ENHANCING MACHINES STATOR WINDING SAFETY IN EXPLOSIVE ATMOSPHERE ENVIRONMENT EXPLORING IGNITION STRESS FACTORS

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Abstract - This paper describes the development, performance evaluation, and experimental validation of an insulation system for high-voltage electrical machines at 11 kV and 13.8 kV, specifically designed for operation in explosive gas environments, with protection type “Ex ec”, and gas group IIC, according to IEC 60079-0 and IEC 60079-7, international standards.

The proposed insulation system was engineered to mitigate surface partial discharge and corona discharge phenomena, ensuring that the energy released remains below the threshold required to ignite the surrounding explosive gas atmosphere.

Research methodology comprises a systematic sequence of experimental trials, including controlled testing on individual bars and coils, followed by comprehensive assessments on a complete wound stator with connection cables. The results provide critical insights into the reliability and safety performance of the insulation system under operational conditions. The final validation executed was the approval in the gas test described on IEC 60079-7 for protection type “Ex ec”. Which confirmed the ability of the stator insulation system in mitigating ignition stress and thus demonstrating the design effectiveness.

Index Terms — insulation systems, explosive atmosphere, ignition, partial discharge, corona inception, ignition energy, hydrogen, partial discharge mitigation, “Ex” certification, enhanced safety machines.

I. INTRODUCTION

Explosive atmosphere environments, present in industries like oil, gas, and chemicals, offers significant challenges due to the catastrophic risks associated with ignition events. The presence of flammable gases in these environments increases the risk of ignition. The electric motors present in such industrial environment could be a potential source of ignition, specially at high voltages, justifying the importance of implementing robust safety measures to mitigate such hazards.[1] Among these measures, stator insulation systems are critical components of electrical machinery, playing a vital role in preventing ignition-related incidents.[2]

This paper addresses the development of a stator insulation system designed to achieve a lower discharge level, ensuring that the energy remains below the threshold required to ignite under explosive atmosphere. However, this publication does not cover other certification requirements for equipment used in such environments.

Electric motors used in explosive gas atmospheres can present ignition risks, particularly at voltages above 6.6 kV, where Partial Discharges (PD) occur and may generate energy capable of igniting flammable gases [3]. To mitigate this risk, stator insulation systems must meet rigorous standards, with a key focus on Minimum Ignition Energy (MIE), under specific conditions [4]. Gases like hydrogen, with low ignition activation energy, requires careful assessment of insulation system performance to ensure safety [5].

Experimental data and theoretical models help identifying ignition thresholds, guiding optimizing insulation systems [6]. The relationship between system design, voltage, and environmental conditions emphasizes the need for robust testing to safety improvement and reliability in explosive atmospheres. The first assessment on this paper subject, was carried out within initial tests on individual coils, including Corona Inception Voltage (CIV) and partial discharge activity [7].

This paper details methodologies and findings from experimental phases, emphasizing precise design, testing, and careful manufacturing to develop insulation systems resistant to high electrical stresses while mitigating ignition risks. The results contribute to optimizing stator insulation for enhanced reliability, supporting further advancements in high-voltage electrical safety. This research aligns with the steady-state ignition test specified in item 6.2.3.1.3 of IEC 60079-7:2015 as part of the certification requirements for Ex ec, group IIC equipment.

II. TECHNICAL OVERVIEW

A. Standards Requirements

The International Standard IEC 60079-0:2017 is part of the IEC 60079 series of standards that focus on equipment for explosive atmospheres. This specific standard provides general requirements for the design, construction, and testing of electrical equipment intended for use in environments were explosive gases, vapors, or dusts may be present. IEC 60079-0 defines fundamental safety principles, markings, and documentation requirements. It serves as a foundation standard for ensuring compliance and reliability in hazardous locations, mitigating risks of ignition and increasing operational safety.

The IEC 60079-7 is the standard, within the IEC 60079 series, specifically focused in electrical equipment with "Increased Safety" protection type for use in explosive atmospheres. This protection method prevents arcs, sparks, or excessive temperatures, reducing ignition risks in hazardous environments. The standard outlines criteria, testing, and compliance requirements to ensure safe and reliable operation while maintaining industrial efficiency. [8]

Considering the standard, in this paper we will cover only the stator winding system for motors with protection type “Ex ec IIC” at 11 kV and 13.8 kV, which is related to item 5.2.10 of IEC 60079-7.

IEC 60079-7 specifies a wide range of requirements for design, materials, construction, and performance characteristics of stator insulation systems operating in explosive atmospheres. The evaluation process for stator insulation systems includes extensive testing under real-world conditions, such as exposure to gases. These gases are grouped by ignition energy and the representative ones for each group are: propane (Group IIA), ethylene (Group IIB) and hydrogen (Group IIC). The addressed one in this paper, Group IIC, has the lowest ignition energy, making it the most challenging to manage. [9] Adherence to the IEC 60079-7 standard and thorough testing protocols are essential for manufacturers to ensure the safety and effectiveness of their systems in critical industrial applications.[10]

B. Key Factors Influencing Ignition Stress

PD and corona inception are key phenomena that significantly affect the ignition stress in stator insulation systems. PD refers to localized electrical discharges within the insulation materials under high electrical stress, which can potentially lead to ignition in explosive atmospheres.[2] The ignition energy of gases, especially hydrogen, plays a critical role in determining the system's vulnerability to ignition. For example, the ignition activation energy in a hydrogen atmosphere has been shown to be as low as 17 µJ [5], highlighting the importance of carefully considering these factors. At voltage levels exceeding 10 kV, the intensity of PD activity increases significantly, intensifying the challenge of maintaining safe operation in hazardous environments. Therefore, insulation systems for such voltages must incorporate advanced design features to suppress PD and manage corona inception effectively.

Another key parameter is CIV, which marks the point at which corona discharge begins, is a crucial parameter in optimizing the design of insulation systems. This voltage indicates the threshold at which ionization occurs, potentially leading to disruptive electrical discharges that can cause ignition. Experimental research shows that ignition risk in gaseous environments is primarily driven by sudden, high-energy events, rather than the gradual accumulation of discharge activity. For instance, PD levels surpassing critical thresholds, such as around 10 nC, can serve as ignition triggers [1]. This finding highlights the need for advanced insulation designs that minimize PD occurrences, even under extreme conditions. Therefore, understanding the relationship between PD, corona inception, and ignition energy is fundamental in assessing the performance of stator insulation systems in explosive atmospheres and mitigating the risk of ignition.

C. Design Optimizations

To improve the resistance of stator insulation systems to ignition, targeted design optimizations focus on factors influencing ignition stress. These optimizations include selecting advanced insulating materials, adjusting insulation layer thickness, and modifying electrical properties to withstand higher electrical stresses and temperatures. Such strategies, extensively analyzed in previous studies [7], are essential to reduce PD, CIV, and the resulting risk of ignition [11]. Adjustments to insulation clearances further enhance the system's ability to contain electrical discharges, preventing their escalation into hazardous ignition events. Enhancements in cable configurations play a crucial role in reducing the likelihood of corona discharge.

Recent analyses of CIV using Design Of Experiments (DOE) methodologies have provided crucial insights into optimizing stator insulation system designs. The number of End-winding Corona Protection (ECP) layers, the use of mica layer protection over the ECP area, and the type of ECP tape were identified as statistically significant factors for enhancing CIV performance [7]. These findings align with broader efforts to optimize stator windings under conditions that simulate real operational environments. They highlight the importance of addressing specific design elements, such as protective layers and materials, to enhance system reliability and mitigate electrical stress.

Integrating these insights into prototypes described in this paper, enabled enhanced configurations confirmation under practical conditions. By addressing ignition stress factors and incorporating DOE findings, the manufacturer can achieve safer and more robust stator insulation systems for hazardous industrial applications.

III. EXPERIMENTAL DETAILS

A. Electrical Test

To evaluate the CIV, a qualitative approach was employed, with a PD acoustic imager serving as the main diagnostic instrument. The imager, configured to operate in PD detection mode (50-70 kHz), proved effective for identifying discharge activity. CIV was determined when recurring discharges were consistently observed at specific points. The testing procedure incrementally increased the voltage from 11 kV to 21 kV, maintaining each voltage level for a minimum of 30 seconds to facilitate comprehensive inspections. These inspections covered all surface of the components, with PD occurrences carefully recorded at each stage. The PD evaluation was conducted using equipment adhering to IEC 60270 standards, including a 1 nF capacitive coupler, a measurement frequency centered at 160 kHz, and a bandwidth of 160 kHz. Since no standardized methodology exists for CIV determination using acoustic imaging, an internal testing protocol was developed to ensure consistent and reproducible evaluations.

B. Ignition Test

Ignition tests are required as part of the conditions to qualify the stator winding insulation system, according to IEC 60079-7, item 5.2.10. Once the insulation system is qualified, it is not necessary to perform the test on every motor, considering it complies with the conditions of a previously approved representative sample.

The ignition test was conducted in an open area on a representative sample (IEC 60079-7, item 6.2.3.1.1). The test was performed in compliance with IEC 60079-7 item 6.2.3.1.3, in an explosive atmosphere with 21 ± 5% hydrogen in air. A sinusoidal AC voltage of 60 Hz was applied, with the test voltage slightly exceeding 1.5 times the rated voltage (rms), remained stable for at least 3 minutes. The voltage was ramped up and down at a maximum rate of 500 V per second. For a rated voltage of 11.0 kV, the applied test voltage was at least 16.5 kV. Similarly, for a rated voltage of 13.8 kV, the applied test voltage was at least 20.7 kV.

These parameters align with IEC 60079-7 safety requirements, ensuring a reliable assessment of the insulation system's ignition resistance under high-voltage electrical stress in an explosive environment.

IV. PROTOTYPING AND INITIAL TESTS

A. Coils Array Evaluation

Considering the analysis of ignition stress factors and the design optimizations envisioned in previously mentioned study, the next step was to perform the high-voltage test of coil arrays, to validate these findings. The evaluation of key parameters such as coil clearances and ECP design, provided critical data on mitigating PD and corona activity. In this experiment the arrangements were subjected to electrical evaluation, in which the voltage was gradually increased up to 21 kV while corona and PDs were monitored thoroughly.

Results revealed that maintaining minimum clearance in critical overhang regions, was effective in reducing corona activity under voltages up to 21 kV. This finding highlights the necessity of adequate spacing to ensure the longevity and safe operation of high-voltage systems. Moreover, the addition of mica protection over the ECP layer proved active in suppressing corona discharges significantly enhancing the robustness of the insulation system and reducing electrical stress.

After diagnostic evaluation discussed, the ignition testing confirmed the efficacy of these design improvements, demonstrating the optimized coil array could withstand voltages higher than the required by standards until failing.

These results show how valuable it is to have a theoretical comprehensive evaluation which associated to meticulous experimental design and assembly practices leaded to high-performance insulation systems guiding the development of safety-focused innovations for high-voltage equipment.

From the success of these coil array tests, the research followed to the prototypes evaluation, where the application of these findings is extended to real-scale stator insulation systems designed for operation in explosive atmosphere environments. These prototypes were subjected to comprehensive testing protocols, simulating industrial conditions to validate their performance, safety, and compliance with international standards. Through these evaluations, the practical application of the design optimizations and experimental insights may be demonstrated.

B. First Prototype Stator Assembly

Assembled based on the positive results obtained with the initial coil array, featuring design then defined, focusing in reaching 11.0 kV requirements stress level. The insulation thickness applied was thicker than the one for standard 11.0 kV machines, focusing in enhancing robustness over this first prototype trial. The design included layers of mica tape for ECP protection and optimized coil-to-coil spacings of 9 mm, using specially designed spacers with predefined sizes and materials. Figures 1 and 2 showcase the stator before and after the application of spacers, emphasizing the critical importance of proper coil positioning.

The production process prioritized minimizing PD, with critical adjustments such as the application of special cable separators to ensure consistent spacing and reduce localized stress concentrations.

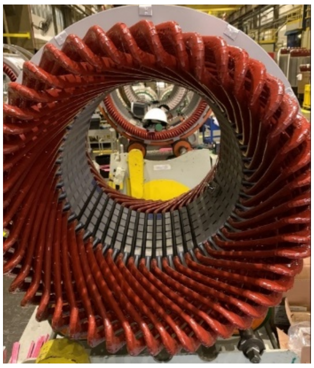

Fig. 1. Prototype before spacers application.

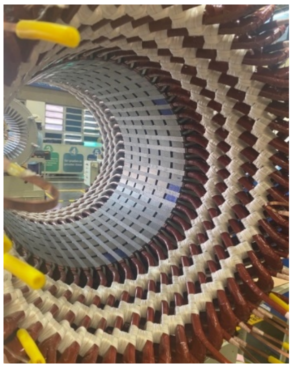

Fig. 2. Prototype after spacers and lashing application.

C. Stator Electrical Evaluation

After assembly, the stator underwent several tests to evaluate and refine its electrical performance. Initial testing was conducted post-impregnation (Fig. 3), a stage where most necessary repairs were made. Subsequently, the stator was sent to the laboratory (LSI) for detailed characterization, including imaging tests (Fig. 4) and PD measurements.

Before cabling, the stator's performance on PD aligned perfectly with the required standards, fig. 5, demonstrating a well-designed insulation system capable of sustaining high-voltage operations. Initial testing after impregnation showed peak PD at maximum 7 nC under 21 kV. Q_{Peak} values, although slightly variable, indicated an acceptable stress distribution, while Q_{IEC} or Q_{Avg} comfortably met the minimum requirements, as these are not related to MIE. These results validated the stator's design and production quality at this stage.

However, after cable routing, PD measurements revealed significant increases in Q_{Peak} values, fig. 6, highlighting the impact of cable arrangement, from maximum values of 7.8 nC to 25.89 nC.

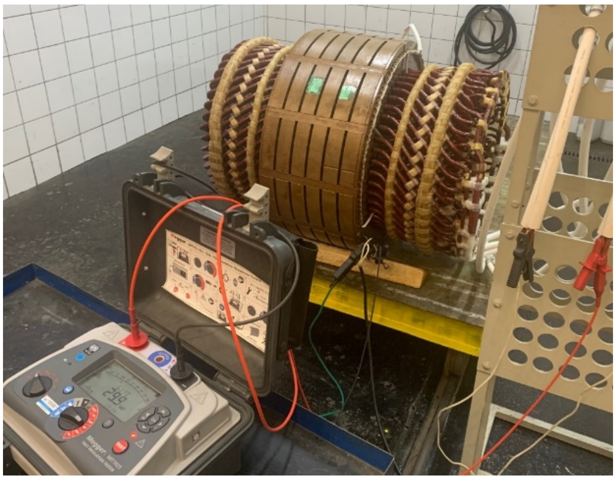

Fig. 3. Initial evaluation of the prototype stator.

These increases demonstrated how impacting cable routing are, resulting in localized discharges, elevating PD levels and potentially compromising the system. This issue highlighted the importance of precise cable arrangement to ensure the stator's safety and performance.

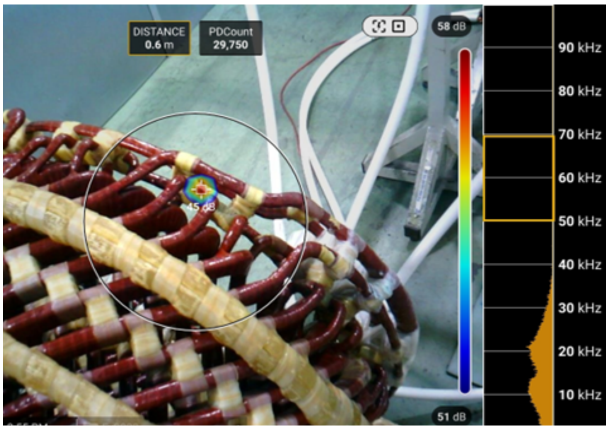

Fig. 4. Imager test example of the prototype stator.

To address this topic, adjustments were implemented in the assembling line, including the application of cable separators, which enhanced spacing consistency and minimized stress concentrations. This modification reduced peak PD to values within acceptable limits in all phases. Additionally, improved insulation uniformity through optimized production processes contributed to more consistent Q_{Ave} values and an even stress distribution across the insulation system.

These changes successfully restored the stator's performance to meet the theoretical ignition energy requirements, confirming the effectiveness of the implemented adjustments. These findings highlight how critical it is to have careful attention to production detail.

D. Ignition Test

The final validation step was the ignition test conducted under a hydrogen atmosphere as described in item III.B. The applied voltage scheme during testing is shown in Fig. 7, this graphic illustrates the voltage applied over time during the complete ignition test carried out within this stator under a hydrogen atmosphere. The test followed a two-step approach, starting with the standard voltage level and then evaluating beyond its limits within the following findings:

- Three-Phase Testing: All three phases (U, V, and W) were subjected to 16.8 kV successfully. Since no ignition occurred, the insulation system was confirmed to meet the 11 kV ignition test requirement.

- Incremental Phase Testing: One of the phases has been selected to be subjected to incremental voltage increases, Phase V. In this evaluation, as shown in fig.7, the ignition occurred at 20 kV (Fig. 8 and 9), exceeding the ignition test requirement and demonstrating the insulation system's robustness.

The ignition test confirmed the stator's suitability for 11 kV applications and its potential for 13.8 kV validation.

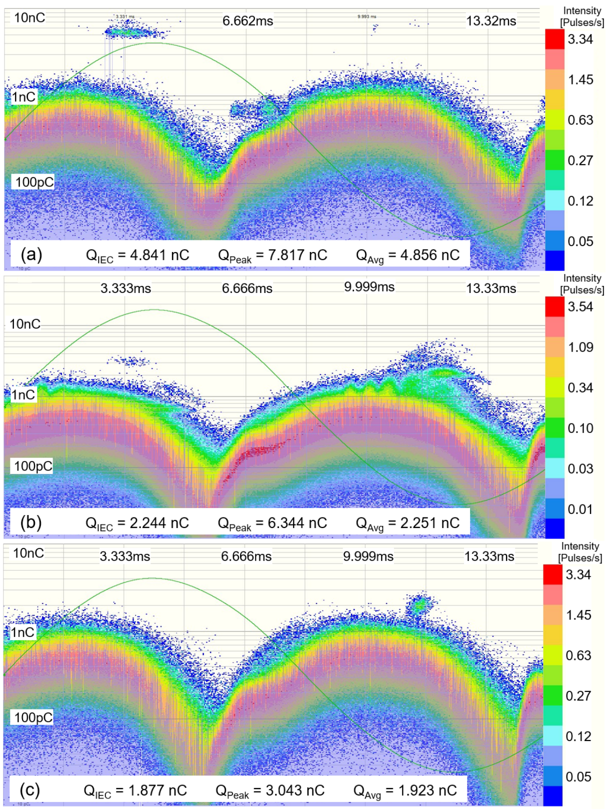

Fig. 5. PD evaluation of the stator before cable routing at 21 kV for (a) Phase U (Q_{Peak}: 7.817 nC); (b) Phase V (Q_{Peak}: 6.344 nC); (c) Phase W (Before: Q_{Peak}: 3.043 nC).

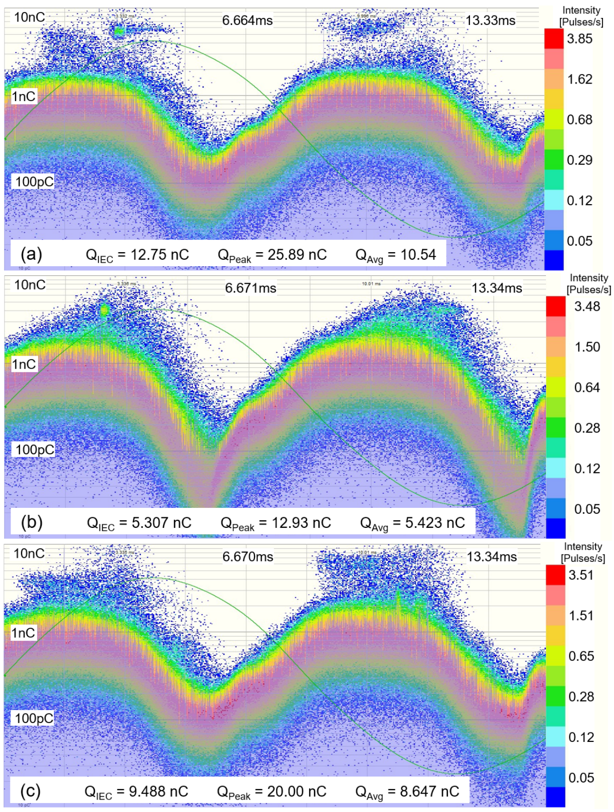

Fig. 6. PD evaluation of the stator after cable routing at 21 kV for (a) Phase U (Q_{Peak}: 25.89 nC); (b) Phase V (Q_{Peak}: 12.93 nC); (c) Phase W (Q_{Peak}: 20.00 nC);

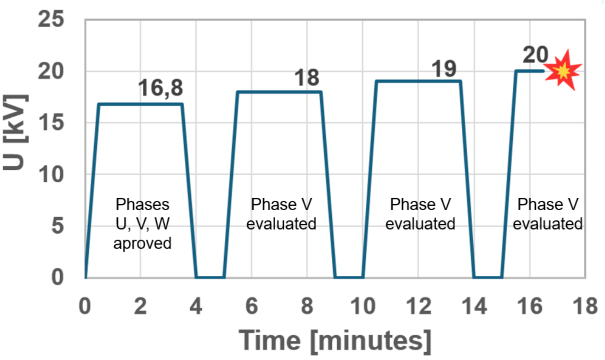

Fig. 7. Voltage scheme applied in the first ignition test of the prototype stator.

V. OPTMIZED PROTOTYPES

A. 11.0 kV and 13.8 kV Prototypes Design

The successful results of the initial prototype provided a foundation for refining insulation designs tailored to each voltage requirement. The defined insulation system has been kept for both new assembled prototypes considering minor adjustments related to the ignition test voltage.

Fig. 8. Prototype stator before ignition.

Fig. 9. First prototype stator ignition at 20.0 kV.

The clearances from the first prototype were kept for the 11 kV stator. For the 13.8 kV prototype, minimum clearances were increased by 1 mm, ensuring the insulation system's robustness under higher electrical stress. Improved layer configurations and coil-to-coil spacings contributed to the containment of electrical stress concentrations. For the 13.8 kV stator, average spacings were increased to over 10 mm, compared to 9 mm in the 11.0 kV design.

Both designs adopted standard mica insulation thicknesses from Micatherm insulation system, tailored to their respective voltage classes, which is thinner than the first prototype. Manufacturing adjustments were also critical to achieving consistent insulation quality.

B. Prototypes Electrical Evaluation

The prototypes' performance was evaluated aiming to understand the relationship between PD levels and ignition risk. **Table I** summarizes the PD results, Q_{Peak}, across key voltage levels, providing valuable insights into each prototype's performance under stress.

The results of the PD measurements during manufacturing reveal a low performance variation at each step, as seen in each Table I measurement. Before frame insertion, Fig. 10, for both types of stators, the initial PD values at operational voltage are modest. As expected, these values increase when the ignition test voltage is applied, a typical behavior, but the peak PD values remain well below the ignition threshold of ~10 nC.

TABLE I
PD RESULTS OF STATORS IN DIFFERENT MANUFACTURING STEPS

Prototype Stator	Applied Voltage (kV)	Phases PD - Q_{Peak} (nC)*		
		U	V	W
11.0 kV				
Before frame insertion	11.0	a = 2.1	b = 2.2	c = 2.9
	17.0	a X 2.7	b X 1.6	c X 2.0
Inside the frame	11.0	a X 1.0	b X 0.9	c X 0.7
	17.0	a X 1.7	b X 2.3	c X 1.6
13.8 kV				
Before frame insertion	13.8	d = 2.7	e = 2.9	f = 2.1
	21.0	d X 1.2	e x 1.3	f x 1.5
Inside the frame	13.8	d X 0.5	e X 0.9	f X 1.0
	21.0	d X 1.4	e X 1.4	f X 1.4

* Values are relative to the initial peak PD measurements of the same stator. Values "a" to "c" stand for phases U to W PD measured at 11.0kV. Values "d" to "f" are related to phases U to W of PD measured at 13.8kV, with subsequent values expressed as multiples of the initial measurement.

After the stator is inserted in the frame, Fig. 11, no major impact on PD performance is observed comparing to initial values, Table I. Even at the higher voltages (17.0 kV and 21.0 kV), PD levels remain consistent for both stators, reinforcing the reliability of the system after this step.

Overall, the results demonstrate that the manufacturing steps had a minor impact on PD levels, the data suggest that the improvements previously identified in the previous development steps, added to a well-executed manufacturing process brought up this reliable insulation performance, highlighting the effectiveness of the design and process control in achieving a high-quality stator with stable PD characteristics under operational and test voltage conditions.

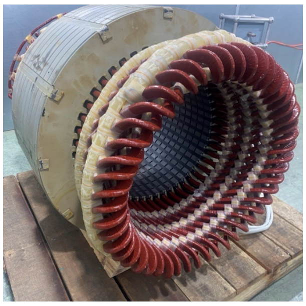

Fig. 10. 13.8 kV prototype stator before frame.

Fig. 11. 13.8 kV prototype stator inside the frame.

C. Prototypes Ignition Test

To evaluate the insulation performance and ignition thresholds of both stators, a controlled ignition test under hydrogen atmosphere was conducted at increasing voltage levels. The goal was to determine the voltage at which partial discharges (PD) escalated to critical levels, leading to ignition. The test results, summarized in **Table II**, show that the 11.0 kV stator experienced ignition at 21.0 kV after 10 seconds, while the 13.8 kV stator withstood up to 24.0 kV before ignition occurred after 30 seconds.

Ignition process, illustrated in Figs. 12 and 13, subjected the tested machines to intense mechanical, thermal, and electrical stresses. Following this test, the stators (Fig. 14) underwent a new PD assessment to evaluate the impact of these extreme conditions on their electrical performance.

Fig. 12. 13.8 kV prototype stator before ignition test.

Fig. 13. Ignition of the 13.8 kV prototype stator.

At operational voltages, even after ignition, both prototypes exhibited low peak PD levels, with values below 3 nC, as seen previously, demonstrating robust insulation performance. Within these findings the validation ignition test was carried out within these samples prior to its electrical evaluation at voltages higher than the required by standards.

TABLE II
FIRST IGNITION TEST RESULTS

Prototype Stator	Applied Voltage (kV)	Result
11 kV	17.0	Approved (3 phases)
	19.0	Approved (3 phases)
	21.0	Ignition in 10 seconds*
13.8 kV	20.8	Approved (3 phases)
	22.0	Approved (3 phases)
	24.0	Ignition in 30 seconds*

* First tested phase.

Fig. 14. Image of the ignition test area with both stators after ignition.

D. Validation

The stators then underwent the validation process involving repeating the hydrogen atmosphere ignition tests under the supervision of a certified entity. In this step both stators were positively certified presenting the results summarized in table III. The 13.8 kV stator sustained voltages up to 22.5 kV, exceeding the required 20.7 kV voltage threshold and the 11.0 kV prototype ignited at 19.0 kV, surpassing the 16.5 kV required by the standard.

The earlier ignition in the ignition test validation stage, when compared to the first test, suggests that repeated testing obviously impacted the stators. However, despite this, both stators met and exceeded ignition test requirements, highlighting the importance of precise manufacturing and insulation design to ensure long-term performance, compliant with IEC 60079-7 standards for hazardous environments.

TABLE III
IGNITION TEST RESULTS

Prototype Stator	Applied Voltage (kV)	Result
11 kV	16.8	Approved (3 phases)
	19.0	Ignition in 40 seconds*
13.8 kV	20.8	Approved (3 phases)
	22.0	Approved (3 phases)
	22.5	Immediate Ignition*

* First tested phase.

After the second ignition test, for validation, PD activity has been evaluated and observed peak PD values have significantly increased across both prototypes (**Table IV**). Data highlights a strong correlation between peak PD magnitudes and ignition thresholds:

11.0 kV Prototype: Ignition occurred at 19.0 kV, with peak PD values across all phases around 10 nC. Aligned with literature that identifies sustained discharges at or above 10nC as critical for initiating ignition process [1].

13.8 kV Prototype: Ignition observed at 22.5 kV, where peak PD values ranged between 10 to 15 nC across phases, reinforcing the association between PD activities above 10 nC and ignition in high-voltage systems.

TABLE IV
PD RESULTS OF STATORS AFTER VALIDATION

Prototype Stator	Applied Voltage (kV)	Phases PD - Q_{Peak} (nC)		
		U	V	W
11 kV	17.0	a X 1.8	b x 2.8	c x 2.2
	19.0	a X 3.6	b X 4.8	c X 2.4
	21.0	a X 6.1	b X 6.2	c X 4.4
13.8 kV	21.0	d X 2.0	e X 1.5	f X 2.0
	22.0	d X 2.7	e X 3.8	f X 4.1
	23.0	d X 4.5	e X 5.3	f X 5.7
	24.0	d X 6.0	e X 5.5	f X 7.8

* Values are relative to the initial peak PD measurements of the same stator from table I. Values range from a to f, with subsequent values expressed as multiples of the initial measurement.

Even after the second ignition tests, both stators consistently showed stable and low peak PD levels, maintaining Q_{Peak} values at the test voltage, also safely below ignition-critical thresholds. This stability is the confirmation of the impact of the insulation design advances and manufacturing standardization. Additionally, the stator successfully met IEC 60079-7 standards for high-voltage applications.

VI. CONCLUSION

The findings of this study reinforce the critical role of optimized stator insulation systems in ensuring safety and reliability in explosive atmospheres. The experimental evaluation demonstrated that strategic design and manufacture refinements, including optimized coil spacing, adjusted insulation thickness, and the use of cable separators, significantly enhanced the insulation system's performance, opposite to the insulation thickness which has not influenced the results. The improved stators exhibited lower PD activity, maintaining stable behavior even at high operational voltages, thereby reducing the risk of ignition in hazardous environments.

Furthermore, ignition tests confirmed the direct correlation between PD activity and ignition voltage, in line with established literature. The 13.8 kV stator, benefiting from increased clearances and optimized insulation design, exhibited superior voltage withstand capabilities, effectively mitigating localized electrical stress. While repeated high-voltage exposure led to a minor reduction in ignition voltage (Table III), the stators consistently surpassed the required thresholds, demonstrating the durability and reliability of the insulation system under extreme testing conditions.

These results emphasize the importance of rigorous homologation processes, experimental validation, and compliance with international safety standards such as IEC 60079-7. By thoroughly understanding the relationship between insulation system characteristics and ignition risks, manufacturers can further refine insulation designs, enhancing the safety of high-voltage equipment operating in explosive atmospheres. The insights gained from this study contribute to advancing insulation system technologies, supporting ongoing efforts to mitigate ignition hazards and improve electrical safety in critical industrial sectors.

VII. ACKNOWLEDGEMENTS

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