leakage current from winding to ground to calculate the impedance of the insulation ground-wall.

Measuring capacitance using residual current was demonstrated in [7] using residual leakage current measured via three current sensors, magnetically summing the currents in each phase. In [8], [9] a single current sensor sums the three phase currents together to measure the common mode current at multiples of line frequency. A cheaper method was investigated in [6] using a shunt resistor based current sensor. Here, we summarize the method presented in [3]. In this method, insulation impedance is measured at inverter drive switching frequencies and multiple harmonics are used.

Two-level converters use pulse width modulation (PWM) to generate the main line voltage required by the machine. Common mode voltages V_{cm}, defined by the sum of the phase voltages to ground in Eq. (2) is also present in PWM voltage waveforms.

$$V_{cm} = \frac{V_a + V_b + V_c}{3} \tag{2}$$

V_{cm} consists of three sources: a third-harmonic of the mains frequency ($3 \times 50 = 150Hz$) due to the three-phase diode rectifier supplying the DC-link, a third-harmonic of the drive fundamental frequency due to the CM component added in the standard space vector modulation to increase DC-link voltage utilization, and finally the higher frequency components due to the inverter switching.

Fig. 2a shows measured V_{cm} at the terminals of an industrial drive operating at 200Hz fundamental frequency (f_m) with a switching frequency (f_s) of 6 kHz. The frequency spectrum of this signal is shown in Fig. 2c, where the harmonics are clearly identifiable. In Fig. 2c, the first harmonic due to diode rectification is clearly visible at point A at 150Hz; the diode ripple is also observable in the time domain in Fig 2a. The first harmonic of the space vector PWM component is identified in Fig. 2c as B, at three times the fundamental modulating frequency i.e. 600Hz. The majority of harmonics result from the instantaneous switching voltage and result in harmonics marked by C and D in Fig. 2c, the harmonics at C being at odd multiples of the inverter switching frequency fs and the harmonics at D being sidebands at multiples of f_m, around even multiples of f_s. The common mode voltage constantly acts on the common mode impedance, resulting in a common mode current flowing through the insulation. Measuring this voltage between the winding and ground and leakage current, allows measurement of the insulation impedance.

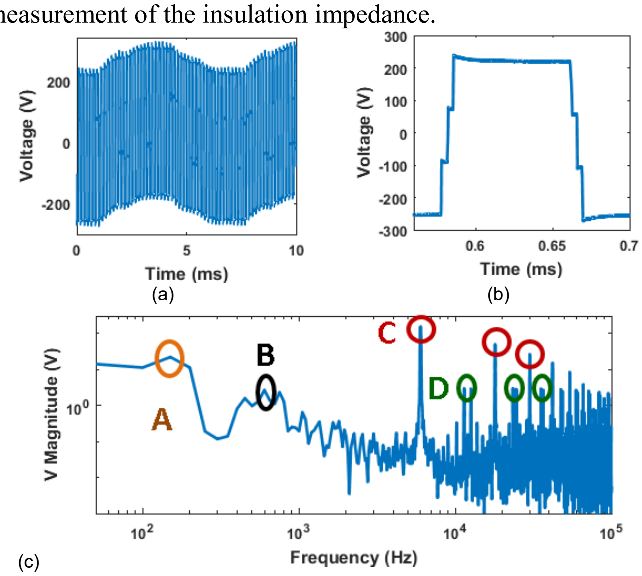


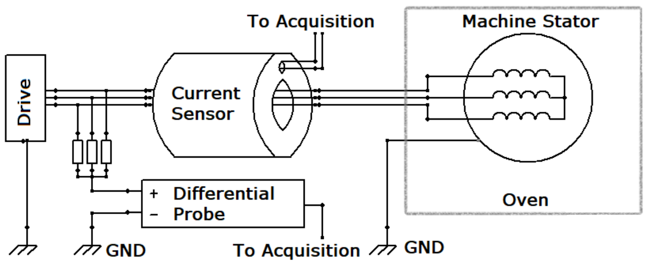
Fig. 2.Common mode voltage (a) time domain, (b) zoomed into a single space vector switching cycle (c) frequency domain

Impedance $Z(\omega)$ of the insulation is calculated in the frequency domain ω by $Z(\omega) = V(\omega)/I(\omega)$ at each frequency. Capacitance and equivalent parallel resistance, representing dissipation, are calculated by applying the parallel RC model in Fig. 1 and calculating the RC values at each frequency using (3)-(4) for capacitance and resistance respectively.

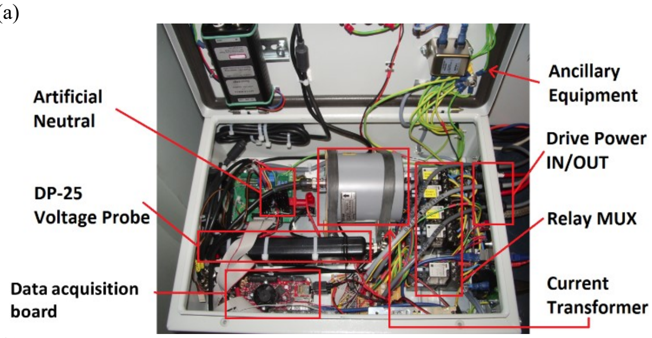
$$C_{eq} = \frac{1}{2\pi f}\frac{1}{|Z|}\sin(-\theta_z) \tag{3}$$

$$R_{eq} = \frac{1}{\frac{1}{|Z|}\cos(\theta_Z)} \tag{4}$$

Fig. 3 shows the experimental setup for the proposed CM impedance measurement. The system uses an ACCT-S-055-MSH closed loop current transformer from Bergoz with a 1MHz bandwidth and a high accuracy of <0.1% full scale. The voltage is measured with a 25MHz bandwidth differential probe connected to an artificial neutral network consisting of three resistors.



(a)



(b)

Fig. 3. Block diagram (a) and photo (b) of the experimental rig for the reference design of the CM impedance measurement systems

II. DATA PROCESSING

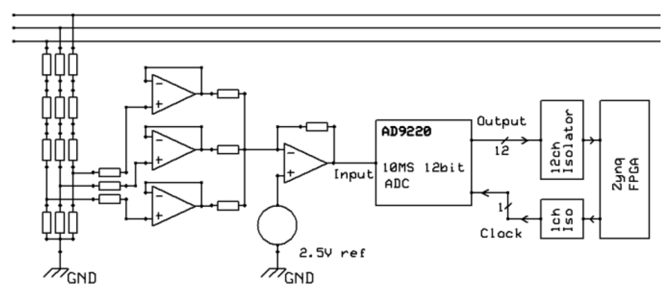
Preliminary testing showed that high speed, in excess of 10MHz, acquisition of voltage and current waveforms is required. Acquisition and processing of the signals are performed, in our test system, by a Zynq 7010 SoC-based processing board combining an FPGA and an ARM A9 CPU, with two 14-bit 125MS/s analog-to-digital converters (ADC). Data from voltage and current signals acquired by the ADCs enters the FPGA, where it is down-sampled to 25MS/s, filtered and passed to the CPU. The signals are then transferred to the frequency domain using the FFTW3 library by the A9 processor. The first 40 harmonics of the odd multiples of inverter switching frequency, from 6 kHz to 486 kHz are selected. Data acquired by the low cost sensors is fed via the FPGA to the CPU for further processing. During each processing cycle, 20ms of Common-mode voltage and currents data is acquired, an FFT of this data is taken and harmonics are selected. In all the experiments the inverter drive is operating at 6 kHz, harmonics are present at odd multiples of this frequency. Using the voltage and current harmonics in the frequency domain, impedance is calculated (Z=V/I) at each frequency. Equivalent capacitance can then be calculated by using the (1)-(2). Each processing cycle repeats at intervals of one minute. The acquisition board cost is not considered as a factor in the sensor system as this device was used primarily to speed up prototyping. Low cost ARM CPUs are widely available as are FPGA devices that would be required in the interface between the hardware. With commercial development the processing system can be integrated into the inverter drive system.

III. SENSORS

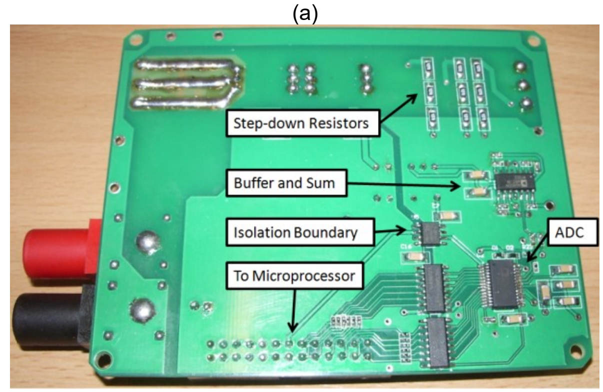
A. Voltage sensors

CMV is the sum of three phase voltage with respect to ground. To measure the CMV in the reference system of Fig. 3, [3] the three phase voltages are summed inside an artificial neutral resistor network and sampled with a high-voltage differential probe with respect to ground. An isolated probe is used since CMV in a typical low voltage inverter system, fed from a 415V three phase supply will have peak voltages in excess of 350V. Any acquisition hardware or user interface must be isolated from this voltage as an accidental ground disconnection or short circuit might apply the inverter voltage to the user. The cost of the isolation probe however is prohibitive for a low-cost application. Here, high-voltage digital isolation is proposed. Each phase voltage is individually stepped down and buffered to a summing amplifier, the output of this amplifier is the common mode voltage. This voltage is then sampled by an Analog/Digital Converter (ADC), at 10MS/s at 12 bit. Data is passed to the processing unit via optical digital isolation chips. The voltage sensing system is shown in Fig. 4. Figure 5 shows the measurement of common mode voltage in the time domain of the system compared to the reference 25MHz differential probe. It can be observed that the isolated ADC provides accurate measurements except for small overshoots of voltage on the transition edges that are not present in the reference sensor. The magnitude of the 6kHz voltage harmonic is shown in Fig. 6 over the course of 13 days of measurement. Although there is an offset due to a calibration error which can be easily compensated, it is evident that that the voltage measured is in agreement with the reference sensor both over a short term in Figure 5 and long term.

The concept of using digital isolation for analogue acquisition is well established. This has been successfully implemented here in measurement of machine common mode voltage. Further refinements are recommended to improve the layout and shielding of the analogue stages to reduce the impact of the high dV/dt present in the inverter output voltage.



(a)



(b)

Fig. 4. Schematic (a) and photo of the isolated CM voltage sampling circuit

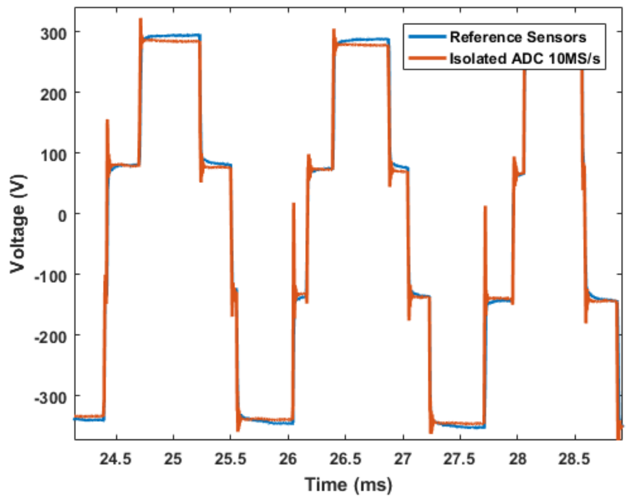
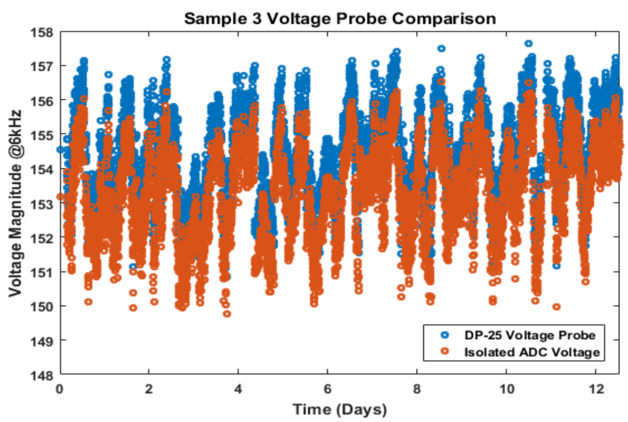
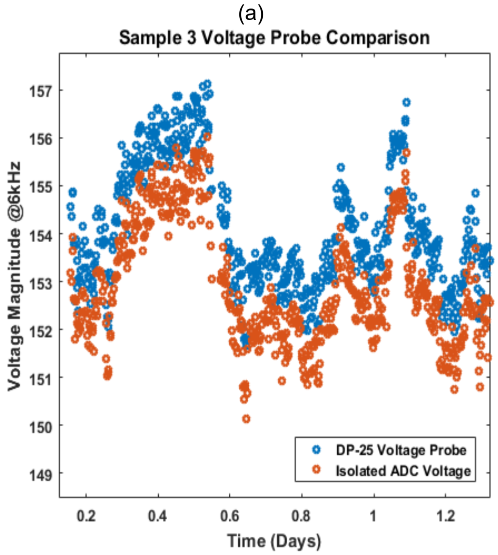


Fig. 5. CM voltage measurement with reference differential probe and proposed circuit



(a)



(b)

Fig. 6.(a) Amplitude of 6kHz component of the CM voltage measured over the course of 13 days with reference differential probe and proposed circuit. (b): zoomed version.

B. High bandwidth current sensor

The sensor in the reference design [3] is able to capture harmonics up to 1MHz with an accuracy comparable to off-line impedance analyser. A sensor with sufficiently high bandwidth has been selected from the CAS range of current sensors from LEM with a bandwidth of 300kHz and a datasheet accuracy of 0.3%. This sensor was repurposed to implement current cancellation to measure the residual leakage current. The sensors in the CAS range have three wires passing through the sensor core for the purpose of allowing the user to change the sensing range suited to the application. To measure leakage current, the three phase wires are instead wired to these three range switching connections. The arrangement of this is shown in Fig. 7. In this experiment the sensor output is then sampled by the ADC on-board of the data acquisition board at 125MS/s at 14 bit. The current sensor provides the required isolation from the high voltage side. Preliminary testing using the ADC with 10MS/s as the voltage sensor is adequate to capture the current waveform. Initial testing of the sensor shows a good representation of current in the time domain. In Figure 8 it can be seen that the current impulses through the insulation capacitance are well captured, there is also a strong noise signal present. Between times 0.17ms to 0.19ms, the current should be zero, as the insulation current has long decayed. The reading present, with a signal at approximately 400Hz, is due to the sensor operation, as CAS range operates on the principle of fluxgate saturation that requires high frequency injection. The harmonics from sensor operation are easily resolved in the frequency domain and do not overlap with the harmonics of interest. Therefore it is feasible to use fluxgate technology for measuring leakage current.

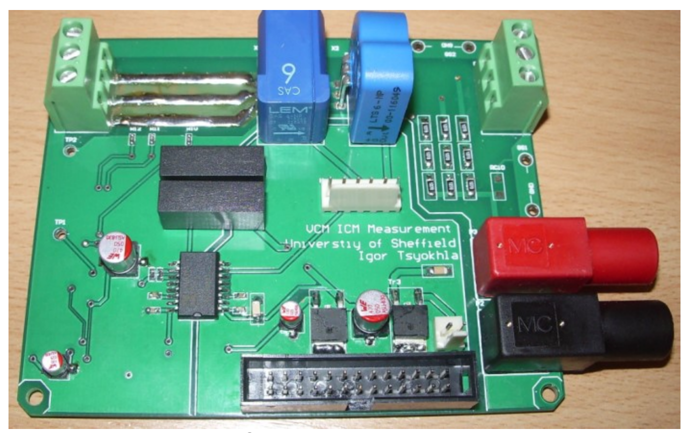


Fig. 7 CM current sensor circuit

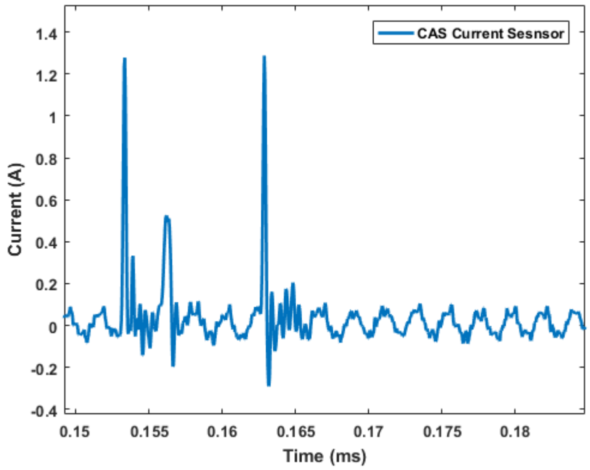


Fig. 8. CM current measurement with CAS sensor

IV. SYSTEM TESTING

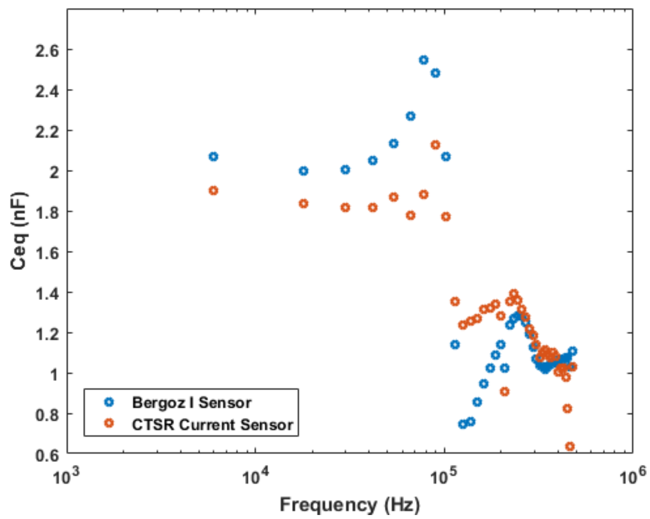


Fig. 9. Capacitance Measurement Comparison CAS Sensor and reference Bergoz sensor.

The sensing boards have been connected in series with an inverter drive, the reference sensors and a machine stator. The machine is a 3.75kW 230V 3 phase servo drive. In the initial tests the machine is driven with 200Hz fundamental frequency and 6kHz inverter switching frequency. The capacitance behavior is measured and compared to the reference high bandwidth, high accuracy sensor. Three features are important to capture with capacitance when using the full bandwidth: the low frequency capacitance, the resonance frequency and capacitance at frequencies higher than resonance. In Fig. 9, the capacitance measurement is shown. The low frequency capacitance is measured by harmonics up to 50kHz, the resonance frequency for this machine is 100kHz and high frequency capacitance is between 200-300kHz. In Figure 9 these three features are captured both by the reference sensors and the CAS sensor. Only the low frequency capacitance characteristic is required for insulation prognosis according to [3]. The low frequency capacitance (<50kHz) remains constant up to the first resonance point therefore averaging of the capacitance at the first four harmonics in Fig. 9 is used. Accuracy of capacitance measurement is evaluated with repeated measurements reported in the histogram of Fig 10. The standard deviation of these measurements is 0.54% away from mean. For this same test the reference sensors returned deviation of 0.1%. Machine testing standards recommend equipment with 0.1% or better accuracy for offline equipment however for continuous monitoring this may not be as important as capacitance is expected to change by up to 50% over the lifetime of machines.

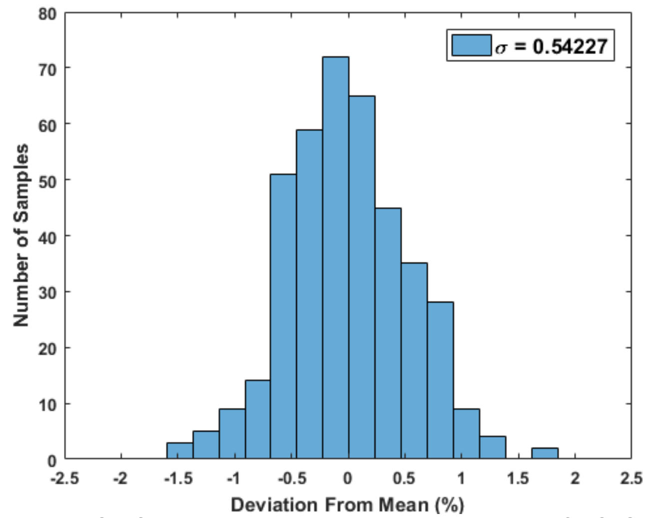


Fig. 10. CM Capacitance at 6kHz measurement deviation for CAS Sensor

V. LONG TERM MONITORING

The low cost sensor system has precision that may be adequate to measure expected capacitance changes over time. A key requirement of monitoring hardware, however, is reliable measurement over the lifetime of the piece of equipment being monitored. To test the low cost sensors the system operated simultaneously with the reference sensors during the accelerated aging experiment in [3]. Data for low cost sensors is available for three samples over 36 days of testing. The accelerated aging experiment operated samples 1 and 2 in parallel, where one sample was driven by the inverter, measured by the equipment, then switching over to measure the second sample, interleaving the measurements. Capacitance data has been averaged over time from the low cost sensors and is shown in Fig. 11.

Each of the samples has a different rate of capacitance decrease due to different rate of acceleration as set by operating temperature. The low cost sensor system is able to capture these different rates over the duration of experiment, however it would be problematic to use the data in Fig. 11 for trending of machine state of health. It can be seen in capacitance data for samples 1 and 2, spikes of data not seen in the reference sensor measurement. It can be concluded that the correlated spikes in samples 1 and 2 are due to the low-cost measurement system. It is shown in Fig. 5 that the voltage acquisition from the isolated ADC agrees with the laboratory sensors, the data processing platform is also the same as used by the laboratory sensors, the deviation therefore must be due to the CAS current sensor. Current sensors can drift over time. In Fig. 11 the deviation is as much as 5% from the overall trend, this is in accordance with the datasheet value of the sensor used. Although this may be acceptable for some applications, in this experiment the deviation makes it difficult to observe even large features, such as the slow temporary increase of capacitance in Sample 3 on day 5. It can be concluded that long term drift make this current sensor not suitable for long term monitoring of the insulation health of motors using the proposed leakage current measurement system.

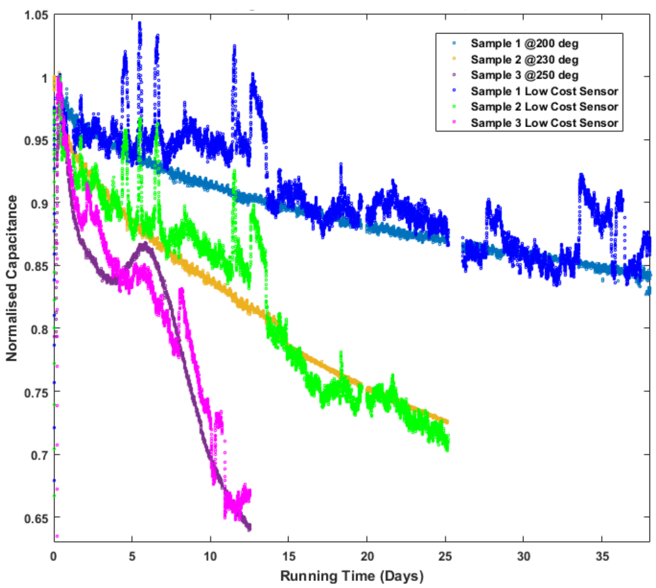


Fig. 11. Low cost system v1 long term results

A. Alternative current sensor

On completion of the first experiment, it was noted that despite disappointing results over long term monitoring, the relative difference of trend was a useful feature that was relatively accurately measured. In the initial experiment it was also concluded that monitoring high frequency harmonics and the dissipation figure was less important as the key parameter the indicates machine health is the low frequency capacitance [3]. A second version of the system was designed using the CTSR range of current sensors from LEM. The sensors are specifically designed to monitor earth leakage in residual current measurement devices. The sensor was adapted for use in magnetic cancellation by placing the three phase wires through the centre of the sensor using a former as shown in Fig. 12. The CRSR sensor bandwidth is 10 kHz, allowing only the first harmonic at PWM frequency of 6kHz to be monitored. Results from the reference sensors in the first experiment suggest that this should be enough to measure the low frequency capacitance. The sensor was tested over an extended period of time to measure its deviation from mean. The histogram is shown in Fig. 13. The measured capacitance has a standard deviation of 0.78% showing a larger spread than the CAS sensor. The impact of a large deviation is seen in Figure 14. In this experiment the temperature of the stator is cycled between 180°C and 220°C with a period of 2 hours per cycle. The capacitance varies with temperature due to the change of dielectric property with temperature. Continuous monitoring allows averaging the capacitance result in time, with the filtering determined by the fastest expected change. Filtering is feasible provided that the noise shape does not change over time. The CTSR version of the low-cost sensor system was installed in a long-term experiment that used elevated temperature and thermal cycling to accelerate the lifetime of the machine stator.

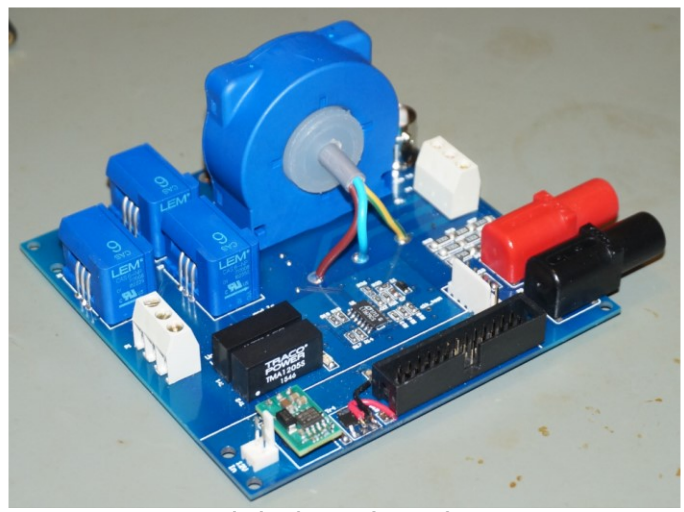


Fig. 12. CTSR Current Sensor System

The normalized equivalent low-frequency ground-wall capacitance at 6kHz is shown in Fig. 15. Capacitance is tracked over 1200 hours (50 days) to determine long-term viability of monitoring. The sample shown in Fig. 15 has a complex lifetime, where the experiment is paused for 600 hours after 300hours of operation. During this pause, the temperature is lowered and thermal cycling turned off resulting in little aging, capacitance decrease due to aging is present before and after this pause. All phases of sample lifetime are captured in the capacitance figure successfully by the low cost system. The trend of capacitance is clearly visible in the low-cost sensor data, as are the decrease and increase of capacitance at experiment pause and resumption. There are no deviations from the reference sensors and the sensor does not drift over time. This sensor shows excellent potential to be used in a monitoring system as the capacitance trend can be captured.

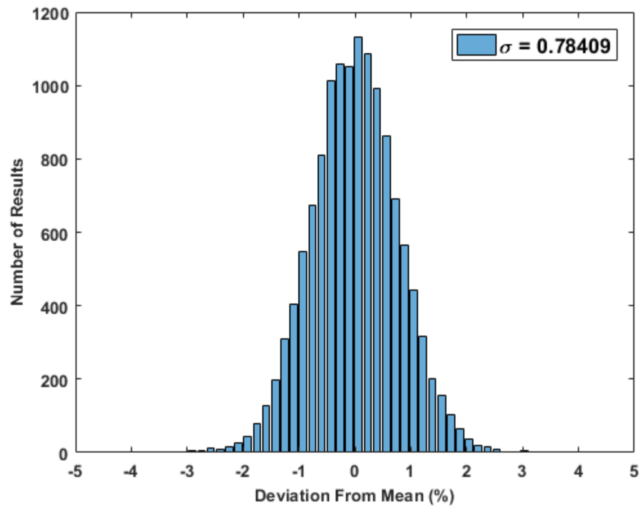


Fig. 13. Histogram of Sensor v2 Deviation

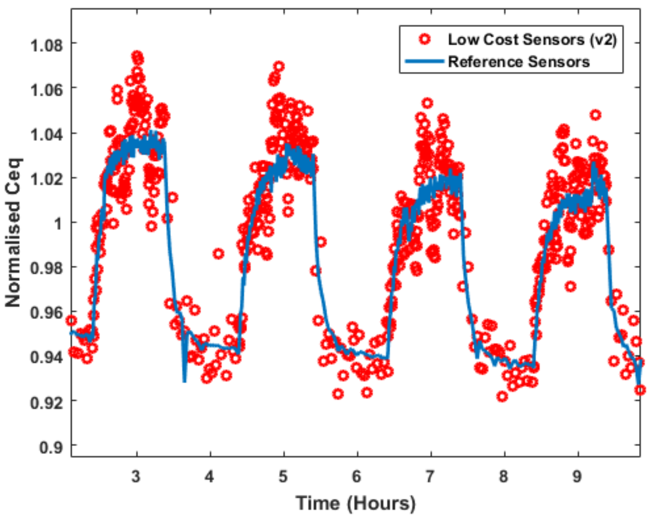


Fig. 14. CTSR Sensor Capacitance Measurement

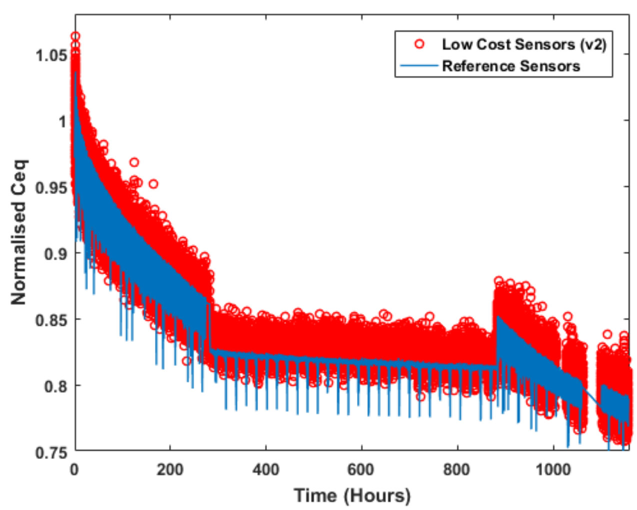


Fig. 15. Thermal Cycling Capacitance Data

VI. Conclusion

For industrial acceptance it is necessary to reduce the cost of insulation monitoring so as to allow large scale testing. Using of-the-shelf hardware is one promising avenue to implement leakage current based stator ground-wall capacitance monitoring. The sampling and dynamic range requirements present a challenge to acquisition and processing, a system was designed and tested with respect to high cost reference laboratory sensors. It was found that the largest barrier to low cost measurement of capacitance are the current sensor requirements. Two families of current sensor from LEM have been tested and compared, the CAS and CTSR. Each of these has their advantages and drawbacks, with CAS range offering better bandwidth and precision, however it was discovered that the long-term accuracy was the most important factor in insulation monitoring. Over relatively short time scales – 6 hours, the CAS sensor is able to provide an excellent measurement of insulation capacitance, however over several days the sensor begins to drift and deviate. These deviations render the CAS range unsuitable for monitoring as significant trend changes of the capacitances become indistinguishable from sensor drift. The CTSR sensor, having lower bandwidth and precision than CAS, shows a superior performance over longer timescales. A machine sample is shown undergoing significant changes in its lifetime, with significant capacitance changes, these are clearly visible both in the reference sensor measurement and the low-cost system that uses the CTSR for current sensing. The low cost monitoring system outlined in this paper, using the CTSR sensor has been shown to be a viable insulation monitoring tool. Isolated voltage sensing and data processing requirements can be easily satisfied with existing low-cost methodology, however one must make compromises when choosing the current sensor. Bandwidth and precision has been sacrificed to for long term stability, however this is acceptable for monitoring provided that the trend is clearly visible

References

[1] K. e. a. H, "Experience With Stator Insulation Testing and Turn/Phase Insulation Failures in the Power Generation Industry," *IEEE Transactions on Industry Applications,* vol. 54, no. 3, pp. 2225-2236, 2018.

[2] O. V. Thorsen and M. Dalva, "A Survey of Faults on Induction Motors in Offshore Oil Industry, Petrochemical Industry, Gas Terminals and Oil Refineries," *IEEE Transactions on Industry Applications,* vol. 31, no. 5, pp. 1186-1196, 1995.

[3] I. Tsyokhla, A. Griffo and J. Wang, "On-Line Condition Monitoring for Diagnosis and Prognosis of Insulation Degradation of Inverter-fed Machines," *IEEE Industrial Electronics,* Vol. 66, n. 10, Oct. 2019 pp 8126-8135.

[4] P. Zhang, K. Younsi and P. Neti, "A Novel Online Stator Ground-Wall Insulation Monitoring Scheme for Inverter-Fed AC Motors," in *IEEE Energy Conversion Congress and Exposition (ECCE)*, 2013.

[5] I. Tsyokhla, A. Griffo and J. Wang, "On-line monitoring of winding insulation health using high frequency common mode voltage from PWM," in *IEEE International Electric Machines & Drives Conference (IEMDC)*, Coeur d'Alene, ID, 2015.

[6] W.R. Jensen, E. Strangas, S. Foster, "A method for online stator insulation prognosis for inverter-driven machines", *IEEE Trans. Industry Applications*, in press. DOI: 10.1109/TIA.2018.2854408

[7] S. B. Lee, J. Yang, K. Younsi and R. M. Bharadwaj, "An online groundwall and phase-to-phase insulation quality assessment technique for AC-machine stator windings," *IEEE Transactions on Industry Applications*, vol. 42, no. 4, pp. 946-957, 2006.

[8] K. Younsi, P. Neti, M. Shah, J.Y. Zhou, J. Krahn, K. Weeber, C.D. Whitefield, "On-line capacitance and dissipation factor monitoring of AC stator insulation", I*EEE Trans. On Dielectrics and Electrical Insulation*, vol. 17, n.5, pp. 1441-1452, Oct. 2010.

[9] P. Zhang, K. Younsi and P. Neti, "A Novel Online Stator Ground-Wall Insulation Monitoring Scheme for Inverter-Fed AC Motors," in *IEEE Energy Conversion Congress and Exposition (ECCE)*, 2013.