

Fuzzy Expert System for Condition Assessment of Medium-Voltage Distribution Cable Insulation in Saline Environments

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ABSTRACT

One cause of damage to medium-voltage cables is electrical treeing. This forms channels resembling tree branches in the cable insulation due to excessive electrical voltage. Electrical treeing can harm cable performance and cause short circuits between phase conductors. Short circuits in medium-voltage power networks increase fire risk and endanger electrical operators. This study aims to develop a non-destructive method for detecting defects in medium-voltage cables. The Arduino Mega and ESP32 microcontrollers were used because of the numerous parameters used to determine cable health and the need for a portable diagnostic tool that can be controlled from a safe distance for the user. This method enables faster damage identification, uses more accessible technology, and achieves greater accuracy through multi-parameter measurements. The research output is a prototype system that assesses the quality of medium-voltage cable insulation into six test parameters and six fuzzy rules based on mechanical and chemical data, resulting in a total of 216 unique rule combinations. The tested cable samples are assessed by an expert system with an accuracy rate of 95% from actual conditions and show a decrease in insulation quality from mechanical and electrical perspectives, which affects the distribution cable's service life.



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1. INTRODUCTION

In the electric power distribution system, medium-voltage cables play a crucial role in delivering electrical energy from substations to consumers. One of the main problems in medium-voltage cables is damage or defects in the cable insulation—an insulating layer that prevents unwanted current flow—which can degrade the quality of the electric current or even cause failure of the distribution system [1]. One cause of damage to medium-voltage cables is electrical treeing, a process that forms branching channels within the cable's insulating material due to excessively high electrical voltage [2]. This high voltage causes a breakdown of the insulation's molecular structure through a carbonization reaction, in which the material is locally converted to carbon, creating microscopic channels that lead to the surface and causing the insulation layer to shrink, as shown in Figure 1.

Damage caused by electrical treeing is often not detected early using electrical methods alone; it also requires consideration of other interrelated parameters, including mechanical stress-induced cable damage, which increases the risk of infrastructure failure, as shown in Figure 2 [3]. The time-consuming

process of monitoring mechanical failures, due to the need for specialized equipment, limits the scope of use of treeing detection technology in medium-voltage cables. To address the aforementioned issues, this study proposes several steps to develop a method for assessing medium-voltage cable defects. These include applying a Fuzzy Logic algorithm for quicker, more accurate condition prediction[4]. The method also establishes a non-destructive monitoring procedure that enables defect detection without direct intervention. Electrical test data will be clustered using fuzzy logic and correlated with other parameters, such as chemical parameters measured by Fourier Transform Infrared Spectroscopy (FTIR), which can indicate insulation damage [5].

Conventional methods for detecting defects in medium-voltage cables are generally destructive or require expensive, difficult-to-access measurement equipment[6]. This poses significant challenges, particularly in terms of cost and time efficiency for routine inspections. This research aims to develop a non-destructive method for assessing medium-voltage cable defects that identifies defects more quickly, uses more accessible technology, and achieves greater accuracy through multi-parameter measurements. Thus, this research will contribute to improving the reliability of the power distribution system and to minimizing losses caused by damage to medium-voltage cables.

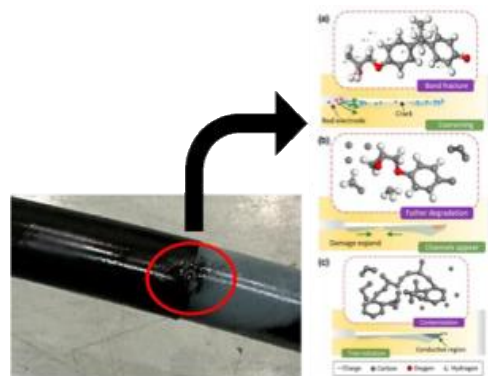


Figure 1. The beginning of the formation of electrical treeing on cable insulation

Despite significant advancements in power asset management, existing condition monitoring systems for medium voltage (MV) cables heavily rely on localized, single-source electrical diagnostics such as partial discharge (PD) or insulation resistance measurements [7]. While these standalone parameters offer valuable insights into immediate insulation defects, they often fail to capture the multi-stress aging mechanisms that simultaneously degrade the cable structure over time. Current fuzzy-based expert systems typically process these diagnostic metrics in isolation without accounting for their non-linear cross-interactions [8]. Consequently, a prominent research gap remains in establishing a unified fuzzy expert system capable of synthesizing diverse electrical parameters into a cohesive, multi-variable health index rather than relying on isolated indicators. Furthermore, the majority of conventional fuzzy logic diagnostic models are developed under controlled laboratory settings or standardized operational assumptions, largely ignoring the severe impact of site-specific environmental stressors [9]. In practical field environments—particularly in tropical, high-humidity, or coastal industrial regions—MV cables suffer from accelerated thermal, chemical, and mechanical degradation due to ambient temperature fluctuations, moisture ingress, and salinity [10]. Existing expert systems lack the necessary environmental input variables and tailored fuzzy membership functions to dynamically adjust asset health assessments based on these geographic factors.

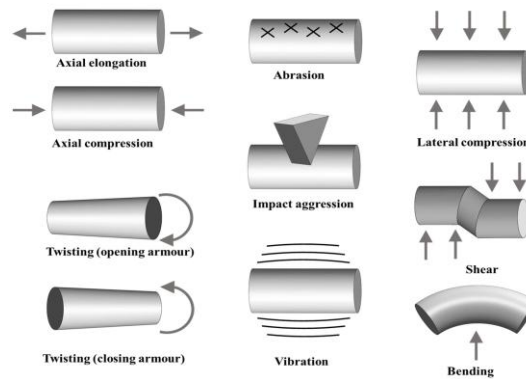


Figure 2. Variations in the form of mechanical stress on cable insulation

Previous research has examined electrical treeing in cables. For example, [11] analyzed applied voltages associated with partial discharge pulses and the effects of treeing damage on medium-voltage substation cables with SF6 gas insulation. A similar study by [12] aimed to determine the effect of insulation degradation on medium-voltage cables in offshore wind power plants. Another study on insulation degradation was conducted by [13]. This study analyzed a decrease in the insulation breakdown voltage in cables exhibiting electrical treeing, caused by their placement around a boiler pump. Research on cable insulation under mechanical stress has also been conducted by researchers [14]. Their title revealed that mechanical stress alters the morphology of the insulation network, thereby initiating electrical treeing and reducing the cable insulation voltage drop. This study will develop an expert assessment system using an Arduino Mega and an ESP32 as the main controllers to assess cable insulation condition. The system will create clusters from mechanical test data (tensile strength and degree of polymerization) and chemical test data (Fourier Transform Infrared Spectroscopy and Scanning Electron Microscopy). The study introduces an IoT-based system using an Arduino Mega, an ESP32, and a fuzzy logic algorithm to assess cable insulation using test data.

2. RESEARCH METHOD

This research is experimental, with tests based on earlier hypotheses. The process follows Figure 3 and includes: (1) planning—identify the problem, review the literature, and draft the design; (2) design and manufacturing—gather tools and materials, and create a prototype (mechanical and electrical); (3) testing—test hardware and software, then analyze results for product development; (4) finalization—use test analysis to make improvements and prepare a report or journal.

2.1. Block Diagram

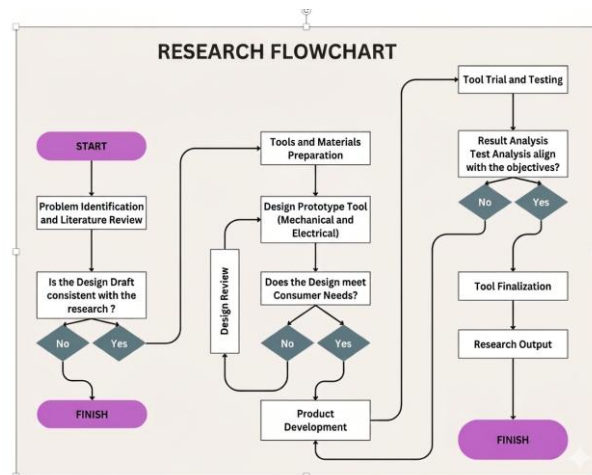


Figure 3. Block diagram

Cable specimens underwent a series of tests to create a fuzzy-logic cluster. Cable specimens underwent a series of tests as follows: first, electrical properties were evaluated using a pre-set circuit, determining the minimum partial-discharge inception voltage and the maximum breakdown voltage after electrical treeing [15]. After electrical testing, tensile strength was measured using a universal testing machine (Autograph) in the PNC Mechanical Engineering Materials Laboratory. The cable insulation specimen was cut with care to avoid defects, then its length, width, and thickness were measured as specified [16] before testing. This research uses N2XSY and A3C-S cables with XLPE insulation. These cables are commonly used for distributing load flows up to 20 kV, as shown in Table 1 below. To assess damage effects, changes in the cable insulation's chemical structure were measured. Fourier-transform infrared spectroscopy in the PNC Environmental Chemistry Laboratory revealed these changes. Scanning electron microscopy revealed microscopic defects due to reduced insulation integrity. Results were correlated with changes in molecular structure [17]. Absorption values within a specific wavelength range indicated the presence of microchannels, leading to electrical treeing and insulation failure. After testing, the data identified clusters in the fuzzy logic algorithm. Insulation quality was assessed with Arduino and ESP32 microcontrollers, and the results appeared via IoT.

Table 1. Specification of X2XSY and A3C-S cable samples.

No	Parameter	X2XSY	A3C-S
1	Conductor Diameter (mm ²)	13,1	13,9
2	Insulation Material	XLPE Insulation, Copper wire/tape screened, PVC Sheathed cable	Extruded XLPE
3	Insulation diameter thickness (mm)	5.5	3,0
4	AC Voltage Test (kV/5 min.)	42	13
5	Max. Current Carrying Capacity at 30°C (Ampere)	320	275
6	Max. DC Conductor Resistance (ohm/km)	0,153	0,438

2.2. Prototype Design

Figure 4 shows a prototype design for a medium-voltage cable insulation condition assessment system. The materials and tools needed to create a prototype of an expert system for detecting insulation quality include an Arduino Mega microcontroller, ESP 32, power supply, HFCT sensor, Rogowski coil, RTC DS3231, Nextion 2.8" LCD, Voltage Divider, 2N3094 Transistor, RC Detector, Lipo Battery, and Mini USB Connector.

The prototype test of the cable insulation condition assessment system includes physical and chemical testing. Results of physical tests, such as tensile strength, are compared with IEC 60227 or SNI 04-6629 standards. Chemical tests follow SNI 046629.3, IEC 60502-1:2009, IEC 840-1987, and SPLN 42-1 standards [18]. If requirements are not met, components are replaced with higher-specification ones to reach minimum standards. This research is conducted on a laboratory scale at the Electrical Machinery Laboratory of the Cilacap State Polytechnic. If the system works and passes lab tests, it can serve as a reference for corona-detection tools for electrical equipment in Cilacap Regency.

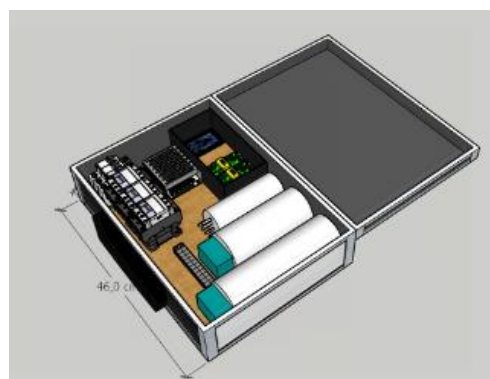


Figure 4. Prototype design

2.3. Fuzzy Clustering

Fuzzy clustering is used as a decision-making system to evaluate various test parameters against predetermined standard limits. The control program is created on a computer and then uploaded to the microcontroller. The Arduino ATmega 2560 microcontroller processes input data, stores it in memory, and uses a set of fuzzy-logic rules to determine whether equipment insulation quality has decreased. These fuzzy rules, defined in the program, establish criteria for determining when parameters indicate reduced insulation quality[19]. If the measured data exceeds the preset values, the Nextion HMI displays the cable insulation condition, the value of each parameter, and recommendations for improvement.

All parameters were then clustered to determine the condition of the cable insulation. Based on the test data, the test was conducted using six inputs: DP, Tensile Strength, CH₄ gas, C₂H₂ gas, % Transmittance, and % Adsorption. The 3x3x2x2x3x2 rule [20] was as follows:

- DP = 3 clusters
- Tensile Strength = 3 clusters
- CH₄ gas = 2 clusters
- C₂H₂ gas = 2 clusters
- % Transmittance = 3 clusters
- % Adsorption = 2 clusters

First, all parameters were tested using the same input parameters while varying membership function values. The results were used to assess the condition of the cable insulation by identifying at least 3 critical parameters that showed significant changes during testing.

3. RESULTS AND DISCUSSION

3.1. Prototype Research Product

Figure 5 illustrates a cable-damage detection prototype utilising a fuzzy-logic algorithm. The control program is developed on a computer and uploaded to a microcontroller. The Arduino ATmega 2560 receives input data, processes it, and stores it in memory. Data is evaluated against predefined fuzzy rules to determine if parameters indicate reduced insulation quality. If measured values exceed set thresholds, the Nextion HMI displays cable insulation status, parameter values, and repair recommendations.



Figure 5. Prototype research product

3.2. Degree of Polymerisation Testing

The degree of polymerisation is the number of monomer units in a polymer chain, which directly affects cellulose's mechanical strength by determining the chain length. Cellulose is a linear polymer composed of glucose units linked at the first and fourth carbon atoms by glycosidic bonds. The degree of polymerisation test was conducted at the Bandung Pulp and Paper Centre (BBPK).

The degree of polymerisation was tested using an intrinsic viscosity method, which included a capillary viscometer and cupryethylene diamine solvent. The procedure followed the ES ISO 5351 standard [21]. Measurement results are presented in Table 1.

Table 1. Degree of Polymerisation Testing

No	Sample	Aging treatment	Degree of Polymerisation
1	T0	Initial state	1909
2	T1	Temperature 120C for 336 hours	1546
3	T2	Temperature 150C for 336 hours	1133
4	T3	Temperature 120C for 672 hours	1023
5	T4	Temperature 150C for 672 hours	1012

The Degree of Polymerization (DP) is a fundamental metric that represents the average number of repeating monomer units in a polymer chain. During the operational lifecycle of an electrical cable, its insulation materials (whether traditional cellulose paper or synthetic polymers like XLPE, EPR, and PVDF) are subjected to continuous environmental and operational stressors. Over time, these stressors break down the macro-molecular chains, leading to a stark decrease in DP. The DP limit value of 200 is relevant because it corresponds to 50% of the insulation's tensile strength. Schoff demonstrated that ageing causes a decrease in DP to 250 and a reduction in tensile strength to 50% of its original value. This relationship, combined with the IEEE insulation strength limit curve, shows that a DP decrease to 200 and tensile strength reaching 50% of its original value marks the insulation's normal operating condition for 180,000 hours (20.5 years).

According to the table, the decrease in the degree of polymerisation indicates a change in the structure of the cellulose bonds in the insulation compared to its initial condition. The cellulose bonds in the insulation break under heat, forming flammable gases that degrade the insulation. The degree of polymerisation curve generally decreases, showing the same characteristic catalytic and environmental acceleration as research by [22], that declare damaged cables for synthetic polymers. The diffusion of transition copper ions from the inner conductor into the insulation matrix acts as a major catalyst that lowers the activation energy required for oxidative chain scission. In subsea cables, ingress of seawater anions similarly attacks the microstructure, causing rapid chain breakage.

3.3 Tensile Strength Testing

Tensile strength testing was conducted with an Autograph tool in the PNC Mechanical Engineering Materials Laboratory. Insulation samples were cut into uniform rectangular shapes using continuous motion to avoid defects. Sample length, width, and thickness were measured before tensile testing. After the fracture, load and elongation values from the Autograph and the fracture area were documented. Insulation service life is often marked by a reduction in tensile strength to 50% or 25% of its initial value. Test results for the tensile strength test are provided in Table 2.

Table 2. Tensile Strength Testing

No	Sample	Aging treatment	Tensile Strength (MPa/mm)
1	T0	Initial state	45,73
2	T1	Temperature 120C for 336 hours	43,55
3	T2	Temperature 150C for 336 hours	32,66
4	T3	Temperature 120C for 672 hours	29,40
5	T4	Temperature 150C for 672 hours	27,22

The test results show that the insulation sample's tensile strength decreased under both the 336-hour and 672-hour ageing conditions. This decrease means the cellulose bonds in the insulation changed, reducing its ability to maintain these bonds in the cable material. As a result, there is excessive heating and reduced insulation strength, especially the axial tensile strength.

3.4 Dissolved Gas Analysis & Fourier Transform Infrared Spectroscopy Testing

Dissolved Gas Analysis (DGA) is a test performed to detect the presence of dissolved gases resulting from temperature or environmental changes that can degrade insulation quality. The effect of thermal ageing on insulation can break down chemical bonds in the insulation. FTIR testing shows that the highest absorption peak occurs in the C-H (aliphatic) group. The graph shows a decrease in %T (% Transmittance) for the C-H (aliphatic) functional group over the wavelength range 3000-2850 cm⁻¹. A

decrease in %T indicates an increase in %Absorption [23]. An increase in %Absorption indicates an increase in the concentration of the C-H (aliphatic) functional group, which is the main component of cable insulation.

Changes in the C-H functional group are caused by the formation of combustible gas when the insulation is thermally aged. In all samples, the most dominant component, the C-H bond, breaks and combines to form a flammable gas. Table 3 shows an increase in combustible gas concentration without a corresponding increase in C-O concentration, because the C-O concentration is formed not from the breakdown of the C-H bonds of the insulation sample used, but from the cellulose paper insulation.

Table 3. Dissolved Gas Analysis Testing

Sample	Combustible Gas Concentration (ppm)					
	H ₂	CH ₄	C ₂ H ₂	C ₂ H ₄	C ₂ H ₆	CO
T0	0	0	0	0	0	0
T1	0	68,52	0	11,16	73,43	92,35
T2	0	21,74	0	29,17	45,40	94,10
T3	0	41,22	0	11,83	39,95	110,30
T4	0	267,39	0	33,45	293,14	438,15

Fourier Transform Infrared Spectroscopy (FTIR) testing was conducted to determine the effect of ageing on changes in the functional group composition of the samples. This testing was conducted at the PNC Environmental Chemistry Laboratory. All samples were tested, and the FTIR results are presented in a graph showing the percentage of infrared transmittance at specific wavelengths.

In the FTIR graph, the vertical axis, %T, represents the percentage transmittance, which is the ratio of the infrared light not absorbed by the sample to the infrared light delivered to the sample. The horizontal axis represents the wavenumber in 1/cm. The infrared region used is 4000–5001/cm, as in the Nieman reference [24].

Table 4. Dissolved Gas Analysis Testing

Sample	%Transmittance	% Absorption
T0	850,61	2,097
T1	565,14	0,161
T2	536,21	1,398
T3	441,70	3,577
T4	437,84	3,257

From Table 4, the FTIR test data result in the % Transmittance parameter, allowing us to determine the condition of the insulation sample. The accepted condition in this study was an increase in the concentration of C-H functional groups (aliphatic), which are the main components of cable insulation. Knowing that an increase in C-H functional groups will occur, it is certain that the DGA test will also show an increase in the concentration of C-H groups. This is evidenced by the test results above, which show increased concentrations of CH₄, C₂H₄, and C₂H₆.

The concentration of C-O bonds also increased, but this was not related to the increase in the concentration of C-H groups. This increase in C-O bonds may be due to changes in the cellulose bond structure in the insulation due to heating [25]. The amount of heat the insulation receives can affect the concentration of CO compounds formed. The higher the temperature and the longer the heating time, the greater the change in the cellulose bond structure in the tested insulation[26].

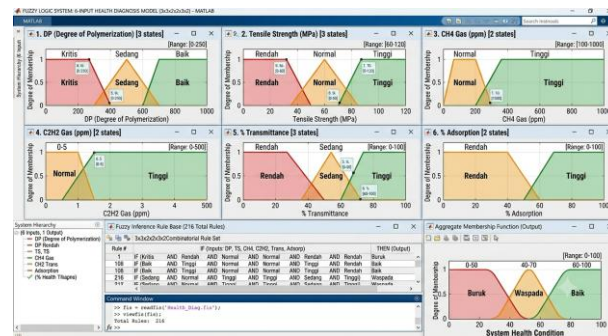


Figure 6. Fuzzy Logic Membership Function

The results of the study indicate that the prototype of the medium voltage cable insulation quality assessment system is capable of clustering various test result parameters with a total of 6 parameters and 6 fuzzy rules as shown in Figure 6. This notation dictates that the system has 6 input variables with varying numbers of membership functions (linguistic states), resulting in a total of 216 unique rule combinations. Based on the test data, the test was conducted using six inputs: DP, Tensile Strength, CH₄ gas, C₂H₂ gas, % Transmittance, and % Adsorption.

This expert system contains six parameters that can be divided into 3 parameters with three membership functions and 3 parameters with two membership functions, and mathematically, it can be achieved through a combination of multiplying the factor numbers $3 \times 3 \times 3 \times 2 \times 2 = 216$ total rules. Writing all 216 combinations out individually is redundant, so they are structured here systematically from equations (1) and (2) below:

$$R = |MF(X1)| \times |MF(X2)| \times |MF(X3)| \times |MF(X4)| \times |MF(X5)| \times |MF(X6)| \quad (1)$$

$$\text{IF } (X1 \text{ is } A1, p) \text{ AND } (X2 \text{ is } A2, q) \text{ AND } (X3 \text{ is } A3, r) \text{ AND } (X4 \text{ is } A4, s) \text{ AND } (X5 \text{ is } A5, t) \text{ AND } (X6 \text{ is } A6, u) \text{ THEN } (y \text{ is } Bk) \quad (2)$$

Equations 1 and Equation 2 are ruled for every combination, with each k rule based on the standard criteria. For example, Rule 45 uses this formula: IF Degree of Polymerization is Critical (A1,1) AND Tensile Strength is Low (A2,1) AND CH₄ Gas is Danger (A3,3) AND C₂H₂ Gas is Abnormal (A4,2) AND % Transmittance is Low (A5,1) AND % Adsorption is Saturated (A6,2) THEN Cable Health Status is Very Poor / Breakdown Risk (B45). The reasoning uses a worst-case dominance logic; for example, if PD is High and DP is Critical, the outcome naturally skews to Critical regardless of environmental factors. The Python code is uploaded to the Arduino to be evaluated against predefined fuzzy rules to determine if parameters indicate reduced insulation quality. If measured values exceed set thresholds, as shown in Figure 10, the Nextion HMI displays cable insulation status, parameter values, and repair recommendations. Recommendations were given according to the standard of each criterion, for example, tensile strength with IEC 60811-501, DP with IEC 60450, and other standards.

The tested cable samples show that the cable has experienced a decrease in insulation quality on both mechanical and electrical fronts, thereby affecting the distribution cable's service life. The ageing condition of the sample will affect the insulation strength of the material tested through a series of electrical tests, namely mechanical test data (tensile strength and degree of polymerisation) and chemical test data (Dissolved Gas Analysis (DGA) and Fourier Transform Infrared Spectroscopy (FTIR)).



Figure 7. Interfacing cable's health index

Based on the input test results, several conditions were identified that indicate the cable's health index. Table 5 clearly shows that different conditions and health index values serve as a reference for other tests and determine repair or maintenance recommendations for the tested cables, and are also directly proportional to the interfacing shown in Figure 7. The test results based on the health index are as follows:

Table 5. Cable health index

Sample	Output Fuzzy Value	Output Fuzzy Expert Condition	Recommended Action	Actual Sample Condition
T0	64,8747	Normal	Schedule regular inspections and monitoring.	New MV cable
T1	60,7776	Normal	Schedule regular inspections and monitoring.	New-aged MV cable
T2	40,5833	Poor	Inspect immediately and prepare for repairs	Damaged MV cable
T3	57,25	Normal	Schedule regular inspections and monitoring.	New-aged MV cable
T4	46,3779	Poor	Inspect immediately and prepare for repairs	Damaged MV cable

The results of the study indicate that the prototype of the medium-voltage cable insulation quality assessment system can cluster various test result parameters into 6 parameters and 6 fuzzy rules. The ageing condition of the sample will affect the insulation strength of the material tested through a series of electrical tests, as well as mechanical test data (tensile strength and degree of polymerisation) and chemical test data (Dissolved Gas Analysis (DGA) and Fourier Transform Infrared Spectroscopy (FTIR)). The tested cable samples are assessed by an expert system with an accuracy rate of 95% compared to actual conditions. This result also showed that the cable had experienced a decrease in insulation quality on both mechanical and electrical fronts, thereby affecting the service life of the distribution cable.

4. CONCLUSION

The results of the study indicate that the prototype of the medium voltage cable insulation quality assessment system is capable of clustering various test result parameters with a total of 6 parameters and 6 fuzzy rules. The tested cable samples show that the cable has experienced a decrease in insulation quality on both mechanical and electrical fronts, thereby affecting the distribution cable's service life. This study aims to develop a non-destructive method for detecting defects in medium-voltage cables. The ageing condition of the sample will affect the insulation strength of the material tested through a series of electrical tests, namely mechanical test data (tensile strength and degree of polymerisation) and chemical test data (Dissolved Gas Analysis (DGA) and Fourier Transform Infrared Spectroscopy (FTIR)).

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