A Novel Online Stator Ground-Wall Insulation Monitoring Scheme for Inverter-Fed AC Motors

Pinjia Zhang, *Member, IEEE*, Karim Younsi, *Senior Member, IEEE*, and Prabhakar Neti, *Senior Member, IEEE*

***Abstract*—Insulation failures are one of the most common failure modes of ac motors, particularly high-voltage motors. Online monitoring of insulation health of ac motors is important for preventing unexpected outages and minimizing the associated financial losses, particularly in critical applications. Previously, an online ground-wall insulation monitoring technique has already been proposed for six-lead ac motors. In this paper, a novel online ground-wall insulation monitoring scheme is proposed for inverter-fed ac motors. This approach is based on measurement of common-mode insulation leakage current for online capacitance and dissipation factor (C/DF) monitoring. The proposed technique can be applied to both three-lead and six-lead ac motors and can also be extended to monitor the insulation health of the cable connecting the inverter and the motor. The proposed technique is demonstrated in the lab environment and correlated with standard offline C/DF measurements.**

***Index Terms*—AC machine protection, ac machines.**

I. Introduction

ONLINE condition monitoring is essential for critical industrial processes to proactively protect the equipment and reduce process downtime and the associated costs. AC motors are one of the most popular power conversion devices used in all industrial processes, such as oil and gas industry, pulp and paper industry, etc. It is critical to monitor the health condition of ac motors in an online and continuous fashion.

For ac motors, the most common failure modes are stator insulation failures, bearing failures, and rotor failures (such as air-gap eccentricity, broken rotor bar, etc.). According to multiple industrial surveys, above 30% of all motor failures are stator insulation failures [1], [2]. This number can be even above 66% for high-voltage motors, according to [3]. The failures of stator insulation can be more critical for inverter-fed motors than mains-fed ones due to excessive electrical stress caused by repetitive voltage switching of power converters [4]–[6].

In addition to their high occurrences, stator insulation failures are critical due to the fundamental difference between electrical and mechanical failures. For mechanical failures, the degradation process is commonly much longer after the incipient stage of the degradation, compared with electrical failures. This typically provides more time to schedule maintenance and repair if necessary. However, electrical insulation failures are believed to happen in a much faster manner, leading to catastrophic failures [7]. As an example, it may take a fraction of second to a few hours for a stator insulation system to fail completely after inception of a turn–turn insulation fault [8]. Therefore, it is highly desired to not only be capable of detecting insulation failures at incipient stage but also capable of monitoring the degradation or aging of insulation of ac motors.

Various offline tests have been commonly carried out in the field for monitoring the degradation of the stator insulation of ac motors [9]–[12]. The most common techniques to assess the stator turn-to-turn insulation are the surge test and the offline partial discharge test [9]; as for ground-wall insulation assessment, the insulation resistance (IR) test, the polarization index test, the dc and ac high potential test, and the capacitance and dissipation factor test are the most popularly applied tests in the industry [9]–[12]. However, most of these tests can only be applied to motors that are disconnected from service during a maintenance outage. The maintenance cycle can be as long as few years depending on the application, which is typically too long to capture the degradation of insulation before the incipient failure. Few efforts have been carried out to perform these offline tests in an online fashion to avoid disconnection of the motor, which could provide monitoring of the degradation of motor insulation in a much shorter period [13]–[16]. Although these approaches are proven effective in a laboratory setting, their application in the field is limited due to their intrusive nature: Additional hardware or modification of existing equipment is required.

A condition monitoring technique based on differential current measurement has been proposed for online condition monitoring of six-lead ac motors [17]–[19]. A high-sensitivity differential current transformer (HSCT) has been developed for measuring the insulation leakage current, which enables the online measurement of insulation capacitance and dissipation factor (C/DF). In this paper, a novel insulation monitoring scheme for inverter-fed ac motors (both six leads and three leads) is proposed to measure the cumulative leakage current of all three phase stator insulation and monitor the health condition of stator insulation in an online and continuous fashion. In Section II, the insulation monitoring technique based on leakage current measurement is briefly reviewed. In Section III, a novel insulation monitoring scheme is proposed for inverter-fed ac motors. An experimental setup and results are presented

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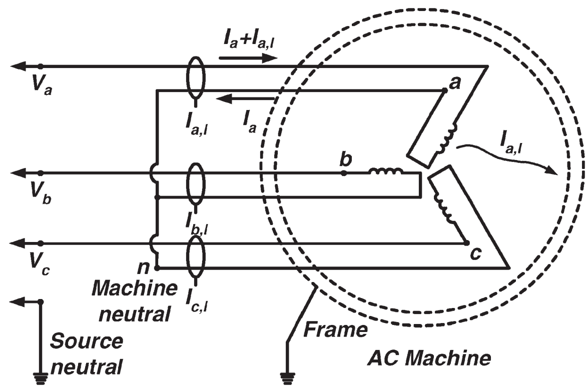

Fig. 1. Online leakage-current-based insulation monitoring scheme for six-lead mains-fed ac motors [17].

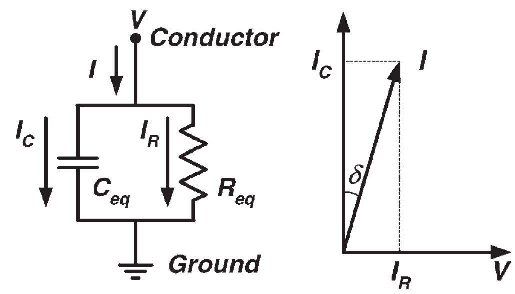

Fig. 2. (a) Equivalent circuit of insulation system. (b) Phasor diagram of insulation leakage current [17].

in Sections IV and V, respectively. The main strength of the proposed technique lies in its online and noninvasive nature.

II. Leakage-Current-Based Online Insulation Monitoring Technique

The motor insulation leakage current flowing from the winding to ground is equal to the difference between the currents in the line and neutral leads of a stator phase winding. The HSCT, which encircles both line and neutral leads of a stator phase winding, measures the insulation leakage current of that phase, as shown in Fig. 1. The measured leakage current I consists of capacitive and resistive components I_C and I_R, with respect to the voltage V, as shown in Fig. 2. Using measured insulation leakage current during a motor's normal operation, indicators of ground-wall insulation health such as C/DF can be derived as [4]

$$C_{\mathrm{eq}} = 2 \times I_C/(\omega V) \tag{1}$$

$$\mathrm{DF} = I_R/I_C \times 100\%. \tag{2}$$

The value of the insulation capacitance can indicate insulation conditions such as moisture absorption, thermal deterioration, or end-winding contamination. The dissipation factor can provide indication of the dielectric losses and the overall condition of the stator insulation [4], [20], [21], [26].

Offline C/DF test is one of the most commonly used offline assessment tests of stator insulation of ac motors. By converting the offline test into an online fashion, it enables online monitoring of insulation health condition and its degradation in a continuous fashion, which is a major breakthrough in area of motor insulation monitoring. However, this technique can only be applied on six-lead motors due to its requirement on accessing both line and neutral lead of each winding.

For inverter-fed ac motors, both six-lead and three-lead configuration exist. Therefore, it is critical to develop an alternative technique particularly feasible for three-lead inverter-fed ac motors.

III. Novel Online Insulation Monitoring Scheme for Inverter-Fed AC Motors

A. *Insulation Leakage Current of Inverter-Fed Motors*

Insulation leakage current in ac motors is driven by the voltage excitation between stator coil and stator frame/stator core. For mains-fed ac motors, this voltage only consists of the fundamental component and has a simple distribution across the winding: The magnitude of this voltage decreases in an almost linear fashion from the line end to the neutral end due to the voltage drop between adjacent turns. For the inverter-fed ac motor, it becomes more complex due to the switching of power switches in the inverter.

The inverter is typically controlled in a fashion so that the ac flowing through the stator winding is almost sinusoidal. However, the voltage driving stator insulation leakage consists of not only the fundamental component, but also multiple components at other frequencies due to switching of the power switches [22], [23]. Among these components, some of the high-frequency components induce both load current in the winding and leakage current, i.e., phase leakage current, flowing through stator winding insulation, similar to the fundamental component. There are also some components in the excitation voltage, i.e., common-mode voltage, which do not cause any current in the stator coil since all three phases are energized at the same voltage potential. Although the common mode voltage does not drive any current to flow through stator coil, it causes leakage currents to flow through the stator insulation due to the voltage stress across the ground-wall insulation. This is referred as common-mode leakage current in this paper.

All the phase leakage currents are driven by the phase-ground voltage in a multiphase fashion, as shown in Fig. 3(a). The capacitance and dissipation factor of each phase can be evaluated separately using a HSCT enclosing the line and neutral leads of the stator winding of each phase. Since the common-mode leakage current is driven by the common-mode voltage, which is the same among all phases, the common-mode leakage current flowing in all the phases are evaluated against the same voltage reference. The phasor diagram of the common-mode leakage current is shown in Fig. 3(b). This is equivalent to the offline C/DF test of all three phases of the stator winding insulation.

The sum of phase leakage current and common-mode leakage current can be measured as the difference between the currents in the line and neutral leads of a stator phase winding, the same way as shown in Fig. 2. Instead of measuring the

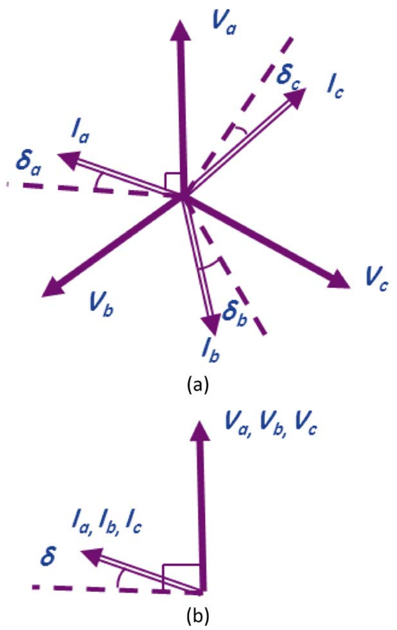

Fig. 3. Phasor diagram of phase and common-mode leakage current. (a) Phasor diagram of phase leakage current. (b) phasor diagram of common-mode leakage current.

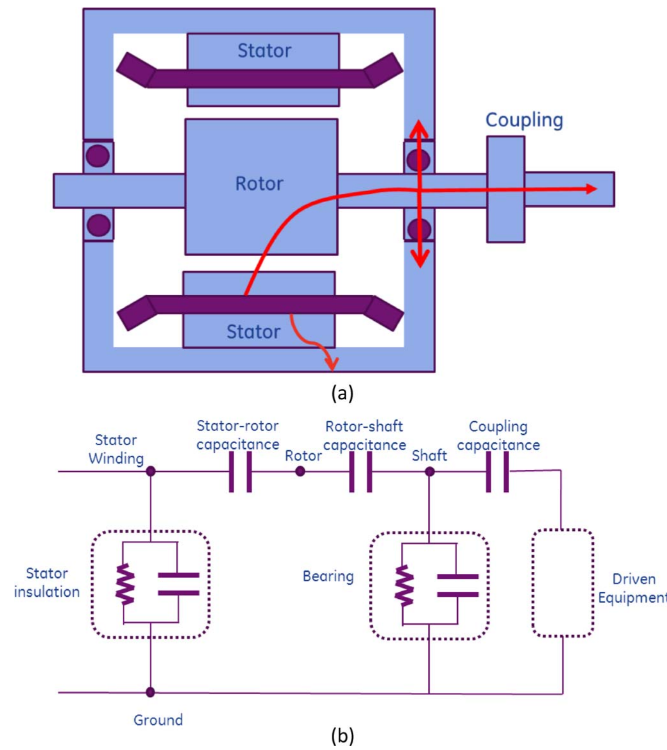

Fig. 4. Common-mode model of ac motors. (a) Path of common-mode current in ac motors. (b) Common-mode equivalent circuit of ac motors.

difference between the line and neutral leads of each phase of stator winding, the total leakage current of all three phases can be measured by enclosing the line leads of the stator winding of all three phases. The total leakage current consists of the sum of both phase and common-mode leakage currents. The sum of phase leakage current shows as the imbalanced component of the leakage currents of three phases since they are induced by three-phase voltages, as in Fig. 3(a). Assuming all the three phase stator winding insulation have similar health condition, the sum of the phase leakage current is negligible. Therefore, it is difficult to compute C/DF of the stator winding insulation solely based on the sum of phase leakage current. However, with the common-mode leakage currents driven by the same common-mode voltage in all the phases, the sum of common-mode leakage current can be used for C/DF evaluation. This enables online C/DF measurement for three-lead inverter-fed motors since the phase leakage current of each phase cannot be measured without access to the neutral lead.

B. Common Model of AC Motors

With the common-mode leakage current measurement, the health condition assessment of three-lead inverter-fed motors is enabled. However, the common-mode voltage not only induces leakage current through stator winding insulation but also causes other phenomena in ac motors.

Due to the capacitive coupling between the stator and the rotor, the common-mode voltage also capacitively induces voltage on the rotor shaft. Such rotor shaft voltage drives current through the bearing back to the stator frame, and may also drives current through the coupling and to the driven equipment, such as gearbox, pumps, etc. The current paths of the common-mode voltage/current are shown Fig. 4(a).

Such phenomenon can be modeled as an equivalent circuit of ac motors, as shown in Fig. 4(b). When measuring the total common-mode current, it is important to consider the remaining current path of the circuit in addition to stator insulation. However, the coupling between the stator winding and the rotor shaft is typically very weak due to the large gap between the stator winding and rotor shaft. Therefore, the actual current flowing from the stator to rotor shaft is typically much smaller than the insulation leakage current, particularly when the insulated bearings are used. In addition, since the condition of the stator winding insulation is evaluated by trending the C/DF over a long time, the variation of the rotor shaft current is negligible compared with the variation in the stator winding insulation due to aging. The C/DF evaluated using the common-mode current would be identical to the three-phase offline C/DF test without removing the rotor. Such tests are common practice in many applications.

C. Novel Scheme of Online Insulation Monitoring for Inverter-Fed AC Motors

The overall scheme of online insulation monitoring for inverter-fed ac motors is shown in Fig. 5. An additional HSCT can be installed anywhere between the inverter and ac motor to measure the total leakage current driven by the common-mode voltage to assess the health condition of stator winding insulation. In addition, HSCTs can also be installed in the terminal box for six-lead motors to measure the leakage current of each phase of the stator winding insulation.

The entire stator winding insulation is excited by the common-mode voltage between the stator coil and stator frame/

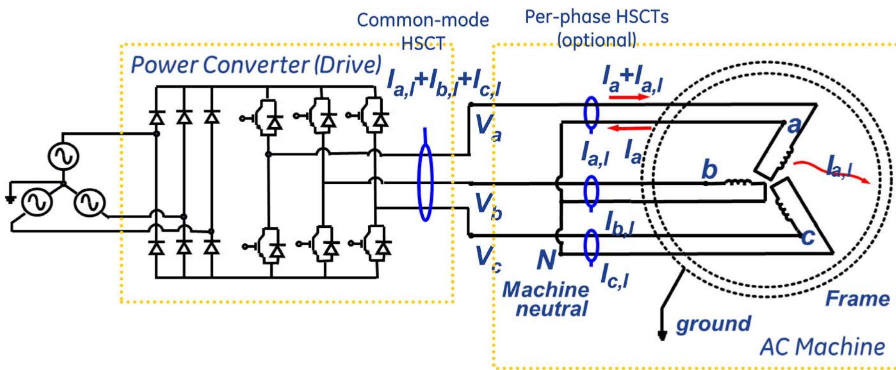

Fig. 5. Novel online insulation monitoring scheme for inverter-fed ac motors.

core in the same voltage level. Therefore, when using the total common-mode leakage current measurement, the capacitance and dissipation factor can be computed the same way as offline tests, i.e.,

$$C_{\mathrm{eq}} = I_C/(3\omega V) \tag{3}$$

$$\mathrm{DF} = I_R/I_C \times 100\%. \tag{4}$$

This is different from the phase leakage current measurement scenario, where the voltage driving leakage current varies through the stator winding; the line-end insulation is excited by full voltage, whereas the neutral-end insulation takes minimal voltage stress. For inverter-fed motors, the line-end insulation is excited by phase-ground voltage, whereas the neutral end takes neutral-ground voltage, which is also the common mode voltage. Therefore, for the phase leakage current measurement, the C/DF can be computed as follows:

$$C_{\mathrm{eq}} = 2 \times I_C/\left[\omega \times (V_{\mathrm{phase-ground}} + V_{\mathrm{neutral-ground}})\right]; \tag{5}$$

$$\mathrm{DF} = I_R/I_C \times 100\%. \tag{6}$$

Therefore, when both total leakage current measurements and phase leakage current measurements are available, it is possible to compare the health condition of line-end stator winding insulation and the neutral end by comparing the phase measurements and the total leakage current measurements. The higher dissipation factor of phase leakage current would indicate the faster degradation of the line-end insulation, whereas the lower dissipation factor of the phase leakage current indicates the faster degradation of the neutral end.

Different from the mains-fed scenario, for inverter-fed ac motors, the leakage current is driven by voltage at multiple frequencies instead of only the fundamental frequency. Therefore, it is possible to compute C/DF at various frequencies caused by the switching of the inverter for insulation health assessment. This information would be very helpful for assessment of insulation health condition for various insulation materials [23] and different aging causes.

In addition of stator winding insulation, cable insulation failure is also quite common in many applications due to the excessive electrical stress caused by the inverter. One of the major differences between inverter-fed and mains-fed conditions lies in the cable length. For inverter-fed ac motors, the cable length may vary from few feet to thousands of feet depending on the application. If two common-mode HSCTs are installed enclosing all three-phase cables, i.e., one at the inverter side and one at the motor side, it is possible to assess the health condition of the cable insulation by computing the difference in leakage current measurement. This is critical for many applications where long cables are used.

The advantages of the proposed online insulation monitoring scheme for inverter-fed ac motors are as follows.

- Noninvasive: HSCT can be installed outside terminal box; even clamp-on installation is possible to minimize installation cost.
- Flexible: The proposed scheme can be applied to both three-lead and six-lead motors and various applications.

D. Implementation Considerations for Different Converter Topologies

For various converter topologies, such as voltage-source pulsewidth modulation (VS-PWM), current-source PWM, load commutated inverter, etc., in most of the cases, common-mode voltage exists [24], [25]. Therefore, the proposed technology can be potentially used on various converter topologies. However, for some of the topologies, depending on the control requirement, the common-mode voltage may be estimated based on the already measured signals. For instance, for VS-PWM converter, it is typical that the dc bus voltage is always monitored; therefore, that the common-mode voltage can be computed based on the dc bus voltage and the switching pattern from the controller. In these cases, no additional voltage sensor would be required to measure the common-mode voltage. However, in some cases, such estimation may be not possible, which would require the presence of voltage sensors to measure the common-mode voltage for calculation of the dissipation factor. It is also suggested to install HSCTs between the voltage sensors and the motor to minimize the impact of input impedance of the voltage sensors.

IV. Experimental Setup

To validate the proposed approach in the laboratory environment, a 480-V 25-hp industrial motor drive (VS-PWM type, single-level) is used to drive a six-lead 100-hp induction

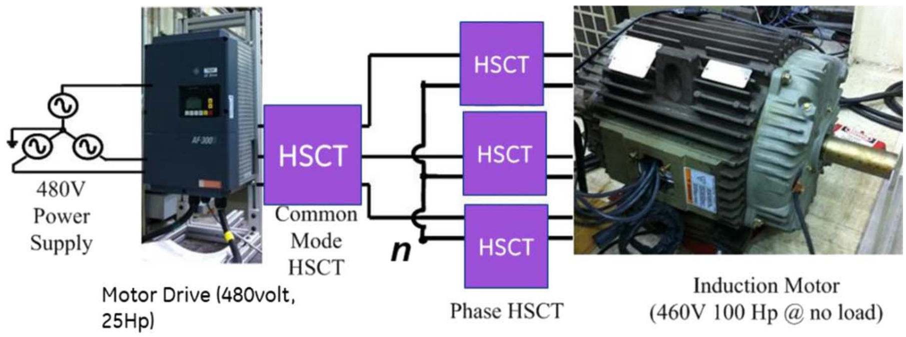

Fig. 6. Overall experimental setup.

motor under no load condition. The switching frequency of the drive is around 3.2 kHz. Four HSCTs are installed: one to measure the common-mode leakage current, and the other three to measure the leakage current of each phase of the stator winding insulation. The three phase-ground voltages, three phase-neutral voltages, and the neutral-ground voltage are also measured. An IOTECH data acquisition system is used to record the data at 1-MHz sampling frequency and 1-s duration periodically. An oscilloscope is used in parallel with the data acquisition system to record the waveform at 100-MHz sampling frequency for better resolution. To compare with the offline C/DF measurement technique, a TETTEX Midas 2880 capacitance bridge is used to measure the C/DF at 60 Hz and various voltage levels.

V. Experimental Results

A. Leakage Current Measurements

The measured phase leakage currents and the phase-neutral voltage of phase A are shown in Fig. 5(a), whereas the measured common-mode leakage currents and the neutral-ground voltage are shown in Fig. 5(b). For each phase of the stator winding, the line-end insulation is excited by the phase-ground voltage, whereas the neutral end insulation is excited by the neutral-ground voltage, which is also the common-mode voltage.

To better understand the frequency component in phase leakage current and the common-mode leakage current, the fast Fourier transforms (FFTs) of both phase and common leakage currents are shown in Fig. 6, together with the FFTs of the voltage driving each leakage current. It can be observed that the major frequency components in the leakage current measurements include fundamental frequency and its multiples, as well as switching frequencies and their multiples. The phase measurement includes all the frequency components in the common-mode leakage current, with additional frequency components such as the fundamental frequency (see Fig. 7). This is due to the difference in voltage excitation driving each leakage current.

For leakage current measurement, the main noise comes from the strong motor currents flowing in the motor cable. However, since the common-mode voltage does not drive any current in the motor, such noise at the common-mode frequencies are minimal compared with the phase leakage current components.

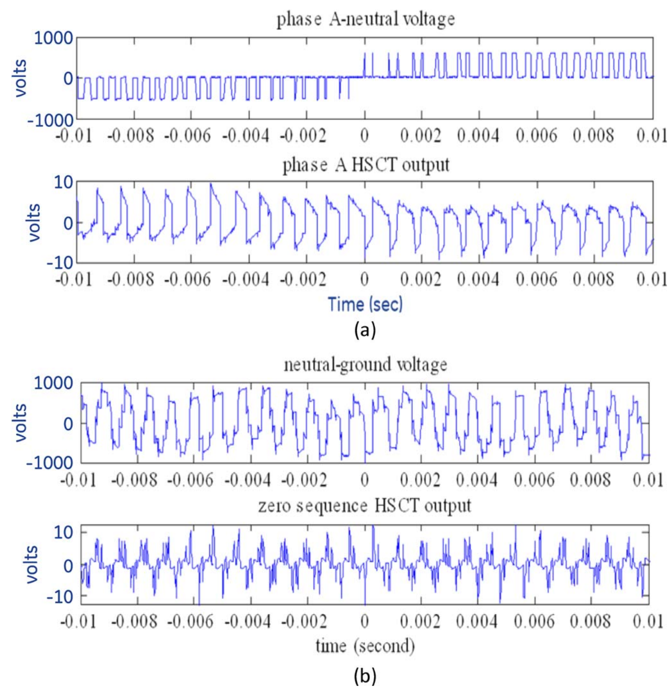

Fig. 7. Insulation leakage current measurements. (a) Phase measurements. (b) Common-mode measurements.

B. C/DF Computation and Comparison

The common-mode leakage current is driven by the common-mode voltage, which is evenly distributed in the entire stator winding. Therefore, the C/DF computed from the common-mode voltage is strictly comparable to offline test since similar voltage excitation pattern applies. However, for the per-phase leakage current measurements, the C/DF computed can be only compared with offline test in an approximate manner, due to the difference in voltage excitation pattern, where the voltage is no longer evenly distributed.

The computed C/DF from phase A leakage measurement and common-mode leakage currents are shown in Table I, with comparison to the offline test using a capacitance bridge. An FFT of the measurement common-mode voltage and leakage currents is conducted to compute C/DF at different frequencies (see Fig. 8). All C/DF computed at 60 or 180 Hz is highly comparable to the offline test. During the online test, the stator winding temperature is slightly higher than room temperature, under which the offline test is conducted. This is the main reason for the difference between DF measured offline and online.

TABLE I
C/DF COMPUTATION COMPARISON—ONLINE VERSUS OFFLINE

C/nF	**60hz**	**180Hz**	**1350Hz**	**1700Hz**	**2050Hz**	**2850Hz**	**3200Hz**	**3550hz**
Offline test	20	NA	NA	NA	NA	NA	NA	NA
Phase leakage current	20.3	19.8	17.8	16.2	15.4	12.0	10.1	9.2
Total leakage current	NA	19.7	17.7	15.8	15.2	12.1	10.0	9.3
DF/%	**60hz**	**180Hz**	**1350Hz**	**1700Hz**	**2050Hz**	**2850Hz**	**3200Hz**	**3550hz**
Offline test	1.2	NA	NA	NA	NA	NA	NA	NA
Phase leakage current	1.5	1.3	1.28	1.27	1.32	1.28	1.42	1.21
Total leakage current	NA	1.3	1.25	1.24	1.30	1.25	1.37	1.19

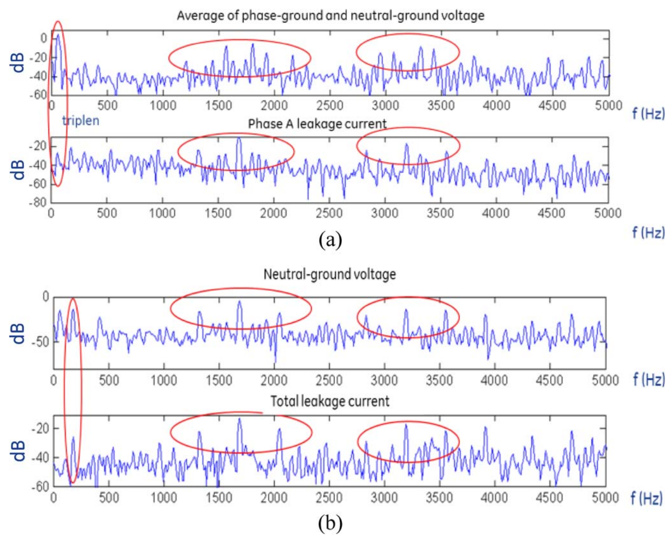

Fig. 8. Frequency analysis of leakage current measurements. (a) FFT of phase leakage current and its excitation voltage. (b) FFT of common-mode leakage current and its excitation voltage.

With the proposed online C/DF measurement approach, the C/DF can be computed under various frequencies, which offers more information for insulation health condition assessment than the standard offline test.

VI. CONCLUSION

Insulation failures are one of the most common failure modes for ac motors. The online monitoring of stator insulation health condition is critical for preventing unexpected process downtime and minimizing the associated financial loss. In this paper, a novel insulation monitoring scheme is proposed based on the measurement of insulation leakage current for inverter-fed ac motors. Instead of the phase leakage current measurement, a common-mode leakage current measurement scheme is proposed to measure the cumulative leakage current of all phases of stator insulation. The cumulative leakage current measurement only enables the monitoring of the overall health condition of the motor insulation without individual phase degradation. The proposed approach is capable of monitoring both six-lead ac motors and three-lead ac motors. For six-lead ac motors, the proposed scheme can be combined with the per-phase leakage current measurement for more detailed diagnostics. It can also be used toward monitoring the health condition of cable insulation between inverter and motor, which is another critical challenge for many applications.

The novel common-mode leakage-current-based monitoring scheme can provide C/DF measurement at multiple frequencies, which are strictly comparable to standard offline C/DF test. Such features can significantly help the monitoring of the insulation health conditions. The importance of the proposed approach lies in its non-invasive and online nature.

REFERENCES

[1] P. O'Donnell, "Report of large motor reliability survey of industrial and commercial installations: Part I," *IEEE Trans. Ind. Appl.*, vol. IA-21, no. 4, pp. 853–872, Jul. 1985.
[2] P. O'Donnell, "Report of large motor reliability survey of industrial and commercial installations: Part II," *IEEE Trans. Ind. Appl.*, vol. IA-21, no. 4, pp. 853–872, Jul. 1985.
[3] "Monitoring und Diagnose elektrischer Maschinen und Antriebe," *VDE*, Frankfurt am Main, Germany, 2001, Allianz Schadensstatistik an HS Motoren 1996–1999.
[4] G. C. Stone, E. A. Boulter, I. Culbert, and H. Dhirani, *Electrical Insulation for Rotating Machines*. Hoboken, NJ, USA: Wiley, 2004.
[5] E. Persson, "Transient effects in application of PWM inverters to induction motors," *IEEE Trans. Ind. Appl.*, vol. 28, no. 5, pp. 1095–1101, Sep./Oct. 1992.
[6] G. Stone, S. Campbell, and S. Tetreault, "Inverter-fed drives: Which motors are at risk?" *IEEE Ind. Appl. Mag.*, vol. 6, no. 5, pp. 17–22, Sep./Oct. 2004.
[7] R. M. Tallam, T. G. Habetler, and R. G. Harley, "Experimental testing of a neural-network-based turn-fault detection scheme for induction machines under accelerated insulation failure conditions," in *Proc. 4th Int. IEEE SDEMPED*, 2003, pp. 58–62.
[8] P. Zhang, Y. Du, T. G. Habetler, and B. Lu, "A survey of condition monitoring and protection methods for medium-voltage induction motors," *IEEE Trans. Ind. Appl.*, vol. 47, no. 1, pp. 34, 46, Jan./Feb. 2011.
[9] G. C. Stone, E. A. Boulter, I. Culbert, and H. Dhirani, *Electrical Insulation for Rotating Machines: Design, Evaluation, Aging, Testing, and Repair*. Piscataway, NJ, USA: IEEE Press, 2004.
[10] D. E. Schump, "Testing to assure reliable operation of electric motors," in *Proc. IEEE Ind. Appl. Soc. 37th Annu. Petrol. Chem. Ind. Conf.*, Sep. 10–12, 1990, pp. 179–184.
[11] *Users Manual—Digital Surge/DC HiPot/Resistance Tester Models D3R/D6R/D12R*, Baker Instrument Co., Fort Collins, CO, USA, 2005.
[12] G. C. Stone, "Recent important changes in IEEE motor and generator winding insulation diagnostic testing standards," *IEEE Trans. Ind. Appl.*, vol. 41, no. 1, pp. 91–100, Jan./Feb. 2005.
[13] J. Yang *et al.*, "A stator winding insulation condition monitoring technique for inverter-fed machines," *IEEE Trans. Power Electron.*, vol. 22, no. 5, pp. 2026–2033, Sep. 2007.
[14] H. D. Kim, J. Yang, J. Cho, S. B. Lee, and J.-Y. Yoo, "An advanced stator winding insulation quality assessment technique for inverterfed machines," *IEEE Trans. Ind. Appl.*, vol. 44, no. 2, pp. 555–564, Mar./Apr. 2008.
[15] S. Grubic, J. Restrepo, J. M. Aller, B. Lu, and T. G. Habetler, "A new concept for online surge testing for the detection of winding insulation deterioration in low-voltage induction machines," *IEEE Trans. Ind. Appl.*, vol. 47, no. 5, pp. 2051, 2058, Sep./Oct. 2011.
[16] S. Grubic, J. Restrepo, and T. G. Habetler, "Online surge testing applied to an induction machine with emulated insulation breakdown," *IEEE Trans. Ind. Appl.*, vol. 49, no. 3, pp. 1358, 1366, May/Jun. 2013.
[17] 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 Trans. Ind. Appl.*, vol. 42, no. 4, pp. 946, 957, Jul./Aug. 2006.
[18] K. Younsi *et al.*, "On-line capacitance and dissipation factor monitoring of AC stator insulation," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 17, no. 5, pp. 1441, 1452, Oct. 2010.

[19] P. Neti *et al.*, "Online detection of endwinding contamination in industrial motors," in *Proc. EIC*, Jun. 5–8, 2011, pp. 265, 270.

[20] H. A. Toliyat and G. B. Kliman, *Handbook of Electric Motors*, 2nd ed. New York, NY, USA: Marcel Dekker, 2004.

[21] *IEEE Recommended Practice for Measurement of Power Factor Tip-Up of Electric Machinery Stator Coil Insulation*, IEEE Std. 286-2000, 2000.

[22] H. Zhang, A. von Jouanne, S. Dai, A. K. Wallace, and F. Wang, "Multilevel inverter modulation schemes to eliminate common-mode voltages," *IEEE Trans. Ind. Appl.*, vol. 36, no. 6, pp. 1645–1653, Nov./Dec. 2000.

[23] G. Ramm and H. Moser, "New multifrequency method for the determination of the dissipation factor of capacitors and of the time constant of resistors," *IEEE Trans. Instrum. Meas.*, vol. 54, no. 2, pp. 521–524, Apr. 2005.

[24] S. Wei, N. Zargari, B. Wu, and S. Rizzo, "Comparison and mitigation of common mode voltage in power converter topologies," in *Conf. Rec. 39th IEEE IAS Annu. Meeting*, Oct. 3–7, 2004, vol. 3, pp. 1852, 1857.

[25] J. Rodriguez, L. Moran, J. Pontt, R. Osorio, and S. Kouro, "Modeling and analysis of common-mode voltages generated in medium voltage PWM-CSI drives," *IEEE Trans. Power Electron.*, vol. 18, no. 3, pp. 873, 879, May 2003.

[26] A. Ginart, I. N. Ali, J. Goldin, P. W. Kalgren, and M. J. Roemer, "Online motor winding early diagnostic based on dynamic leakage current monitoring," in *Proc. IEEE Aerosp. Conf.*, Mar. 5–12, 2011, pp. 1, 9.

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