Quantifying the Probability of Partial Discharge in VFD Fed Electric Motors under Voltage Harmonics Concentration

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***Abstract*—Partial discharges (PD) diagnostics are considered as reliable techniques for the insulation health assessment of various electrical components of the power system. Generally, PD diagnostic tests are performed in laboratory by ignoring the effect of harmonic pollution in test voltage waveform. However, the operation of electric motors (EMs) fed by variable frequency drives (VFD) produces harmonic distortion in the sinusoidal test voltage waveform. During low speed operation of VFD, the influence of harmonic distortion in test voltage waveform is increased. The additional distortion parameters in the test voltage waveform can significantly increase the PD activity in the EM insulation. Therefore, for correct understanding of PD data, it is essential to consider the actual harmonic spectrum of the test voltage waveform during online PD measurement. This paper presents a methodology for the quantification of the probability of PD in VFD-fed EMs under different concentration of voltage harmonics. For the experimental work, PD diagnostic tests have been performed under variable operating conditions of eight EMs and PD severity is investigated by calculating the PD characteristic parameters at different harmonic distortion levels. Also, the probability density functions and cumulative distribution functions for several probability distributions were evaluated to statistically process the PD data at different harmonic levels. Finally, the distribution fitting tools have been implemented to find an appropriate distribution that can precisely characterize the probability of PD under different concentration of voltage harmonics. The proposed method may be utilized for studying the effect of harmonic distortion on PD activity and estimating the lifetime of stator insulation in EMs.**

Keywords—Electric machines (EMs), harmonics, partial discharges (PD), probability distribution, power quality (PQ), variable frequency drives (VFD).

I. INTRODUCTION

In industrial and commercial applications, the performance of the electrical motors (EMs) is required to be improved with the advanced design and engineering, in contrast to the pneumatic and mechanical systems. The variable frequency drive (VFD) fed EMs play an important role in reducing the operational cost and energy utilization while upholding a high efficiency operation [1]-[3]. However, the performance of EMs is significantly affected when VFD is operated at low speed for prolonged time that many causes the premature insulation failure of the stator windings [4]-[6].

The partial discharges (PD) diagnostics is an extensively accepted method for evaluating the health condition of stator insulation in EMs [3], [7]-[11]. Generally, a pure sine wave of the test voltage is assumed during PD diagnostic tests performed in laboratory. However, the operation of EMs fed by VFD produces harmonics in the sinusoidal test voltage waveform. During low speed operation of VFD, the influence of harmonic distortion in test voltage waveform is increased. It has been noticed that the harmonic components present in the test voltage waveform can increase the PD severity in stator insulation of EMs. During online PD measurement, ignoring the harmonic concentration in test voltage waveform may lead to a false PD data analysis and cause the indeterminate maintenance schedule [12], [13]. Consequently, for proper assessment of the stator insulation degradation, it is important to comprehensively understand the effect of distorted voltage waveform on PD diagnostics in VFD-fed EMs.

Previously, several researchers have explored the impact of power electronic drives fed EMs on the stator insulation lifetime [3], [14]-[24]. For instance, Ref [25] presented the power quality (PQ) and reliability issues related to the application of VFD-fed EMs. Refs [23], [24] investigated that the occurance of PD in the stator winding causes the premature failure of the insulation in inverter fed EMs. Furthermore, the authors also proposed a methodology for the assessment of stator insulation lifetime in PD regime. In Refs [14], [20], the authors examined the time domain and frequency domain PD characteristics influenced by the repetitive impulse voltage in EMs driven by inverters. Moreover, they have also studied the PD phase distribution and insulation lifetime behavior. In Ref [12], the effect of harmonics present in the test voltage on PD patterns analysis has been investigated. Ref [15] presented a comparison based study by analyzing the effect of both sine wave test voltage and multi-level inverter voltage on the PD behavior and the degradation of the insulation in twisted wire pairs. The effect of harmonic pollution present in the test voltage on the insulation characteristics of epoxy resin has been investigated in Ref [26]. Moreover, the authors have investigated that the development of electric tree due to the distorted voltage waveform eventually reduced the insulation lifetime.

In summary, the previous studies have investigated the impact of selective harmonic components present in the voltage waveform on PD activity. None of the current study presented the effect of actual harmonic distortion produced in the applied voltage waveform during the variable speed (VS) operation of VFD-fed EMs on the PD behavior. Furthermore, there is a need to quantify the probability of PD activity due to voltage harmonic distortion in VFD-fed EMs based on the experimental data.

In this paper, a procedure has been introduced to quantify the probability of PD under different concentration harmonics produced in the voltage during variable operating conditions of VFD-fed EMs. For the experimental work, VFD is operated at VS varied from 5% to 100% of the full speed. Accordingly, the harmonic distortion in sinusoidal voltage waveform developed in the VFD-fed EM. By changing the speed, total harmonic distortion (THD_v) was varied from 5.2% to 40.44% and online PD measurements were carried out at different harmonic compositions in the applied voltage waveform. From the measured PD signals, the severity of PD was evaluated during different harmonic regimes using several PD characteristic parameters (PDCP). These parameters include PD inception voltage (PDIV), accumulated apparent charge (q_a), discharge current (I), number of PD pulses (m), discharge power (P), and quadratic rate (D). The statistical characteristics of PD data were assessed under different harmonic regimes using several distribution functions. Lastly, the distribution fitting tools were applied to discover an appropriate distribution that can precisely describe the probability of occurrence of PD under different voltage harmonic concentrations.

The rest of the paper is ordered as follows: In Section II, the overall methodology is presented. Section III presents the online experimental test setup and the technique for online measurement. In Section IV, the PD measurement results and discussions are presented. Finally, Section V presents the conclusions.

II. METHODOLOGY

The methodology adopted to quantify the probability of PD under different harmonic concentration in the voltage developed during VS operation of VFD-fed EMs is presented in Fig. 1.

In this experimental work, total eight 12-pulse VFD-fed EMs were used. Previously, it has been explored that 12-pulse VFD-fed EMs typically produce 5th and 7th harmonic components and their concentration increases during low speed operation VFD [6]. Consequently, the harmonics present in the test voltage can be analyzed at adjustable speed of VFD-fed EMs by employing a non-intrusive condition monitoring technique. Furthermore, online PD diagnostics can be carried out and PDCP may be determined VFD-fed EMs at different harmonic distortion levels. Several probability distribution functions including Generalized extreme value (GEV), Weibull, Normal, and Gamma distribution can be assessed to determine the probability density function (PDF) and cumulative probability distribution (CPD). Finally, the distribution fitting tools may be employed to discover an appropriate distribution that can precisely characterize the probability of occurrence of PD under different voltage harmonic concentrations.

III. LABORATORY EXPERIMENT

This section discusses the experimental setup employed in the laboratory tests and online PD measurement procedure.

A. Online Experimental Setup

Fig. 2 (a) and (b) present the block diagram of online PD experimental test setup and a photograph of laboratory bench, respectively. The experimental test setup consisted of a VFD-fed EM attached with a 3-phase variable power supply source. The output voltage obtained from the AC power supply source can be varied from 320 V to 680 V. The voltage harmonic distortion in the supply source was investigated separately using PQ analyzer and found negligible harmonics due to the measurement of THD_v less than 5%.

The PD diagnostics test setup consists of a coupling capacitor (C), quadrupole, PD meter, and data acquisition system. One phase of the EM is attached to C (10 nF) that communicates the PD current signal to the quadrupole. The quadrupole transforms the PD current signal to PD voltage signal that is assessable by the PD measuring system. PD measuring system consists of a data acquisition device that converts the PD analog signals to digital samples.

As per IEC TS 60034-27 recommendations [27], PD measurement system has been tuned at 1 MHz to limit the attenuation of the detected PD signal. The basic noise level and linear error have been restricted to 0.1 dB and 0.2 pC, respectively. The PD measurement system was calibrated according to the procedures recommended by IEC TS 60270 [28].

B. Measurement Procedure

The overall procedure adopted to study the PD severity and the measurement of PDCP comprises of two steps. In the first step, VFD-fed EM was operated in manual mode of operation

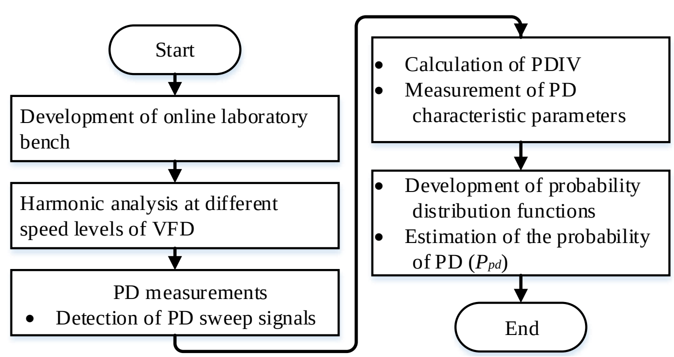

Fig. 1. Procedure adopted to quantify the probability of PD under voltage harmonics produced by VFD-fed EMs

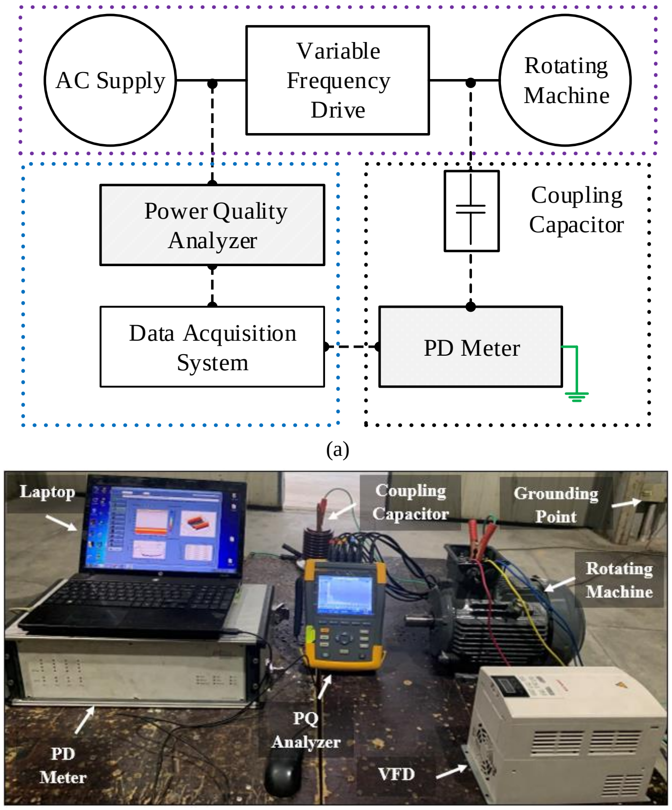

Fig. 2. (a) Block diagram of experimental test setup and (b) photograph of laboratory bench for online PD diagnostics

and the speed of the EM was manually adjusted at 100% of the full speed. At this speed, the thermal stability is achieved and the PDIV was measured by steadily increasing the applied voltage. The experiments were repeated by measuring PDIV at different speed of VFD by varying the speed in small steps ranging from 100% to 5%.

In the second step, the influence of VS operation of VFD-fed EM on PD diagnostics was studied by estimating the PDCP at different harmonic distortion levels. For this purpose, a constant test voltage, equal to the PDIV measured at the speed equal to 100% of the full speed, was applied and the speed was varied from 5% to 100%. Accordingly, the harmonics produced in VFD-fed EM were recorded and PD measurements were carried out. Based on the measured PD signals, different parameters including PDIV, q_a, m, I, P, and D were calculated to evaluate the PD intensity and the condition of stator insulation. The detailed procedure for the calculation of PDCP has already been explained in [29].

IV. RESULTS AND DISCUSSIONS

In this section, the variations in THD_v and PDIV by changing the speed of VFD-fed EMs is presented. Furthermore, the PDCP and the probability of PD are assessed based on the results of online PD measurements.

A. Partial Discharge Inception Voltage

Under various speed levels of VFD-fed EMs, both the THD_v and PDIV were determined and results are presented in Figs. 3 and 4. From Fig. 3, it can be observed that THD_v increased by reducing the speed of VFD-fed EMs from 100% to 5%. For example, when speed of VFD was 100%, THD_v was 5.2%. When speed was decreased to 5%, THD_v increased to the maximum values of 40.4%.

The voltage waveform with specific harmonic components produced at VS was applied for 5 minutes and PD activity was investigated under different harmonics levels by measuring its corresponding PDIV. It was observed that the harmonic pollution present in the applied voltage waveform reduced the PDIV. From Fig. 4, it can be seen that the increase in THD_v from 5.2% to 40.4% due to reduction in the speed of VFD reduced the PDIV from 480 V to 420 V.

B. Online Partial Discharge Measurements

Fig. 5 presents online PD measurements carried out at different voltage harmonic distortion levels developed during VS operation of VFD-fed EMs. Form the detected PD sweep signal of 50 ms reference time (T_{ref}), the PD activity was determined by calculating the PD amplitude (q_i) and number of PD pulses per cycle (n). Initially, the speed of VFD-fed EM was made 100% and test was performed using almost a sinusoidal applied voltage waveform (THD_v=5.2%), the results are presented in Fig. 5 (a). From Fig. 5 (a), it was observed that the absence of substantial harmonic components in the voltage at 100% speed of VFD-fed EM produced low values

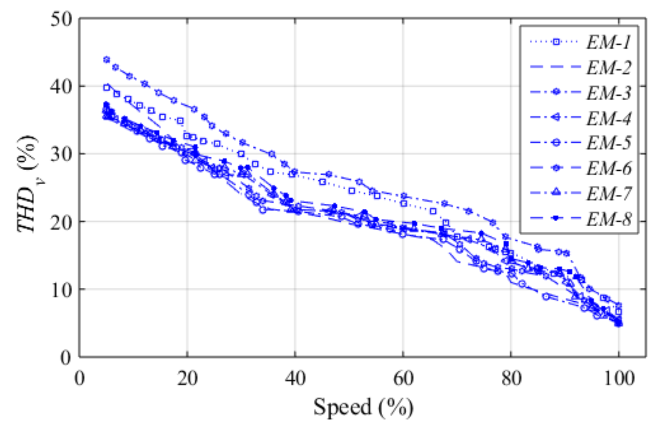

Fig. 3. Variation in THD_v by changing the speed of eight VFD-fed EMs (*EM-1* to *EM-8*)

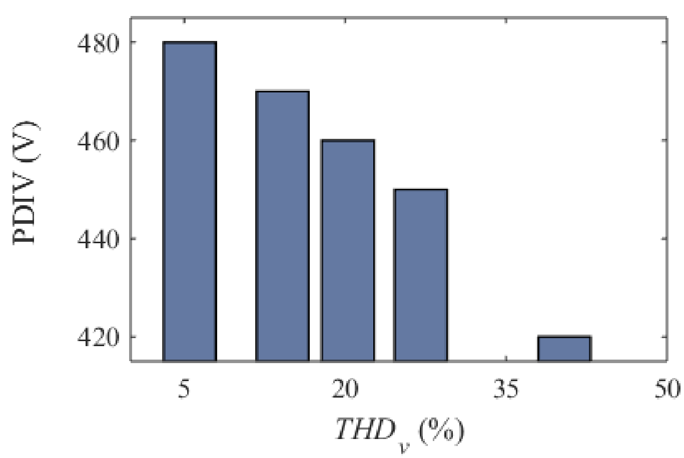

Fig. 4. PD inception voltage measured at different THD_V levels

of both q_i and n. The speed of VFD-fed EM was varied to increase the harmonic contents in the applied voltage waveform and PD activity was investigated at THD_v of 14.4%, 27.1%, and 40.4%, as shown in Fig. 5 (b), (c), and (d), respectively. From Fig. 5 (b), (c), and (d), it can be observed that both q_i and n increase by increasing the voltage harmonic components.

The I, q_a, n, P and D were assessed under different voltage harmonic contents and results are displayed in Table I. From Table I, it was established that the PDCP is considerably affected by THD_v. When THD_v level was increased from 5.2% to 40.4%, the I, q_a, n, P and D increased up to 5, 4.2, 1.7, 4.8, and 83 times, respectively. Therefore, the increase in the PDCP increases the level of PD severity and ultimately the failure risk level of the stator insulation is increased.

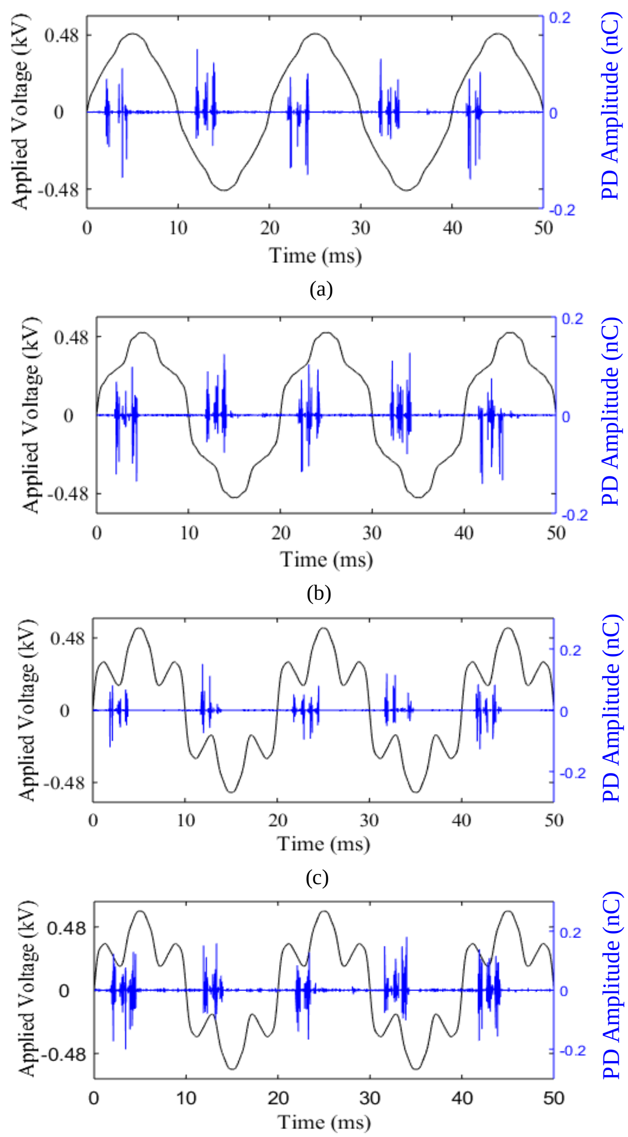

Fig. 5. PD activity captured at various THD_v levels (a) 5.2%, (b) 14.4%, (c) 27.1% and (d) 40.4%, respectively

TABLE I. AVERAGE VALUES OF PDCP MEASURED AT DIFFERENT *THDv* LEVELS

THD$_v$	**5.2%**	**14.4%**	**27.1%**	**40.4%**
Average discharge current (*A*)	1.41E-05	2.18E-05	6.02E-05	8.34E-05
Accumulated apparent charge (*C*)	7.91E-10	9.23E-10	1.32E-09	1.86E-09
Discharge power (*W*)	5.81E-03	9.95E-03	0.39E-02	1.41E-02
Quadratic rate (C^2/s)	8.56E-13	1.38E-12	5.50E-11	7.23E-11
Repetition rate	11	15	17	19

The phenomenon of the increase in the PDIV and PDCP with the increase in harmonic pollution in the test voltage waveform can be described in three different ways. Firstly, the introduction of harmonic components increases the peak magnitude of the test voltage waveform, and accordingly, PD activity is increased at high magnitude of the applied voltage waveform. Secondly, the increase in the harmonic contents causes the sufficient temperature rise of the stator winding [6]. PD electron gain thermal energy at high temperature, and moreover, the relative air density is reduced. Subsequently, the electrons gain additional energy and produce PD by covering additional distance between the collisions. Thirdly, the increase in the harmonic component improves the equilibrium temperature of the stator winding and the requirement of extra energy from bombarding electrons is decreased. Therefore, PD is energetic and more powerful at high value of voltage harmonic components.

C. Estimation of the Probability of Partial Discharges

The probability of occurrence of PD (P_{pd}) was assessed based on the PDCP calculated from PD magnitude i.e., q_a. q_a is directly related to the apparent charge, that is calculated by the sum of individual apparent charge (q_k) of all the PD pulses beyond a definite minimum amplitude during a selected T_{ref} [28]. It is calculated using (1)

$$q_a = \sum_{k=1}^{m} q_k \tag{1}$$

where q_k represents the apparent charge of k pulses measured by the PD meter and m is the total number of PD pulses in a PD sweep signal. The test was performed for 36 time and q_a of PD sweep signal was calculated. The minimum value, below which the existence of individual PD pulse was ignored, is 5 pC.

Using various probability distributions functions, the PDF and CDF to characterize the q_a at different harmonic levels were determined. Fig. 6 presents the PDF and CDF for several probability distributions employed at THD_v of 5.2%, 14.4%, 27.1%, and 40.4%. The distribution fitting tools were implemented to find an appropriate distribution that precisely characterize the probability of PD under different concentration of voltage harmonics

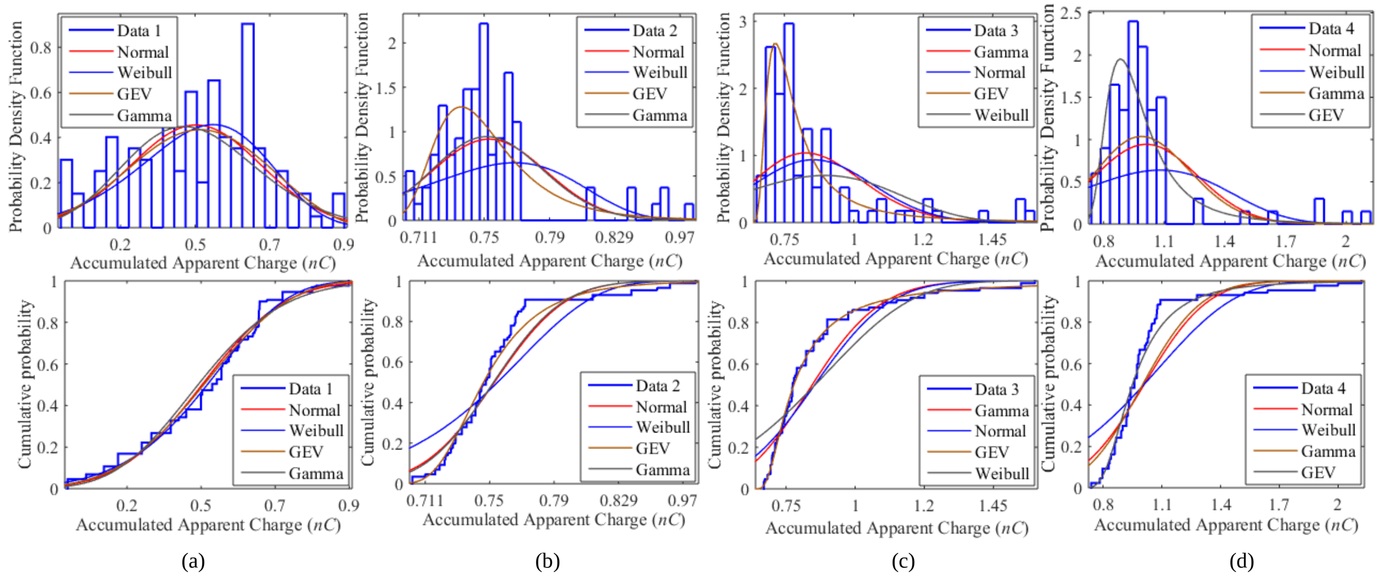

Fig. 6. PDF (top) and CDF (bottom) to characterize the q_a at different harmonics levels THD_v = (a) 5.2%, (b) 14.4%, (c) 27.1% and (d) 40.4%

Generalized extreme value (GEV) distribution, presented by Jenkinson in 1955, describes the distribution function of standardized maxima or minima. GEV consists of three parameters including the location parameter (μ), the shape parameter (ξ), and the scale parameter (σ). Depending upon the value of ξ, GEV distribution family can be divided into three distribution classes. These are the Gumbel distribution when $\xi = 0$, Weibull distribution when $\xi < 0$, and Freshet distribution when $\xi > 0$ [30].

To investigate the appropriate distribution function for the captured PD data, R-squared (R^2) goodness-of-fit hypothesis was carried out. Based on the results of R^2 goodness-of-fit hypothesis, the plausibility of GEV distribution was established.

The results of R^2 goodness-of-fit hypothesis at different concentration of voltage harmonics using Normal, GEV, Weibull, and Gamma probability distributions are presented in Table II. Out of four levels presented in the paper, GEV has the maximum value of the coefficient of varience (CD) in the three levels. The CDF for q_a using three parameters GEV distribution was calculated by (2) [31].

$$P(z;\mu,\sigma,\xi) = exp\left\{-\left[1+\xi\left(\frac{z-\mu}{\sigma}\right)\right]^{-\frac{1}{\xi}}\right\} \quad (2)$$

To investigate the effect of voltage harmonic distortion on PD activity, the average value of q_a measured at almost sinusoidal voltage waveform having THD_v=5.2% was considered as a reference value ($q_{a,r}$). The cumulative probability of occurrence (P_o) of the q_a magnitude above $q_{a,r}$ at each harmonic level is calculated using (3).

$$P_o = 1 - P(z;\mu,\sigma,\xi) \quad (3)$$

Therefore, the total probability of occurrence of PD (P_{pd}) at different voltage harmonic concentrations is estimated using (4).

TABLE II. R^2 GOODNESS-OF-FIT FOR DIFFERENT *THDv* LEVELS USING VARIOUS PROBABILITY DISTRIBUTIONS

THD_v	Generalized extreme value	Weibull	Gamma	Normal
5.2%	0.6817	0.6997	0.7137	0.6752
14.4%	0.8137	0.7695	0.7578	0.5812
27.1%	0.9412	0.4981	0.4132	0.3998
40.4%	0.9013	0.5532	0.5527	0.5567

$$P_{pd} = P_o \times \frac{q_a}{q_{a,r}} \quad (4)$$

The P_{pd} calculated under different levels of voltage harmonics is presented in Fig. 7. From Fig. 7, it was found that the increase in THD_v of the applied voltage waveform significantly increases the P_{pd}.

V. CONCLUSIONS

This paper explores the influence of different harmonic concentration produced in the test voltage during variable operating conditions of VFD-fed EMs on the probability of occurrence of PD (P_{pd}). Based on the experimental findings, it has been found that the VS operation of VFD-fed EMs produces voltage harmonic distortion. The harmonic distortion present in the voltage sine wave is a huge challenge for the reliable operation of VFD-fed EMs. Accordingly, the THD_v of the test voltage waveform was increased from 5.2% to 40.4% and the values of I, q_a, n, P, D, and m increased to 5, 4.2, 1.7, 4.8, 83, and 1.6 times, respectively.

The P_{pd} was assessed as a function of q_a and it was observed that the increase in THD_v of the applied voltage waveform significantly increases the P_{pd}. The increase in P_{pd} increases the severity level of PD and ultimately the risk of premature insulation failure of the stator windings in VFD-fed EMs is increased.

In future research work, a method for the evaluation of risk of stator insulation failure because of the harmonic components present in the test voltage waveform in VFD-fed EMs is recommended.

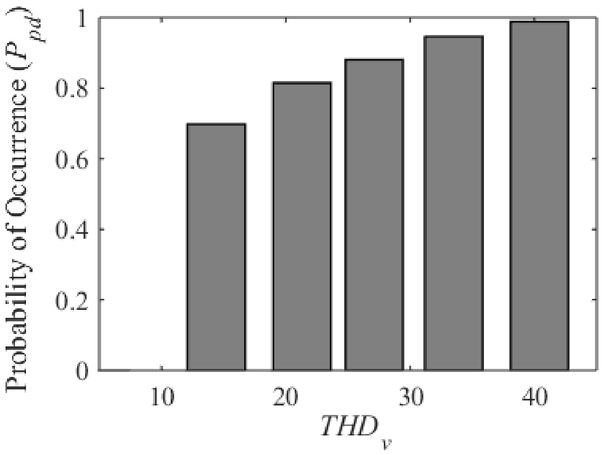

Fig. 7. Estimated probability of occurrence of PD activity under different harmonic compositions

REFERENCES

[1] T. IEC, "60034-25: 2014," *AC Electrical Machines Used In Power Drive Systems-Application Guide*.

[2] A. Hughes and W. Drury, *Electric motors and drives: fundamentals, types and applications*: Newnes, 2013.

[3] G. C. Stone, H. G. Sedding, and C. Chan, "Experience With Online Partial-Discharge Measurement in High-Voltage Inverter-Fed Motors," *IEEE Transactions on Industry Applications,* vol. 54, pp. 866-872, 2018.

[4] Y. Li, M. Liu, J. Lau, and B. Zhang, "A novel method to determine the motor efficiency under variable speed operations and partial load conditions," *Applied Energy,* vol. 144, pp. 234-240, 2015.

[5] G. Bucci, F. Ciancetta, E. Fiorucci, and A. Ometto, "Uncertainty issues in direct and indirect efficiency determination for three-phase induction motors: remarks about the IEC 60034-2-1 standard," *IEEE Transactions on Instrumentation and Measurement,* vol. 65, pp. 2701-2716, 2016.

[6] W. Hassan, F. Mahmood, M. Akmal, and M. Nasir, "Optimum operation of low voltage variable-frequency drives to improve the performance of heating, ventilation, and air conditioning chiller system," *International Transactions on Electrical Energy Systems,* p. e12481, 2020.

[7] T. IEC, "60034-27-2," *Rotating Electrical Machines—Part 27-2: On-Line Partial Discharge Measurements On The Stator Winding Insulation Of Rotating Electrical Machines,* 2012.

[8] W. Hassan, F. Mahmood, G. A. Hussain, and S. Amin, "Risk assessment of low voltage motors based on PD measurements and insulation diagnostics," *Measurement,* p. 109151, 2021.

[9] G. Stone, "A perspective on online partial discharge monitoring for assessment of the condition of rotating machine stator winding insulation," *IEEE Electrical Insulation Magazine,* vol. 28, 2012.

[10] T. Lebey, P. Castelan, G. Montanari, and I. Ghinello, "Influence of PWM-type voltage waveforms on reliability of machine insulation system," in *8th International Conference on Harmonics and Quality of Power. Proceedings (Cat. No. 98EX227),* 1998, pp. 994-998.

[11] W. Hassan, F. Mahmood, G. A. Hussain, S. Amin, and J. A. Kay, "Feature Extraction of Partial Discharges During Multiple Simultaneous Defects in Low-Voltage Electric Machines," *IEEE Transactions on Instrumentation and Measurement,* vol. 70, pp. 1-10, 2021.

[12] M. Florkowski, B. Florkowska, J. Furgał, and P. Zydron, "Impact of high voltage harmonics on interpretation of partial discharge patterns," *IEEE Transactions on Dielectrics and Electrical Insulation,* vol. 20, pp. 2009-2016, 2013.

[13] W. Hassan, F. Mahmood, A. Andreotti, M. Pagano, and F. Ahmad, "Influence of Voltage Harmonics on Partial Discharge Diagnostics in Electric Motors Fed by Variable Frequency Drives," *IEEE Transactions on Industrial Electronics,* 2021.

[14] P. Wang, G. C. Montanari, and A. Cavallini, "Partial discharge phenomenology and induced aging behavior in rotating machines controlled by power electronics," *IEEE Transactions on Industrial Electronics,* vol. 61, pp. 7105-7112, 2014.

[15] G. C. Montanari and P. Seri, "The effect of inverter characteristics on partial discharge and life behavior of wire insulation," *IEEE Electrical Insulation Magazine,* vol. 34, pp. 32-39, 2018.

[16] G. C. Montanari and P. Seri, "A partial discharge–based health index for rotating machine condition evaluation," *IEEE Electrical Insulation Magazine,* vol. 34, pp. 17-23, 2018.

[17] K. K.-f. Yuen and H. S.-h. Chung, "Use of synchronous modulation to recover energy gained from matching long cable in inverter-fed motor drives," *IEEE transactions on power electronics,* vol. 29, pp. 883-893, 2013.

[18] J.-P. Strom, J. Korhonen, J. Tyster, and P. Silventoinen, "Active *du/dt*—New output-filtering approach for inverter-fed electric drives," *IEEE Transactions on Industrial Electronics,* vol. 58, pp. 3840-3847, 2010.

[19] M. Tozzi, A. Cavallini, and G. Montanari, "Monitoring off-line and on-line PD under impulsive voltage on induction motors-part 1: standard procedure," *IEEE Electrical Insulation Magazine,* vol. 26, pp. 16-26, 2010.

[20] R. Ghosh, P. Seri, R. E. Hebner, and G. C. Montanari, "Noise rejection and detection of partial discharges under repetitive impulse supply voltage," *IEEE Transactions on Industrial Electronics,* vol. 67, pp. 4144-4151, 2019.

[21] Y. Wang, T. Balachandran, Y. Hoole, Y. Yin, and K. S. Haran, "Partial discharge investigation of form-wound electric machine winding for electric aircraft propulsion," *IEEE Transactions on Transportation Electrification,* vol. 6, pp. 1638-1647, 2020.

[22] R. Machines-Part, "Rotating electrical machines-Part 18-41: Qualification and Type Tests for Type I-Electrical Insulation Systems Used in Rotating Electrical Machines Fed from Voltage Converters," *IEC TS,* pp. 60034-18, 2014.

[23] T. Billard, T. Lebey, and F. Fresnet, "Partial discharge in electric motor fed by a PWM inverter: off-line and on-line detection," *IEEE Transactions on Dielectrics and Electrical Insulation,* vol. 21, pp. 1235-1242, 2014.

[24] V. Madonna, P. Giangrande, G. Migliazza, G. Buticchi, and M. Galea, "A Time-Saving Approach for the Thermal Lifetime Evaluation of Low-Voltage Electrical Machines," *IEEE Transactions on Industrial Electronics,* vol. 67, pp. 9195-9205, 2019.

[25] A. T. de Almeida, F. J. Ferreira, and D. Both, "Technical and economical considerations in the application of variable-speed drives with electric motor systems," *IEEE Transactions on Industry Applications,* vol. 41, pp. 188-199, 2005.

[26] S. Bahadoorsingh and S. Rowland, "Investigating the impact of harmonics on the breakdown of epoxy resin through electrical tree growth," *IEEE Transactions on Dielectrics and Electrical Insulation,* vol. 17, pp. 1576-1584, 2010.

[27] T. IEC, "60034-27: 2006," *Off-line partial discharge measurements on the stator winding insulation of rotating electrical machines,* 2006.

[28] I. E. Commission, "High-Voltage Test Techniques: Partial Discharge Measurements; IEC 60270," *International Electrotechnical Commission: Geneva, Switzerland,* 2015.

[29] W. Hassan, G. A. Hussain, F. Mahmood, S. Amin, and M. Lehtonen, "Effects of Environmental Factors on Partial Discharge Activity and Estimation of Insulation Lifetime in Electrical Machines," *IEEE Access,* 2020.

[30] A. Bücher and J. Segers, "On the maximum likelihood estimator for the generalized extreme-value distribution," *Extremes,* vol. 20, pp. 839-872, 2017.

[31] M. Pinheiro and R. Grotjahn, "An introduction to extreme value statistics," ed, 2015.