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Analysis of Off-Line and On-Line Partial Discharge in High Voltage Motor Stator Windings

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Abstract – The off-line and on-line partial discharge (PD) in the stator winding of three high-voltage (HV) motors (1,400 HP, 6.6 kV) is measured and analyzed in this paper. The off-line PD is measured at high values between 24,300～36,100 pC after 18 years of motor operation. Spare replacement motors were not available for testing the degree of deterioration of the stator windings in standstill status. Therefore, on-line periodic analysis was conducted to monitor the trend of PD after installing a ceramic sensor (110 pF, 6.6 kV) in the terminal box for each phase of each motor. In the stator winding of the No.1 and No.2 HV motors, which showed high magnitudes of off-line PD and low magnitudes of on-line PD, defects are expected to appear in the neutral end of the winding. On the contrary, in the stator windings of the No.3 HV motor, which exhibits high off-line and on-line PD magnitude, defects are expected to appear in the terminal end of the winding where a voltage close to the phase voltage is applied.

Keywords: Partial discharge, Stator winding, High voltage motor, Off-Line, On-Line, Ceramic sensor, Defect

1. Introduction

High-voltage (HV) motors used in power plants usually employ an air-cooled system, and infiltration of foreign objects such as dust may occur. In extreme cases, a mixture of dust and sealing oil not only cover the end-winding but also lead to surface tracking. In particular, the end-winding exposed to gradual surface tracking over a long period of time can reach the stator core resulting in a sudden breakdown of the phase-to-ground insulation [1].

A sudden insulation breakdown of an HV motor in-service lowers the reliability of the power generation. It is not only difficult to repair the damage in the short term, but it also involves considerable financial losses due to loss in revenue. Therefore, inspection and insulation diagnostic tests are regularly performed to estimate the degree of deterioration in order to prevent insulation breakdown in large-capacity HV motor stator windings. An insulation diagnostic test is provided during the preventive maintenance period for an overall evaluation of the insulation condition, wherein insulation resistance, polarization index, alternating current, dissipation factor, and partial discharge (PD) magnitude are measured [2, 3]. Furthermore, the detailed analyses of the AC current, dissipation factor, and PD magnitude can verify the condition of infiltration of foreign objects [4, 5].

Above all, PD in HV motor stator windings is an important indicator for the degree of insulation deterioration, and the insulation condition is diagnosed through a general analysis of the pulse number, pulse magnitude, and pattern of the in-service PD [6, 7]. Since the turbine generator analyzer (TGA) capable of diagnosing in-service HV motor stator windings was developed in Canada in 1980, epoxy-mica capacitors have been installed across North America for PD measurements, and diagnostic tests are being performed regularly [8]. TGA devices measure the normalized quantity number (NQN) and the maximum PD magnitude (Q_m, mV) to estimate the internal condition of the localized insulation. This makes it possible to analyze the PD pattern and trend and thus predict the defective conditions and prevent insulation breakdown.

In this study, the off-line PD in stator windings of three boiler feed-water pump (BFP) HV motors (1,400 HP, 6.6 kV) is measured at high values between 24,300～36,100 pC. Since spare replacement motors were not available for checking the degree of deterioration of the stator windings, on-line periodic analyses were conducted to monitor the PD trend after installing a ceramic sensor (110 pF, 6.6 kV) in the terminal box for each phase of each motor (total of 9 couplers).

2. Experimental Method

2.1 Measurement of off-line PD

Off-line PD tests were conducted to analyze the insulation condition of the stator windings of HV motors (1,400 HP, 6.6 kV) after 18 years of operation. In order to check the PD in the HV motor stator windings, a HV supply and control system that consist of Mobile Insulation Diagnosis & Analyzing System (MIDAS) containing a

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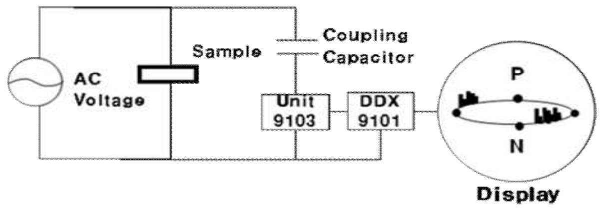


Fig. 1. Detection circuits for the PD measurement

Schering Bridge, coupling capacitor, coupling unit, and PD detector, were used. For the PD test, voltage was applied to the HV motor stator windings by connecting them to the MIDAS (Tettex Instruments, 2880).

The detection circuit for the PD measurement used in this paper is shown in Fig. 1. The coupling capacitor (Tettex Instruments, 9,000 pF) transmitted the signal streams flowing through the windings to the broadband matching unit (Tettex Instruments, 9103), where they were amplified. Then the PD magnitude and pattern were analyzed with a PD detector (Robinson, DDX 9101) having a frequency range of 30～400 kHz. The PD magnitudes of the HV motor stator windings were measured at 24,300～36,100 pC at the phase voltage of 6.6 kV (3.81 kV). The background noise during the PD measurements in the on-site environment was in the 530～700 pC range.

2.2 Measurement of on-line PD

The off-line PD magnitudes of the HV motor stator windings were measured at 24,300～36,100 pC, and PD sensors were installed to analyze the insulation condition regularly during motor operation. A domestically developed ceramic sensor (110 pF, 6.6 kV) [9] was installed in phases A, B, and C (total of three sensors), as shown in Fig. 2(a). To transmit the voltage signals (mV) for the analysis of the PD in the three ceramic sensors, coaxial cables were laid and connected to the junction box outside the HV motor. Fig. 2(b) shows how the TGA (TGA-B, IRIS Power Engineering) and notebook computer at the junction box were installed. The TGA separates PD from system noise based on pulse time-of-arrival characteristics. The NQN, Q_m magnitude, and PD patterns were analyzed to monitor the trend for the purpose of evaluating insulation deterioration in operating motors. And on-line PD signals are measured by a digital phosphor oscilloscope (5GS/s, 1GMz, Tektronix, TDS5104B) in the No. 1, No. 2 and No. 3 HV motors.

(a) ceramic sensors

(b) on-line PD testing system

Fig. 2. Installation of ceramic sensors and on-line PD testing system in HV motor

3. Test results and Discussion

The nominal ratings of the HV motors (1,400 HP, 6.6 kV) used for boiler feedwater pumps that were operated in a thermal power plant for the last 18 years are outlined in Table 1. The insulation diagnostic tests on the stator windings of the HV motors for the boiler feedwater pumps indicated that there was excessive infiltration of foreign objects. Intensive dust accumulations were indeed confirmed by visual inspection after separating the rotors. The re-diagnosis after cleaning and drying confirmed that the alternating current, dissipation factor, PD magnitude, etc. were improved to levels within the grading standards. Final insulation reinforcement was performed [5] after the inspection.

Table 1. Nominal ratings (NR) of HV motors

HV motors	No.1～3	Number of poles	2
NR Capacity [HP]	1,400	Insulation class	F
NR Voltage [kV]	6.6	Production year	1993
NR Current [A]	103	Manufacturer	WH

3.1 Analysis of off-line PD measurement

The results of the off-line PD measured in the 3-phase-resolved state of phases A, B, and C after the completion of the insulation reinforcement of three HV motors are presented in Table 2. The background noise was between 530～700 pC, and the PD magnitudes of the No. 1, No. 2, and No.3 HV motor stator windings were measured at 35,200 pC, 36,100 pC, and 24,300 pC, respectively, at the rated phase voltage (3.81 kV). Thus, the PD magnitudes measured in a field environment of a power plant can be understood to include the background noise. The discharge inception voltage (DIV) was 2.7 kV for each of the No.1 and No.2 HV motors, and 2.5 kV for the No.3 HV motor. As the external AC voltage was increased in supplying HV motor stator windings, it created PD magnitude. The DIV

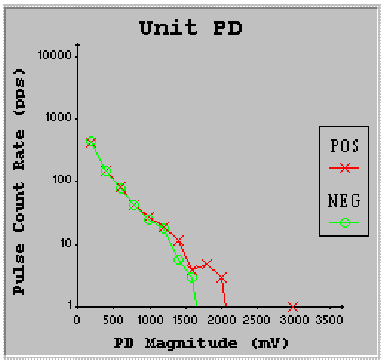
Table 2. PD magnitude of three HV motors

HV motors	Background noise [pC]	DIV [kV]	PD magnitude [pC] at 3.81[kV]
No. 1	530	2.7	35,200
No. 2	550	2.7	36,100
No. 3	700	2.5	24,300

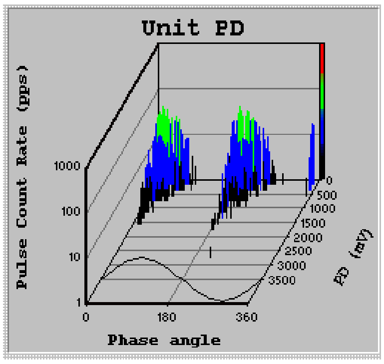
represents the voltage when the PD magnitude exceeds 1,000 pC, which is higher than the background noise.

As measured by the new criteria for judging the insulation deterioration set forth by the Yokosuka Research Laboratory Report of Japan [10], the PD magnitudes of the stator windings of the No. 1 and No. 2 HV motors are rated as "poor," requiring a replacement of the stator winding. The stator winding of the No.3 HV motor falls under the grading category of "caution," requiring an annual trend monitoring via off-line diagnosis. The other HV motor for BFP is occurred the failure during normal operation. The PD magnitude of this HV motor is measured at 37,000 pC.

The PD magnitudes in the stator windings of No.3 HV motor with ceramic sensor (110 pF), when line-to-ground voltages of 3.81 kV were applied, are shown in Fig. 3. Figs. 3(a), and (b) show the results of the measurements with TGA-B as described above, where the number and magnitude of the PD pulses were plotted in two dimensional (2-D) and the numbers and magnitudes of the PD pulses versus the ac phase angle were plotted in three dimensional (3-D). Fig. 3(a) demonstrates similar sizes of positive and negative polarity PD.



(a) 2-D



(b) 3-D

Fig. 3. 2-D and 3-D analysis of off-line PD in No. 3 HV motor

Table 3. Off-line Q_m and NQN characteristics of No. 3 HV motor

HV motor with ceramic sensor (110 pF)		No. 3
NQN	+	2,803
	-	2,465
Qm[mV]	+	1,450
	-	1,333

The off-line NQN and the maximum PD magnitudes (Q_m) of No.3 HV motor with ceramic sensor (110 pF) were measured using TGA-B as shown in Figs. 3 (a), (b) and the results are listed in Table 3. The measurements of No.3 HV motor stator windings revealed in NQN and Q_m. By measuring the NQN and Q_m magnitude, it was found that the NQN was 2,803 positive polarity and 2,465 negative polarity and the Q_m was 1,450 mV positive polarity and 1,333 mV negative polarity in No.3 HV motor.

3.2 Analysis of on-line PD measurement

The on-line NQN and the maximum PD magnitudes (Q_m) of the three HV motor stator windings were measured for phases A, B, and C using TGA-B, and the results are listed in Table 4. The measurements in June 2011 and January 2014 of phases A and C of the No.1 HV motor stator windings revealed the increasing trend in NQN and Q_m. By measuring the Q_m magnitude, it was found that phase A increased from 43 mV positive polarity and 24 mV negative polarity to 75 mV positive polarity and 37 mV negative polarity respectively. The increase of the indictors was more substantial in phase C, where it increased from 17 mV positive polarity and 13 mV negative polarity to 47 mV positive polarity and 29 mV negative polarity. In contrast, phase B did show any considerable drop in NQN and Q_m between June 2011 and January 2014. The measurements in April 2012 and January 2014 of phase A of the No.3 HV motor stator windings revealed a little change in NQN and Q_m. In April 2012 and January 2014 of phases B and C of the No.3 HV motor stator windings revealed the increasing trend in NQN and Q_m. By measuring the Q_m magnitude, it was found that phase B increased from 117 mV positive polarity and 107 mV negative polarity to 200 mV positive polarity and 183 mV negative polarity respectively. And the phase C increased from 125 mV positive polarity and 117 mV negative polarity to 148 mV positive polarity and 120 mV negative polarity respectively.

The initial measurements with the newly installed ceramic sensors revealed that the highest Q_m in the No.1 and No.2 HV motor stator windings was below 60 mV, proving a good insulation condition. It was also observed that the No. 3 HV motor stator windings had a high Q_m in phase A with 330 mV positive polarity and 198 mV negative polarity, indicating slightly advanced insulation deterioration [11]. Thus, an overall comprehensive analysis of the diagnostic test data on the on-line and off-line PD provided a clear overview of the differences [12, 13].

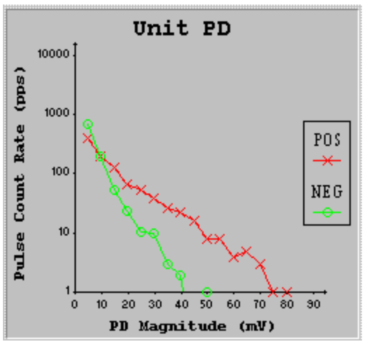
Figs. 4(a), (b) and Figs. 5(a), (b) show the results of the measurements with TGA-B as described above, where the numbers and magnitudes of the PD pulses were plotted in two dimensional (2-D) diagrams and three dimensional (3-D) diagrams.

The Q_m of phase A of the No. 1 HV motor stator windings is shown in Figs. 4(a), (b) where the magnitude of the positive pulse was measured to be higher than that of the negative pulse. As indicated in Table 4, the PD pattern was estimated as slot discharge since the PD magnitude of the positive polarity is higher than that of the negative polarity [14]. It is suspected that this is due to the frequent start-and-stop operation and the resultant unperceivable but continuous dislocations triggered by the vibrations in the slots of stator windings, which led to semiconductor substrate damage and consequent slot discharges [6]. Slot discharge was observed for phases A, B and C of the No. 1 HV motor and the phase B of the No. 2 HV motor, and the results representative of slot discharge is shown in Fig. 4(a) (a ratio of + Q_m /- Q_m > 1.5).

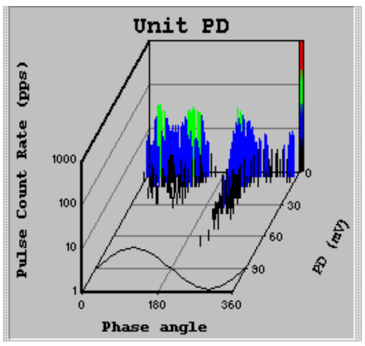
Table 4. On-line NQN and Q_m characteristics of three HV motors

HV motors No. 1~3			No. 1 '11-6-28	No. 1 '14-1-22	No. 2 '12-8-9	No. 3 '12-4-24	No. 3 '12-11-23	No. 3 '14-1-22
A	NQN	+	86	134	107	543	654	569
	NQN	-	50	63	69	283	480	514
	Qm[mV]	+	43	75	59	330	298	300
	Qm[mV]		24	37	53	198	258	318
B	NQN	+	122	45	33	246	232	458
	NQN	-	64	29	10	272	278	342
	Qm[mV]	+	56	27	34	117	139	200
	Qm[mV]	-	30	16	-	107	159	183
C	NQN	+	33	98	65	275	289	299
	NQN	-	24	55	56	255	237	203
	Qm[mV]	+	17	47	41	125	133	148
	Qm[mV]	-	13	29	34	117	112	120

The reason why Q_m of phase A of the No. 3 HV motor stator windings demonstrates similar sizes of positive and negative polarity PD, as illustrated in Figs. 5(a), (b) is the voids within the main insulation materials of the stator windings. The voids within the main insulation materials are formed either through an inadequate fusion of varnish and resin during production or through the stripping of the insulation layer during operation. When HV is applied to these voids, PD occurs. The insulation breakdown trigged by the PD within the main insulation materials progresses slowly. Unfortunately, the characteristics of PD related to the main insulation materials involve the internal system, and no corrective measures are possible. Therefore, in case of high PD magnitude within the main insulation materials, the windings must be replaced. Internal discharge was observed for phases A and C of the No. 2 HV motor and the phases A, B and C of No. 3 HV motor, and the

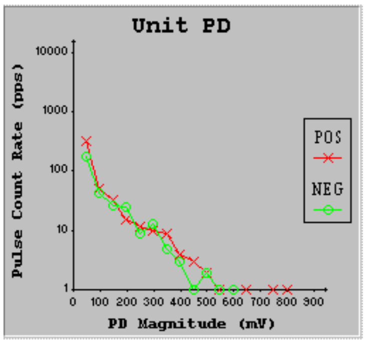


(a) 2-D

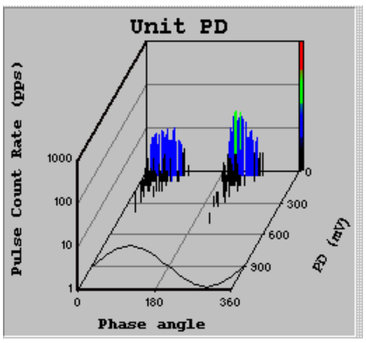


(b) 3-D

Fig. 4. 2-D and 3-D analysis of on-line PD in phase C of No. 1 HV motor



(a) 2-D



(b) 3-D

Fig. 5. 2-D and 3-D analysis of on-line PD in phase A of No. 3 HV motor

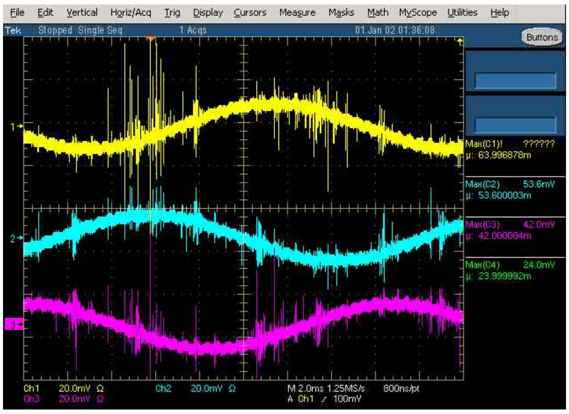
measurements representative of internal discharge is shown in Fig. 5(a). As shown in the Fig. 3(a) and Fig. 5 (a) of the No. 3 HV motor stator windings, the off-line and on-line PD patterns were almost the same in sizes of positive and negative polarity PD.

In Figs. 6(a) and (b), two types of on-line PD signals are measured by a digital oscilloscope(5GS/s, 1 GMz) in the No. 1 and No. 3 HV motors. The results are shown with the oscilloscope set at a sampling rate of 1.25 MS/s and resolution time of 800ns. PD signals containing the low peak (less than 100mV) are shown in Fig. 6(a) for phase A of No.1 HV motor. And PD signals containing the low peak (more than 50mV) are measured the phases B and C of No. 1 HV motor. However, PD signals containing the high peak (more than 300mV) are shown in Fig. 6(b) for phase A of No.3 HV motor. And PD signals containing the high peak (more than 100mV) are measured the phases B and C of No.3 HV motor. As shown in Fig. 6 PD signals only with high repetition rate could be detected by a conventional PD detector. The PD measurements obtained with the commercial PD instrument and with a digital oscilloscope are in good agreement, as can be observed in Figs. 4, 5 and 6.

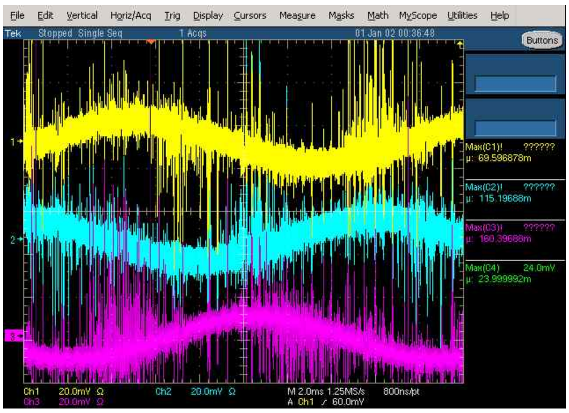
As explained above, an overall comprehensive analysis of the diagnostic test data on the on-line and off-line PD gives a clear overview of the differences [12, 13]. In the off-line diagnostic test, the same amount of voltage is applied to all the stator windings of the HV motors using an external power supply. On the other hand, in the on-line diagnostic test, the applied voltages to individual windings were different because of the voltage distribution. If the phase voltage (3.81 kV) is applied to a 6.6 kV class HV motor in the off-line diagnostic test, a uniform voltage of 3.81 kV is applied to the winding insulation. However, if the phase voltage is applied in the on-line state, 3.81 kV is applied to the terminal end of the winding, and voltage decreases to 0 V towards the neutral of the winding. For example, if the terminal end of the winding is defective, a similar PD magnitude is measured in both on-line and the off-line states. If the winding of the middle portion is defective, however, 1.9 kV is applied during the on-line diagnostic test and 3.81 kV is applied in the off-line diagnostic test. As a result, the PD magnitude measured during operation is lower than that measured during an outage. Thus, it can be concluded that the PD magnitude is strongly dependent on the applied voltages.

In fact, the measurement of the off-line PD magnitudes of the No. 1 and No. 2 HV motors while applying the phase voltage yielded values of 35,200 pC and 36,100 pC, respectively, and the No.3 HV motor showed a PD magnitude of 24,300 pC. The measurement of the on-line PD magnitudes of the No. 1 and No. 2 HV motors yielded as low as 60 mV at first, and the No. 3 HV motor showed a relatively high PD magnitude of 318 mV. This is because the stator windings of the No. 1 and No. 2 HV motors with a low PD magnitude have defects in the windings towards the neutral end. Therefore, the No. 1 and No. 2 HV motor stator windings is expected to operate without problems since the voltage applied at the weak portion of the winding is low. However, No. 3 HV motor stator winding requires regular diagnostic tests, because of the defects located in the terminal end of the winding, where the voltage is high (3.81 kV).

In general, even in the case of high PD magnitudes, it may take years before these high magnitudes pose serious problems. Even in the face of a high risk of breakdown in the windings, a sufficient length of time is required for the planning of ordinary maintenance or replacement of windings. PD tests may be monitored, and the degree of deterioration of the ground-wall insulation materials is traceable. By presenting the results of the study, the grounds for the quick decision-making of the discretionary staff as to the further operation of a HV motor can be provided. At any rate, if the PD magnitude keeps increasing during operation, off-line diagnostic tests and a gross examination needs to be conducted.



(a) Phases A, B and C of No. 1 BFP



(b) Phases A, B and C of No. 3 BFP

Fig. 6. PD signals from two HV motors

4. Conclusion

While applying the phase voltage (3.81 kV) in the off-line diagnostic test, PD magnitudes were measured on stator windings of the No.1, No.2, and No.3 HV motors. The measurement yielded 35,200 pC, 36,100 pC, and 24,300 pC, respectively. The No.1 and No.2 HV motors showed on-line PD magnitude as low as 60 mV, and the on-line PD magnitude of the No.3 HV motor was as high as 330 mV. In the stator windings of the No. 1 and No. 2 HV motors, which showed high magnitudes of off-line PD and low magnitudes of on-line PD, defects were expected to appear close to the neutral end of the winding. Therefore, the No.1 and No.2 HV motor stator windings could operate without problems as the voltage applied to the weak portion of the winding is low. However, the No.3 HV motor stator windings required a careful trend management through regular diagnostic tests, since the defects are located in the line end, where the applied voltage is close to the phase voltage (3.81 kV). Slot discharge is observed in phases A, B and C of the No.1 HV motor and in phase B of the No.2 HV motor. Internal discharge was observed in phases A and C of the No.2 HV motor and in phases A, B and C of No.3 HV motor. The off-line and on-line PD patterns of the No.3 HV motor stator windings were almost the same in terms of the size of positive and negative polarity PD.

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