PD Testing of Motors for Hostile Environments

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Abstract – The use of electrical motors in hostile environments continues to increase. One example is electrical submersible pumps used for oil and gas production. Additionally, ESPs are being used in wells with increasingly more expensive intervention costs and high productivity. As intervention costs increase, the necessity for longer downhole equipment life also increases. Go/No-Go tests such as hipot, surge test, insulation resistance and winding resistance are good to evaluate the actual (at the factory) condition or integrity of the equipment but they inadequately address long-term aging issues associated with the motor. The use of Partial Discharge testing for hostile environment motors, particularly in factory acceptance tests, may give users and manufacturers additional insight into the quality of construction of the motor and potential life shortening discrepancies in the winding insulation. Additionally, due to the construction of the motors

Index Terms – Partial Discharge, Epoxy Insulation, MgO Insulation, Hostile Environment, Electrical Submersible Pump, ESP.

I. PARTIAL DISCHARGE BACKGROUND

The subject of partial discharge in rotating machines has been well covered in other publications. However, in many publications, the discussion of factors affecting partial discharge in a machine winding has been limited, and key factors are ignored, particularly influences of hostile environments.

In its simplest form, partial discharge is a dielectric breakdown of a portion of an insulating system, usually at a void or discontinuity, without a dielectric breakdown of the entire system.[1] Partial discharge (PD) can occur either internal to the insulation material due to voids or holidays, in the interface between different insulating materials, or in the interface between insulating materials and conductive surfaces (including surface discharge). In any of these three environments, exposure to partial discharge can damage electrical insulation materials and ultimately lead to early failure of the insulation system.

Partial discharge testing involves application of an AC voltage ramped up to or near operating voltage of the insulating system. PD causes a high frequency signal to be superimposed on the power frequency carrier wave, which can be measured and interpreted using oscilloscope or special purpose PD analytical machines. Five values are typically captured during testing:

- Test voltage – Maximum voltage applied to the insulation system
- Inception voltage – the voltage (during ramp up) at which PD begins
- Extinction voltage – the voltage (during ramp down) at which PD terminates
- Qmax – peak PD value (pC or mV)
- Phase angle of the individual discharges

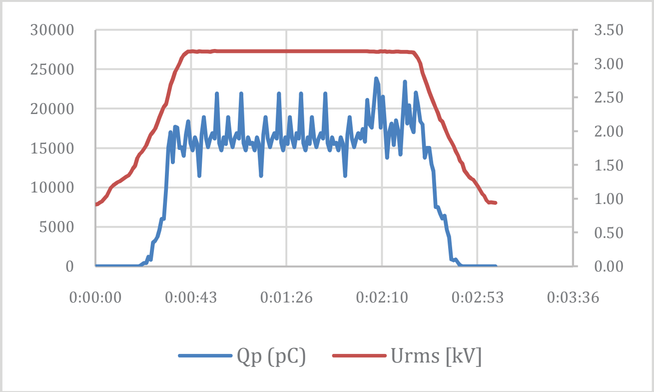


Fig. 1 - Time Based PD Results (Qp and test voltage)

Fig. 1 shows a typical time-based results graph for a 2.3kV electrical submersible pump (ESP) motor showing peak measured PD level in pico-Coulombs as well as test voltage at atmospheric conditions. As voltage is ramped up, discharge begins at a level below operating voltage (Inception voltage). Once a stable test voltage is reached, this voltage level is held for ~30 seconds in order to capture phase based discharge counts, shown in Fig. 2.

Table 1 - PD Tabular Results

Test #	**123456**			
Test Voltage	3000			kV
Inception Voltage	1.46			kV
Extinction Voltage	1.42			kV
Q_{max}	25,790			pC
Conversion Factor	2000	pC	14.8	mV

A peak discharge value is captured (Qmax). As voltage is ramped down following the test, PD continues until some voltage, typically lower than inception voltage, is reached and PD is terminated (extinction voltage). These results are tabulated in Table 1, along with a conversion factor between mV and pC that is unique to each insulation system tested.

Fig. 2 shows the result of the 30 second capture period during which test voltage is held constant. The graph shows the phase angle of individual discharges, relative to the power supply waveform (X Axis). The discharge level (nC) is shown in the Y axis. Relative density of the captured discharge pulses is indicated by changes in color (grayscale in figure). From this data, the location and type of discharges that are occurring can be inferred [1,2]. In the test shown in Fig. 2, the indicated PD is at or near the copper of the winding.

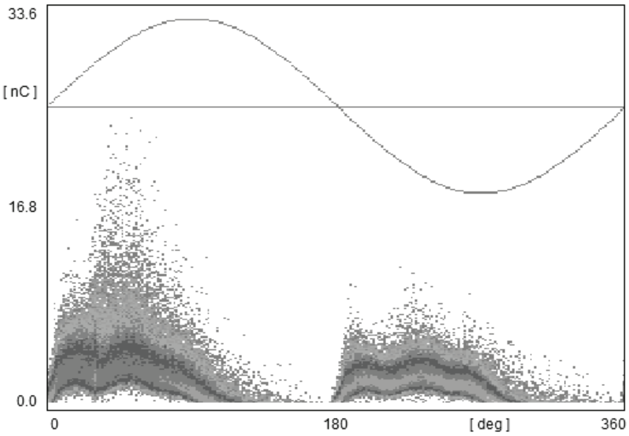


Fig. 2 - Phase Angle Test Results (Qp and Density)

II. FACTORS INFLUENCING PARTIAL DISCHARGE

Many factors affect the location and intensity of a PD pulse. The three most discussed aspects include the following:

- Size of void or discontinuity in insulation
- Electric field at the void or discontinuity
- Dielectric strength of the material in the void or discontinuity

The *size* of the void (or discontinuity) is a result of the physical construction of the insulating material. It defines the "gap" across which the discharge occurs. Generally speaking, a larger void creates a larger peak discharge, although this is not absolute, as other factors can affect discharge.

For most *cavities* in insulation, the material in the void or discontinuity is air trapped during construction of the insulating material.

The *strength* of the electric field includes many factors that are not typically discussed in analysis of discontinuities [3].

III. E-FIELDS IN WINDING INSULATION

Energy (*W*) is the most basic term used for conversion or switching between systems. Based on the First Law of Thermodynamics, energy in a system is constant, regardless of whether the system is electrical, magnetic, mechanical, chemical or nuclear. In the electromagnetic/mechanical systems, energy is defined as force * distance (*Fs*), Volts * charge (*Vq*), or Amp-turns * Webers (*NIφ*) [5]. Since energy is a constant, regardless of system, the following relationships hold:

$$W = Fs = Vq = NI\varphi \tag{1}$$

The electric field intensity [E] is the "strength" of the electric field surrounding an electric charge. It is defined as the force (F) exerted on a unit positive charge at a given point. In SI units, *E* has units of Newtons/Coulomb, which is dimensionally equivalent to Volts/meter. *E* is a vector and has both a magnitude and a direction across an object.

$$\vec{E} = \frac{F}{q} = \frac{V}{s} \tag{2}$$

The second term in context is the Electric Flux Density (*D*) Electric Flux Density (*D*) is simply the electric charge per unit surface area of a volume surrounding a charged item, and is proportional to the number of electrons available for electrical activity in that volume.

A. Impact of Permittivity of Insulating material

D and *E* are related by the permittivity of the medium in which *D* resides. Given a particular flux density, the permittivity of the medium determines the strength or *intensity* of the electric field in that medium [4]. These two terms are related by (3) where ε is the *permittivity* of the medium surrounding the charged surface.

$$\vec{E} = {}^{D}/_{\varepsilon} \tag{3}$$

To determine the field strength at any point throughout the dielectric, first recognize the electric flux density *D* and the permittivity of the dielectric,ε. The proposition is relatively difficult since charge per unit length cannot be directly measured. The magnitude of the overall effective field intensity is known, however, as is the relative permittivity of the insulation at different temperatures. The overall effective field intensity in V/m (N/C) can be calculated by dividing the applied voltage by the distance across the insulating material.

$$E = {}^{V}/_{d} \tag{4}$$

Observe *d* is the distance between the center conductor and the sheath and *V* is the applied voltage. Assuming a generally homogenous dielectric material, *D* can then be estimated.

$$D = \frac{V\varepsilon_r\varepsilon_0}{d} \tag{5}$$

$$E = \frac{D}{\varepsilon_r\varepsilon_0} \tag{6}$$

Consider an air filled void in an insulating material. As discussed above *D* is constant, regardless of which material surrounds the charged surface, whether it is a point charge or a long conductor. The *D* field, then, will be constant in both the dielectric material (insulation) and in the voids. Because field intensity is a ratio of electric flux density *and* permittivity, *E* will be different.

Consider an epoxy material, with voids, that is subjected to a charge density of 1000 Coulomb/m^2. Epoxy resin has a relative permittivity of ~3.8, while the voids are filled with air which has a relative permittivity of ~1. The magnitude of the electric field intensity in both the dielectric and the cavities is shown below.

$$E_{epoxy} = {10^{-12}}\big/_{(3.8 * 8.85X10^{-12})} = 0.297 \qquad (7)$$

$$E_{void} = {10^{-12}}\big/_{(1 * 8.85X10^{-12})} = 1.13 \qquad (8)$$

Thus, the E field in the voids is 3.8 times larger in magnitude than the E field in the dielectric medium. The only thing that changes in the equation is the relative permittivity of the dielectric material vs. the voids. Consequently, E_{void} can be calculated directly if $E_{dielectric}$ is known, along with the relative permittivity of the dielectric and the voids. The same calculation can be accomplished with other dielectric (insulating) materials such as varnish, polyimide tape, or even magnesium oxide (MgO).

B. Impact of Inconsistencies in Conductor Construction

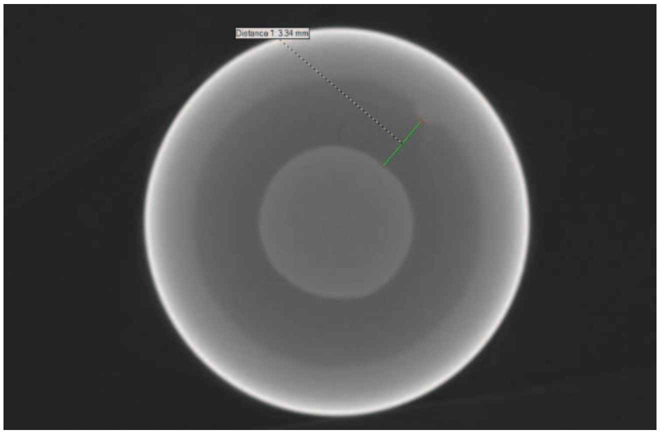


Fig. 3 - CT Scan of Conductor

The potential across the insulation between the conductor and the adjacent components is impacted by the variations in the insulation system. Inconsistencies in the cable insulation depend on three influences: the material, manufacture, and environment [3].

- The insulation is made up of material, contamination, and voids.
- The manufacturing interface consists of the interstices, outerstices, end, terminal, and joints.
- The environmental factors include the atmosphere and load.

Each of these areas can affect the field intensity in a given area, and can increase the likelihood of discharge. Specifically, irregularities in the surface of the conductor cause a concentration of electric field at the anomalies due to the concentration of charge at the peak. Similarly, the interfaces between two components represent a variation in electric field across the anomalies.

The reason for this propensity of charge from an electric field to concentrate on a peaked surface is well known. The relationship can be derived from Coulomb's law, which calculates the force one point charge exerts on a second point charge.

$$F = \frac{kq_1q_2}{r^2} \qquad (9)$$

Where

F - Force (Nm)
k - Coulumb's constant ($(4\pi\varepsilon o)^{-1}$ ~ 9x109 $N{\cdot}m^2/C^2$)
q_1 - charge of point 1 (Coulomb)
q_2 - charge of point 2 (Coulomb)
r - separation of charges (meter)

The electric force is directly proportional to the voltage (potential) of the conductor. The potential for any conductor of radius r having charge q at its surface is the same as the potential for a point charge q at distance r.

The electric field at a point charge is the ratio of the force acting on the charge and the value of the charge.

$$E = \frac{F}{q} \qquad (10)$$

Combining the above two equations allows the relationship between an electric field and a point charge to be developed. The constant *k* includes the relative permittivity, permittivity of free space, and the spherical surface area factor of 4π [6]. Although voids and irregularities are rarely spherical, the general form of the mathematics is similar, and the general ratios would apply. In addition, space-charge effects would impact the results, and in some cases (with large trapped charge in a void) would dominate.

$$E = \frac{kq_1q_2}{q_2r^2} = \frac{kq}{r^2} \qquad (11)$$

Consider, then, two conductive surfaces in the same electric field, and in contact with each other (voltage is constant).

The equation for electrostatic potential for point charge is

$$V = k\,{Q}\big/_{r} \qquad (12)$$

Now assume an object made up of two charged conducting spherical shells one of radius *R* and one of radius *r* (*R*>*r*) touching each other externally. The potential for any shell of radius *r* having charge *q* at its surface is the same as the potential for a point charge *q* at distance *r*.

Compare the charge on *r* and *R*. Since *r* (and the related surface area) is less, charge on its surface has to be more than that on the larger sphere in order to maintain a constant potential over the entire surface. The ratio of the charge densities for two spheres then would be

$$\frac{\sigma_{small}}{\sigma_{big}} = \frac{{q}\big/_{4\pi r^2}}{{Q}\big/_{4\pi R^2}} \qquad (13)$$

$$\frac{\sigma_{small}}{\sigma_{big}} = \frac{\frac{r}{R}Q \big/ 4\pi r^2}{\mathrm{Q} \big/ 4\pi R^2} \Rightarrow \sigma_{small} = \frac{\mathrm{R}}{r}\sigma_{big} \tag{14}$$

and

$$\frac{\sigma_{small}}{\sigma_{big}} = \frac{\frac{r}{R}Q \big/ 4\pi r^2}{\mathrm{Q} \big/ 4\pi R^2} \Rightarrow q \propto \frac{\mathrm{R}}{r}\mathrm{Q} \tag{15}$$

The ratios of the field stress of the small surface to the large is shown in (16).

$$\frac{E_{small}}{E_{large}} \propto \frac{k\frac{\mathrm{R}}{r}\sigma_{big} \big/ r^2}{kQ \big/ R^2} \propto \frac{R^3}{r^3} \tag{16}$$

The stress from electric field at an irregularity in the conductor or grounded surface as part of the insulation system increases the field stress proportional to the cube of the ratios of the radius of the irregularity and the radius of the conductor.

IV. HOSTILE ENVIRONMENT OF ESP

Now consider the requirements for a hostile environment. These motors are two-pole three-phase squirrel cage induction machines. The winding is random wound. Typical horsepowers ratings range from 40Hp to 1,600 Hp (60Hz, ~3500 RPM). The author’s experience in testing ESP motors covers the entire range. A typical cross section taken from API 11S1 is shown in the figure below [4]

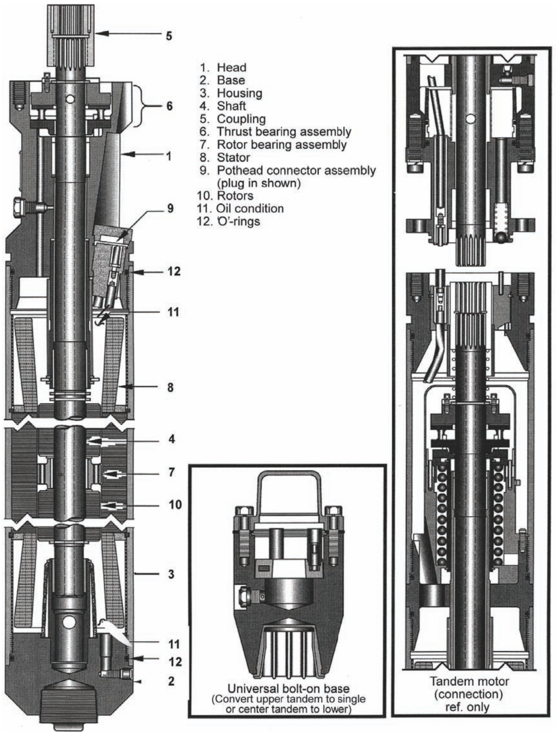


Fig. 4 - Typical ESP Cross Section [4]

Electrical submersible pumps (ESPs) are installed downhole in a well environment containing hydrocarbon liquids, salt water, various chemical contaminants such as carbon dioxide and hydrogen sulfide, and hydrocarbon gases with oxygen [4]. These materials are under various pressures from atmospheric to 275.8 bar (4000 psi) or more. The well bore temperature ranges from 27°C (80^{o}F) to in excess of 204 °C (400^{o}F).

In some locations, such as deep water applications, horizontal wells, and in Russia, ESPs dominate the application[5]. In many of these environments, intervention costs run into the tens of millions of dollars (US$). The combination of these two factors has led to increased interest in expanding ESP life.

Corresponding with this hostile application for ESPs, the demand for increased production from ESP locations has resulted in increases of operating voltage. Historical operating voltages have been 1-2.5kV, while current motor designs reach nearly 7kV[6]. This increase in voltage causes additional stresses on the insulation systems. As a result, there is increased concern regarding the long-term life expectancy of these insulation systems.

Partial discharge testing of ESP motors offers benefits in evaluating construction of the motors and the quality of the insulation systems.

V. PARTIAL DISCHARGE IN HOSTILE CONDITIONS

The application of downhole motors subjects the insulation systems to higher pressures than conventional motors. Bottomhole pressure in the wellbore is largely transferred to the motor insulation through the seal chamber section of the ESP system. Shaver & Cain have contended that this eliminates all partial discharge in the insulation systems [6]. Their argument is based on application of Paschen’s law, which states that, at higher pressures, breakdown voltage of a gas is approximately proportional to the product of the pressure and gap length. Specifically

$$V_B = \frac{Bpd}{ln\left(\frac{Apd}{\ln\left(\frac{1}{\gamma}+1\right)}\right)} \quad (17)$$

Where
VB -Breakdown Voltage
p -Pressure(pa)
d -gap length(m)
A -gas constant 1 $(pa*m)^{-1}$ (20 for air)
B -gas constant 2 $(pa*m)^{-1}$ (487 for air)
γ -second Townsend coefficient (~0.01 for air μm voids)

Holding the size of a void constant, then, breakdown voltage is proportional to the pressure in the void. Umemura et al have experimentally verified these results.[7]

The assumption made is that bottomhole pressure transfers directly into the voids of insulation. The limiting assumption may have some applicability in tape installations which allows transfer of ambient conditions into cavities. Reference is also made to previous tests on motors under high gas pressure, where gas migration and diffusion allow the internal voids to assume a pressure similar to that external to the insulation. However, in varnish and epoxy applications for liquid (oil) filled motors, the assumption is not supportable. Any gas is removed from the motor housing during assembly. Any flaws in the insulation are not sufficient for the migration of the relatively dense and viscous insulating oils which fill the motors.

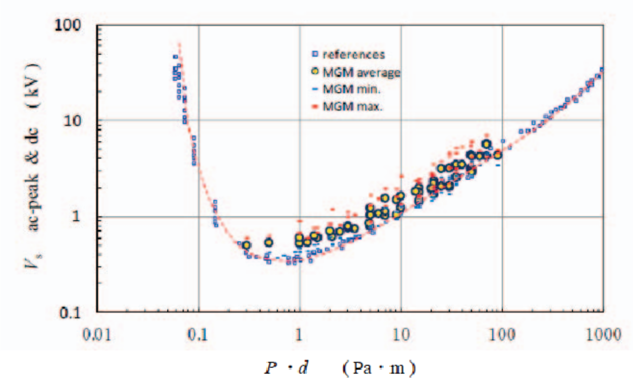


Fig. 5 – Paschen's Curve for Air [7]

With no migration of the oil, the change in pressure inside the void of an epoxy or varnish insulation (at a constant temperature) is directly proportional to the change in volume of that void. A similar argument can be made for highly compacted MgO insulations. The change in volume of the void is equal to the change in volume of the material surrounding the void. The change in volume of a material due to external pressure is related to the bulk modulus of that material. According to Rice & Rice, the modulus of epoxy resins varies from 5 GPa to 25 GPa [15]. The change in volume is determined by (18).

$$\Delta V = \frac{P}{k} * V \quad (18)$$

Where
ΔV -Change in Volume
P -Pressure (Pa)
k -Bulk Modulus

The pressure inside the void which is directly proportional to the change is shown.

$$P_{void} = \left(1 + \frac{\Delta V}{V}\right) * P_{initial} \quad (19)$$

Assuming the pressure initially in the void at construction is 1 atm (101.3 kPa), the pressure inside the void at depth is shown in Fig. 6 for both low modulus (5 GPa) and high modulus (25 GPa) materials.

As can be seen, the pressure inside epoxy voids does not change substantially with increases in well depth or environmental pressure. Applying Paschen's law, the breakdown voltage of air does not change in any significant manner as shown in Fig. 7.

The two curves show a limiting impact of less than two percent (2%) on the pressure inside the insulation cavity. The consequence is less than two percent change in electric field breakdown on insulation of solid materials, even at extreme pressure differences.

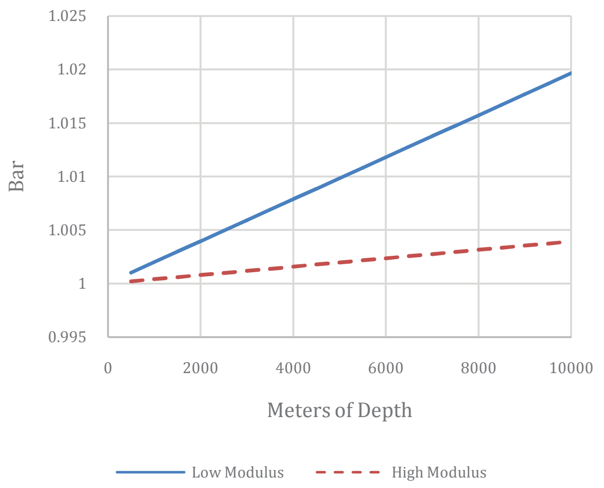


Fig. 6 - Pressure Inside Epoxy Voids

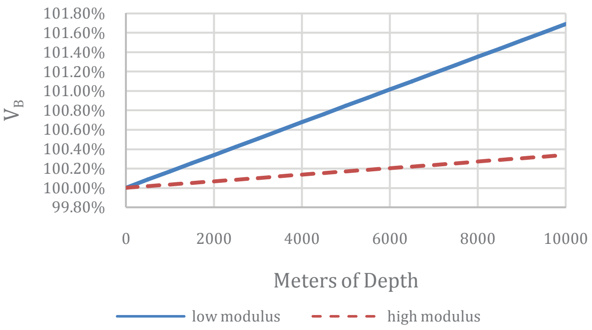


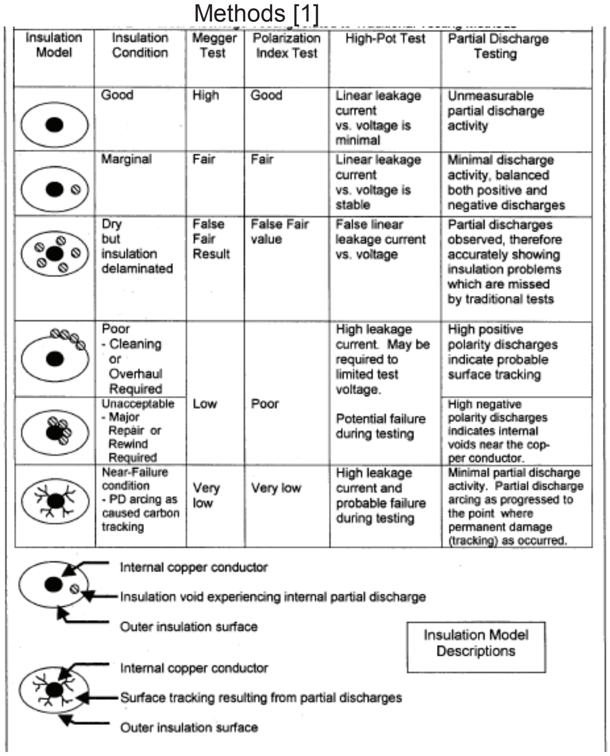
Fig. 7 - Breakdown Voltage

VI. TEST RESULTS OF MOTOR UNDER PRESSURE

Recent partial discharge tests were made on an ~700Hp oil filled motor, random wound motor with indicated partial discharge at the copper region, similar to that shown in Fig. 2. The levels of charge detected at ambient conditions were in the 10-30 nC range, a relatively large amount of discharge. Inception level was at or very near operating voltage.

In an attempt to reduce the indicated partial discharge, the oil filled motor was placed in simulated service with pressures applied of 456 bar (~6,600 PSI). This method has reduced PD in previous tests, particularly those with indications of discharge near the surface of the insulation (near the laminations). In this case, however, multiple additional partial discharge tests were conducted at various internal motor pressure levels with no indication in a change in either inception level or measured maximum PD level. No change was noted in the position of the discharge. The results of these tests are consistent with the theoretical description above.

Table 2- Partial Discharge Testing related to Traditional Test Methods [1]



Insulation Model	Insulation Condition	Megger Test	Polarization Index Test	High-Pot Test	Partial Discharge Testing
	Good	High	Good	Linear leakage current vs. voltage is minimal	Unmeasurable partial discharge activity
	Marginal	Fair	Fair	Linear leakage current vs. voltage is stable	Minimal discharge activity, balanced both positive and negative discharges
	Dry but insulation delaminated	False Fair Result	False Fair value	False linear leakage current vs. voltage	Partial discharges observed, therefore accurately showing insulation problems which are missed by traditional tests
	Poor - Cleaning or Overhaul Required	Low	Poor	High leakage current. May be required to limited test voltage. Potential failure during testing	High positive polarity discharges indicate probable surface tracking
	Unacceptable - Major Repair or Rewind Required				High negative polarity discharges indicates internal voids near the copper conductor.
	Near-Failure condition - PD arcing as caused carbon tracking	Very low	Very low	High leakage current and probable failure during testing	Minimal partial discharge activity. Partial discharge arcing as progressed to the point where permanent damage (tracking) as occurred.

Internal copper conductor
Insulation void experiencing internal partial discharge
Outer insulation surface

Insulation Model Descriptions

Internal copper conductor
Surface tracking resulting from partial discharges
Outer insulation surface

VII. IMPACT OF PD ON MOTOR WINDINGS

Partial discharge in motors, including motors in hostile environments, is typically indicative of other problems in the motor [19]. PD in a motor can be a result of the design of the motor itself [17,18,19]. Even motors which would normally have low PD from design will have increased PD when manufacturing defects are found in the insulation [6,15,19].

The impact of partial discharge on motor windings has been demonstrated in previous works [1,13,6,14,16,17,18]. A summary of these effects and impacts is shown below:

1. When discharge occurs over time, the insulation is progressively damaged. The discharge may result in further turn-turn faults or turn-ground fault.
2. Partial discharge can show problems in the construction of windings. The issue is particularly evident when excessive PD exists on one winding, compared with the other two windings of a particular machine.
3. Partial discharge comparison between machines of the same general design can indicate problems in manufacturing of the motor. Since random wound motors by definition vary in construction, different construction techniques must be carefully evaluated.
4. Partial discharge can occur in either the tape wound, the varnish, or the epoxy portions of the insulating materials. The characteristics of the discharge as measured during offline PD tests can indicate the location of the discharge. The discharge characteristics are primarily determined from the phase related PD as shown in Fig. 2 [1]. A summary of these analyses taken from Paoletti and Golubev is shown below:

VIII. CONCLUSIONS

The value of partial discharge testing of hostile environment motors, including ESP, increases under three conditions: increased voltage stress from high operating voltages, increased ambient stress from the environment, and increased intervention costs for high production wells. PD testing of these elegant motors has significant value.

Partial discharge in a motor can show problems in the design of the motor, the manufacture of the motor, or in the quality of the insulating materials used.

There are several factors which impact PD in hostile environment motors, including ESP. The factors include strength of the E field, size of a void in the insulating materials, irregularities in the metallic surfaces of the motor conductors, and permittivity of the insulating material, as well as terminations, connections, and transitions.

Despite claims by some parties, clear evidence demonstrates that partial discharge occurs, even under higher pressure conditions downhole, particularly for those motors with varnish or epoxy materials. As a result, offline partial discharge testing can indicate problems with the motor that would otherwise show up under operating conditions.

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X. VITAE

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He has been awarded the IEEE Richard Harold Kaufmann Medal "for development of theory and practice in the application of power systems in hostile environments." He was recognized with six IEEE Awards for his Standards development work. He has been awarded numerous times for the over 150 technical papers he has co-authored. He has published fourteen books used in university level classes. He is acclaimed in Who's Who of American Teachers and Who's Who of the Petroleum and Chemical Industry of the IEEE. Honorary recognition includes Phi Kappa Phi, Tau Beta Pi, and Eta Kappa Nu.

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