# APPENDIX – DATA ANALYSIS OF RESULTS THRU 2019

The following summarizes the analysis of the PD levels, given by Qm number, for all data collected with Iris equipment up to the end of the year 2019 with over 685,000 results. Since it has been well established that it is ambiguous to compare PD results obtained using different types of sensors, data analysis requires separation of the database based on sensor type. The two basic types of sensors used in the data collection are: 80pF capacitors (cable-type and epoxy-mica type) and stator slot couplers (SSC). Furthermore, data will be separated based on gas cooling pressure and operating voltages.

# 1 CAPACITORS – (AIR-COOLED MACHINES)

The most widely employed sensors are the 80pF couplers used on motors, hydro-generators, and small turbine generators. There are two methods of sensor installation for the capacitive couplers, the directional (TGA) and the differential (PDA) methods.

## 1.1 DIRECTIONAL METHOD (TGA)

The directional method is used primarily on motors and small turbine generators and occasionally on small hydro-generators.

***Qm values for air-cooled machines with directional capacitive couplers (TGA)***

| Rated kV | < 6 | ≥ 6 < 10 | ≥ 10 <13 | ≥ 13 <16 | ≥ 16 <19 | ≥ 19 | |
|---|---|---|---|---|---|---|---|
| **25%** | 10 | 25 | 35 | 51 | 39 | 40 | 25% of the results have Qm levels below this value |
| **50%** | 20 | 67 | 85 | 115 | 80 | 96 | 50% of the results have Qm levels below this value |
| **75%** | 59 | 145 | 196 | 235 | 207 | 225 | 75% of the results have Qm levels below this value |
| **90%** | 209 | 331 | 415 | 430 | 313 | 566 | 90% of the results have Qm levels below this value |
| **95%** | 358 | 507 | 670 | 619 | 486 | 842 | 95% of the results have Qm levels below this value |

As shown here, the majority, 75%, of the results obtained with the directional mode installation (BUS) of capacitive couplers are below ~200mV for machines rated less than 12kV, 235mV for machines rated 13-15kV, 207mV for 16-18kV, and 225mV for those >19kV.

Additionally, there is an approximate doubling of the Qm levels between the 75% and the 90%, which supports the definition of *rapid deterioration* as doubling over a twelve-month interval [IEC 60034-27-2]. There are a few machines with PD much higher than the 90$^{th}$ percentile with Qm levels >500-900mV. These machines are suspected to have significant deterioration.

## 1.2 DIFFERENTIAL METHOD (PDA)

The differential method is used primarily on large hydro-generators having an internal circuit ring bus.

There are two major differences in the directional and differential installations: one is the method of time-of-arrival noise separation and the second is the actual location of the couplers. Since both time-of-arrival noise separation techniques work similarly, this difference should have little impact to the test results.

However, the difference in the sensor locations can greatly affect the results. A differential (PDA) installation in a larger hydro-generator uses sensors normally placed within one meter of the junction between the incoming phase bus and the first coil/bar in the circuit. A sensor at this location will be extremely sensitive to any pulses originating within the coil/bar since the magnitude of the pulse will be amplified when it reaches the impedance mismatch between the bus and the coil/bar. Thus, it is reasonable to assume the results obtained with the couplers at this location will be higher than when the couplers are located outside the machine housing typical of directional (TGA-BUS) installations. However, when comparing the directional (TGA) results to the differential (PDA) results, though there are some minor variances, there is little significant difference between the statistical summaries for windings rated less than 16kV. Thus, it is safe to say that for a 13.8kV winding, regardless of installation type, the PD levels should be less than ~250mV and those machines with PD higher than 500mV need further investigation.

***Qm values for air-cooled machines with differential capacitive couplers (PDA)***

| Rated V | <10 | ≥10 <13 | ≥13 <16 | ≥16 <19 | ≥ 19 | |
|---|---|---|---|---|---|---|
| **25%** | 10 | 38 | 38 | 39 | 52 | 25% of the results have Qm levels below this value |
| **50%** | 25 | 72 | 97 | 131 | 146 | 50% of the results have Qm levels below this value |
| **75%** | 51 | 132 | 202 | 338 | 380 | 75% of the results have Qm levels below this value |
| **90%** | 149 | 289 | 387 | 625 | 837 | 90% of the results have Qm levels below this value |
| **95%** | 285 | 452 | 580 | 856 | 1094 | 95% of the results have Qm levels below this value |

# 2 CAPACITORS – (GAS-COOLED) (TGA)

Since the occurrence of PD is extremely dependent on the electrical breakdown point of the gas medium, PD results from air-cooled machines are typically higher than machines cooled with either hydrogen or pressure carbon dioxide. Therefore, it is not advisable to compare the results from machines using different gas mediums. Since most hydro-generators (PDA installations) are air-cooled, all of the tests for gas-cooled machines with capacitors were obtained using a TGA instrument and directional sensor installation. Most of the hydrogen-cooled machines have high rated loads and frequently suffer from problems with the core iron arcing. PD or noise activity at the machine terminals, outside the hydrogen environment, can make stator winding insulation condition difficult to interpret. As a result, stator slot couplers (SSC) are the recommended sensors in these applications to avoid misdiagnosis resulting from the capacitive sensor detecting core-iron problems in addition to stator winding problems.

***Qm values for non air-cooled machines with directional capacitive couplers (TGA)***

| Rated V | 13-15kV[1] | | | | 16-18kV | | | | > 19kV | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **H2 (kPa)** | **76-138** | **145-207** | **214-345** | **Over 345** | **76-138** | **145-207** | **214-345** | **Over 345** | **145-207** | **214-345** | **Over 345** |
| **H2 (psig)** | **11-20** | **21-30** | **31-50** | **>=51** | **11-20** | **21-30** | **31-50** | **>=51** | **21-30** | **31-50** | **>=51** |
| **25%** | 26 | 19 | 14 | 8 | 32 | 27 | 12 | 13 | 41 | 12 | 10 |
| **50%** | 67 | 41 | 31 | 19 | 123 | 41 | 32 | 28 | 88 | 41 | 31 |
| **75%** | 166 | 93 | 67 | 76 | 216 | 158 | 89 | 53 | 121 | 85 | 91 |
| **90%** | 359 | 182 | 179 | 148 | 397 | 435 | 207 | 125 | 193 | 145 | 377 |
| **95%** | 603 | 272 | 415 | 194 | 513 | 956 | 335 | 307 | 226 | 169 | 807 |

As expected, the PD results for gas-cooled machines are much lower than for the air-cooled machines. This is especially observable at higher pressures, where 75% of the tests for all operating voltages operated above 31psig are below 100mV and 90% generally below ~200mV, less than observed on the air-cooled machines (Section 1.1). At the lower operating pressures, the PD levels are generally much higher, with a few machines having extremely high PD of Qm levels >400mV, which would require more tests and investigation.

[1] Fluctuations from previous years due to a large influence by one or more manufacturers

# 3 STATOR SLOT COUPLERS (SSC) – (GAS-COOLED)

***Qm values for non air-cooled machines with SSC sensors- Slot PD***

| Rated V | 13-15kV | | | | 16-18kV | | | 19-22kV | | | 23-26kV | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (kPa) | 76-138 | 145-207 | 214-345 | > 345 | 75-207 | 214-345 | >345 | 75-207 | 214-345 | > 345 | 214-345 | > 345 |
| H2 (psi) | 11-20 | 21-30 | 31-50 | > 50 | 11-30 | 31-50 | > 50 | 11-30 | 31-50 | >50 | 31-50 | >50 |
| 25% | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 50% | 1 | 1 | 2 | 1 | 2 | 0 | 0 | 8 | 1 | 1 | 0 | 0 |
| 75% | 16 | 8 | 16 | 6 | 12 | 5 | 3 | 34 | 14 | 6 | 16 | 6 |
| 90%[2] | 57 | 37 | 41 | 15 | 32 | 30 | 8 | 149 | 47 | 21 | 56 | 16 |
| 95%[2] | 97 | 85 | 53 | 32 | 49 | 56 | 13 | 629 | 68 | 39 | 117 | 30 |

The preferred sensor for turbine generators rated higher than 100MVA is a stator slot coupler (SSC). The sensor is placed within the slot of the highest voltage bar either directly beneath the wedge or between the top and bottom bars in the slot. There is little difference in the results obtained from the two installations [2]. Since these machines are operating in a hydrogen environment, the overall slot PD is quite low relative to the air-cooled windings. It should be observed that though most of the machines have slot Qm values less than ~30mV, there are a few with levels higher than 60-200mV. These should be subjected to further tests and inspections. The SSC is a high frequency antenna that detects the pulses and through pulse analysis, the TGA can discriminate between pulses originating in the high voltage insulation and those from core-iron arcing or external sources. Furthermore, the SSC/TGA test setup can identify whether the PD originates in the slot or in the endwinding [15]. The endwinding PD is slightly lower than the slot PD, with 90% of all the tests less than ~20mV. There are, however, a few machines with Qm levels higher than 25mV, and these machines require additional attention.

***Qm values for non air-cooled machines with SSC sensors- Endwinding PD***

| Rated V | 13-15kV | | | | 16-18kV | | | 19-22kV | | | 23-26kV | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| H2 (kPa) | 76-138 | 145-207 | 214-345 | > 345 | 75-207 | 214-345 | >345 | 75-207 | 214-345 | > 345 | 214-345 | > 345 |
| H2 (psi) | 11-20 | 21-30 | 31-50 | > 50 | 11-30 | 31-50 | > 50 | 11-30 | 31-50 | >50 | 31-50 | >50 |
| 25% | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 50% | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 |
| 75% | 1 | 1 | 5 | 1 | 3 | 1 | 4 | 1 | 3 | 6 | 1 | 3 |
| 90% | 10 | 6 | 13 | 7 | 11 | 6 | 9 | 8 | 11 | 16 | 13 | 7 |
| 95% | 20 | 10 | 23 | 27 | 17 | 16 | 16 | 10 | 17 | 31 | 51 | 16 |

# 4 STATOR SLOT COUPLER – (AIR-COOLED)

***Qm values for air-cooled machines with SSC sensors***

| Slot PD | | |
|---|---|---|
| Rated V | 13-15kV | 16-24kV |
| 25% | 0 | 0 |
| 50% | 2 | 0 |
| 75% | 29 | 10 |
| 90% | 81 | 48 |
| 95% | 144 | 125 |

| Endwinding PD | | |
|---|---|---|
| Rated V | 13-15kV | 16-24kV |
| 25% | 0 | 0 |
| 50% | 1 | 0 |
| 75% | 9 | 1 |
| 90% | 42 | 8 |
| 95% | 60 | 17 |

There are a few air-cooled machines being monitored with stator slot couplers. As previously described, because of the differences in the electrical breakdown points of the gas mediums, it is not recommended to compare results from air-cooled machines to those from gas-cooled ones. It is not surprising that the PD levels for the air-cooled machines with SSCs are generally higher than the gas-cooled ones. The majority of these machines have slot Qm levels less than ~30mV, but there are a few with extraordinarily high slot PD, >90mV, that would require further investigation.

[2] Fluctuations from previous years due to a large influence by one or more manufacturers