Abstract — Partial discharge (PD) diagnostic is regarded as a powerful method for diagnosing the potential electrical insulation defects in a medium voltage (MV) and high voltage (HV) switchgear. This paper proposes a method, termed as a risk-based approach, to identify the severity of several critical electrical defects in MV/ HV switchgear based on partial discharge testing. To accomplish this, several defects have been artificially created in a MV switchgear. Testing was carried out to investigate the characteristics of PD signals using non-intrusive sensors. Accordingly, the specific PD intensity of the discharge pulse has been considered as stress parameters and then statistically modelled by suitable probability distribution. In this way, the probability of dielectric failure has been quantified. The consequences of dielectric failure, and hence the failure of the switchgear are given by the power outage cost and repair expenditures. The risk assessment is made by combing both of these factors. The estimated risk is an indication of the criticality of the fault and can be specified as low, medium, high, or maximum. In this way, the proposed approach can be easily adopted by asset manager for risk assessment of switchgear in the petroleum and chemical industries.

Index Terms — Cumulative energy function, insulation defects, MV/ HV switchgear, partial discharge measurements, Probability distributions, risk assessment,

I. INTRODUCTION

Metal clad switchgear form an integral part of the power distribution network, located in both the primary and secondary substations. There is a wide variety of switchgear based on their operating voltage and construction. Major components inside the switchgear are instrument and protection transformers (CT- current transformer, PT- potential/ voltage transformer), bushings, bus bars (bare or insulated), cable connections and circuit breakers. All these components are well designed for their operating voltages and hence surrounded by certain insulating materials, having a certain voltage withstand strength (also called as breakdown strength). The purpose of an insulation is to stop the unintentional discharge of electrical energy through air to ground or between the power phases. These insulation materials go through various stresses named as TEAM stresses (T- Thermal, E- Electrical, A- ambient, M- Mechanical) [1]. Under these stresses, the insulation materials gradually lose their breakdown strength due to incipient faults. A well-known incipient fault is partial discharge within an insulator, major is a major cause of insulation degradation of insulation [2]. Partial discharge is the breakdown of a small part of an insulation under operating- or over-voltage stress, due to voids, cavities, cracks or impurities in the insulation, which does not bridge the two electrodes (i.e. live conductor and ground) [3]. The reason of the partial breakdown is that these cavities, void or air bubbles have less electrical permittivity and hence undergo enhances electric field stress across them, resulting in breakdown of the cavity. As a result of partial discharge a flow of charge is resulted across the insulator and high frequency voltage and current pulses are superimposed on the power voltage and current waveforms. These high frequency pulses can be detected using high frequency current or voltage sensors installed on the line. Moreover, such a PD activity causes initiation of airborne transient electric and magnetic fields, which can be detected by high frequency electric or magnetic sensors [4].

The detection of a partial discharge activity provides an early alarming sign of an insulation degradation. Once PD starts, it may take a few years, days or even hours until the complete insulation breaks down leading to the flashover or arc across the insulator depending upon the severity of stresses. An arc is a high energy discharge which produces extremely high temperature, greater than the temperature at the surface of the sun, and a force equivalent to being hit by a hand grenade [5]. In such a case, the feeder powered though this switchgear has to wait for the maintenance or replacement time, if a backup is not present. There are various economic consequences of switchgear failure, depending upon the application [6]. For example, if the switchgear feeds a process industry or a manufacturing plant, the outage cost can be extremely high. Therefore, risk assessment studies are performed on various electrical equipment including switchgear to assess their reliability and safety of operation [7], [8].

In industry, the risk assessment studies of various equipment are being performed on the basis of global statistics, physical inspection and user experience [9], [10]. Such risk assessments can be less precise and time consuming, leading to an inappropriate maintenance plan. In this work, risk assessment studies for a medium voltage (MV) switchgear is performed, by incorporating the two major factors, i.e. failure probability and failure costs, as shown in Fig. 1 [6], [11]. Among these two, usually the economical factor plays a dominant role. The economic risk analysis leads to an estimation of the costs arising by the failure of the insulation system. The major failure costs include maintenance and repair cost, outage/ interruption
cost and penalty as well as the provisional solution expenditure. The maintenance and repair costs depend upon the type of installation and the availability of spare parts. The outage or interruption cost is the cost due to the loss of power and penalty, resulting from the switchgear being out of power. It depends on the importance and the location of installation, serving a certain customer or locality [11].

The technical part of the risk assessment is the failure probability which has to be considered. In order to assess the risk of failure, the health condition of the insulation has to be determined along with the physical properties of the insulation defect. The knowledge of various aging stages and the physical phenomena between PD inception voltage and the breakdown is needed. For example, PD can be categorized into internal, surface or corona. All of these PDs exhibit different behavior under various TEAM stresses. [3], [4]

The failure probability was determined based on PD diagnostics. In this regard, a metal clad switchgear was tested under various PD conditions, including internal, surface and corona discharges. Two PD characteristic parameters (apparent charge q0 and cumulative energy E0) were used to classify the PD type as well as PD intensity, which are further used to determine the failure probability. This failure probability is combined with the failure costs, which incorporate the failure consequences, to conduct risk assessment.

The rest of the paper is organized as follow. Section II, briefly describes the methodology being adopted in this work; Section III explains the PD diagnostic procedure, adopted in this research, which includes the description of PD sensor used, test setup and determination of PD characteristic parameters used to calculate the failure probability. The detailed procedure to conduct the risk assessment is given in Section IV. Finally, in Section V, conclusions are drawn.

II. METHODOLOGY

A four step risk assessment approach is used in this work as described below:

1. In the first step, a sensitive PD measurement is conducted to detect critical PD faults.
2. A simple PD classification approach is used to classify the type and the location of PD defects.
3. Insulation failure probability is calculated from the combined factors of PD characteristic parameters, trend of PD activity, criticality of the defect, and design aspects of the switchgear.
4. In the last step, risk assessment is made based on the combined aspects of the insulation failure probability and failure consequences.

The first 2 steps are accomplished in Section III, whereas the last two steps are completed in Section IV. The above methodology is explained in Fig. 2.

![Fig. 1 Risk assessment dependencies](image)

In this paper, the risk assessment of metal clad switchgear is performed while incorporating all the above mentioned factors. The failure probability was determined based on PD diagnostics. In this regard, a metal clad switchgear was tested under various PD conditions, including internal, surface and corona discharges. Two PD characteristic parameters (apparent charge q0 and cumulative energy E0) were used to classify the PD type as well as PD intensity, which are further used to determine the failure probability. This failure probability is combined with the failure costs, which incorporate the failure consequences, to conduct risk assessment.

The rest of the paper is organized as follow. Section II, briefly describes the methodology being adopted in this work; Section III explains the PD diagnostic procedure, adopted in this research, which includes the description of PD sensor used, test setup and determination of PD characteristic parameters used to calculate the failure probability. The detailed procedure to conduct the risk assessment is given in Section IV. Finally, in Section V, conclusions are drawn.

III. PD DIAGNOSTICS

A. PD Sensor

The D-dot sensor is a differential electric field probe. The sensor is made from a standard bulkhead SMA jack. The sensor used in the PD measurements was installed on a grounded plane as shown in Fig. 3. The compiled assembly was installed inside the switchgear compartment in the vicinity of the PD location. The sensor measures the time rate of change of the electric flux density resulted from a PD activity (which is directly proportional to the displacement current density in the line due to the PD pulse) [12]. The electric flux density D and electric field E are directly related as

\[ D = \varepsilon_0 E \]

where \( \varepsilon_0 \) is the permittivity of air.

The D-dot sensor works like a short monopole antenna, whose capacitance is extremely small and it acts as a differentiator to transient electric fields. Therefore, the sensor’s output is the derivative of the incident electric field and integrating this output produces the actual incident electric field. However, when the length of the probe approaches a quarter wavelength of the incident wave (\( l = \lambda/4 \)), the sensor loses its derivative properties and captures the actual incident electric fields [13]. The standard SMA jack with a protruding center conductor as shown in Fig. 3 has a cut-off frequency of 18 GHz.
Decreasing the length of the conductor will increase its bandwidth but at the same time reduce its sensitivity.

Fig. 3. D-dot sensor mounted on a grounded plane.

B. PD Test Setup

The measuring setup was arranged in the laboratory as shown in the Fig. 4. Combined measurements using conventional and unconventional PD measurements were carried out in this work. The circuit breaker was put in the closed position and the outgoing side of only one phase of the switchgear was open circuited while the other two phases were grounded. The open ended phase was energized and used to study various PD conditions by creating artificial PD defects on it. The switchgear was placed on a wooden base and its case was grounded through a single point. The D-dot sensor, as an unconventional probe, was fixed inside the upper portion of the switchgear compartment.

For the conventional PD measurements, the coupling capacitor and coupling device (pulse transformer) were installed after capacitive divider (before the switchgear). The coupling capacitor transfers the PD energy from the electrical network to the measuring system by means of the capacitance between circuit nodes. The coupling device is usually an active or passive four terminal network (quadruple) and converts the input PD current pulse to output voltage signals to be displayed on the digitizer (oscilloscope). Apparent charge is calculated either by calibrating the peak value of the pulse or by calibrating the integral (area under the curve) of the PD pulse. For unconventional measurement, D-dot sensor was used to capture the high frequency electric field transient waves in the vicinity of the PD source.

Fig. 5 shows the switchgear and measuring equipment. PD pulses were measured by both the conventional and the unconventional (D-dot sensor) methods at various voltage levels. Measurements were conducted under the following PD conditions, also depicted in Fig. 6:

- Defect-A: PD between pin to plate (corona).
- Defect-B: PD in void (epoxy-resin solid insulation with air bubble).
- Defect-C: Surface discharge at the insulator surface.
- Defect-D: Corona due to multiple bare conductors.

Fig. 6. Discharge sources: (a)- PD between pin-to-plate (corona), (b)-PD in void, (c)-Surface discharge at the insulator surface, and (d)-Corona due to multiple bare conductors.
C. PD Test Results

The measurement system was calibrated through conventional setup according to IEC60270 standard, by injecting a known amount of charge to the system and observing the measured results [14]. Since the capacitance of a test object affects the circuit characteristics, the standard specifies that re-calibration must be performed for each new test object. PD current pulses and radiated UHF signals were captured simultaneously with the oscilloscope triggering on the conventional current pulse so that PD events that did not excite UHF signals would still be recorded (the sensor outputs would be zero). In these measurements, a time base of 5 µs was used in order to record the detail of PD signals accurately. All of the measurements were performed in a commercial switchgear, so that the measured signals experience the same reflections and attenuations as encountered in an online system. Applied voltage was varied from 3 kV to 22 kV to capture a variety of measurements having different discharge levels. Fig. 7 shows a (de-noised) signal measured by the conventional (pulse transformer) and unconventional method (D-dot) under fault condition (b) (PD in void in Fig. 6). Amplitudes in this figure are not to scale because the amplitude of D-dot sensor has been amplified numerically during the signal processing for a better comparison.

D. PD Characteristic Parameters and PD Classification

Two PD characteristic parameters are used to estimate the PD intensity and classify the PD defects [15]:

a) PD amplitude (apparent charge)

b) Cumulative energy

The apparent charge \( q_a \) has been calculated by integrating the measured current pulse (recorded by the conventional method) up to the first zero crossing of the pulse and multiplying the calibration factor with the result.

The cumulative energy \( E_c \) is calculated using equation (1).

\[
E_c = \frac{t}{R} \sum_{i=1}^{N} V_i^2
\]  

where \( \Delta t \) is the sampling duration (the time interval between the two samples captured by the oscilloscope), \( R \) is the input resistance of the oscilloscope, and \( V_i \) is the PD signal’s sample amplitude for an individual sample.

The correlation between the apparent charge and the cumulative energy from four different PD defects were plotted in Fig. 6. The correlation plots for all defects tested under the selected PD defects (Fig. 6) are shown on the same scatter plot in Fig. 8. It is found that the order-of-magnitude relationship between the cumulative energy and the apparent charge levels varies significantly among various PD sources. Due to the large variation in the cumulative energies in the same charge range, the PD sources can be clearly distinguished and thereby identified. [15]

Moreover, it can be observed from Fig. 8 that corona and surface discharge signals are located near the two axes, whereas the void signals located in the middle of the quadrant. It is obvious from the literature that corona and surface discharges are less dangerous for an insulator compared to internal PDs or void. Hence, it can be concluded that the PD signals plotted near any of the axes are less dangerous. The PD signals located near the horizontal axis have high apparent charge but have less discharge energy, which means signals are short duration, whereas the signals plotted near the vertical axis have less PD charge but long duration, representing it less dangerous. On the contrary, the signals plotted in the middle of the quadrant represent more severe defects, having high energy and greater apparent charge.

IV. RISK ASSESSMENT MV SWITCHGEAR

In this section, the risk assessment of MV switchgear was made by combining both the probability of insulation failure \( P_f \) and estimation of the failure consequences \( C_f \) [16].

A. Probability of Insulation Failure

For each insulation defect, the \( P_f \) was calculated using both peak amplitude \( q_a \) and cumulative energy \( E_c \) of PD signals obtained by performing a series of experiment. Accordingly, the probability density functions (PDF) and cumulative distribution functions (CDF) were plotted against \( q_a \) and \( E_c \) data using different probability distributions. Fig. 9 presents both PDF and
CDF plotted against defect B using five probability distributions including Normal, Weibull, Generalized extreme value (GEV), Gamma, and Rayleigh. The distribution fitting tool i.e. R-square hypothesis test was employed to discover a suitable probability distribution function that can accurately characterize the uncertainties observed for the individual PD data. The GEV, a continuous probability distribution, was introduced by Jenkinson in 1955 for extreme event modeling [17]. Based on the results of distribution fitting tool, the plausibility of GEV probability distribution was established to evaluate the $F$. For different probability distribution functions, the values of coefficient of determination calculated using R-square hypothesis test are presented in Table 1.

![Fig. 9. Several distributions plotted against defect B (epoxy) data, cumulative energy (a) PDF and (b) CDF and PD amplitude (a) PDF and (b) CDF.](image)

### TABLE 1

<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>RESULTS OF R-SQUARE GOODNESS OF FIT HYPOTHESIS (COEFFICIENT OF DETERMINATION)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PD feature</td>
<td>Normal</td>
</tr>
<tr>
<td>$E_c$</td>
<td>0.6478</td>
</tr>
<tr>
<td>$q_a$</td>
<td>0.7578</td>
</tr>
</tbody>
</table>

From Table 1, the GEV probability distribution has the highest values of the coefficient of determination against both $q_a$ and $E_c$ data. The PDF of GEV distribution can be estimated using (2) [18]:

$$F(u) = \frac{1}{\sigma} (1 + 3u)^{-1} \exp - (1 + 3u)^{-\frac{1}{3}}$$

where

$$u = \frac{z - \mu}{\sigma}, u > \mu - \frac{\sigma}{3}$$ for $\zeta > 0$

$\zeta (0, \infty)$, $\sigma (0, \infty)$, and $\mu (-\infty, \infty)$ represent the shape, scale, and location parameters, respectively. Based on the value of $\zeta$, the GEV distribution function combines the Weibull ($\zeta < 0$), Gumbel ($\zeta = 0$), and Fréchet ($\zeta > 0$) distributions into a single distribution family. The CDF $P_c(u; \zeta)$ for $q$ and $E_c$ data using GEV distribution was evaluated by (3).

$$P_c(u; \zeta) = \exp - (1 + 3u)^{-\frac{1}{3}}$$

The magnitudes of both $q_a$ and $E_c$ estimated very close to the insulation failure were taken as the reference values and represented by $q_{a,ref}$ and $E_{c,ref}$, respectively. The probability of occurrence $P_c(u)$ of each PD impact i.e. $q_a$ and $E_c$ at maximum value was calculated using (4):

$$P_c(u) = 1 - P_c(u; \zeta)$$

Therefore, the probability of failure ($P_f$) using only the impact of $q_a$ can be calculated using (5):

$$P_f = \frac{1}{n} \sum_{i=1}^{n} P_{f1}$$

where, $P_{f1}$ is the probability of occurrence of $q_{a,max}$. $q_{a,ref}$ is the magnitude of $q_a$ very close the insulation failure, and $q_{a,max}$ is the maximum value of apparent charge observed. Similarly, the probability of failure by considering the impact of $E_c$ can be calculated. The total probability of failure can be calculated by considering the impact of both parameters, as in Equation (6), where $n$ is the number of parameters whose impact is to be considered for risk assessment.

$$P_f = 1 - P_c(u)$$

The $P_f$ calculated for four insulation defects is presented in Table 2. It can be seen that the failure probability is highest for the PD in epoxy (defect B), which are obviously the most sever ones, as seen in Fig. 8.

### TABLE 2

<table>
<thead>
<tr>
<th>TABLE 2</th>
<th>ESTIMATION OF PROBABILITY OF FAILURE FOR ALL TYPES OF THE DEFECT USING AN APPROPRIATE DISTRIBUTION FUNCTION.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defect type</td>
<td>$q_{a,max}$ (nC)</td>
</tr>
<tr>
<td>A</td>
<td>18.83</td>
</tr>
<tr>
<td>B</td>
<td>16.25</td>
</tr>
<tr>
<td>C</td>
<td>1.57</td>
</tr>
<tr>
<td>D</td>
<td>0.8</td>
</tr>
</tbody>
</table>

### B. Estimation of Failure Consequences

The estimation of the $C_0$ of switchgear can be made using several technical and non-technical parameters. These parameters are either monetarily accessible or monetarily inaccessible which include: 1) availability of spare material/ parts, maintenance time, and the technical staff required to maintain the damaged components, 2) outage cost that includes the maintenance expenditures of the damaged component and safety implications, 3) customer interruption costs that includes the costs of non-delivery of energy and the penalties coming from critical customers’ contracts, 4) cost paid due to third party loss, and 5) reputation/ image of the utility. Some monetarily inaccessible parameters are subject to customer’s demand and company’s requirement [16], [18]. The information about such costs is often available within the utilities and some are determined from historical data or user experience. Based on the market survey and experience of...
asset manager, the failure consequences are given in Table 3.

### TABLE 3
SEVERITY OF FAILURE CONSEQUENCES DETERMINED BASED ON THE MARKET SURVEY AND EXPERIENCE OF ASSET MANAGER

<table>
<thead>
<tr>
<th>Monetarily accessible</th>
<th>Human resources/rectification time</th>
<th>Customer interruption/additional damages</th>
<th>Purpose/Station</th>
<th>Reputation/image</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. 1-10% of total amount, instrument/tools and other cleaning and degreasing material.</td>
<td>1. 8-10% of material price, unskilled and semiskilled.</td>
<td>1. 0.5-1 hour interruption and no additional damage of the components.</td>
<td>1. Negligible, standby or redundant arrangement.</td>
<td>1. Negligible effect.</td>
</tr>
<tr>
<td>2. 10-30%, indications, interlocking, auxiliary contacts, control circuitry.</td>
<td>2. 11-18%, semiskilled and skilled.</td>
<td>2. 1-2 hours failure and slight damages.</td>
<td>2. Low, domestic and commercial buildings, water storage, swimming pools, HVAC fans, etc.</td>
<td>2. Low effect.</td>
</tr>
<tr>
<td>3. 30-40%, closing coil, opening coil, UVT, blocking coil, motor kit, insulation material.</td>
<td>3. 18-22%, skilled and semiskilled.</td>
<td>3. 2-5 hours breakdown and significant damages.</td>
<td>3. High, process industry, production units.</td>
<td>3. Medium effect.</td>
</tr>
<tr>
<td>4. 40-50%, HV parts including CT, PT, bushing, bus bar, switch disconnecter cubical.</td>
<td>4. 22-25%, connection, testing and commissioning by professionals.</td>
<td>4. 6-26 hours breakdown and major impairment and high liability of third party</td>
<td>4. Very high, Hospitals, fire hydrant system, oxygen makeup in ICU, etc.</td>
<td>4. High effect.</td>
</tr>
</tbody>
</table>

The severity level of $C_s$ based on impact parameters and their aspects is given by (7), [16].

$$C_s = \sum_{i=1}^{r} w_t \times \ell_i$$

where $w_t$ represents the weighting factor and $\ell_i$ represents the severity weight of $t^{th}$ impact parameters. $w_t$ is determined using (8):

$$w_t = \frac{\tau}{n_t}$$

where $\tau$ and $n_t$ represent the total number of impact parameters and the number of severity levels of $t^{th}$ impact parameter, respectively. The $C_s$ and severity classes ($6_s$) are linearly distributed (from $c = 1$ to $6$) using (9). From (9), $C_s(min)$ and $C_s(max)$ are the minimum and maximum values of $C_s$.

$$\begin{cases} 
C_s > \frac{(C_s(max) - C_s(min))}{6_s} \times \mu & \mu = c - 1 \\
C_s < \frac{(C_s(max) - C_s(min))}{6_s} \times \mu & \mu = c 
\end{cases}$$

The estimated $P_i$ and $C_s$ classes and corresponding ranges are presented in Table 4. This table can be developed based on the PD expert opinion or user experience or some sample historical data. It can be seen that the failure probabilities due to A, C and D defects are low frequency, whereas the failure probability due to fault B lies in likely range.

### TABLE 4
ESTIMATED PROBABILITY AND SEVERITY CLASSES AND CORRESPONDING RANGES

<table>
<thead>
<tr>
<th>Level</th>
<th>Probability class</th>
<th>Probability range</th>
<th>Severity class</th>
<th>Severity range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Very unlikely</td>
<td>$P_i \leq 10^{-3}$</td>
<td>Insignificant</td>
<td>$C_s \leq 15$</td>
</tr>
<tr>
<td>2</td>
<td>Rare</td>
<td>$10^{-3} &lt; P_i \leq 10^{-4}$</td>
<td>Low</td>
<td>$15 \leq C_s &lt; 22$</td>
</tr>
<tr>
<td>3</td>
<td>Low frequency</td>
<td>$10^{-4} &lt; P_i \leq 10^{-3}$</td>
<td>Moderate</td>
<td>$22 \leq C_s &lt; 28$</td>
</tr>
<tr>
<td>4</td>
<td>Likely</td>
<td>$10^{-3} &lt; P_i \leq 10^{-2}$</td>
<td>High</td>
<td>$28 \leq C_s &lt; 32$</td>
</tr>
<tr>
<td>5</td>
<td>Very frequent</td>
<td>$10^{-2} &lt; P_i \leq 10^{-1}$</td>
<td>Very high</td>
<td>$32 \leq C_s &lt; 36$</td>
</tr>
<tr>
<td>6</td>
<td>Critical</td>
<td>$P_i \geq 10^{-1}$</td>
<td>Critical</td>
<td>$C_s \geq 36$</td>
</tr>
</tbody>
</table>

### C. Risk Diagram

Risk diagram is made by coupling both $P_i$ and $C_s$ classes. After setting down risk levels, these couplings are associated with a specific risk factor. For six probability and six consequences classes, four failure risk levels are introduced. Eq. (10) presents the risk matrix ($R_{C,P}$) containing both $C_s$ and $P_i$ and in six rows and six columns, respectively. The $R_{C,P}$ can be graphically represented by a risk assessment rectangle whose axes are the two independent factors “probability of failure” of the identified PD defect and “consequences of failure”, which are both represented by the specific levels. The area of the rectangle determines the possible risk level as shown in Figure 10. From Figure 10, the diagonal of the rectangle is uniformly distributed into four segments and each segment represents a specific risk level. In the risk diagram, risk areas including low, medium, high and maximum risk are marked. Each area involves different actions as shown in the Table 5, [19], [20]

$$R_{C,P} = \begin{bmatrix}
(1,1) & (1,2) & (1,3) & (1,4) & (1,5) & (1,6) \\
(2,1) & (2,2) & (2,3) & (2,4) & (2,5) & (2,6) \\
(3,1) & (3,2) & (3,3) & (3,4) & (3,5) & (3,6) \\
(4,1) & (4,2) & (4,3) & (4,4) & (4,5) & (4,6) \\
(5,1) & (5,2) & (5,3) & (5,4) & (5,5) & (5,6) \\
(6,1) & (6,2) & (6,3) & (6,4) & (6,5) & (6,6)
\end{bmatrix}$$

Fig. 10. Risk diagram based on failure probability and failure consequences levels
D. Risk-Safety Relationship

Risk and safety are mutually exclusive and a binomial relation exists between them. Safety is the condition of a system with zero risk level. However, in a practical system, a residual value of failure risk always exists because of random behavior of the machines, humans, and insulation degradation of the HV components. Therefore, safety level of a system is characterized as a function of risk level, $z = f(y)$ [21].

To identify the safety levels of several critical defects in MV/ HV switchgear, the safety diagram for the switchgear is shown in Figure 11. From Figure 11, the diagonal of the rectangle is uniformly distributed into four segments and each segment represents a specific safety level. In safety diagram, safety areas including maximum, high, medium, and low safety are marked.

The combined evaluation of risk and safety levels of insulation defects in MV/ HV switchgear based on probability-severity coupling is presented in Table 5. Form Table 5, it can be seen that the safety level is at maximum when the risk is at low level, and vice versa.

![Safety Diagram](image)

**TABLE 5**

<table>
<thead>
<tr>
<th>Level</th>
<th>Risk</th>
<th>Safety</th>
<th>Probability - Severity Couplings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Low</td>
<td>Maximum</td>
<td>(1,1) (1,2) (1,3) (2,1) (2,2) (3,1)</td>
</tr>
<tr>
<td>2</td>
<td>Medium</td>
<td>High</td>
<td>(1,4) (1,5) (2,3) (2,4) (3,2) (3,3)</td>
</tr>
<tr>
<td>3</td>
<td>High</td>
<td>Medium</td>
<td>(1,6) (2,5) (2,6) (3,4) (3,5) (3,6)</td>
</tr>
<tr>
<td>4</td>
<td>Maximum</td>
<td>Low</td>
<td>(4,6) (5,5) (5,6) (6,5) (6,6)</td>
</tr>
</tbody>
</table>

V. CONCLUSIONS

In this paper, risk assessment study of a medium voltage (MV) switchgear is conducted based on the partial discharge (PD) diagnostics and consequences of failure of switchgear. PD measurement is considered as a reliable technique for the indication of health of a certain high voltage (HV) or MV equipment. Therefore, PD measurements done on a commercial MV switchgear, are used to determine the failure probability of an MV switchgear. Four PD defects were artificially created in the switchgear, which include internal PD, surface and two different corona sources. The probability of dielectric failure has been quantified by using two PD characteristic parameters, i.e. apparent charge and cumulative energy of PD signals. From the four PD defects, it was determined that the internal PD has relatively higher failure risk compared to corona and surface discharges. The consequences of dielectric failure, and hence the failure of the switchgear are given by the power outage cost and repair expenditures. The estimated risk is an indication of the criticality of the fault and can be specified as low, medium, high, or maximum. In this way, the proposed approach can be easily adopted by an asset manager for risk assessment of switchgear in the petroleum and chemical industries.

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VII. REFERENCES

research expertise and interests include high voltage engineering, power system protection and control in modern smart grids and power system analysis.

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VIII. VITAE

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