USE OF CONVENTIONAL AND UNCONVENTIONAL TECHNIQUES TO IDENTIFY PARTIAL DISCHARGE ACTIVITY IN ISOLATED PHASE BUSBARS

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ABSTRACT

In most power stations, the Isolated Phase Busbar (IPB) provides a crucial linkage between the generator, generator circuit breaker and the step up transformer. In some cases, this linkage extends to the station/unit transformer, excitation transformer, voltage transformers and start up frequency converter units. Despite being an important element, maintenance on the IPB is often overlooked when compared to the primary assets.

This paper presents a case study from multiple generating units at a thermal power station in the UK where various conventional and unconventional techniques were used to identify partial discharge activity within the 15.5kV IPBs. Out of the three generating units at the site, partial discharge activity was verified on two of the units, whilst significant activity was not recorded on the third unit. All three units are understood to have similar maintenance activity performed on the IPBs.

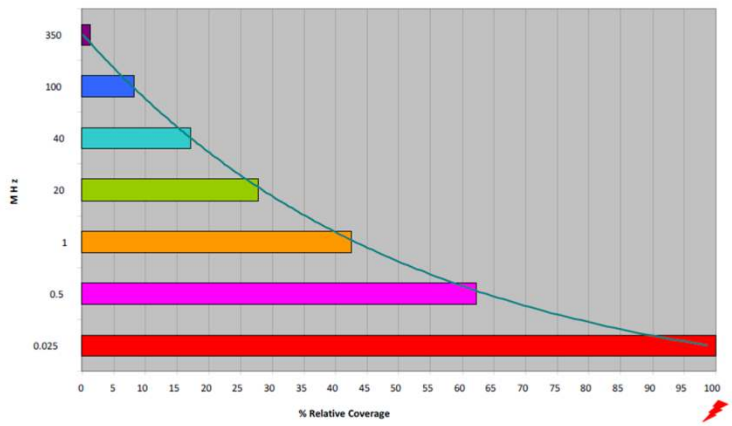
A number of conventional techniques, such as reliance on the 80pF and 9000pF high voltage coupling capacitors for periodic and continuous measurement were used to initially diagnose activity from the "system side" of the machine. In order to further understand the discharge activity, use of unconventional techniques such as Electro Magnetic Interference (EMI) and Radio Frequency Interference (RFI) were utilised. These techniques were applied to the three machines, on all phases and where appropriate at different locations, for example with the use of the RFI surveyor. Finally, an inspection of the IPB on the two units with high discharge activity was undertaken and the results correlated to the observed test patterns. The discharge mechanisms and a number of key learnings from the case study are further discussed.

INTRODUCTION

Many online condition monitoring techniques have been developed in the past 40 years to detect partial discharge (PD) activity in High Voltage (HV) plant assets. Partial discharge analysis has become well established and is usually considered to be the conventional way to detect PD and is backed up by the IEC 60270 standard [1]. Other competing methodologies – including Electromagnetic Interference (EMI), Radio Frequency Interference (RFI) and Acoustic diagnostic methods – have no such standard at the time of writing and have not been widely adopted in industry for testing on generators and IPBs. However, these 'unconventional' techniques have proven very effective at identifying sources of PD; in some cases, going further than partial discharge analysis in establishing potential locations for discharge sources.

Conventional PD Techniques

Partial discharge analysis, bus (directional) technique, is a time-domain technique used for condition monitoring of insulation systems in thermal rotating machines. Each partial discharge event is quantified in terms of its polarity, amplitude, frequency, and phase relationship [2]. PD measurements often follow the IEC 60270 standard, which specifies the test circuits and calibration setups required as well as measured and derived quantities. Most systems now display PD information as Phase-Resolved Partial Discharge (PRPD) patterns, where each pulse observed over the measurement period is plotted in relation to the phase of the power frequency, often with colour to denote repetition rate. Due to a significant amount of research – both academic and industrial – each known defect has an associated PRPD pattern that can be used by test engineers to classify and evaluate potential problems with HV insulation systems [3] [4] [5]; furthermore the recognition patterns for generator PD activity is given in IEC 60034-27-Part 2. Conventional partial discharge analysis, unlike some other testing methods, has no absolute scale of discharge severity. What may seem to be high levels in one machine could in fact be very stable and unchanging over long periods of time – which is no cause for concern. However a doubling of any discharge activity levels over 6 months and a change in PRPD patterns would warrant further investigation [6] [7]. This highlights the importance of data trending to this technique. There is currently some debate on the 'correct' procedure of PD measurement – primarily on the subject of noise. Some suggest that frequencies below 40MHz are too noisy to obtain useful information and so apply a high pass filter through the use of 80pF coupling capacitors [8] [9]. However, many others point to the fact that high frequencies attenuate very quickly and so by only monitoring these frequencies a lot of information about the system is lost [10] [11] [12] [13] [14]. This is because these 80pF couplers can only 'see' a short distance into the winding [6] [15] (Figure 1).



Measurement frequency vs relative winding coverage [15]
Figure 1

Some PD testing companies are using higher capacitance couplers – in some cases up to 9nF [6] [16] – as a result. There are, however, still several problems with partial discharge analysis as it stands today. Another issue is the difficulties with calibration. Due to the unique complex geometries of each machine's stator windings it is exceptionally difficult to calibrate each to a set standard [12] [13] [17]. This means that it is almost impossible to directly compare results from different machines or diagnose fault conditions from the first measurement [7]. High levels of PD are not indicative of insulation degradation if it is stable [17].

Unconventional PD Techniques

Several techniques have been developed, which have proved relatively successful in the detection of PD. The lack of an accepted standard has limited their reach in industry. A technical specification has recently been drawn up by the IEC technical committee 42 (TS 62478 [18]) to cover these unconventional techniques. EMI and RFI are narrowband frequency domain techniques that display results in both frequency spectra and zero-span plots. By analysing the different patterns, the presence and type of discharge can be identified. However, in some cases, relying on unconventional PD techniques to detect the magnitude of the defect can be difficult, especially in absence of historical results. There are several measurement sensors that can be used to gather data that is both conducted to earth (HFCT, TEV probe, or coupling capacitor) or radiated (antenna).The frequencies at which certain PD patterns are observed can provide some location information for signals conducted to earth [19]. Radiated signals are strongest closest to their source, which allows for another location method.

CASE STUDY

CCGT site in North Lincolnshire, UK used in this case study
Figure 2

The site that was chosen for this paper is a Combined Cycle Gas Turbine (CCGT) site located in North Lincolnshire, UK. It was commissioned in 1996 and consists of three units – two gas turbine (Units 1 and 2) and one steam turbine (Unit 3). The station was mothballed for approximately three years between 2012 and late 2015. The total capacity of the station is approximately 734MW. All of the units have two types of capacitive couplers permanently installed for PD monitoring; four 9nF couplers (three at the line end and one on the neutral) and six 80pF couplers at the line end to allow for time of arrival disturbance separation. Three of the 80pF capacitors are installed at the line terminal bushings of the generator, while the remaining three 80pF capacitors are installed at the terminal bushings of the excitation transformer, some 15 meters away from the capacitors installed at the generator end.

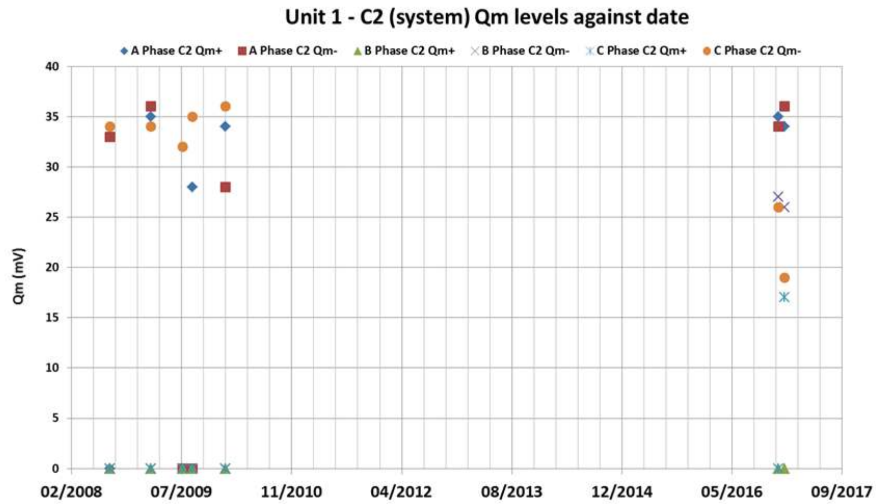
Following a re-wind of Unit 2 generator in 2016, the routine PD testing showed a significant increase in the PD activity. This prompted the asset owner to pay closer attention to the generator and system side results (i.e. system side results in this case refers to the IPB and associated equipment related activity) on all three units. In Bus type configurations, the generator side PD results are often referred to as C1, whilst system side is referred as C2. The results from the system side are further discussed in this paper. The generator PD data is only presented where it adds value to the understanding of system side (C2) activity. All three units are believed to have undergone similar maintenance activities.

The EMI data was taken from the C1 coupler (80pF) for each phase to allow for some discrimination to better identify sources of discharge. The RFI data was taken from multiple locations along the IPB using a monopole antenna. The generators were not in-service at the time of the RFI tests. i.e. the RFI survey covered the 15kV IPBs that were energised up to the 15kV generator circuit breaker, as the IPB section between the generator circuit breaker and the generator was not energised during the test.

UNIT 1

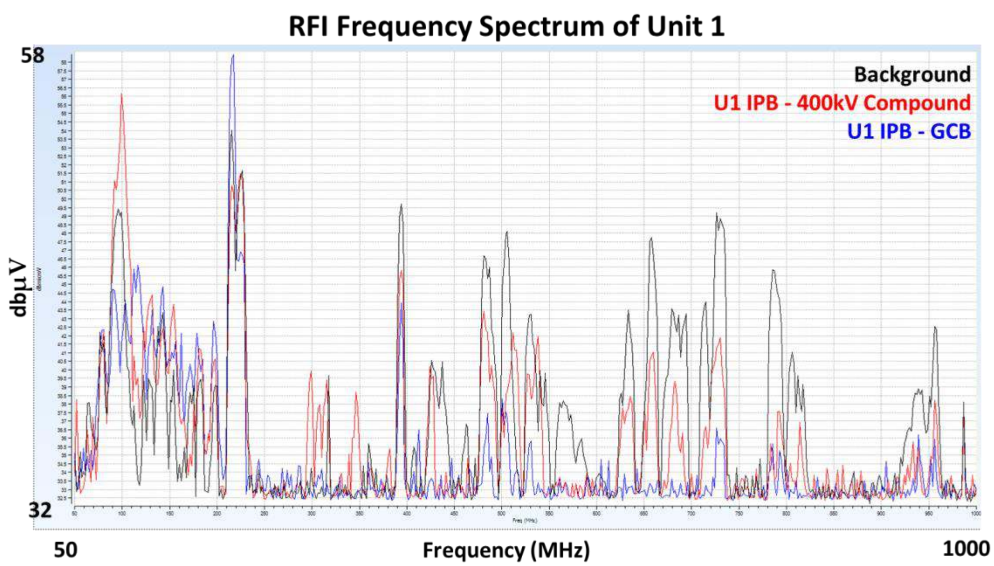
Figure 3 shows a comparison of C2, system side activity, on Unit 1. The data is taken from connection to the 80pF capacitors, and relies on periodic measurements. In this case, system side refers to PD activity external to the generator, and this includes the PD activity between the two 80pF couplers.

The key observation that can be noted in Figure 3 is the low level PD activity on the system side of Unit 1. As these PD measurements were taken at periodic intervals, the unit loading has varied over time and the results indicate that the PD activity on the system side does not change significantly due to load and temperature variations. As the Qm levels on the system side are not of significant concern, the PRPD between the two couplers (i.e. IPB region between the generator terminal bushings and the excitation transformer terminal bushings) and the system (i.e. from the excitation transformer to the step up transformer) are not discussed.



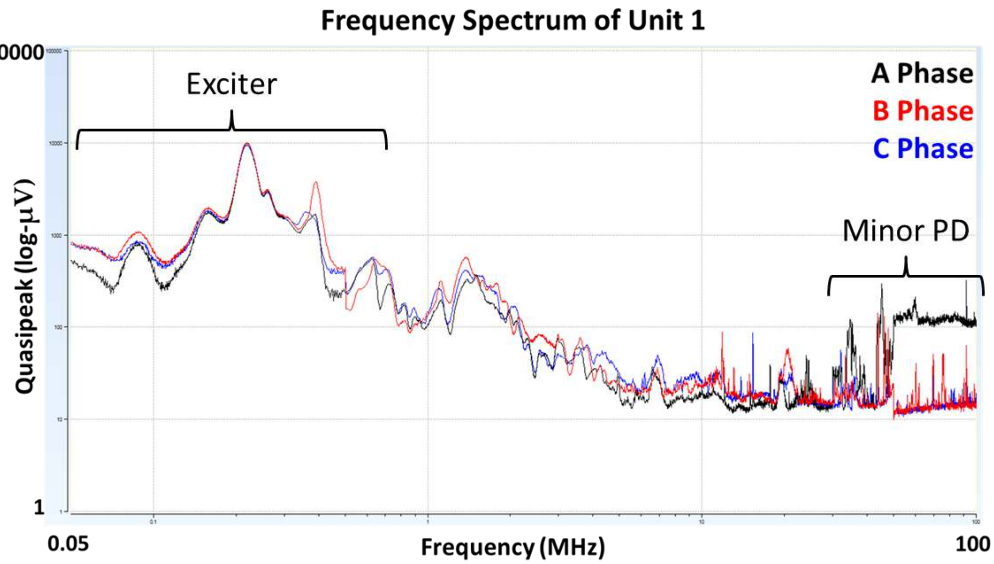
Unit 1 C2 (System) Qm Levels taken from Periodic Online Measurements
Figure 3

Both RFI and EMI results showed little PD activity as seen in Figures 4 and 5.



RFI Frequency Spectrum Survey on Unit 1 IPBs
Unit Not in Service at the Time of the Survey
Figure 4

If PD was present in the RFI frequency spectrum, it would be evidenced by a broadband increase over the background trace. Unit 1 shows no such increase over the background at any of the measurement locations.

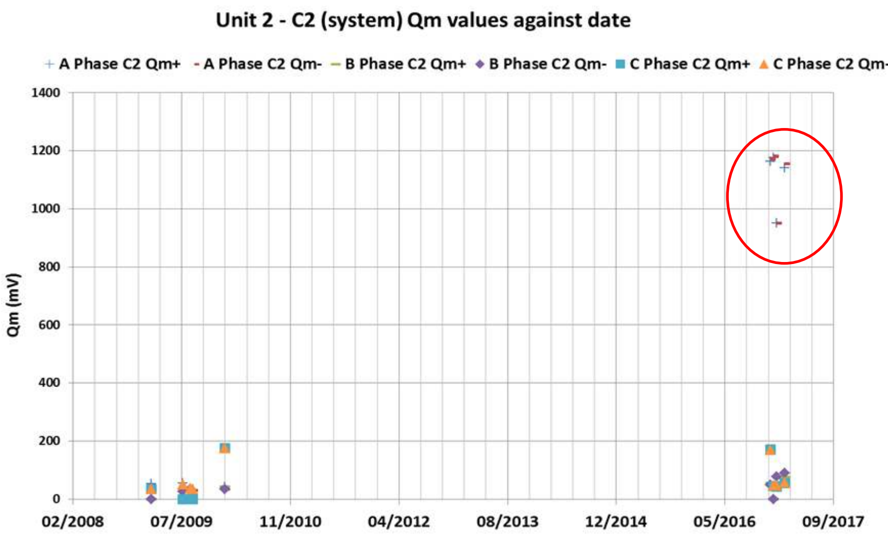


Unit 1 – EMI Frequency Spectrum Results; Unit in Service at the Time of Test Connections to the C1, Machine Side, 80pF Couplers
Figure 5

The EMI frequency spectrum showed no significant evidence of PD activity across the spectrum. At frequencies below 1MHz the generator excitation system is dominant. Some minor PD is noted at high frequencies above 30MHz, which is a region of the spectrum known to be influenced by the IPB [20] [21] [22]. Most bus systems show some evidence of minor PD due to the fact that most bus systems are often overlooked with no inspections or maintenance performed on a scheduled basis. Based on data observations from Figure 3-5, it can be concluded that the IPBs on Unit 1 historically did not have significant PD activity and this pattern of low PD activity has continued to date (2016/17).

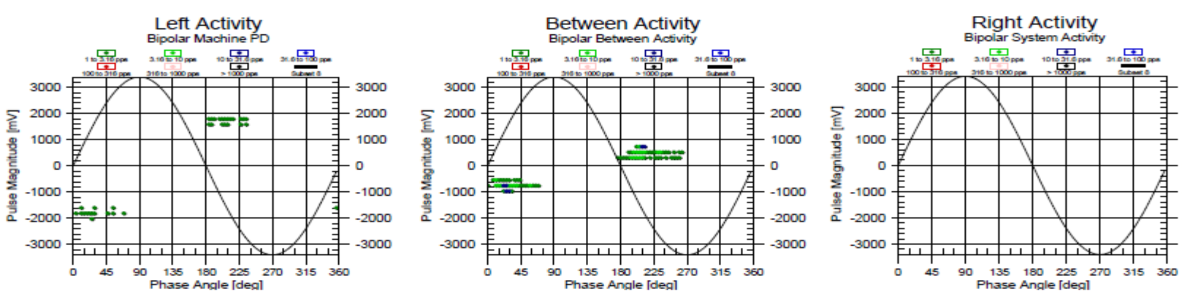
UNIT 2

Figure 6 shows an overtime comparison of C2, system side, PD activity on Unit 2. A number of key observations can be noted from this figure. Firstly, the magnitude of PD activity on the system side has increased significantly in late 2016 and early 2017. This increase in magnitude is only associated with Phase A, as the Qm+ and Qm- levels, circled in the image are significantly higher than the other measurements. Similar to Unit 1, these measurements were taken by connecting to the 80pF capacitors at periodic intervals.

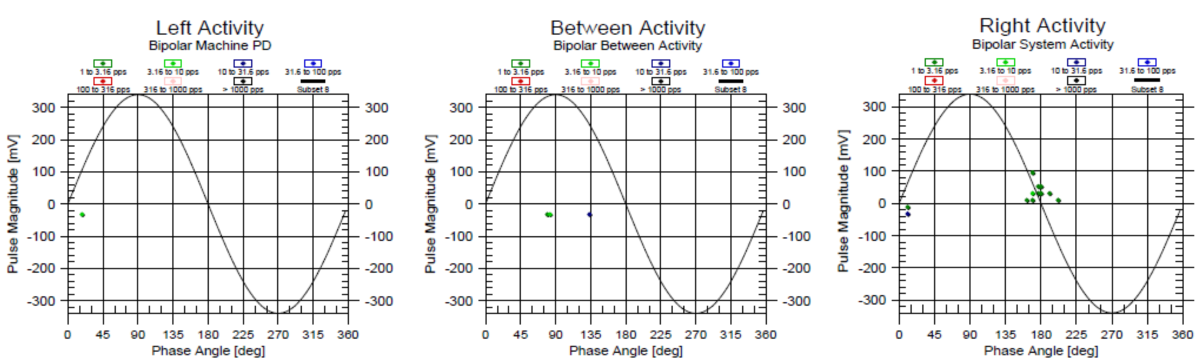


Unit 2 C2 (System) Qm Levels taken from Periodic Online Measurements
Figure 6

As the increase in Phase A – PD magnitude is of particular interest, the PRPD patterns from 2017 (Figure 7) and 2010 (Figure 8) is further analysed below. The left figure is generator activity, the centre figure is activity between the two couplers which is primarily in the IPB and associated equipment, and the right figure is activity in the system side from the IPB and step up transformer.



Unit 2 PRPD from Phase A – 2017 Result.
Figure 7

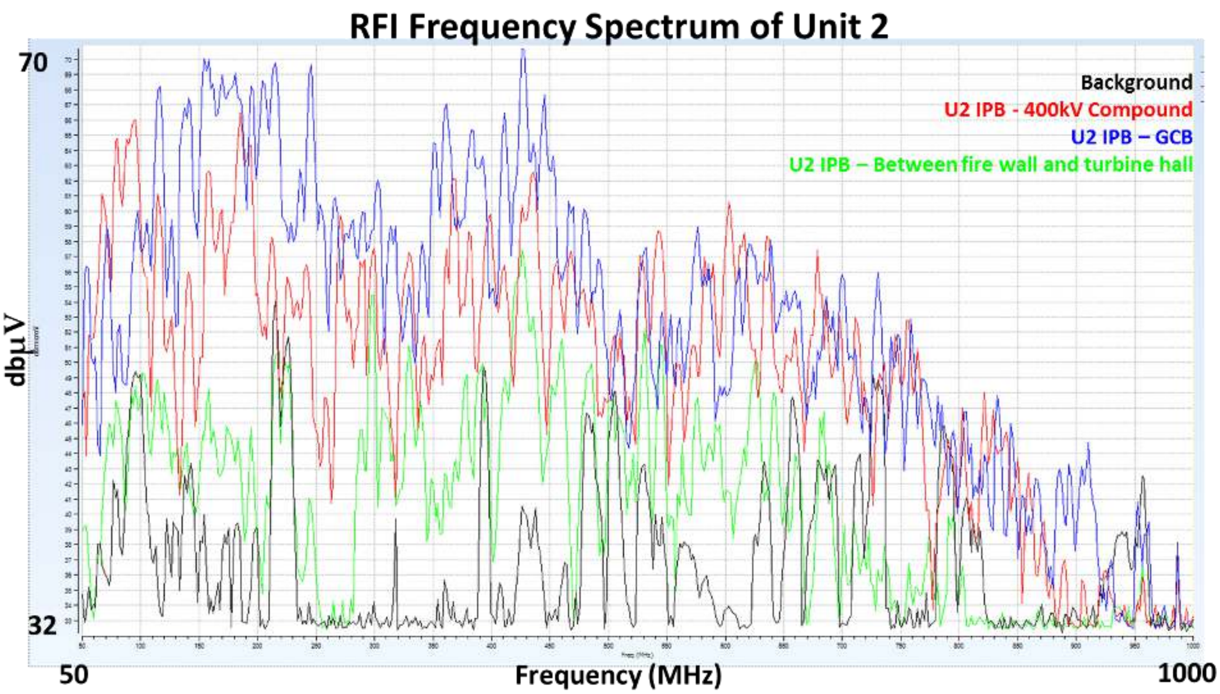


Unit 2 PRPD from Phase A – 2010 Result.
Figure 8

Based on Figure 7, significant PD activity can be noted on Phase A - generator side, however, slightly lower magnitudes, but still significant PD activity can be seen between the two couplers (centre figure), whilst no PD activity was noted to be originating from the system side (i.e. IPB region from the excitation transformer where the couplers are located to the step up transformer). It is to be noted that the time of arrival disturbance separation technique for classifying PD activity in this case, has an uncertainty range associated with it. This uncertainty range was advised as one meter from the coupler location, therefore, in this case if the PD activity is originating a meter either side of the coupler at the generator terminal bushing, this technique will not be able to clearly differentiate if it is associated with generator or between coupler related activity. Therefore, in some cases, where significant PD activity occurs at extreme close proximity to the generator line terminal bushing where the coupler may be installed, consideration to above needs to be given when analysing the results.

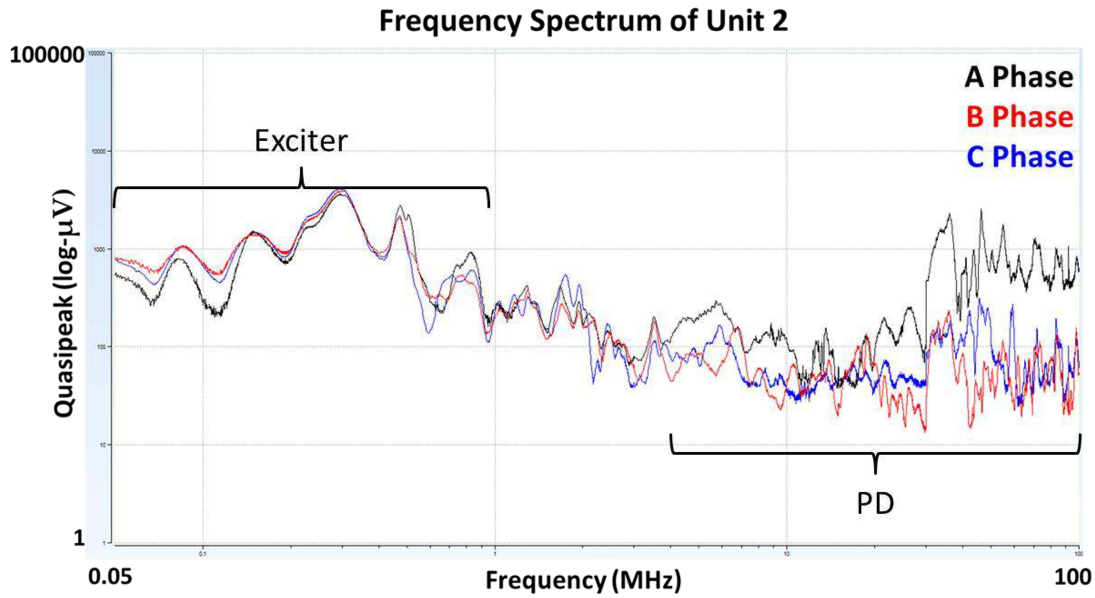
The absence of PD activity from the system side (right figure in Figure 7) is of particular interest in this case. From the same figure, it can be noted that significant PD activity is occurring in the IPB between the two couplers. The RFI results shown in Figure 9 show a supplementary test result on the system side IPBs. As previously mentioned, the RFI survey was carried out with the unit not in service, and it only covered the IPBs between the generator circuit breaker and the step up transformer. It can be noted that the RFI result completely contradicts the results from the 80pF couplers.

Whereas based on Figure 8, no PD activity was seen on the generator, between couplers and system side in 2010.



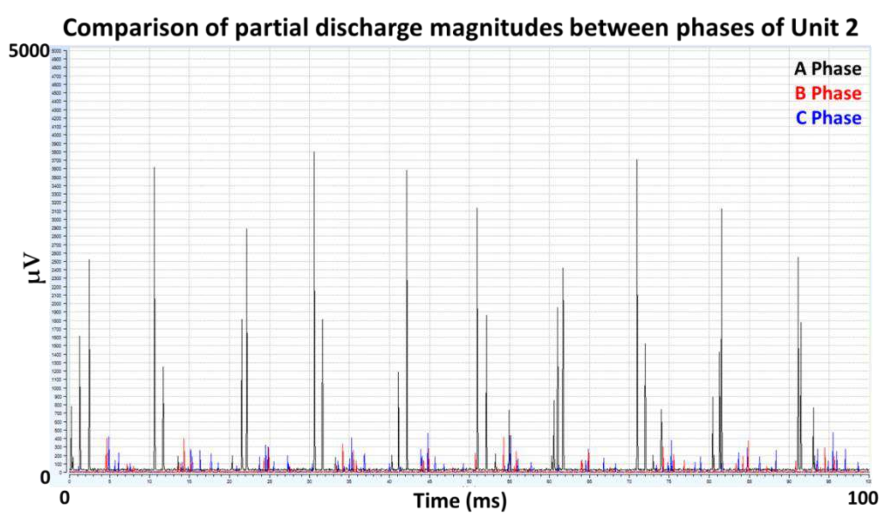
RFI Frequency Spectrum Survey on Unit 2 IPBs
Unit Not in Service at the Time of the survey
Figure 9

As noted, the RFI survey was carried out with the unit not in service; hence, Figure 9 only has traces of the IPB at the step up transformer (400kV Compound), between the firewall and turbine hall and the IPB links to the Generator Circuit Breaker (GCB). The RFI frequency spectra show a notable increase in activity especially at the GCB, where only one side of the IPB from the step up transformer was energised at the time of the survey. This increase is broadband in nature, which is characteristic of PD activity. RFI signals increase in strength when closer to the source [23]. Although the RFI survey cannot determine the phase(s) associated with the PD activity, it can provide an indication on the originating source of the discharge. In this case, the presence of activity in the IPB, between the GCB and the step up transformer, suggests a possible limitation of the 80pF capacitors in detecting system side activity.



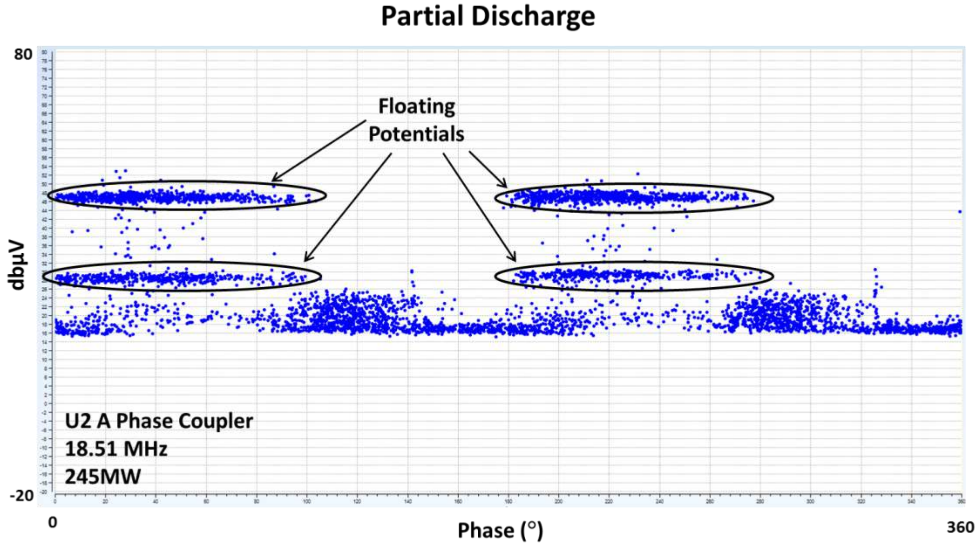
Unit 2 – EMI Frequency Spectrum Results
Unit in Service at the Time of Test, Connections to the C1, Machine Side, 80pF Couplers
Figure 10

The EMI frequency spectrum showed significant evidence of PD activity, especially in the IPB region of the spectrum. A comparison of time domain signatures measured around 34MHz can be found in Figure 11. It shows the substantial differences between discharge activity measured on the A phase compared to the other two.



Comparison of Partial Discharge Magnitudes between Phases in Unit 2
Measured in the Time Domain at 34 MHz
Unit in Service at the Time of Test
Connections to the C1, Machine Side, 80pF Couplers
Figure 11

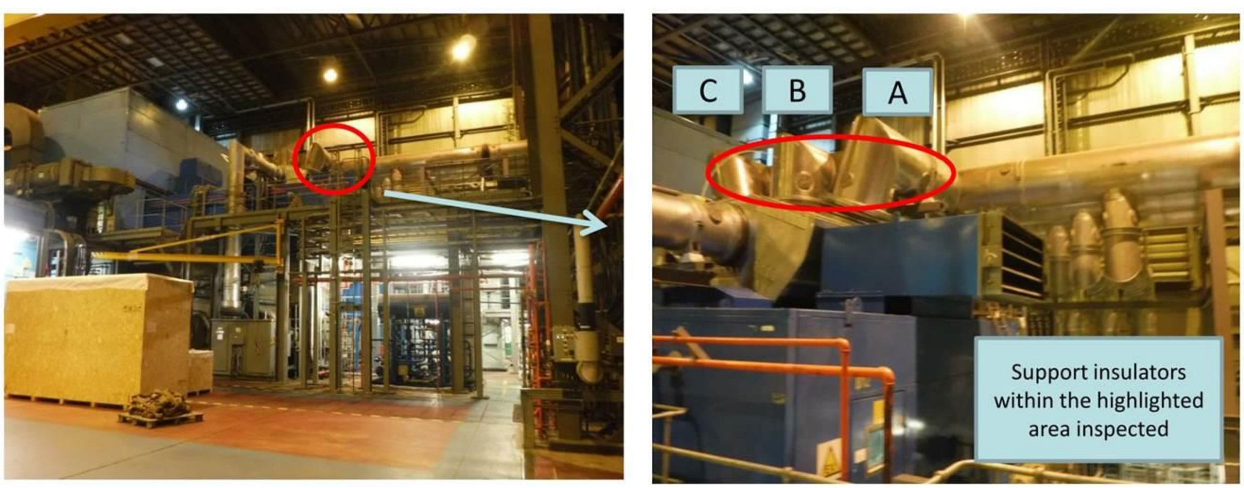
Further analysis in the time domain was performed through the use of PRPD plots, which appeared to show several floating potentials (Figure 12). This could be indicative of damaged IPB insulators or insulators not making proper contact with the centre conductor.



PRPD Plot Measured at 18.51 MHz Measured from Unit 2 A Phase C1 Coupler
Figure 12

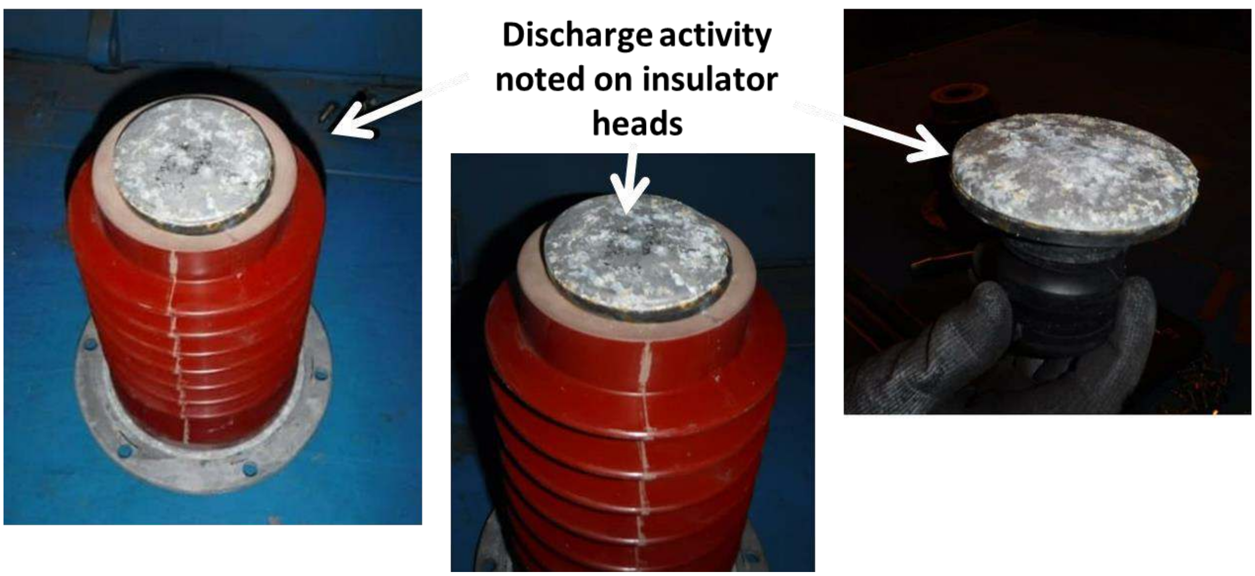
Following the EMI testing, a mini outage was enforced on Unit 2 to investigate the condition of the IPB insulators close to the generator terminals (Figure 13). Evidence of PD activity was found on both the insulator heads and centre conductor on the A phase (Figures 14 and 15); whereas no such evidence was found in either B or C phases.

Whilst the A phase - IPB support insulators that were inspected and found to have evidence of PD activity were in close proximity to the generator terminal bushing with the 80pF coupler, however, they were some 3-4 meters from the coupler. This suggests that the uncertainty range possibly extends more than the suggested one meter guideline.



The Region of IPB Insulators on Unit 2 that were Inspected for
Evidence of PD Activity during the Mini Outage
Figure 13

Inside the A phase of Unit 2 IPB; Evidence of PD was Found on both the Bus and the Insulator heads
Figure 14

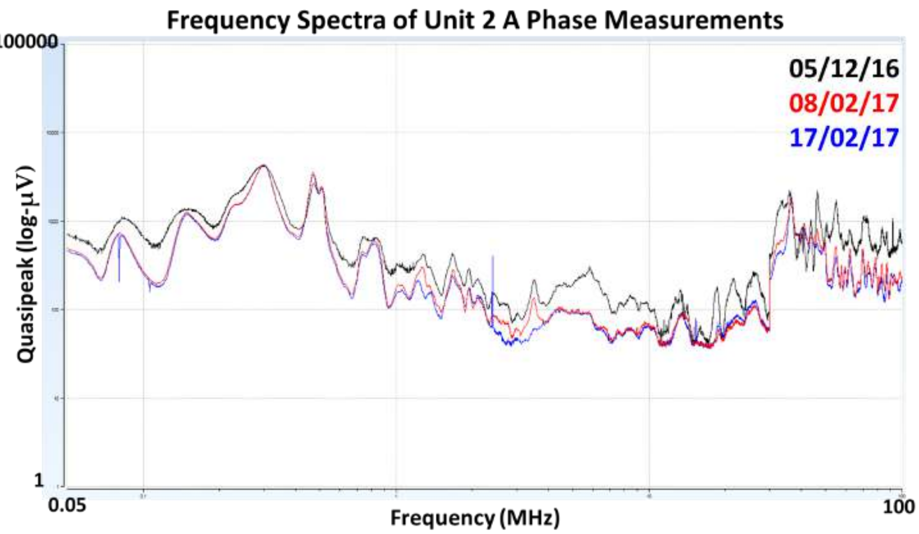


Evidence of PD Activity on the Insulator Heads taken from Unit 2 A Phase IPB
Figure 15

Following this discovery, efforts were made by the site to clean the insulator heads. Subsequent EMI surveys, taken at similar loads to the original testing, show that these efforts have decreased the PD activity but not eliminated it (Figure 16). The initial maintenance effort included removal of the IPB support insulators on all phases between the generator and the GCB, and cleaning of the insulator surface contact areas (noted as insulator heads in Figure 15). The repeated effort in later February 2017 only focused on Phase A support insulators located 3-4 meters from the generator line terminal bushing. It was during the later February 2017 works it was found that some of the support insulators heads were not making good contact with the aluminium conductor. Site experience shows that it can be difficult to confirm if the three insulators at a particular location have made adequate contact with the conductor unless the support insulator at a location prior to the location being worked on is removed and used for inspection.

An important observation in Figure 16 is that a lower uplift in EMI spectra was recorded in the frequencies not associated with the IPBs (i.e. lower frequencies than approximately 30MHz) after performing repair works on the IPB. This leads to a question that validates further research that does IPB associated activity extend lower than 30MHz.

It is rather interesting to note that the partial discharge testing relying on conventional techniques conducted in later February 2017 by connecting to the 80pF couplers did not indicate a lower Qm magnitude in the between coupler region.

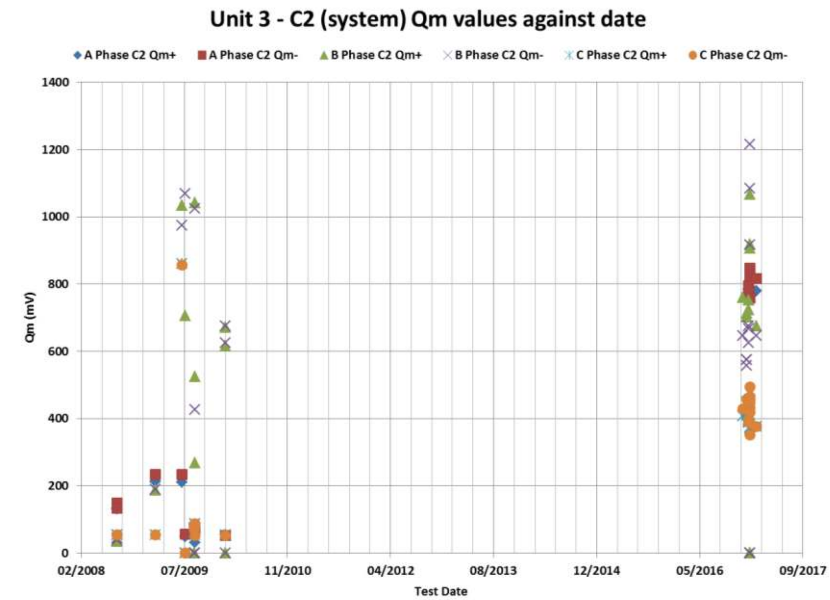


Overlay of Unit 2 EMI Frequency Spectra before and after Maintenance Activities were Performed
Figure 16

Based on data observations from Figure 6-16, it can be concluded that the PD activity on Unit 2 is only on the A phase. The primary source via visual inspection was confirmed to be in the IPBs of A phase. The EMI spectra, in this case, have been more effective in detecting changes in PD activity in the IPBs when compared to the conventional techniques.

UNIT 3

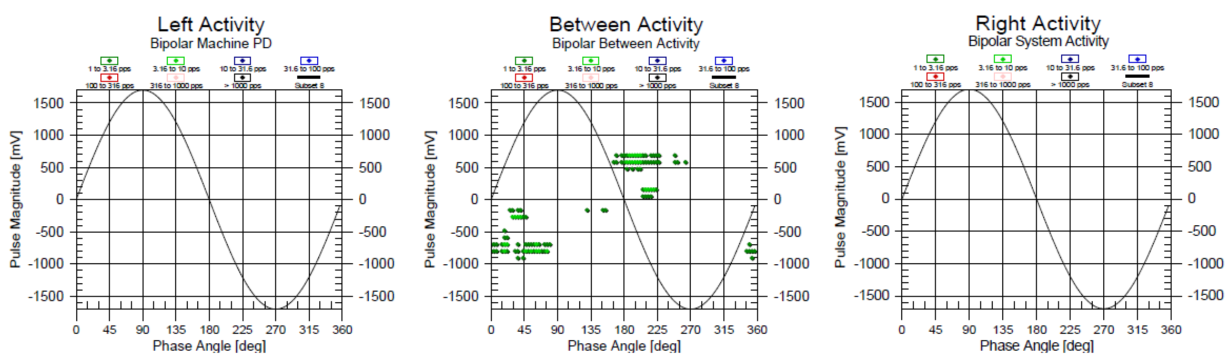
Investigations on Unit 3 also found significant PD activity in the IPBs. Figure 17 shows the comparison of C2, system side, PD activity on Unit 3 against test date. Similar to the other units, these measurements were taken by connecting to the 80pF capacitors at periodic intervals. A number of key observations can be noted from this figure. Firstly, the magnitude of PD activity on the system side is historically higher than the other two units at this site. Several measurements on B Phase taken in 2009/10 have significant variation. Possible reasons for the variation in test results may be associated with internment discharge activity within the IPBs or the one second test measurements that were taken historically. All phases show increases in Qm magnitude in measurements taken in 2016/17 – with the largest change occurring on A Phase.



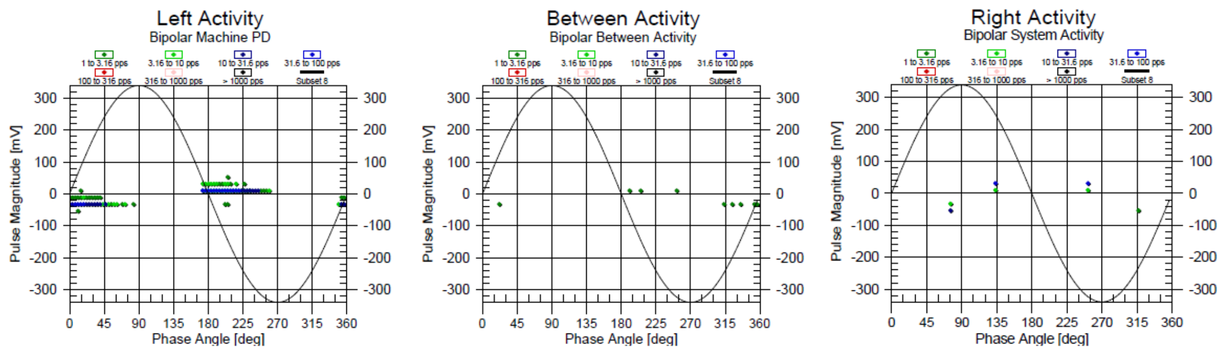
Unit 3 C2 (System) Qm Levels taken from Periodic Online Measurements
Figure 17

Based on the five second test measurements from February 2017, the highest magnitude activity, Qm, in the IPB occurs in A phase, and then followed by C and B phases respectively. Similar to the evidence seen in Figure 7 and 8 on Unit 2, no activity has been recorded on the system side, which contradicts the RFI results shown in Figure 20.

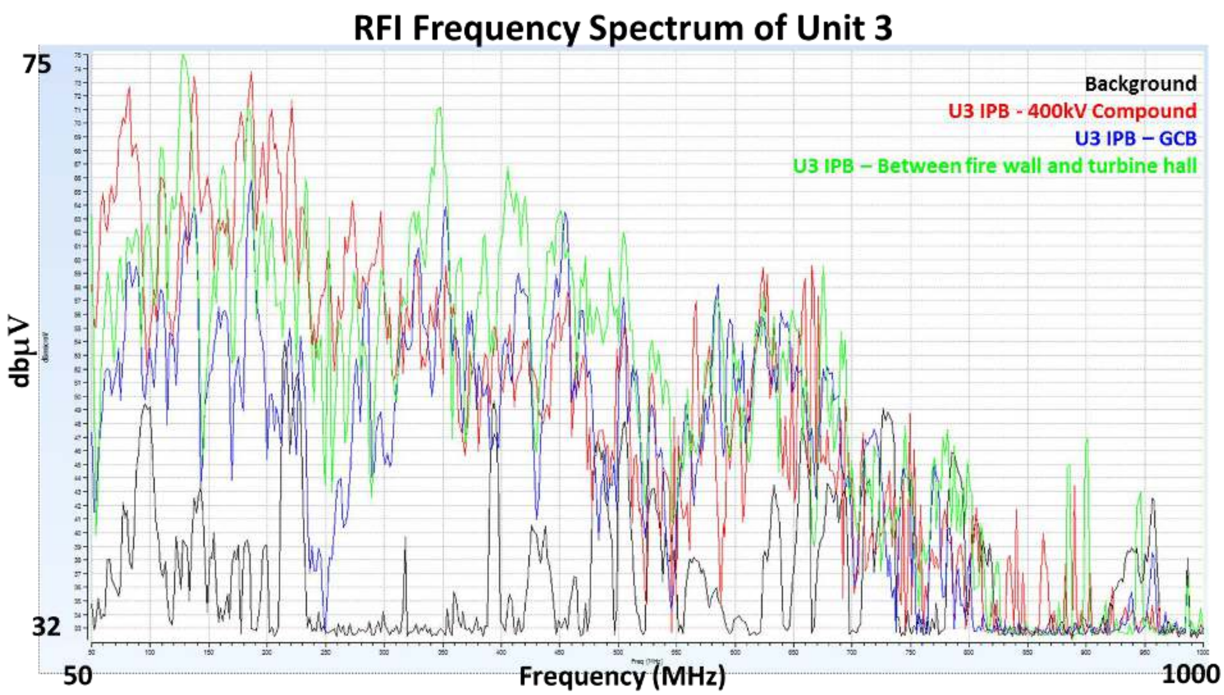
From Figure 18 and 19, it can also been noted that the PD activity between the couplers has increased over time. For example, there was low magnitude activity in 2010 (note the y axis scales vary between Figure 18 and 19); whereas this increased over time and significant increase is seen in 2017.



Unit 3 PRPD from Phase A – 2017 Result.
Figure 18

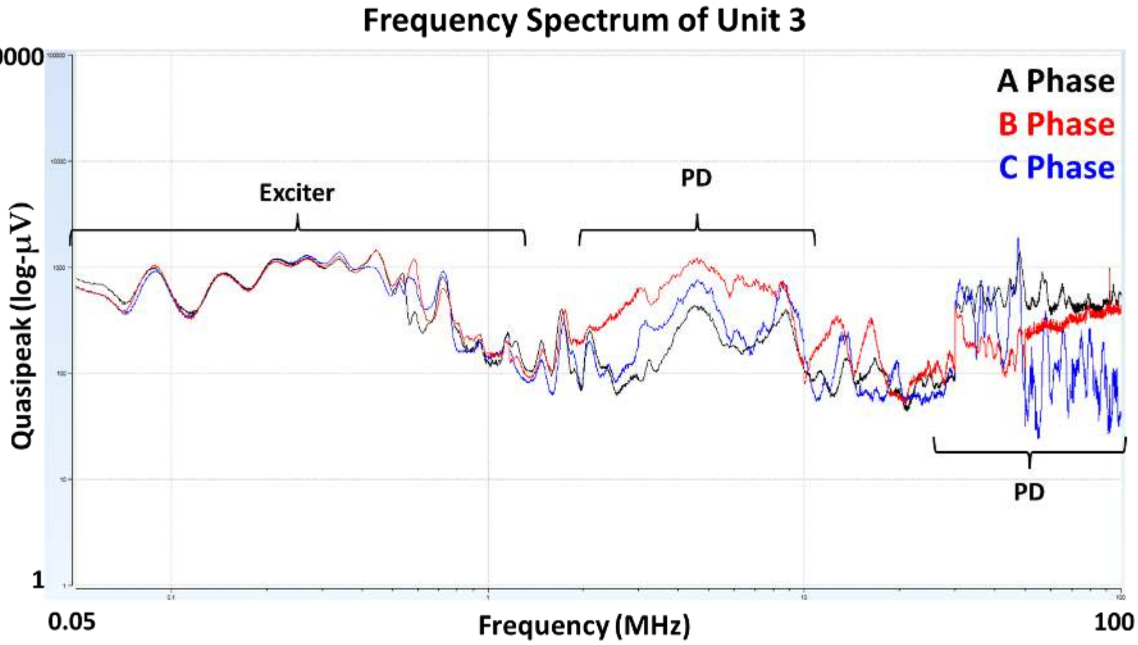


Unit 3 PRPD from Phase A – 2010 Result.
Figure 19



RFI Frequency Spectrum Survey on Unit 3 IPBs
Unit Not in Service at the Time of the Survey
Figure 20

The RFI spectra for Unit 3 also show the characteristic broadband signature of PD when compared to the background trace; in this case the signals have similar strength along the entire length of the IPB. Similar to the RFI survey carried out on Units 1 and 2, Unit 3 generator was not in service at the time of the survey.



Unit 3 – EMI Frequency Spectrum Results
Unit in Service at the Time of Test, Connections to the C1
Machine Side, 80pF Couplers
Figure 21

The EMI spectrum of Unit 3 shows similar levels of IPB discharge to that found in Unit 2. There are also strong levels of PD in the frequency range 2-10MHz, the highest being found on B phase. Test results from the conventional partial discharge testing indicated a similar pattern on B phase, the source of the discharge was located close to the generator terminals. Inspections in late 2016 confirmed an oil and hydrogen leak on the B phase generator terminal bushing, possibly due to an O-ring failure in the bushing. The contaminated oil leaking out of the bushing is a possible source of increase in PD magnitude on B phase. Temporary repairs have been carried out and the post repair results via conventional test techniques suggest that the repair has been effective. The asset owner continues to monitor the bushing status.

CONCLUSIONS

A number of condition monitoring techniques were applied to 3 generating units at a UK power station; all correctly diagnosed the absence of PD in Unit 1 and the presence of PD in the other two units. Conventional PD techniques struggled to locate the source of the PD, especially on Unit 2, as it suggested that there was no discharge activity beyond the C2 'system' coupler (Figure 7). This was contradicted by an inspection of the entire bus up to the GCB – which is further along the bus than the C2 coupler and the associated region of uncertainty. RFI test results (Figures 9 and 20) also disputed the conventional assessment as they suggested activity between the GCB and the step-up transformer that should appear as system activity. The unconventional techniques were effective in detecting PD activity in the IPBs. The results concurred with the conventional testing regarding which phases had the greatest discharge magnitudes. Further investigation into EMI testing with different measurement sensors is needed to continue this work; comparing traditional neutral monitoring with a HFCT as well as utilising the 9nF capacitive couplers installed at the generators' terminals. Particular note should be made to variation in the spectra at low frequencies that are known to be attenuated when measuring using 80pF couplers. Also if any response is dampened when measuring at the neutral end and how significant an influence one discharging phase (as per Unit 2 A phase) has on the spectrum.

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BIOGRAPHY

Michael Hughes-Narborough is a test engineer and has been employed at Doble PowerTest since April of 2016. Michael performs EMI Testing and PD surveys on power stations throughout the UK as well as developing interpretation methods for EMI and PD. He received a Master of Engineering Degree in New and Renewable Energy from Durham University in the UK in 2014.

Ami Singh is an Electrical Engineer with SSE, a UK based energy utility. Prior to joining SSE in October 2015, Ami was an electrical asset engineer with a New Zealand power generation utility for about 10 years. He has authored a number of papers on transformer asset management and equipment condition assessments. Apart from power transformers, his areas of interest include generators, high voltage cables, earthing systems and switchgear.