Automated Impulse PD Testing for Early Detection and Classification of PD in the Stator Insulation of Low Voltage VFD Motors

Cheolhui Park*, Hyeonjun Lee*, Marcos Orviz Zapico**, Sang Bin Lee*, David Diaz Reigosa**, and
Fernando Briz del Blanco**, and Greg C. Stone***

* Dept. of Electrical Engineering,
Korea University,
Seoul, Korea

** Dept. of Electrical Computer & System Engineering,
University of Oviedo,
Gijon, Spain

*** Qualitrol – Iris Power,
Mississauga, ON, Canada

***Abstract*—Electrical stresses in industrial variable frequency drive (VFD) motors are increasing with the increasing voltage and dv/dt levels, and with the advent of wide bandgap power devices. This increases the likelihood of partial discharge (PD) in VFD motors, and is expected to increase the risk of stator insulation failures in low voltage (LV) motors for which the insulation is not resistant to PD. To ensure that PD does not occur during operation, LV VFD motors are qualified for PD-free operation in the design or manufacturing stages. However, the PD inception voltage of qualified LV motors decreases with insulation aging exposing them to the risk of PD-induced failure. In this work, an automated off-line test method for VFD-embedded PD testing is proposed. The main idea is to perform PD testing at motor standstill at a voltage higher than the operating voltage to identify PD activity in the insulation early, before it occurs during operation. A series of impulse voltage tests are proposed for stressing the different components of insulation for identifying PD in terminal-end ground, phase, and turn insulation. Testing on a LV, VFD motor verifies that PD can be identified whenever the motor is stopped to provide early warning of insulation failure.**

Keywords—AC Motors, Antennas, Fault Diagnosis, Impulse Testing, Off-line Testing, Partial Discharge, Stator Insulation Testing, Variable Frequency Drives.

I. INTRODUCTION

There is a recent trend in variable frequency drives (VFD) towards increasing the voltage and dv/dt levels, and replacing silicon-based power semiconductor devices with wide bandgap devices that allow faster switching of higher voltages. This has contributed to improving the efficiency, reliability, and power density of VFD driven motor systems, which is crucial in many industrial drive applications. However, the higher voltage and dv/dt levels also result in an increase in the electrical stresses on the stator insulation [1]-[3]. When motors are operated with pulse-width modulated (PWM) variable frequency drives (VFD), the high dv/dt increases in the voltage overshoot at the motor terminals [3]-[6]. It has been shown in a number of studies that this can result in high electrical stresses in the ground and phase insulation at the terminal end of the motor for VFD systems with short rise-time and long cables. The high dv/dt also causes uneven distribution of voltage across the winding, which applies high electrical stress on the turn insulation in the terminal end. Over-voltage in the stator insulation components is known to be high enough to cause partial discharge (PD) in low voltage (LV) VFD motors [3]-[6]. Considering that LV stator insulation is not resistant to PD, it can accelerate insulation aging leading to significant reduction in the insulation lifetime [7].

The conventional insulation tests for LV motors such as the insulation resistance, capacitance, hi-pot, or surge tests have limitations in detecting PD-induced stator insulation aging, since they are 1) only capable of testing ground insulation and/or 2) pass/fail tests that do not have diagnostics value [2]-[3]. Many different mitigation techniques such as filters or surge arrestors have been studied and applied to reduce the electrical stresses to suppress PD [7]-[9], but require additional hardware that increases the system cost. To ensure that PD does not occur for the given VFD and motor under the actual operating environment, IEC standards for qualification of the insulation for PD-free operation based applying impulse voltages have become available [10]-[12]. In this test, the worst-case impulse voltages that the motor is expected to encounter during operation are applied to the motor off-line to confirm that PD does not occur in the turn, phase, and ground insulation. This test is usually performed during the design stage or as a quality assurance (QA) test [13]-[14], but the PD inception voltage (PDIV), which is the minimum voltage at which PD occurs, decreases with insulation aging [15]-[17], as illustrated in Fig. 1. If the PDIV of a motor qualified for PD-free operation decreases to a voltage lower than the operating voltage, PD will occur during motor operation leading to

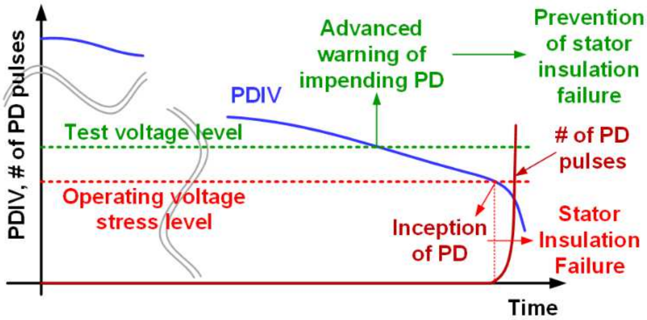


Fig. 1 1) Decrease in PDIV with insulation aging (time); 2) inception of PD with PDIV below operating voltage leading to insulation failure; 3) concept of PD detection at elevated test voltage level for prevention of failure.

premature insulation failure, as shown in Fig. 1.

Once the VFD and motor are installed, insulation testing requires the motor to be stopped and VFD to be disconnected, which makes it is difficult to perform the test frequently. VFD-embedded testing of stator insulation for automated assessment of stator insulation has been attempted in [18]-[20] for this reason. Methods for measuring the impedance of the insulation based on test voltages injected into the motor are proposed in [18]-[19] for assessment of the "average" condition of the insulation. However, they are not as effective as detecting PD that provides an indication of the "weakest" part of the insulation where it is most likely to fail. A concept for VFD-embedded impulse PD testing was proposed in [20] by the authors; however, it is not effective for detecting PD in the ground insulation, and the insulation component with PD cannot be identified. On-line detection of PD also has been studied, where PD is detected with a UHF antenna while the motor is operating [21]-[22]. However, it is a challenge to detect PD due to the switching noise, and PD can only be detected if the PDIV falls below the operating voltage level, as shown in Fig. 1, which makes it difficult to provide "early" warning of PD aging.

Stator insulation failures due to PD are expected to become a serious problem for LV industrial motors with the increasing voltage and dv/dt levels in VFDs. Given the technological trend and limited means of testing available, a test capable of providing early warning of PD-induced aging for VFD motor insulation is highly desirable. It is also desirable to identify the insulation component where PD is occurring so that suitable preventive measures can be applied to suppress PD. In this work, a series of VFD-embedded off-line tests at elevated voltage levels is proposed for early detection of PD in LV motors. Impulse voltage tests for applying increased voltage in the turn, phase, and ground insulation are given for detecting PD and identifying the component with PD. The proposed method is verified on a 540 V, VFD-motor system to show that automated impulse PD testing at increased voltage levels can be performed whenever the motor is stopped for early identification of PD.

II. IMPULSE PD TEST

Since the organic materials used for LV random wound stator insulation is not resistant to PD, it must be ensured that PD does not occur when the motor is driven by PWM VFDs, to prevent PD-induced failure. The test procedure for qualifying the motor for PD-free operation has been developed as IEC standards in [10]-[12]. PD measurement under impulse voltage excitation is described in IEC 61934 [10], and the details on the test configuration and acceptance criteria for ensuring PD-free operation are given in IEC 60034-18-41 and IEC 60034-27-5 [11]-[12]. It is important to confirm that PD does not occur in the turn, phase, and ground insulation under the worst case impulse voltages that the actual motor experiences during service to prevent insulation failure. Therefore, PD testing under fast risetime impulse voltage is preferred, since it is representative of actual in-service voltage stresses.

The impulse voltage can be applied to the stator winding with any type of commercial surge tester used for turn insulation testing. A surge tester consists of a boost converter that supplies high voltage dc that charges a capacitor, through an RLC series circuit that includes the stator winding, as shown in Fig. 2. The capacitor is charged to the desired test voltage and discharged onto the RLC circuit to apply the impulse voltage to the stator winding, as shown in Fig. 2. The PD signal can be measured using a UHF antenna, coupling capacitor, directional electro-magnetic coupler, or high-frequency current transformer according to [10]. The measured signal must be high-pass filtered for eliminating the interference from the high magnitude impulse voltage to observe the small, high frequency PD pulses with high resolution [10]. The waveforms of the applied impulse voltage, and high-pass filtered PD signal measured with a HF antenna are shown in Fig. 2.

The guidelines for the minimum test voltage level, impulse rise-time, and stator winding/ground configuration for impulse PD testing are given in [11]. The minimum impulse voltage to be applied to the turn, phase, and ground insulation components to confirm the absence of PD are specified in the standard. The voltage levels are determined based on the dc link voltage and voltage overshoot measured at the motor terminals of the actual VFD-motor system with the worst case operating environment for temperature, aging, etc taken into account. The impulse rise-time between 100 to 500 ns is suggested for testing turn insulation PD considering that it is difficult to adjust the risetime with commercial surge testers. The motor is qualified for use with the given inverter if PD is not observed at the predetermined minimum voltages for the turn, phase, and ground insulation. The motor should not be operated with the inverter if PD is present at the minimum voltages. Successful cases of applying the impulse PD tests by motor manufacturers are reported in [13]-[14], [17], where the likelihood of PD induced failures have been reduced through modifications in the insulation system design.

III. AUTOMATED VFD-EMBEDDED IMPULSE PD TESTING

A. *Main Concept of Proposed Method*

The main concept of the proposed test method is to use the VFD to perform the off-line impulse PD test described in II, whenever the motor is stopped [20]. It is desirable to perform the impulse PD test regularly even if the motor has passed the IEC 60034-18-41 test for PD-free operation in the design or QA stage, since the PDIV decreases with insulation aging. If

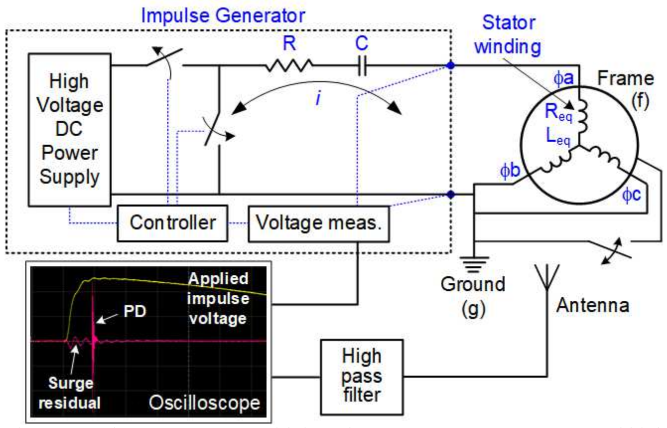


Fig. 2 Impulse PD test setup with impulse generator, UHF antenna, and high pass filter for PD detection (measured impulse voltage and PD pulse shown).

PDIV drops below the operating voltage, PWM VFDs with switching frequency in the kHz range can produce up to thousands of PD pulses per second leading to accelerated insulation aging. Therefore, it is advantageous to perform the test with the impulse voltage level elevated “above” the operating voltage, since the decrease in PDIV can be detected “before” it reaches the operating voltage level, as illustrated in Fig. 1. This could provide advanced warning of impending PD activity allowing the maintenance personnel to take preventive measures to reduce the likelihood of in-service failure. The impulse voltage stress on the stator terminal end insulation can be increased above the operating voltage with minimal modifications to the IGBT drive circuit by adjusting the gate resistance of the driver circuit as will be described in III.B. A set of impulse voltage tests on the 3 phases for stressing the different insulation components are proposed for extracting information on the presence and location of PD.

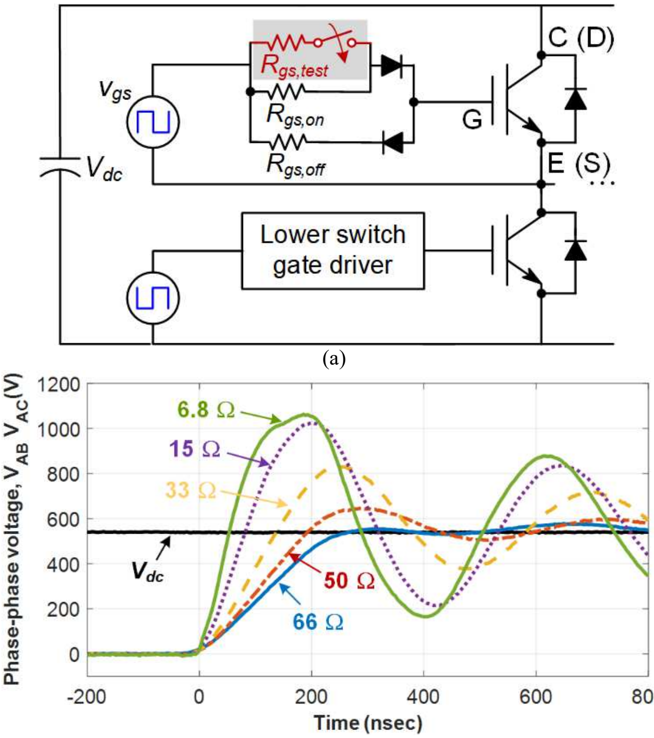
B. Increase in Peak Impulse Voltage

It was shown in [20], [23] that the peak impulse voltage applied to the terminal end insulation can be elevated by increasing the voltage overshoot. A simple and effective means of increasing the voltage overshoot is to increase the dv/dt by decreasing the gate resistance, R_g, in the gate drive circuit of the switching device, as shown in Fig. 3(a). The role of the gate resistance R_g is to limit the gate current, dv/dt, and voltage overshoot for device protection, and to suppress electromagnetic interference due to voltage ringing. The equivalent capacitance between the gate and emitter (or source) is charged at a faster rate, if the series RC time constant is lowered by decreasing the value of R_g [20]. This results in faster rise-time (higher dv/dt), which reduces the critical cable length at which voltage doubling occurs at the motor terminal due to voltage overshoot [8]. The voltage overshoot due to voltage reflection results in higher terminal voltage for a given cable length and allows impulse PD testing to be performed at a voltage higher than the operating voltage level. The voltage stress due to voltage reflection is highest at the terminal end of the stator and decreases towards the neutral end.

The value of R_g can be adjusted with active gate drive circuits [24] or with modifications to the drive circuit, as shown in Fig. 3(a). One way of reducing R_g is to temporarily connect a resistor in parallel to $R_{gs,on}$ (R_g=$R_{gs,on}$//$R_{gs,test}$). The motor terminal end phase to phase voltage measurements with R_g decreased from 66 Ω to 50 Ω, 33 Ω, 15 Ω, and 6.8 Ω are shown in Fig. 3(b). The motor was fed from a VFD with dc link voltage, V_{dc}, of 540 V through a 10.8 m cable. The results show that the dv/dt and peak impulse voltage overshoot at the terminal end can be controlled by adjusting the value of R_g for impulse PD testing. PD in the terminal end turn insulation is more likely to occur with faster dv/dt during the voltage rise, and PD in the terminal end ground or phase insulation is more likely to occur due to the increase in the peak of the voltage impulse [3]-[4], [11]. Decreasing R_g increases the electrical stress in the terminal end insulation above the in-service voltage stresses, making it possible to provide early warning of PD.

C. Impulse Voltage (v_{imp}) Test

The impulse voltage test can be performed by applying voltage pulses as outlined in the IEC 60034-18-41 standard with the motor configured as shown in Fig. 2 [11] using the VFD. The value of R_g can be decreased for increasing the dv/dt and peak voltage for stressing the terminal end insulation. The impulse voltage of the standard test can be applied to each phase using the VFD, by turning one of the upper switches on and off, while the lower switches of the other phases are turned on. To apply v_{imp} to phase A, S_1 of the VFD shown in Fig. 4 is switched on for a short interval with S_6 and S_2 turned on and S_3, S_4, S_5 turned off. This applies v_{imp} with increased dv/dt and voltage overshoot between the terminal ends of phase A and B, v_{AB} (and phase A and C, v_{AC}), as shown in Fig. 3(b). The switches can be operated similarly to apply v_{imp} to the terminal ends of phases B and C.



(a)

(b)

Fig. 3. Adjustment of R_g in the gate drive circuit for controlling dv/dt and peak impulse voltage overshoot: (a) example of gate drive circuit for decreasing R_g; (b) V_{dc} and motor terminal phase to phase voltage waveforms with R_g values of 66, 50, 33, 15, and 6.8 Ω.

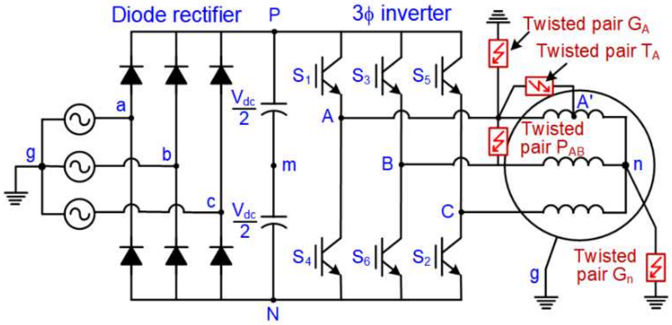


Fig. 4. VFD and ac motor with 3 phase Y connected voltage source with typical grounding configuration.

When phase A is excited with lower R_g, the voltage stress on the turn insulation of the phase A terminal end is higher than the operating voltage stress. Turn insulation stress (and PD) is influenced by the 1) reduced impulse rise-time (faster dv/dt) and 2) increased “jump” voltage (“increase” in voltage from 0 to the peak of the impulse) [11]. The voltage stress on the terminal end phase insulation between phases A and B (and phases A and C) is also increased with lower R_g due to the voltage overshoot, as shown in Fig. 3(b). Phase insulation PD is influenced by the peak-to-peak voltage, according to [11].

The voltage stress on the ground insulation of the terminal end is also increased above the operating voltage stress with reduced R_g due to voltage overshoot. Unlike the cases of turn or phase insulation, the voltage stress on the terminal end ground insulation of the excited phase depends on the instant of when v_{imp} is applied. This is because the terminal end voltage with respect to ground fluctuates depending on which diodes of the rectifier in Fig. 4 are active. It also depends on whether the source is connected in Y or Δ, and how it is grounded [25]. In this paper, the case of a Y-connected source with the neutral point solidly grounded shown in Fig. 4 is assumed. Measurements of the midpoint of the dc link (m) with respect to ground, v_{mg}, is shown in Fig. 5 with v_{imp} applied to phase A at the valley and peak of v_{mg}. It can be seen that v_{mg} fluctuates at 3 times the source frequency, and voltage v_{Am} is super-imposed on v_{mg} fluctuating at 180 Hz. Since PD in the ground insulation is influenced by the “peak to peak” voltage [11], maximum voltage stress ($v_{Ag,max}$) can be applied to the ground insulation when v_{imp} is applied at the valley and peak of v_{mg} (975 V), as shown in Fig. 5. The minimum voltage stress ($v_{Ag,min}$) can be applied when a single pulse is applied only at the valley of v_{mg} (876 V), as shown in Fig. 5. The two cases of $v_{Ag,max}$ and $v_{Ag,min}$ show that there is a 100 V difference in the ground insulation voltage stress. One possible way of identifying the timing of the peak and valley of v_{mg} for synchronizing v_{imp} without voltage measurements is to observe the fluctuation in v_{dc} while discharging v_{dc} onto the motor winding. The instants of v_{mg} peaks and valleys can be stored for controlling the timing of the pulses. The arguments above show that it is possible to identify PD occurring in the terminal end turn, phase, and ground insulation, with voltage stress higher than the in-service voltage stress with the v_{imp} test. The neutral end to ground voltage stress is lower than that of the terminal end with v_{imp} excitation, as shown in the v_{ng} waveforms in Fig. 5.

D. Identification of Insulation Component with PD

It is possible to identify if PD is in the terminal end turn, phase, or ground insulation with the v_{imp} tests described in III.C. Information on the stator insulation component with PD provides important information on the weakest part of the insulation system that is most likely to fail with insulation aging. This is valuable for the motor manufacturer since the insulation component with PD can be selectively strengthened to increase the PDIV during the design or manufacturing process. It is more efficient to reinforce the weakest insulation component rather than the whole insulation system to prevent insulation failures. It is also possible for the end user to apply effective preventive measures to suppress PD. A filter can be added to lower the peak voltage stress, and a surge arrestor can be added to lower the dv/dt depending on the cause and location of PD. Identifying the insulation component of PD can help improve the reliability of the motor since the likelihood of PD can be reduced.

The voltage stress on the terminal ends of the turn, phase, and ground insulation can be controlled with the $v_{imp,max}/v_{imp,min}$ tests performed on each phase with maximum and minimum ground voltage stress applied (total of 6 tests). The observability of PD with each test depends on the defective insulation component with PD, as summarized in Table I, where PD in the turn, phase, and ground are denoted as T, P, and G, respectively, and the phase terminal at which they are located are represented with subscripts, A, B, and C. The neutral terminal is represented with subscript n.

If PD is occurring near the terminal end turn insulation, it can be detected with v_{imp} applied to the phase with turn PD. PD in the turn insulation cannot be detected with $\underline{v_{imp}}$ applied to other phases, as shown in Table I. If PD is in the phase insulation, it can be detected with v_{imp} applied to any of the two phases adjacent to the phase insulation with PD, but not the other phase. Turn or phase insulation stress is independent of whether the ground voltage stress is maximum or minimum, and therefore, PD can be detected with $v_{imp,max}$ or $v_{imp,min}$, as summarized in Table I. PD near the terminal end ground insulation can be detected when $v_{imp,max}$ is applied to have

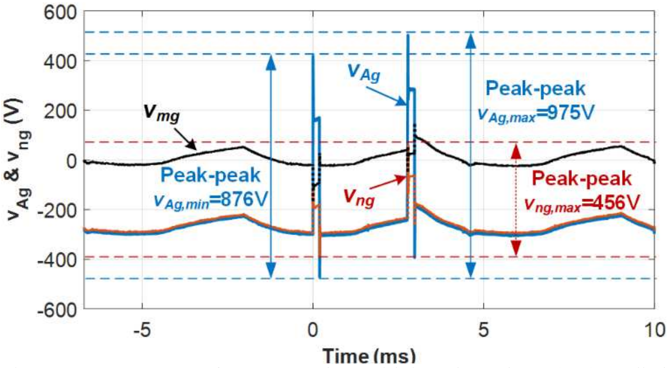


Fig. 5. Measurements of v_{mg}, v_{Ag}, and v_{ng} with impulse voltage (v_{imp}) applied to phase A at the valley and peak of v_{mg}.

Table 1. Detectability of PD with v_{imp} tests for PD located in the terminal end turn, phase, and ground insulation of phase A, B, and C (max and min refer to v_{imp} applied with maximum and minimum ground voltage stress, $v_{imp,max}$ and $v_{imp,min}$).

	V_{imp} test (ϕA)		V_{imp} test (ϕB)		V_{imp} test (ϕC)	
	max	min	max	min	max	min
G_A	O	X	X	X	X	X
G_B	X	X	O	X	X	X
G_C	X	X	X	X	O	X
P_{AB}	O	O	O	O	X	X
P_{BC}	X	X	O	O	O	O
P_{CA}	O	O	X	X	O	O
T_A	O	O	X	X	X	X
T_B	X	X	O	O	X	X
T_C	X	X	X	X	O	O

maximum ground voltage stress in the phase with PD before it is detected with $v_{imp,min}$, as shown in Table I. The detectability of PD with each of the 6 tests is summarized in Table I for the 9 different locations of PD in the terminal end turn, phase, and ground insulation. Since the detectability for each PD location is different for the 6 v_{imp} tests, it is possible to narrow down on the insulation component with PD for making adjustments for suppressing PD, in addition to detecting PD at an early stage with voltage stress higher than the stress experienced during motor operation.

E. *Detection of PD*

The purpose of the proposed automated PD test method is to detect the "presence" of PD to warn the user of decreasing PDIV at an early stage. Since it is only necessary to detect the presence of PD at elevated voltage, it is sufficient to apply 5 to 10 pulses to determine if PD exists [11]. Among the different options for detecting PD pulses listed in [10], HF antennas are considered in this work due to their low-cost benefits. It was shown in [20] that a simple antenna made from coaxial cables is sufficient for detecting whether PD exists. Search coils installed in the machine for measuring airgap or leakage flux that are recently being actively investigated for fault detection or control purposes [26]-[31] can also be used for detecting PD, as will be shown in IV.

The PD signal is a low amplitude pulse in the range up to 10s of mV superimposed on v_{imp} with a frequency range up to 100s of MHz. High-pass filtering of the antenna signal is essential for separating the low magnitude PD pulses from the high magnitude v_{imp} signals in the kV range [10]. It is demonstrated in [20] that PD pulses under impulse voltage excitation can be detected automatically with radio frequency electronics.

IV. EXPERIMENTAL RESULTS

A. *Experimental Setup*

The proposed PD detection method was verified on a 380 V AC motor stator shown in Fig. 6(a) using a commercial inverter stack with dc link voltage of 540 V and IGBTs rated at 1,200 V. To emulate the case where the PDIV in the terminal end ground, phase, and turn insulation decreased to above operating voltage, twisted pairs were carefully adjusted to produce PD at the desired voltages. The twisted pair for producing ground PD at 950 V was installed between the terminal and neutral ends of phase A and ground (G_A, G_n), as shown in Fig. 4. For PD in the terminal end phase (P_{AB}), a twisted pair with PDIV of 1,300 V was installed. A twisted pair with PDIV of 550 V for emulating turn PD (T_A) was also installed between the terminal end and midpoint of the phase A winding, A', as shown in Fig. 4. The twisted pairs were installed inside the motor along with the search coil and coaxial cable antennas for PD detection, as shown in Fig. 6(a).

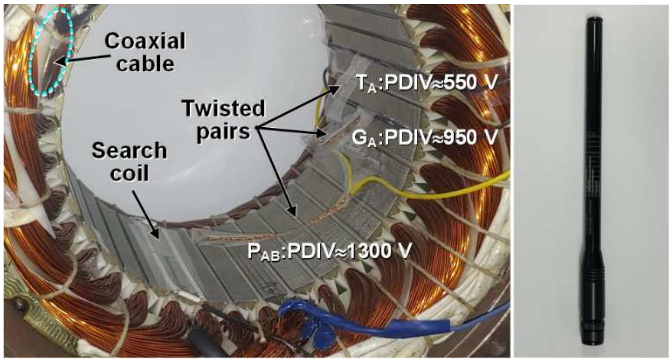
Testing was performed with the rotor removed, and the stator connected to the VFD through a 10.8 m cable. Voltage overshoot was produced to increase the voltage stress when performing the V_{imp} test by reducing the value of R_g to 6.8 Ω. PD pulses were measured with 1) monopole coaxial cable (1 cm of the conductor exposed) installed in the endwinding, 2) a search coil wound around a stator tooth, and 3) an external radio antenna (70 to 1,000 MHz bandwidth), as shown in Fig. 6(a)-(b). The antenna signals were high pass filtered with commercial filters at 185 MHz and observed with an oscilloscope while synchronized to the impulse voltage.

B. *Experimental Results*

The test results with v_{imp} applied with maximum and minimum peak-to-peak terminal ground voltages, $v_{imp,max}$ and $v_{imp,min}$, as described in III.C (Fig. 5), are shown in Fig. 7(a)-(b), respectively. For each case, the terminal and neutral end voltage, v_{Ag} and v_{ng}, measurements are shown with the radio antenna PD signals with twisted pairs G_A and G_n connected. The results show that PD occurs only in the terminal end ground insulation when the maximum peak-to-peak voltage ($v_{imp,max} \approx 980$ V) is applied, since it exceeds the PDIV of twisted pair G_A (950 V). The impulse shown in Fig. 8(a) is the second impulse applied at the peak of v_{mg}. PD could not be observed under $v_{imp,min}$ excitation, since peak to peak v_{Ag} is lower than the PDIV (< 880 V). PD also could not be observed when v_{imp} was applied to phases B and C, as expected. Detection of PD with $v_{imp,max}$ excitation and not with $v_{imp,min}$ excitation indicates that PD is occurring in the terminal end ground insulation of the excited phase, as described in III.D (highlighted in Table I). The peak to peak voltage is higher than the in-service v_{Ag} stress under $v_{imp,max}$ excitation due to the overshoot, allowing early warning of PD activity. There is no PD in the neutral end ground insulation (G_n) under both cases of v_{imp}, since the peak-to-peak v_{ng} is very low (<330 V and <240 V under $v_{imp,max}$ and $v_{imp,min}$). The results clearly show that PD in the terminal end ground insulation can be identified with the $v_{imp,max}$ and $v_{imp,min}$ tests.

The PD measurements obtained with the internal search coil and coaxial cable antennas are shown in Fig. 7(a) when PD is present under $v_{imp,max}$ excitation. It can be seen that the PD signal can be detected with any type of low-cost antenna used, although there is a difference in the signal to noise ratio. The PD signal can be distinguished from noise by observing whether the high frequency PD signals are present at the instant of the peak impulse voltage when the switch is turned on.

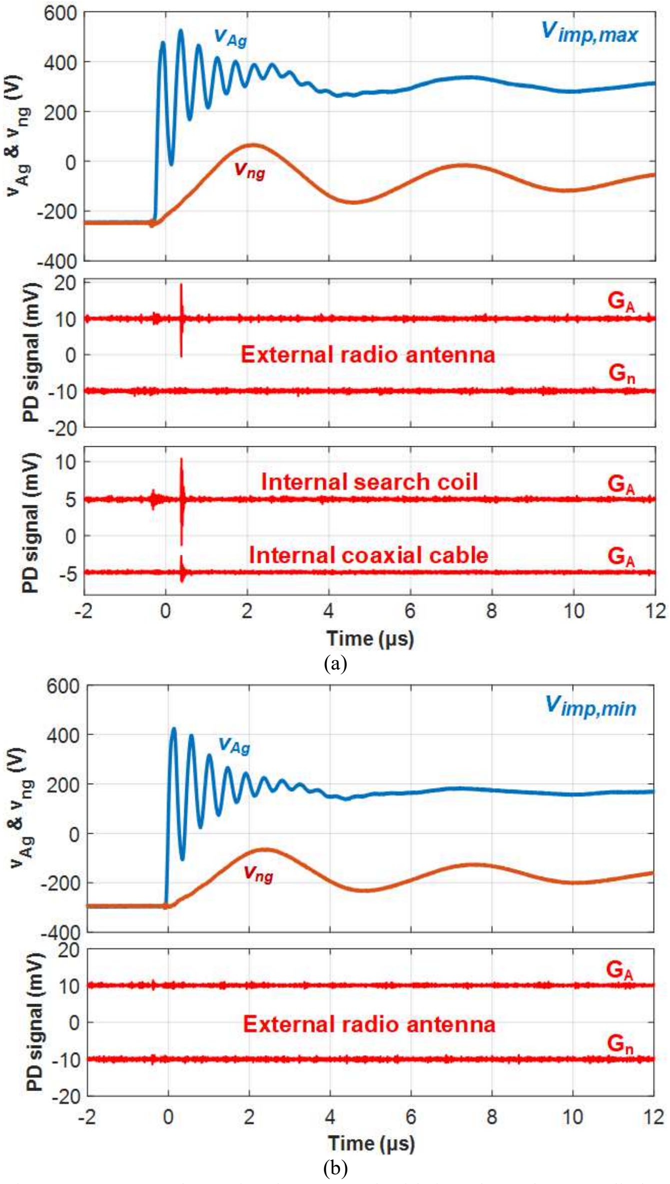
The peak-to-peak voltage in the phase insulation is independent of the instant of when v_{imp} is applied, unlike the



(a) (b)

Fig. 6. Experimental setup of PD sources and antennas for PD detection: (a) twisted pairs for producing PD in ground (G_A), phase (P_{AB}), and turn (T_A) insulation with controllable PDIV; internal co-axial cable and search coil antennas for PD detection; (b) external radio antenna for PD detection.

case of ground insulation, and PD can be observed if the voltage stress exceeds the PDIV. The peak to peak voltage stress on the phase insulation under v_{imp} excitation is higher than the ground voltage stress at 1,449 V, as shown in the v_{AB} waveform in Fig. 8(a). PD could be observed in the twisted pair P_{AB} since the phase voltage stress exceeds the PDIV of 1,300 V, as shown in Fig. 8(b). PD occurred in twisted pair P_{AB} regardless of whether v_{imp} was applied at the peak or valley of v_{mg}, and when v_{imp} was applied to phase A or B, since the phase insulation between the terminal end of phase A and B is stressed. There was no PD in twisted pair P_{AB} with v_{imp} applied to phase C, as expected. Occurrence of PD with both $v_{imp,max}$ and $v_{imp,min}$ excitation, and in 2 phases (A and B) indicates that PD is occurring in the terminal end phase insulation, as highlighted in Table I.



(a)

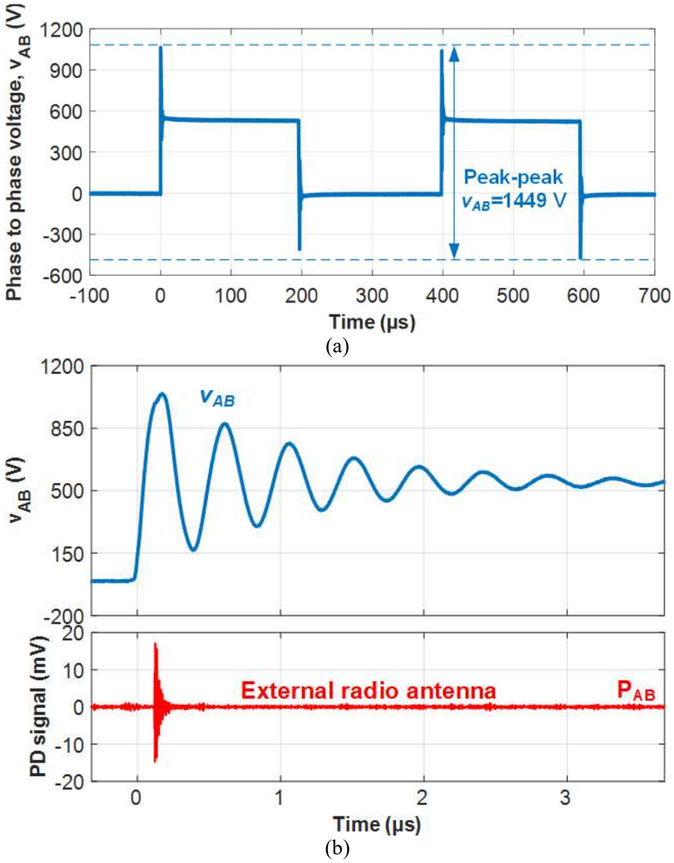
(b)

Fig. 7. v_{Ag}, v_{ng}, and PD signals measured with impulse voltage applied at instant when peak-to-peak ground voltage is (a) maximum ($v_{imp,max}$) and (b) minimum ($v_{imp,min}$). PD signals measured with external radio antenna and internal coaxial cable and search coil antennas with twisted pair connected between terminal and neutral ends and ground (G_A, G_n of Fig. 4).

The jump voltage in the turn insulation is also independent of whether v_{imp} is applied at the peak or valley of v_{mg}, as in the case of phase insulation. PD in the twisted pair T_A can be observed if the voltage stress, $v_{AA'}$, exceeds the PDIV of T_A (550 V), as shown in Fig. 9(a). PD in the terminal end turn insulation can be distinguished from that of the phase insulation by observing PD under v_{imp} excitation of other phases. If PD is occurring in the turn insulation of phase A, there is no PD in T_A with v_{imp} applied to phases B or C, since the voltage stress, $v_{AA'}$, is low, as shown in Fig. 9(b). If PD is observed with v_{imp} applied to adjacent phases B or C, this indicates that PD is occurring in the terminal insulation of phase AB or CA, respectively, as highlighted in Table I, which allows turn and phase PD to be distinguished. When applying v_{imp} with the value of R_g reduced, the turn voltage stress is significantly higher compared to the in-service stress, since turn voltage stress is mainly influenced by the shorter rise-time and higher jump voltage. This allows turn insulation PD to be detected before PD occurs during motor operation providing advanced warning of turn insulation aging. The results given in Figs. 7-9 confirm that the proposed v_{imp} tests allow PD in the terminal end ground, phase, and turn insulation to be detected and located at voltage stresses higher than the operating levels for providing early warning of PD.

V. CONCLUSION

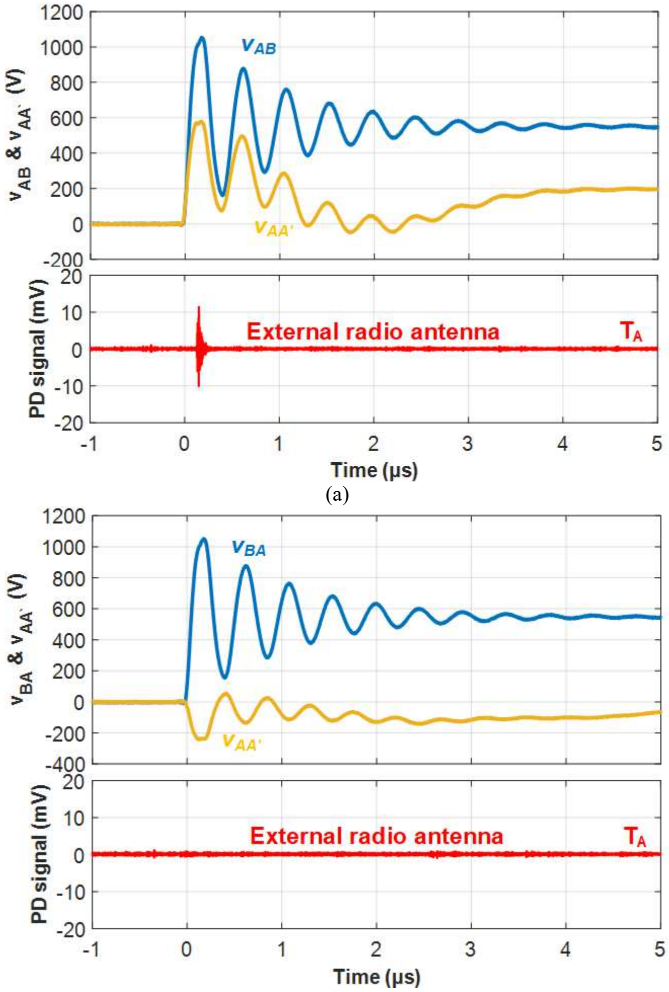
PD-induced stator insulation failures are expected to become a problem with the increasing electrical stress on



(a)

(b)

Fig. 8. v_{imp} excitation in phase A: (a) v_{AB} waveform and peak-to-peak phase voltage stress; (b) zoomed in view of v_{AB} with PD signal measured with twisted pair P_{AB} between terminal end of phase A and B (Fig. 4)



(a)

(b)

Fig. 9. v_{AB} (v_{BA}), $v_{AA'}$, and turn insulation PD signal measured with v_{imp} applied to phases (a) A and (b) B. PD signal measured with twisted pair T_A between A and A' (Fig. 4)

industrial VFD motors due to increasing dv/dt and voltage levels. In this work, an automated VFD-embedded PD test method for performing off-line PD testing whenever the motor is stopped, is proposed. The proposed PD test can be performed with voltage stresses higher than the operating voltage stress levels to identify PD activity in the insulation before it occurs during operation. In addition, a series of tests based on applying a set of six impulse voltages can be used for stressing the different components of insulation for identifying PD in turn, phase, and ground insulation of terminal end. The experimental results on a LV motor was provided to verify the claims made in the paper. It was shown that the proposed method can provide automated and remote testing for early warning of PD with minimal hardware modifications. It can also provide valuable information on the weakest component with PD that is likely to fail for design modifications and applying preventive measures for improving the reliability of the industrial VFD motor.

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