EFFECT OF APPLIED VOLTAGE FREQUENCY ON PARTIAL DISCHARGE IN XLPE CABLE INSULATION

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Abstract- Monitoring the insulation condition of underground power cables is a common precautionary practice and taking corrective actions whenever required is very important to ensure the reliability of the electrical network. Underground power cables represent the arteries of any electrical network as they connect between different substations especially in urban areas where the clearances are extremely limited for use of overhead feeders. Partial Discharge (PD) measurement represents the most popular testing method to check the insulation condition of Medium Voltage (MV) and High Voltage (HV) underground power cables. This paper presents an experimental investigation to determine the relation between the test voltage frequency and the behavior of PD parameters using offline PD testing. The results show that there are some clear differences in the PD characteristics when tested using 60 Hz voltage and VLF voltage of 0.1 Hz. Since VLF testing is becoming more common, it is important to understand the differences in the PD at two frequencies.

Keywords– PD, Power Cable, Frequency, VLF

I. INTRODUCTION

Partial discharge or PD is well known phenomena in the insulation of electrical equipment and has been recognized since the beginning of the 20thcentury as a harmful ageing process for electrical insulation [1]. It is defined as "localized electrical discharge that only partially bridges the insulation between conductors and which can or cannot occur adjacent to a conductor" [2]. In addition, PD events are defined as microscopic ionizations that occur in small insulation volumes due to non-uniform electrical fields [3]. PD testing has became one of the most popular and useful methods to monitor the insulation condition of many high voltage equipments including power cables. PD testing might be done directly after manufacturing during routine or type testing, before commissioning at the site, or after sometime of operation to estimate the insulation condition and to recommend a corrective action if required.

Cable insulation condition assessment using PD technique helps in determining the insulation status so that a corrective action could be taken as needed before a failure occurs to the cable thereby resulting in forced outage. In this paper, the behavior of PD parameters in Medium Voltage (MV) power cables is studied and analyzed at power frequency (60 Hz) and at Very Low Frequency (VLF) of 0.1 Hz. At each frequency, the voltage is varied between three levels: (1) below the Partial Discharge Extinction Voltage (PDEV), (2) at Partial Discharge Inception Voltage (PDIV) and (3) above the PDIV. In all cases, sinusoidal voltages are used for cable testing [5]. The paper introduces the measurement systems, the tested power cables, along with the created defects for this study. Afterwards, the studied PD parameters are reported and analyzed. Finally, conclusions and recommendations are provided.

II. SYSTEMS FOR PD MEASUREMENT

As mentioned above, PD testing was conducted at power frequency (60 Hz) and at VLF (0.1 Hz) For 60 Hz, measurement "DDX-7000" system shown in Figure 1 was used.

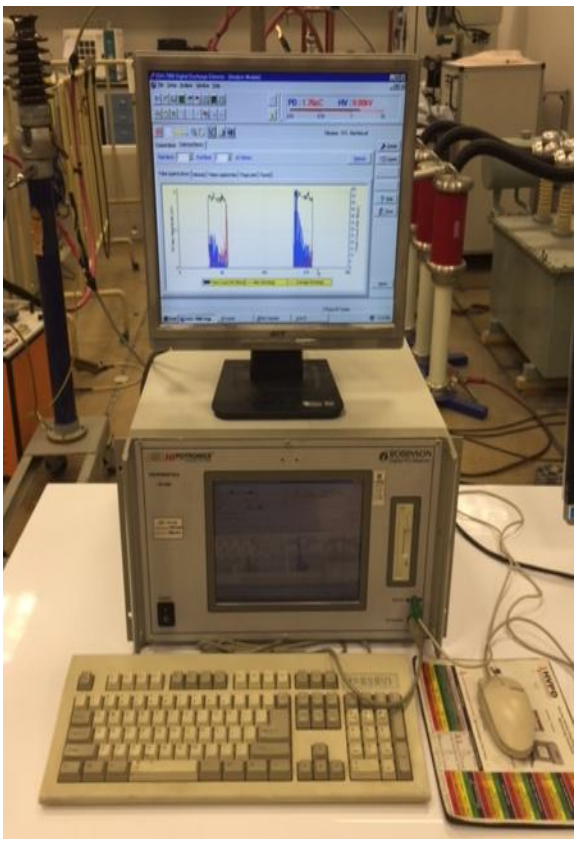

Figure 1: DDX-7000 used for 60 Hz PD measurement.

DDX-7000 displays the resulting PD patterns when the test voltage using the HVAC source and the control unit shown in Figures 2&3, respectively are used.



Figure 2: 60 Hz HVAC source used.



Figure 3: Control unit of the HVAC source used.

For PD measurement at 0.1 Hz, the instrument named "be-suite" shown in Figure 4 was used. It consists of two parts. First part, PD30-E, is used to inject the test voltage. Second part, HVA28, receives the tests data through software installed on the control unit [4].



Figure 4: b2-suite used for measurement at VLF. HVA28 is on the left side and PD30-E is on the right side.

Test circuits for both frequency levels are given in Figures 5 & 6. They differ because of the connection requirements of the two measuring instruments (DDX-7000 & b2-suite).

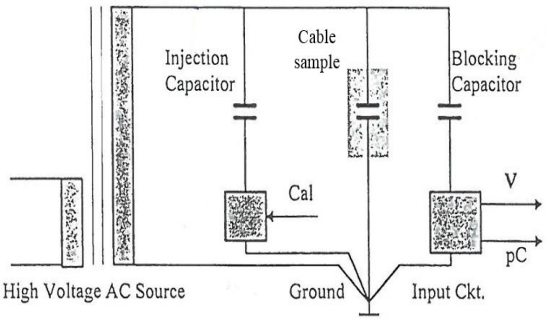

Figure 5: Test circuit diagram for 60 Hz.

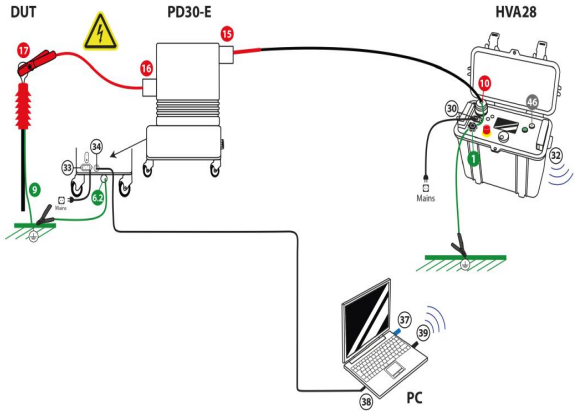

Figure 6: Test circuit diagram for 0.1 Hz.

III. CABLE SAMPLE & DEFECTS CREATED

The cable used for testing is a single core, cable with copper conductor. It is 15 kV rated, XLPE insulated cable. Further technical data are given in Table 1 below.

Table 1: Power cable technical data

Item	Value
Conductor Size (mm^2)	50
Diameter of conductor (mm)	8.1
Nominal insulation thickness (mm)	4.5
Diameter over insulation (mm)	18.7
Nominal outer sheath thickness (mm)	1.7
Overall diameter (mm)	26
Weight of cable (kg/km)	1124

In order to have PD in cable, three defects were created. The first defect (see Figure 7) was created by removing one of the conductor strands and then placing it vertically on the rest of the conductor's body. This defect will disrupt the electric field uniformity causing it to be more intense at one point.

Therefore, the enhanced stress can cause PD at that particular point if sufficient voltage is applied.

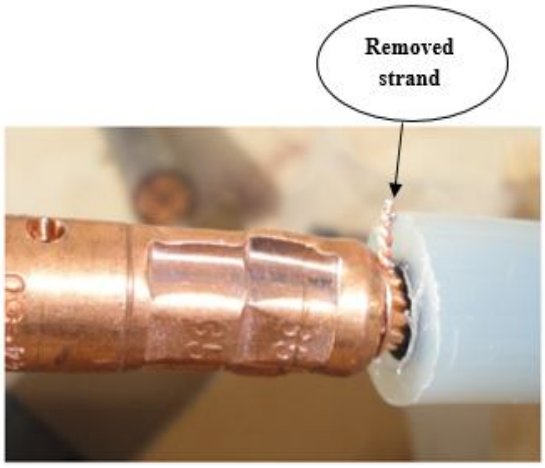

Figure 7: First defect.

The second defect was created by making "V-shape" cut on the insulation surface as shown in Figure 8. The area within the defect will have electrical stress which is different than the electrical stress in the XLPE insulation. As a result, PD may be generated at the defect point if a suitable voltage is applied to the cable.

The third defect (see Figure 9) was created by improper removal of the insulation shield. This can cause non-uniformity of the electrical field at such a site and the electrical stress on the insulation surface may become greater at that particular point as compared to the remaining parts of the insulation surface. Therefore, PD may be initiated at that point when a suitable voltage is applied

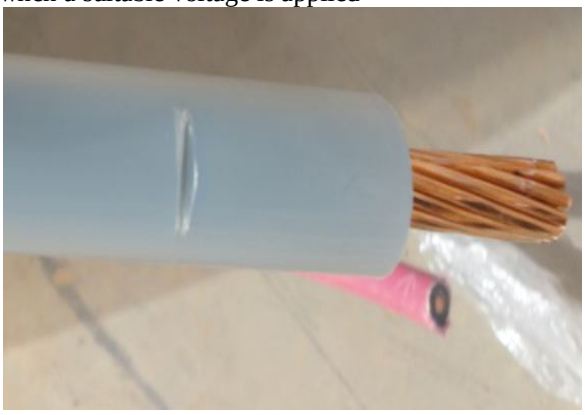

Figure 8: Second defect.

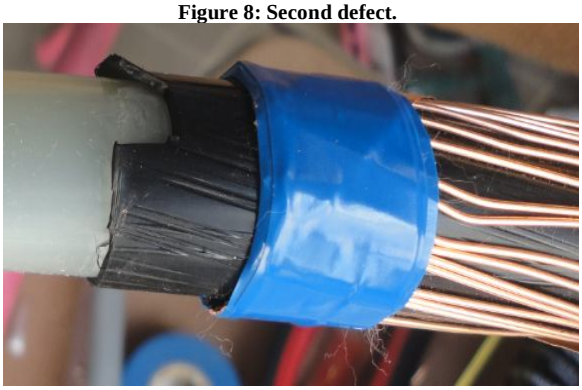

Figure 9: Third defect.

IV. PD MEASUREMENTS

During this investigation, several PD parameters were measured at both frequencies using the three different applied voltage levels as mentioned earlier. The objective of applying voltage lower than PDIV was to ensure that the test circuit is reliable and the calibration process used is accurate. PDIV was applied to observe the PD behavior at just the inception conditions. Voltage higher than PDIV was applied to monitor the effect of increased electrical stress on the PD behavior as compared to the case of PDIV. The PD behavior at both frequencies (60 Hz & 0.1 Hz) was studied by comparing PD magnitude and pulse count characteristics.

4.1: Results at PDIV & PDEV

First we determined the PDIV and PDEV levels. PDIV is the applied voltage level which is just sufficient to initiate the PD. PDEV is the applied voltage level at which the PD turns off when voltage is gradually decreased after PD starts occurring [6]. PDIV is often greater than PDEV due to several reasons [7]. At both test frequencies. Table 2 gives the measured PDIV & PDEV levels for both frequencies for the tested cable.

Table 2: PDIV & PDEV at both frequencies.

Frequency (Hz)	PDEV level (kV)	PDIV level (kV)
60	11.3	14.5
0.1	5.8	7.6

The values shown in Table 2 imply that higher test voltages are required at power frequency (60 Hz) than at VLF (0.1 Hz). Thus, PD inception stress at VLF is lower than at power frequency. Table 3 shows the test voltages applied during this study for both type of test voltages.

Table 3: Test voltages at both frequencies.

Actual applied test voltage			
Frequency (Hz)	Below PDEV (kV)	At PDIV (kV)	Above PDIV (kV)
60	10.5	14.5	17.5
0.1	4	7.6	10

4.2: PD level

At both frequencies, the PD magnitude increased as the test voltage was increased which is as expected and thus verifies the accuracy of the measurements carried out.

4.2.1: PD level at 60 Hz

Figures 10, 11 and 12 show the 60 Hz PD behavior as the voltage is increased. These figures display the magnitude of PD versus the angle of the applied voltage.

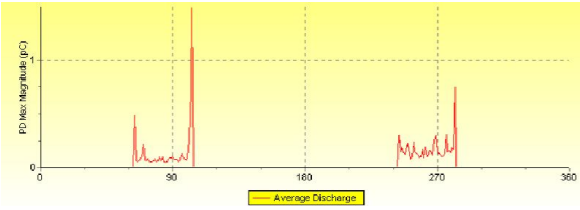

Figure 10: PD level at 10.5 kV (below PDEV level, f = 60 Hz).

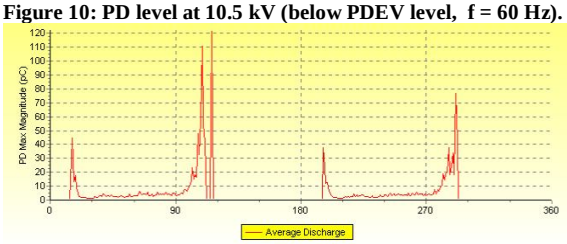

Figure 11: PD level at14.5 kV (at PDIV level, f = 60 Hz).

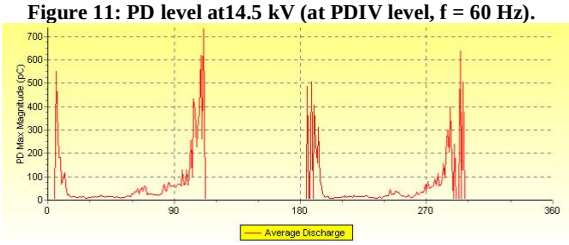

Figure 12: PD level at 17.5 kV (above PDIV level, f = 60 Hz).

Figures 10, 11 & 12 show that the PD level increases as the applied voltage is increased. PD patterns shown in Figure 10 are due to background noise and external discharges and do not represent partial discharge in the tested cable and are of low magnitudes. In Figure 11, PD level is significantly higher because of the PD inception in cable. Figure 12 shows much higher PD level when voltage is further increased. This suggests that because of the increase in voltage, there is increased stress and thus results in a higher PD level in this case as compared to at the PD inception condition.

4.2.2: PD level at 0.1 Hz

At VLF (0.1 Hz), PD patterns are shown in Figures 13 to 15 for every applied voltage.

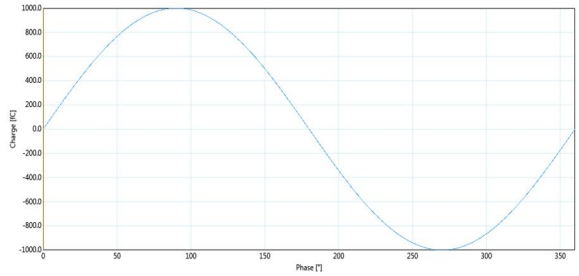

Figure 13: PD level at 4 kV (below PDEV level, f = 0.1 Hz).

Figure 13 shows that in this case, no PD is observed. Unlike other voltage levels applied at this frequency, the unit of PD used in this case is fC. In spite of this level magnitude, no PD event was observed. This means that all the resulting discharges are lower than such background noise level. Moreover, the used instrument (bs-suite) seems to have a very low noise level, so sensitive PD measurements could be performed.

Figures 14 represents the PD behavior at the inception condition. Here several discharges appear in both half cycles and PD level varies between 15 & 50 pC.

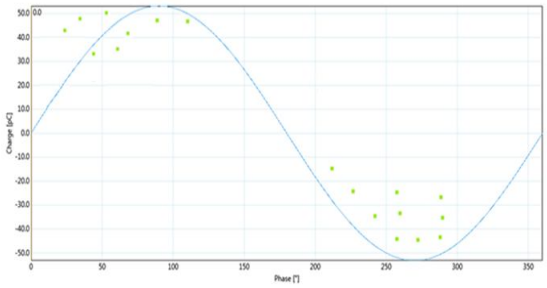

Figure 14: PD level at 7.6 kV (at PDIV level, f = 0.1 Hz).

When the voltage was increased above the PDIV (Figure 15), higher PD level was measured as compared to the case of 7.6 kV. This is as expected since a higher applied voltage level is associated with higher stress within the defects and consequently a higher PD level. In this case, PD varies between 18 & 58 pC.

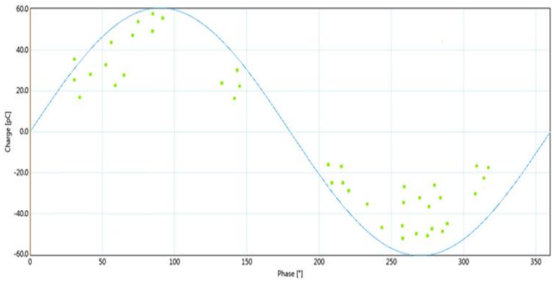

Figure 15: PD level at 10 kV (above PDIV level, f = 0.1 Hz).

4.3: PD pulse count

Based on the measurement, pulse count showed that PD occurs in intermittent manner generating a number of PD pulses. More pulses were generated as the applied voltage was increased. This was observed at both test voltage frequencies confirming the concept that increased test voltage results in higher electrical stress and subsequently more pulses are generated which is an indication of more intense PD activity.

4.3.1: Pulse count at 60 Hz

At 10.5 kV (below PDEV level), pulses were generated only around the peak value of the applied voltage in both half cycles. At this voltage level, pulse count varied between 4 and 35, which are low values and represent the background noise pulses.

At PDIV level of 14.5 kV, pulse count increased significantly resulting in 5 & 300 pulses as the minimum and maximum pulse count, respectively. This big increase in the number of pulses represents the PD inception at PDIV level. Furthermore, when voltage was increased above PDIV to 17.5 kV, the resulting pulse count varied between 5 and 200. Table 3 summarizes the pulse count at 60 Hz at different voltages.

Table 3: PD Pulse count characteristics

Voltage level (kV)	Max. pulse count	Corresponding Phase angle (°)	Min. pulse count	Corresponding Phase angle (°)
10.5	35	82	4	65
14.5	300	30	5	15
17.5	200	232	5	7

4.3.2: Pulse count at 0.1 Hz

The PD pulse characteristics was also studied at VLF. At 4 kV (below PDIV level), no PD pulses were detected as noted earlier. At 7.6 kV (PDIV level), PD inception occurred resulting in 18 pulses. These were generated at different cable lengths starting from the cable's near end as indicated on the X-axis of Figure 16 below.

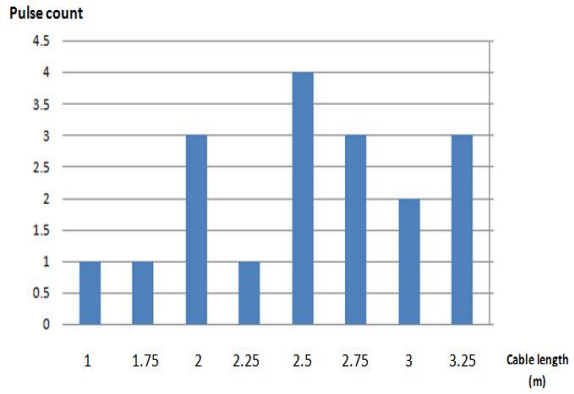

Figure 16: Pulse count (at PDIV level).

Similarly at 10 kV (above PDIV level) 41 pulses were generated due to the increased electrical stress resulting from the increased applied voltage level. These pulses are represented in Figure 17 below.

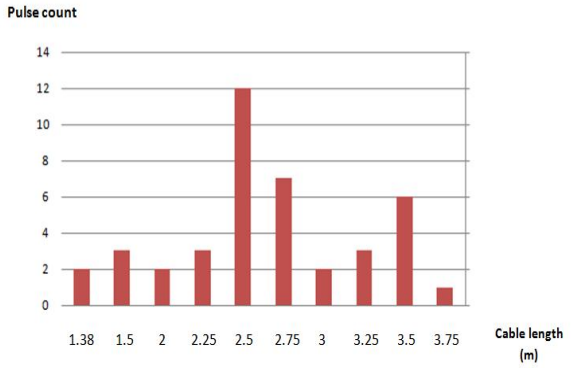

Figure 17: Pulse count (above PDIV level)

DISCUSSION

PD measurement as an effective method of power cables assessment has been applied widely in the world. In this study, the voltage and frequency variation were employed to monitor the PD behavior within a cable having defects created in advance.

The results show that there is a large variation in the PDIV for the same cable when 60 Hz and 0.1 Hz test voltages are used. This results in test voltages differences between the both frequencies. At 0.1 Hz, the PDIV is significantly lower as compared to 60 Hz case. Also the PD magnitude and pulse count are lower in case of 0.1 Hz. This represents an advantage of VLF testing since the damage caused to cable insulation at 0.1 Hz will be much lower than at 60 Hz during the cable condition assessment.

Large variation between PDIV & PDEV measured values for both frequencies is mainly due to time periods of the two types of voltages. Duration of each cycle in VLF is much longer than the corresponding value for 60 Hz. Since PD in cavities and defects needs initiating electrons which have time lag effects, at VLF one would expect lower voltage to initiate the discharge when compared with 60 Hz which occurred in our experiments (see Table 2).

Based on the test voltages and the measured PD parameters such as the discharge level, maximum PD level and the pulse count, PD testing at VLF has the advantage of lower power consumption. In addition, the instrument used has advantageous of being much smaller and lightweight as compared to the system used for PD testing at 60 Hz. However, test instrument of 60 Hz measure more parameters than instrument used for VLF testing which gives it the advantage of being capable to provide more comprehensive PD measurements at 60 Hz.

For both frequencies, PD level or the apparent charge measured in (pC) increases as the applied voltage increases which is as expected and thus verifies the correctness of the measurements.

CONCLUSION

The following conclusions can be made from this study:

1. At voltage below PDEV level, no PD is measured and any discharges measured at this voltage represents the background noise level and external discharges.
   At PDIV level, PD inception condition is observed and significant PD levels are measured when compared to the background noise levels.
2. Above PDIV level, significantly higher PD levels are measured as compared to those measured at PDIV level. This is as expected and is caused by increased electrical stress.
3. The PDIV and PDEV levels for 0.1 Hz are lower than those for 60 Hz.
4. The PD charge as well as pulse count is more for 60 Hz than for 0.1 Hz test voltage corresponding to PD inception conditions.
5. For in field condition assessment, PD testing using VLF has some clear advantage as compared to 60 Hz testing.

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