Quasi-PRPD Pattern Analysis of Surface Discharges Arising on a Porcelain Bushing of an ESP unit under Rectified DC Voltage

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Summary **–**Surface discharges occurring on a porcelain bushing under DC voltage not only causes an incipient fault condition but also can degrade the pertinent location once the surface deposition layer or the insulation material gets carbonized. Naturally, it becomes important to identify and analyze the surface discharges occurring on bushing. The current practice on analyzing surface discharges initiated under DC voltage employs partial discharge test methods that focuses on counting the PD events occurring over a time span. The method is sensitive but provides no information about the possible source of fault condition. In this context, a non-conventional, pattern based partial discharge analysis method on understanding the characteristics of electrical discharges occurring on the surface of a polluted bushing under DC voltage is studied. Initially, a half-wave bridge rectifier unit that produces an uncontrolled DC voltage is selected and employed. Later, the surface of the polluted bushing is energized, and the signals initiated by the surface discharges occurring on the surface contaminated bushing are recorded. Instead of counting the PD events, the pattern manifested by the surface discharges is correlated to the AC voltage input of the rectifier. Once this is accomplished, the pertinent findings are validated on an actual bushing installed in an electrostatic precipitator unit that is applied for cleaning producer gas of a biomass gasification plant.

Keywords: Partial discharge, DC, QPRPD pattern, bushing, electrostatic precipitator.

1. INTRODUCTION

Feed through type bushings are considered as one of the crucial components in a wet electrostatic precipitator (ESP) unit [1, 2]. As per the construction, the bushings suspend the high voltage electrodes concentrically into the cleaning chamber providing sufficient electrical clearance to the grounded vessel at the point of suspension [3, 4, 5]. Naturally, the surface condition of the feed through bushings have significant impact on the operating condition, performance, and cleaning efficiency of the wet ESP unit [2, 6]. Despite all, the bushings of ESP units applied for producer gas cleaning suffer premature failure even without meeting half of their expected life/service time [2]. The reduction in the life of the insulation is attributed to the cleaning process which removes the pollutants from the gas but contaminates all the exposed surfaces. The currently practiced maintenance program exercised to optimize the ESP units are inadequate in revealing the same [2, 3]. The reason for the failure is due to the surface discharges occurring on the tar polluted bushing [2]. Eventually, the surface discharges cause insulators to suffer mechanical fracture demanding a complete replacement which involve procedures that are hazardous to human and environment [1, 2, 6, 7]. In addition to this, the deposition layer on the bushing is carbonized as the surface discharges produces tracking areas of high conductivity that bridges the insulation, rendering it unusable. It might be possible to prevent the premature failure of the bushings, provided its status is constantly monitored. For this purpose, a prior knowledge on the aspects of tar and their influence over the dielectric condition of the insulator becomes a necessity. In all, the aspects of tar

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and the strategies to reduce their production during gasification has received wide attention [1]. Subsequently, the typical behaviour of tar contaminated bushing under AC voltage over a wide frequency has been already investigated [2, 8, 9, 10]. Following this, it is attempted to understand the typical pattern manifested by the surface discharges occurring on a tar polluted indoor bushing under DC voltage. Such an attempt is desirable since DC voltage is the practical choice in ESP units.

The currently available literatures mainly focus on the environmental issues of tar and/or aims at resolving issues related to gasification and cleaning efficiency of ESP unit [11–14]. The other aspects such as influence of individual and collective behaviour of tar under AC and DC voltage requires more attention [6]. In this regard, the authors have already attempted to study the collective behaviour of tar species deposited on the bushing surface over wide frequencies [2, 8, 9, 10, 15, 16, 17]. During this, the time dependent behaviour of multiple compounds of tar deposited on the surface of bushing and their overall influence over the performance and operating efficiency of a wet ESP unit is studied. The outcome of this finding is reported in [2] and may emerge as an input while developing a time-based maintenance protocol. However, the actual requirement is the development of an online monitoring tool which constantly monitors the condition of the bushing as well as the performance and cleaning efficiency of the ESP unit [15, 16]. In this context, this paper attempts to resolve the characteristics of discharges arising on surface deposited bushings under DC voltage.

2. PRESENT LITERATURES

The literatures that are relevant to the present study are discussed below:

2.1 Dielectric nature of tar

The currently available information on tar addresses mostly on bulk conductivity of individual and collective compounds in dry and liquid state [7,12,13,14]. In addition, literatures indicate that several compounds of tar that are dipolar in nature [18]. These compounds such as toluene, phenol etc., manifest dipole moments ranging from 0.13 D to 1.396 D [18]. At the same time, certain species like benzene, naphthalene, 1-methylnaphthalene etc. are individually unipolar and non-conductive [12–14]. It is proven that aromatic hydrocarbon compounds must be considered as non-conductive in their pure form and that the presence of any impurity leads into an increase of their conductivity in consequence of the raising amount of free charge carriers like electrons and/or ions [18]. This indicates that multiple compounds together manifest an entirely different behaviour due to dissociation and molecular reaction like radial reaction and polymerization [18].

2.2 Discharges and tracking on the polluted surface of the bushing

Pollution and moisture on the insulator surface cause unpredictable distortions in the electric fields as the depositions introduces non-uniformity in the surface conductivity [19–21]. Pertinent discharges initiated on the surface under DC voltage manifest as intermittent pulses with respect to time eventually causes partial breakdown and/or tracking on the surface. It is well established that the partial breakdown on the insulator surface is due to the high tangential component of the electric field [22, 23]. Pertinent magnitude of the streamer currents is attributed to the high lateral capacitance are in the range of mA [23]. These currents are displaced to higher conductivity region and if the current density is quite high forms dry bands. Naturally, these dry bands interrupt the high currents which in turn initiates the arcing in these localized spots [2]. Alternatively, a theoretical consideration suggests an explanation correlating the tracking with bond energies.

2.3 Diagnostic measurements

The collective data obtained from diagnostic test methods may provide an opportunity for an early detection of the bushing surface degradation [8, 9, 19, 20, 21]. Naturally, a clear discrimination between wet and dry surface deposition becomes possible [2]. The subsequent attempts to understand such discharges involve conventional partial discharge measurements under AC voltage [2, 6, 20]. So, the dynamic in nature of the AC sinusoidal waveform enables the charges to replenish and rebuild during each half cycle henceforth manifests a specific phase resolved PD (PRPD) pattern [2]. This behaviour appears once the recorded PD signals are synchronized to the phasor representation of the AC test voltage. Nevertheless, the DC voltage is the practical choice in any industrial ESP unit irrespective of their application [4, 5]. As in the case of DC voltage, the space-charge would normally accumulate with respect to time and the respective criteria that drives the discharge activity might be different, henceforth requires a thorough investigation. Also, the sensitive pattern-based analysis is not possible as the deduced mechanisms and the corresponding methods are inadequate.

In summary, it appears that there is an increasing interest in development of a maintenance program for monitoring the bushing of an ESP unit [3]. For this purpose, the prior knowledge on behaviour of tar compounds on the bushing surface becomes a necessity. This includes a thorough understanding on discharge behaviour initiated by the dry and wet tar depositions under DC voltage. Considering this, this study investigates on surface discharges arising on the tar polluted bushing initiated by the DC voltage. These objectives are resolved in two steps viz.,

1. Developing a new sensitive pattern-based method for analysing electrical discharges initiated under DC voltage.
2. Investigation on surface discharges of tar contaminated bushing using pattern analysis.

Both the information collectively might define the complete behaviour of tar depositions on the bushing surface under DC excitation. It is believed that gaining such knowledge might help in enhancing cleaning measures of producer gas, improvising the performance and operating condition of stand-alone power conversion devices of biomass power plant.

3. PD ANALYSIS UNDER DC

The test circuits used during PD measurements under AC and DC excitations are quite similar while the analysis and interpretation of measured data are different [2, 17, 20–24]. The former (PD under AC) uses PRPD analysis while the later (PD under DC) counts PD pulses and their individual time difference. The applied AC based PD signal analysis and interpretation procedures cannot be directly extended to the data measured under DC voltage since the synchronization to the phasing of the applied frequency is not possible [17, 24]. The current trend during PD investigations under DC voltage is a quality check procedure [22, 23]. The PD pulses are of different upper and lower limits and are recorded with their appropriate time stamps [24]. The recorded data are fed to the pulse counters in which values for upper and lower limits to the size of the PD can be set. Depending on the pulse counter values, the quality level of the insulation is ensured through a “GO” or “NO-GO” result [23]. Hence, to achieve more accurate information, precise measurements on number of PD events per minute are required [23, 24].

Quasi–Phase resolved PD Pattern (QPRPD) [17]: The discharges under AC excitation has every opportunity to recombine and replenish under every half cycle therefore emerges as a dynamic PD signal. On contrary, the discharge mechanism under DC is quite different. There might be a few additional PD events which might occur during the transient part of the DC voltage which may reflect in the PD signal. Otherwise, the charges at the PD location build-up with respect to time and doesn’t recombine or diffuse into the surrounding dielectric medium. Naturally, the present PD analysis under DC voltage doesn’t employ pattern analysis instead counts the PD events occurring over a wide period. Nevertheless, there exists an alternative approach. As the DC voltage is generated using a simple rectifier configuration, it might be possible to correlate the PD events occurring on the bushing surface of the test samples to its AC input. In this way, there is an opportunity to study the pattern manifested by the PD signals initiated by the DC voltage. The same is termed as “*Quasi-Phase resolved PD pattern*” or simply the QPRPD pattern. Although the PD events initiated under DC remains uncorrelated, their distribution remains dependent on phasor of AC input, thereby enabling such pattern-based analysis.

4. EXPERIMENTS

Initially, a bushing sample polluted with several compounds of tar species (refer [2]) on its surface is selected and subjected to experimental investigation. This implies initiating electrical discharges on the surface of the tar layered bushing. The insulator from which the sample was extracted had been exposed to several layers of tar, aerosols, and moisture. These layers of contaminations were glazed on its surface during its service time in the wet ESP unit. The surface discharges occurring on the chosen tar polluted sample is measured through PD measurements. Figure 1a and 1b pictorially describes the tar polluted bushing sample selected. The chosen test sample contains locations of partial abridgement caused by the surface discharges resulting in tracking phenomena. These areas indicating the possibility of tracking are surrounded by black depositions that exhibit in contrast to the glazed tar deposition high surface conductivity. These locations are evaded as the pertinent results may not actually reveal the behaviour of tar species. Subsequently, pattern manifested by the surface discharges initiated by the tar compounds is analyzed. An electrode arrangement is used for providing mechanical support and facilitating experiments on the chosen sample. Figure 2 shows the electrode arrangement that is employed. The electrode arrangement comprises of a base, two arms and two electrodes. The electrodes are made of steel and the support unit (base and arms) is made of hard paper that exhibits excellent dielectric properties. The broken insulator sample is placed on the base of the electrode arrangement while the electrodes inserted into the arms appropriately. The present study employs angular provision of 45 degrees and 2.5 cm of spacing. Once all the precautionary measures are ensured, discharge experiments are exercised on the test sample and respective data are recorded and analyzed.

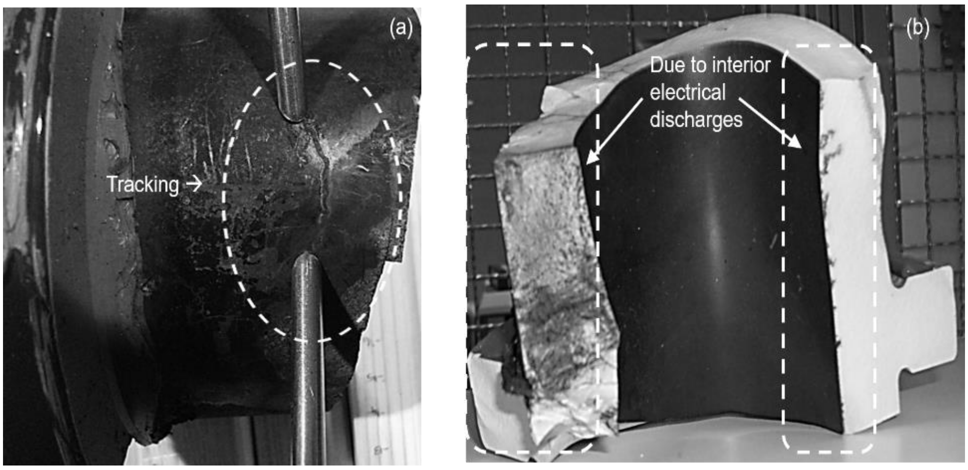

Figure 1. Pictorial description of the test sample of a tar contaminated bushing adopted in the present study (a) Surface view (b) Internal view.

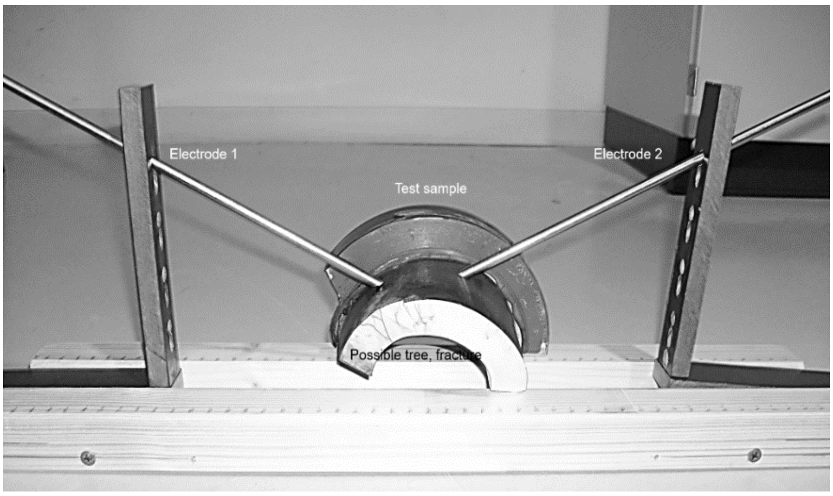

Figure 2. Photo of the test electrode used for housing the test sample and injecting the high voltage DC on the tar contaminated insulator.

Precedingly, the measurement circuit is calibrated to a pulse resembling a PD event. In this way, the signal detection sensitivity and accuracy are ensured. Later, the noise level is recorded as baseline data and the respective pattern is analyzed. Once this is accomplished, the PD level (QIEC) and the respective

QPRPD pattern manifested by the chosen polluted bushing sample under positive and negative DC voltage is investigated. The pattern termed as Quasi-PRPD or simply QPRPD is produced by synchronizing the PD events to AC voltage input to the rectifier unit. This is possible as the PD events though initiated / governed by the DC voltage, is nothing but rectified from the AC voltage. For this purpose, a high voltage DC test setup is used. Figure 3a shows the setup used for generating high voltage DC and measuring / recording surface discharges, respectively. Figure 3b shows the AC voltage input to the rectifier and the DC voltage used for testing purposes. The adopted high voltage DC setup uses a half-wave uncontrolled bridge rectifier and coupling or filter capacitor of 10 nF respectively. The adopted DC setup can generate up to ± 135 kV DC and can maintain a larger capacitive load for minimizing the ripple. To measure / record PD signals a high frequency current transformer (HFCT) is applied. The signals from the HFCT are transmitted to a digital PD detector the respective PD level (QIEC) and the QPRPD pattern are studied.

(a) (b)

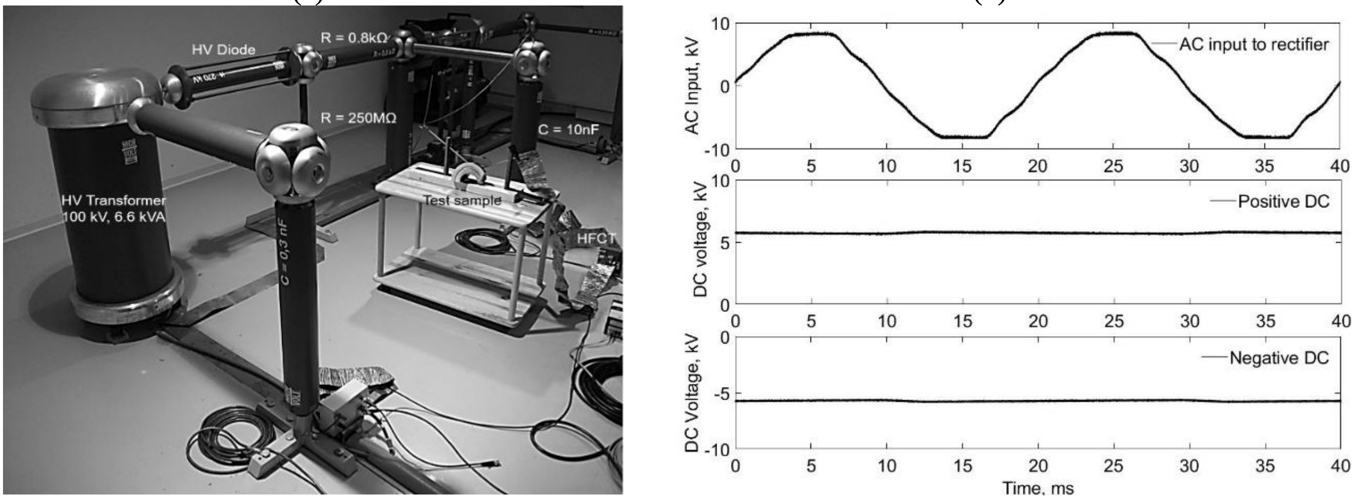

Figure 3. Setup used for generating the high voltage DC and measuring signals pertaining to the surface discharges arising on the tar polluted bushing sample.

4.1 Quasi-PRPD (QPRPD) pattern analysis

Measuring PD initiated under DC voltage has recently gained its attention. Since there are no standardized procedures, the currently available literatures discuss only on interpretation of discharges in-terms of classical and stochastic approaches. The PD events at DC starts as soon as the electric field intensity exceeds the breakdown strength of the material and/or the interface. After providing sufficient time for the polarization mechanism to occur and the space charges to accumulate, the effective DC field applied becomes constant initiating localized discharges on the dry and wet patches of tar species deposited on the surface of the bushing. To measure these discharges, the classical approach derives apparent charge (q_c) from the currents recorded from the terminals and analyzes the number of PD events by comparing the lower and higher threshold of charge magnitude along with time information (t_c). In addition, the time resolved charge magnitude is analyzed to obtain more information. The stochastic approach in-turn discusses the statistical quantities of charge intensity, pulse distribution and so on. Three parameters i.e., charge (q_i), time (t_i) and instantaneous voltage (v_i) are recorded and their intensity, magnitude and its repetition over measurement duration are keenly observed to arrive at a decision. Depending on the lower and higher threshold settings, the discharge magnitudes (q_m) and their repetition frequency (f_t) are recorded and analyzed to understand the '*GO/NO-GO*' situation. In any case, the time requirement for the classical and stochastic approaches are around 30 to 60 minutes as the same is demanded by the polarization phenomena. The currently available data are based on simpler configurations such as needle plane electrode, emulated void conditions on samples, etc., and the same is extrapolated on actual high voltage apparatus. As in the present case, a simple half-wave rectifier is used for generating DC voltage, henceforth there is an opportunity to exercise classical approach and establish a phase correlation to the PD events recorded. Once again, this may reduce the time duration as the discharge events mask the effect of polarization and can be eliminated or at least minimized. The pattern formed may be correlated to the phase of AC voltage input to the rectifier as the same is triggered in the same reference frame. To analyze this, the PD events are recorded using classical detection method.

4.1.1 Under positive DC voltage

The typical behaviour of PD phenomena in cavities and/or voids under DC voltage has been always under investigation. During this, the pattern manifested by the charging and discharging activities initiated by the DC electric field and space charge accumulation are investigated. At the same time, the characteristics and pattern of surface discharges are often reported as erratic. Pertinent data are obtained by conducting experiments on simplified electrode configurations. In the present study, the typical pattern manifested by the surface discharges appearing on the tar polluted bushing sample is investigated. The PD pulses occurring during surface discharge activity under positive DC voltage is synchronized to the AC voltage input to the rectifier and the corresponding pattern is studied. In this way, the PD analysis under DC for a prolonged duration is avoided and it is attempted to verify the possibilities of developing pattern analysis which may simplify the decision-making process at onsite. The usual expectation during pattern analysis is to observe the stability, intensity and repeatability of the PD pulses with respect to a reference frame. This forms the first step. In the present context, the PD events at DC appeared as individual pulses with respect to the time of occurrence. Once correlated to the phasor notation of the AC voltage input to the rectifier, manifested a typical pattern reflecting the typical discharge activity.

Figure 4 shows the QPRPD pattern of PD inception at + 9 kV DC. As expected, the PD events manifested as stable bipolar pulses throughout the phase. In all, the stronger PD events appear in third and fourth quadrant while the weaker events appear in the first and second quadrant. This might be due to difference in charging and discharging behaviour on the surface of tar polluted bushing caused by the lateral capacitance and non-uniform conductivity of the tar deposition. Unfurling these PD events (initiated under DC voltage) in time would eventually require a larger measurement duration for making an interpretation and to arrive at '*GO* or *NO-GO*' decision. In addition, it also could be noted that the intensity of negative PD pulses appears higher than the positive counterpart. Further increase in test voltage intensified the respective PD events. Nevertheless, the phase correlation remains unaltered.

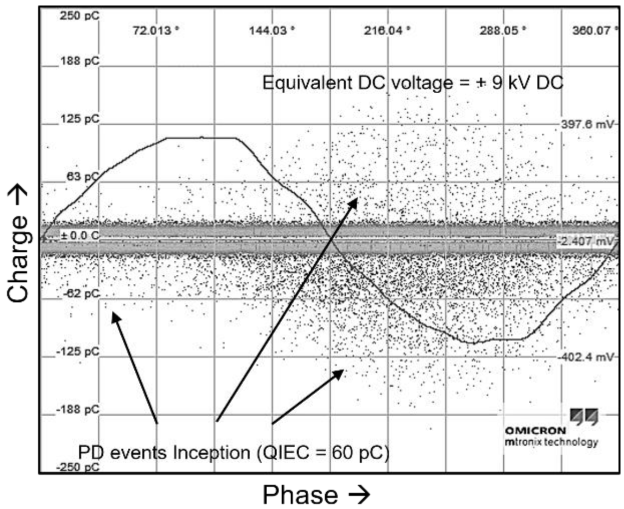

Figure 4. QPRPD pattern of surface discharges arising on the surface of tar contaminated bushing under positive DC voltage of +9 kV.

Figure 5 shows the QPRPD pattern of PD events appearing under +12 kV DC. The PD pulses appear stable distributed throughout the phase. In all, the PD signals appeared more dominant in third quadrant in both polarities. Further increase in test voltage increased the intensity of PD events but doesn't change the phase correlation. The PD events appear in first, second and fourth quadrants as stable and strong pulses in both polarities, however not as intense as it is in the third quadrant. At the same time, the intensity of negative pulses seems to be quite larger than the positive counterpart. All these specific patterns seem to repeat irrespective of the magnitude of test voltage. The only difference is the intensity and magnitude has increased and the pulse distribution seems to be appearing throughout the phase. The degree of pulse distribution seems to be quite higher in third quadrant than the first quadrant. After this, the charge-time behaviour manifested by the PD events are analyzed.

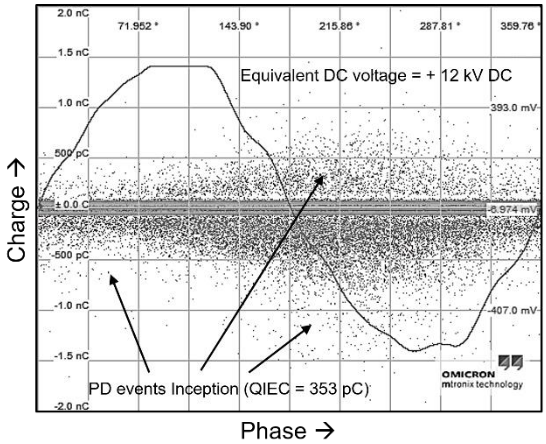

Figure 5. QPRPD pattern of surface discharges arising on the surface of tar contaminated bushing under positive DC voltage of +12 kV.

Figure 6 shows the charge-time (*q-t*) behaviour of surface discharges which arise in the presence of positive DC test voltage of + 10 kV. Two observations could be made from Figure 6. First, the discharges appeared intermittent throughout the measuring time. Second, the magnitude of intermittent PD events reduces with respect to time and the apparent charge level seems to stabilize in the range of 400 pC. This might be due to the positive space-charge formed at the interface of electrode and tar layer of the contaminated sample. Consequently, a higher electric field intensity is required to initiate a noticeable discharge event. This also might be the reason for the intermittent discharge behaviour. In due course of time, the polarization of dipolar tar species and the positive space-charge seems to be equalized between the test electrodes causing a reduction in the magnitude of the discharge event which stabilizes around 400 pC. Following this, the typical behaviour of PD events and the respective QPRPD pattern initiated by the surface discharges under negative DC voltage on the chosen tar polluted bushing is studied.

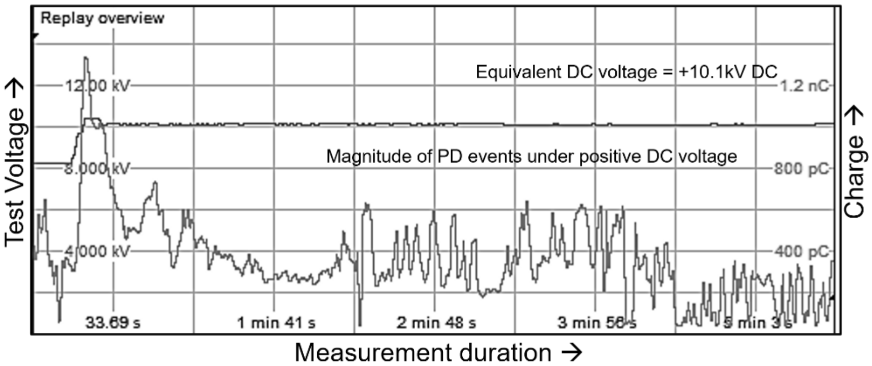

Figure 6. Charge-time (q-t) characteristics of surface discharges arising over the tar contaminated bushing under positive DC voltage of +10 kV.

4.1.2 Under negative DC voltage

The PD events initiated by the surface discharges on the chosen test sample under negative DC voltage is shown in Figure 7. Comparatively, the events manifested by the surface discharges seems to emerge with a better PD and phase resolution. Upon phase correlation, the QPRPD pattern appeared at the third and fourth quadrant i.e., spanning from the peak value of the negative AC input voltage. Such pattern-based observations cannot be made by employing the currently practiced PD at DC analysis method. At the same time, the PD pulses starts to appear as the DC test voltage reached – 6.5 kV, which is relatively lower than its positive counterpart. The corresponding PD level at the inception is around 46 pC which seems to increase with the test voltage, whilst the pulses appeared invariably in third and fourth quadrant, respectively. In addition, as in the previous case, it appears that there are few pulses or discharge events that are uncorrelated to the phase of the test voltage and is not stable and repeatable. Nevertheless, these erratic PD events (shown in Figure 7) appear as quite meagre.

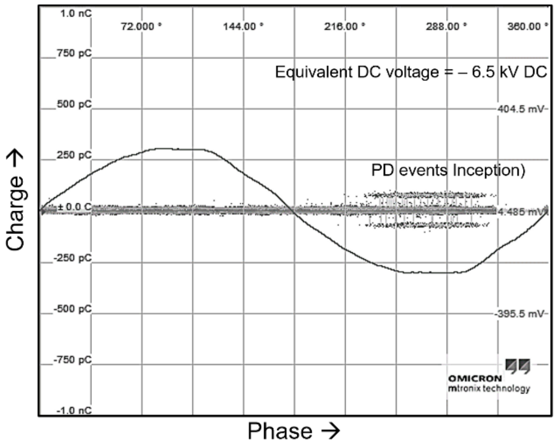

Figure 7. QPRPD pattern of surface discharges arising on the surface of tar contaminated bushing under negative DC voltage of – 6.5 kV.

Figure 8 shows the QPRPD pattern of surface discharges arising under –9.5 kV DC. Comparatively, the intensity and magnitude of PD events increased but remained correlated to third and fourth quadrant (spanning from peak value in the negative cycle of AC voltage). In addition, the magnitude of the erratic pulses is mildly increased and are surprisingly spanned throughout the phase with more intensity in the first quadrant. The same could be observed in QPRPD pattern shown in Figure 8. It could be observed from Figure 8 that under further increase in DC voltage, the severity of surface discharges increased drastically which manifested as elevated level of PD level from 46 pC to 144 pC. The intensity of pulses in the respective QPRPD pattern becomes higher occupying the complete third and fourth quadrant. This confirms the fact that the negative DC voltage might induce more stress conditions than the positive counterpart. The number of such uncorrelated PD events appeared more intense with the increase in the test voltage. To analyze this, the QPRPD pattern manifested by the surface discharges under –12 kV DC is studied.

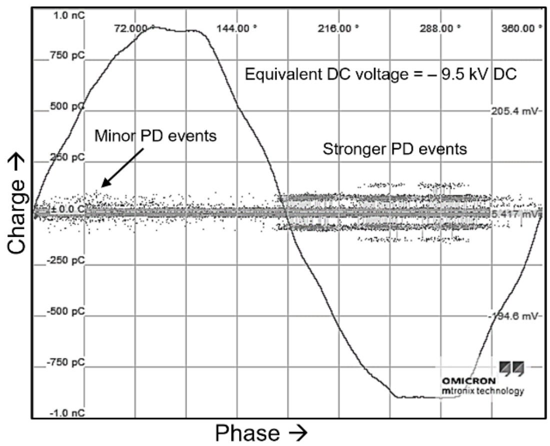

Figure 8. QPRPD pattern of surface discharges arising on the surface of tar contaminated bushing under negative DC voltage of –9.5 kV.

Figure 9 shows the QPRPD pattern of surface discharges arising on the tar polluted bushing sample under –12 kV DC. As expected, further increase in the test voltage to –12 kV DC increased the intensity of discharge activity. The respective PD pulses appeared distributed throughout third and fourth quadrant of the phase. Pertinent intensity and magnitude of PD pulses representing the surface discharge activity appeared more dominant i.e., in the negative polarity of AC voltage input to the rectifier unit. In addition, the magnitude and intensity of erratic pulses appeared correlated to the same phase while the intensity seems to be slightly elevated, but not as intense as the pulses at the third and fourth quadrant.

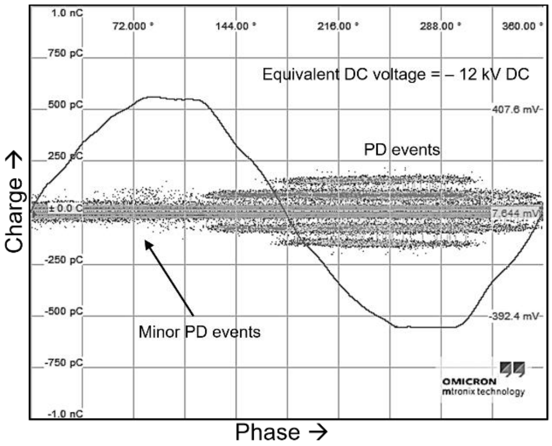

Figure 9. QPRPD pattern of surface discharges arising on the surface of tar contaminated bushing under negative DC voltage of –12 kV.

Figure 10 shows charge-time (*q-t*) behaviour of surface discharges arising on tar species under negative DC voltage of 10.4 kV. On contrary to the positive counterpart, the electrical discharges appeared continuous throughout the complete measurement duration. The apparent charge level reached 800 pC at the start and reached a level close to 1.2 nC after the 90s of the total measuring time. There are some intermediate discharge events at the beginning which may be due to the initial formation of negative surface charges causing a reduction of the field strength at the negative electrode. In other words, at the beginning the surface charge on the dry tar layer is of smaller magnitude than the velocity of charge injection at the negative test electrode causing the charge pulses appearing as a momentary drop in charge-time characteristics. Subsequently, the value of the apparent charge reached to a stable value after around 90s indicating that the equilibrium of charge injection is reached. From here, any prolongation of measurement time resulted in continuous charge-time behaviour.

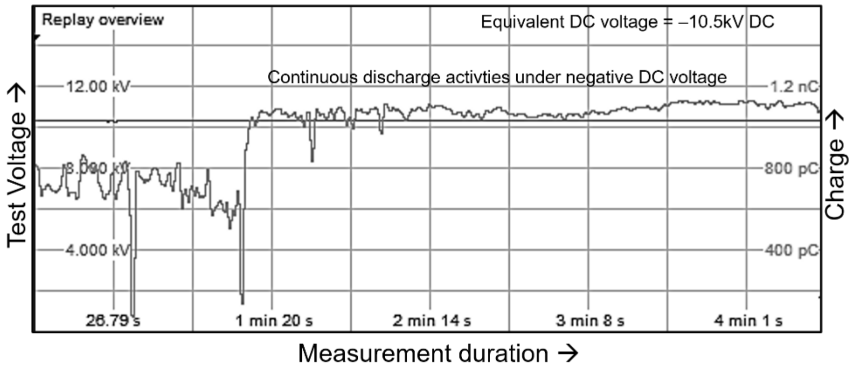

Figure 10. Charge – time (q-t) characteristics of surface discharges arising over the tar contaminated bushing under negative DC voltage of –10.4 kV.

In summary, it can be concluded that the stress condition corresponding to the positive and negative polarity are different. Under positive DC, the QPRPD pattern of PD events appeared somewhat distributed in the third and fourth quadrant of the phase. Further increase in the magnitude of test voltage increased the magnitude and intensity of the PD events, however the pulses seem to span slowly from third and fourth quadrant to the complete phase. The corresponding charge-time behaviour under positive DC emerged to be intermittent with several charging and discharges. This indicates possibilities of charge recombination which keeps the procedure dynamic. Under negative DC, the QPRPD pattern of PD events remain deterministic and appeared at the peak of the negative cycle of the AC voltage and remains distributed in the third and fourth quadrant. Contrary to the positive counterpart, further increase in test voltage did increase the magnitude and intensity of PD events but did not alter the phase correlation. The pulses remained in the third and fourth quadrant and is not distributed throughout the complete phase. In addition, the charge-time behaviour of discharge activity under negative DC emerged to be continuous. After compensating for the polarization mechanisms and space-charge accumulation, the pulses stabilized from 800 pC to 1.2 nC. Once this is complete, the PD signals are unfurled in time domain and analyzed.

5. VALIDATION

The experimental validation involved a wet ESP unit (shown in Figure 11) used for laboratory purposes. The adopted ESP unit comprises of cylindrical collecting electrode, coiled discharge electrodes and uses for DC voltage for cleaning purposes with efficiency equal to 96%. The operating voltage of the chosen ESP unit is –35 kV DC generated through a full bridge rectifier unit while the current required during gas cleaning process through negative corona discharge process is around 20 mA. The online PD test setup comprises of a high frequency current transformer (HFCT) as a measuring sensor and a PD detector over wide measuring frequency (DC to 20 MHz). The high voltage electrode passes through the insulator and remains suspended in the cleaning chamber. The HFCT is connected to the ground strip of the ESP tank thereby remains close to the location of the insulator and the discharge signals are electromagnetically decoupled from the same. Following this, the PD measurement setup is calibrated to a known pulse of magnitude 100 pC and later the baseline noise level is analyzed to ensure the detection sensitivity and accuracy.

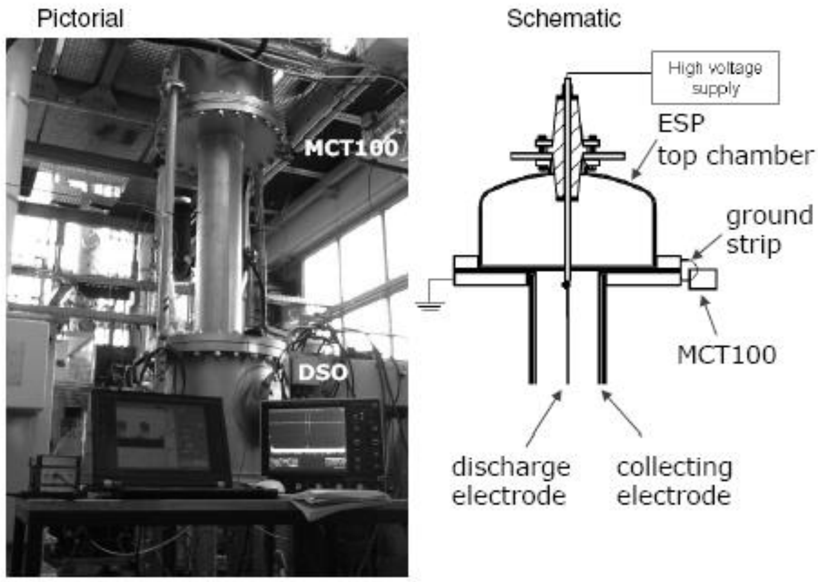

Figure 11. Pictorial description of the actual ESP unit and the PD measurement test setup adopted.

The QPRPD pattern of severely contaminated surface conditions on the bushing is shown in Figure 12. During this measurement, it is important to note is that strong bipolar discharges appeared even at an ESP operating voltage of –5 kV. These discharges manifested as stable, bipolar pulses correlated to the third and partly first and fourth quadrant of the AC voltage input to the rectifier unit. As the ESP operating voltage is close to –5 kV DC, the corona discharges occurring in-between the electrodes are absent. So, it could be concluded that the pertinent PD pulses are strictly due to the discharge activities on the surface of the tar contaminated bushing. Being a full bridge rectifier, the pulses appear in both positive and negative cycle, respectively. The PD pulses initiated by the discharges in the crack appeared as bipolar and correlated mostly in the third and fourth quadrant of the AC input voltage. Clearly, the tar contaminations along with the moisture and aerosols has penetrated in the minor crack related defect developed in the bushing. Later, a physical investigation was made to reconfirm the presence of a crack in the bushing. Nevertheless, considering the QPRPD pattern, these PD events could be closely correlated to the surface discharges arising on the tar contaminated bushing. Following this, the insulator surface deposition is dried due to indirect heating, the operating voltage of the ESP unit is thereby increased from –5 kV to –20 kV and the PD signals are recorded.

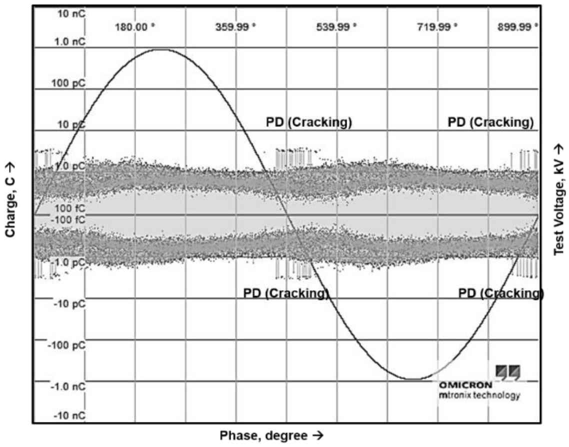

Figure 12. QPRPD pattern of the inception of surface discharge arising over the surface of a tar contaminated cracked bushing installed in a wet ESP.

Figure 13 shows the respective QPRPD pattern of corona, surface, and crack discharges. It becomes clear from Figure 13 that it is possible to discriminate the ESP operation and defective conditions in the ceramic support insulator. In any case, both the discharges i.e., the corona emerging under ESP operation and the surface and crack discharges manifested typical and unique QPRPD pattern. As expected, the QPRPD pattern corresponding to corona manifests its typical behaviour appearing stable pulses which increases with the magnitude of the test voltage while the crack discharges appeared a different pattern. In all, the corona discharges are voltage dependent henceforth increases and decreases with the magnitude of the test voltage. At the same time, the discharges in the crack appeared time dependent, i.e., increased with time until it reached a threshold value. Beyond this value, it stopped appearing or some cases manifested pulses in a reduced magnitude. It is expected that further increase in test voltage might cause a complete failure of the bushing.

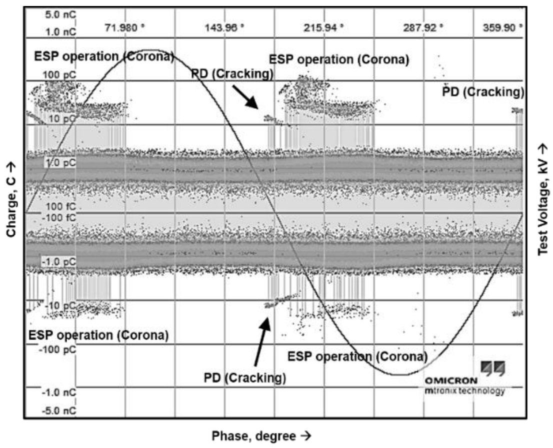

Figure 13. QPRPD pattern of the severe discharges arising over the surface of tar contaminated cracked bushing in the wet ESP unit under nitrogen flushing.

Figure 14 shows the nature of the charge-time (q-t) relation of surface discharges measured with respect to time. It could be observed from Figure 14 that the surface discharges are continuous in nature. This is quite reasonable since the applied voltage negative DC. At the start of measurements, the test voltage was close to –5 kV DC and corresponding magnitude of discharges are quite small. Further increase in test voltage to –20 kV DC increased the discharge activity to a value close to 250 pC which seems to stabilize with respect to time. There are few momentary drops which are caused due to the sudden reduction in the test voltage caused by spurious discharges that occurred in the cleaning chamber. Nevertheless, the apparent discharge level stays approximately close to 250 pC while the corresponding current drawn for the clean operation is close to 20 mA.

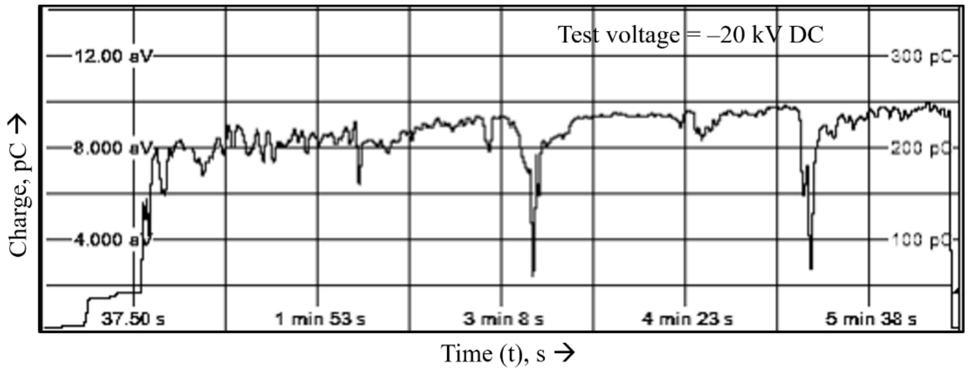

Figure 14. Charge-time (q-t) characteristics of surface discharges arising over the tar contaminated bushing installed in an ESP unit at –20 kV DC.

In summary, it appears from the experimental study that the surface discharges on the tar contaminated bushings manifested distinct behaviour. Subsequently, the discharges between electrodes and on the surface of the insulator due to contaminations could be clearly discriminated. The discharges that might result in a mechanical fracture or failure also could be easily identified through the QPRPD analysis. After all, the QPRPD pattern is nothing but a reincarnation of PRPD pattern with slight modification. It appears that the surface discharges under positive voltage is intermittent while the same under negative voltage is continuous. This once again confirms that the negative voltage induces more stress than the positive counterpart.

6. INFERENCES

There are few interesting observations made from the present study which are listed below –

- It appears from the experimental study that the surface condition of the tar polluted bushing could be identified using the QPRPD based pattern analysis. The typical behaviour of discharges initiated under DC voltage manifested as strong and stable pulses whose intensity is directly proportional to the magnitude of the test voltage. These pulses when correlated to their time of occurrence doesn't manifest any pattern, however, carries the information regarding the discharges. Comparing the charge magnitude, repetition rates, time of occurrence with the threshold levels might provide an opportunity to understand the severity. Nevertheless, this method requires a measurement duration of atleast 30 mins to 60 mins. At the same time, synchronizing these discharge pulses to the phase of the AC voltage input to the rectifier unit manifested a specific pattern doesn't have any time restriction and the corresponding QPRPD pattern might reveal the diagnostic status of the indoor or outdoor bushing. Pertinent measurement duration can be restricted to few minutes which is an advantage. Henceforth, the proposed approach may be used alone or along with the currently practiced DC measurement methods to clearly understand the diagnostic condition of the bushings.
- During measurements, the PD inception under positive and negative DC voltage emerged under different values. Comparatively, the PD inception under positive DC voltage appeared as the voltage reached + 9 kV DC while the same for the negative voltage appeared under – 6.5 kV DC. The reason for the difference in PD inception voltage with respect to the polarity of DC voltage is attributed to the field distribution and space charge accumulation and recombination.
- Further experiments on the wet ESP unit validated the possibilities of using the proposed QPRPD pattern analysis and the time resolved PD analysis approaches. In all, the QPRPD pattern analysis employed provided an opportunity to identify the cracking effect or development of crack in the porcelain bushing from the surface discharges and the ESP operation.

Thus, it appears from the experimental study that the QPRPD pattern analysis and the time resolved PD analysis methods can be used in understanding the diagnostic condition of the tar polluted busing installed in wet ESP unit. The proposed method may be used in addition to the routine procedure adopted in making interpretation on discharges initiated under DC voltage.

7. CONCLUSION

A systematic experimental study on test samples and actual ESP unit is conducted. The experiments on the test samples and on an actual insulator proved that it is possible for an early detection of surface depositions on an actual bushing. So, the online PD monitoring methods that are popularly used on HV apparatus onsite could also be employed not only to keep track of the condition of the bushing, but also to monitor the operating condition of ESP units. Furthermore, measurements and analysis on test sample with tar contaminations would give a deeper understanding about the physics of the ageing phenomena using a diagnostic testing and monitoring tools. With this data, it is intended to cross-verify the possibilities of modifying the existing maintenance tools popularly employed on wet ESP units. This forms the future scope of this experimental work.

ACKNOWLEDGEMENTS

The authors extend their sincere thanks to the funding agencies for their support in development of this work. This project is started within the ERA-Net Bioenergy "EMF-project" funded by the German Federal Ministry of Food and Agriculture through its Agency of Renewable Resources FNR (FkZ: 22018407). Further work was carried out within the junior research group NWG-TCKON funded by the German Federal Ministry of Education and Research through the *Projektträger Jülich PtJ* (FkZ: 03SF0442). This experimental work forms a part of the Ph.D. thesis titled "*Diagnosis of a High Voltage Bushing of an Electrostatic Tar Precipitator Unit*" of Mr. Philipp Schröder, supervised by Dr. York Neubauer and Dr. Saravanakumar Arumugam. The authors thank the University of Rostock, High Voltage and High Current Technologies, Rostock, Germany for providing high voltage laboratory facilities for conducting experiments on the test samples. The authors also thank Prof. Sascha Kosleck, University of Rostock, Institute of Ocean Engineering, Germany for his invaluable support.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest associated with this manuscript.

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