APPLICATION OF ARTIFICIAL INTELLIGENCE TO THE PROBLEM OF SELECTING THE APPROPRIATE DIAGNOSTIC FOR CABLE SYSTEMS

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ABSTRACT

Cable System Management requires an assessment of the health of the cables system. It is increasingly common for the assessment of aged cable systems to be made through the application of diagnostics measurements. There are a plethora of these techniques and embodiments; such that even an informed user has great difficulty making a rational choice on the most appropriate technique. To aid this decision making a Knowledge Based System has been developed that takes the knowledge of many diverse experts and delivers a robust framework by which rational, reproducible and transparent choices may be made. This paper discusses the development of the system and provides a number of illustrative case studies.

KEYWORDS

Diagnostic Techniques, Knowledge Based Systems, Expert Systems, Artificial Intelligence

INTRODUCTION

The proactive management of cable systems (accessories and cables) is of increasing interest to utilities the world over. One of the most useful tools available in this asset management process is a diagnostic approach to estimate the "health" of the system. There are a great many diagnostic techniques that are available for many of the specific cases that a utility may encounter. However the multitude of techniques presents its own challenge to a user; the most important of which is "how to select the most appropriate diagnostic for a particular set of circumstances". The selection problem is complex because

- Not all utility systems are constructed in the same way or experience the same issues; thus prior history or peer recommendation are likely not to be useful
- The selection process requires multiple pieces of information that cannot be represented in a simple table or flow diagram.

To address these issues a Knowledge Based System (KBS) has been constructed, using Expert Systems and Fuzzy Logic, to assist utilities in selecting a short list of diagnostics that are suitable for their particular circumstances. The approach described in this paper solicits expert opinion from users, manufacturers and standardisation bodies. This knowledge is captured in databases that may then be interrogated by a user through the provision of some key information on the system to be diagnosed. The user provided input includes: the age of the cable system to be tested, the type of insulation system (PE, Paper, EPR, or hybrid combination) and likely remediation actions.

The output from the KBS is a short list of appropriate diagnostics to which the utility may apply engineering judgment to effect the final selection. The judgment process is assisted by the format of the output which provides the percentage of agreement between the contributing experts, thereby preserving the context of all the potential diagnostics. The expert recommendations are also presented with perspectives of total cost and total time required. Thus this paper will describe:

- Issues faced by diagnostic users.
- Limitations of classic approaches (flow diagrams, tables, etc).
- Available Artificial Intelligence tools including the Expert Systems & Fuzzy Logic used here.
- Challenges of acquiring expert opinion.
- Practical implementation of the methodology, including application to hybrid circuits (mixtures of EPR, Paper and PE based insulations).
- A case study where this approach was implemented successfully.

ISSUES FACED BY DIAGNOSTIC USERS

Table 1: Selection of Diagnostic Techniques proposed for MV Cable System Assessment

General Class	Implementation
Simple Withstand	DC Hipot
	VLF Hipot
Monitored Withstand	DC Hipot & Leakage
	VLF Hipot and Leakage
	VLF Hipot & Tan Delta
	VLF Hipot & Partial Discharge
Dielectric	Tan Delta
	Dielectric Spectroscopy (frequency or time domains)
	Recovery Voltage
	Leakage Current
Partial Discharge	Elevated Voltage (Offline)
	Operating Conditions (Online)
Combined	Partial Discharge and Dielectric Loss Estimation (Damped AC)

There is a wide range of cable system diagnostic testing techniques available for evaluating the condition of underground cable systems. For many of these techniques, there are also variations on the same basic technology. To determine the correct technique for a given application, an engineer should consider:

- Effectiveness – Does the technique do what is intended?
- Maturity – Has the technique been deployed long enough to assure its effectiveness? (Much of the benefit of diagnostic testing comes from a comparison with measurements on other circuits. Useful comparative data may be unavailable for immature or changing technologies/techniques).

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- Accuracy – How often does the technique deliver the correct assessment?
- Clarity – Does the technique provide an answer that is easy to understand and actionable?
- Fit – Does the technique probe the causes of the failures that afflict the cable system in service?

The selection process is further complicated by the fact that the engineer has to consider all of the points above with reference to different classes and implementations of diagnostic techniques (Table 1 shows a selection for medium Voltage (MV) cable systems [**Error! Reference source not found.**]. All of this has to be accomplished for the specific cable system architecture (composition, age, service performance etc).

CLASSIC SOLUTIONS

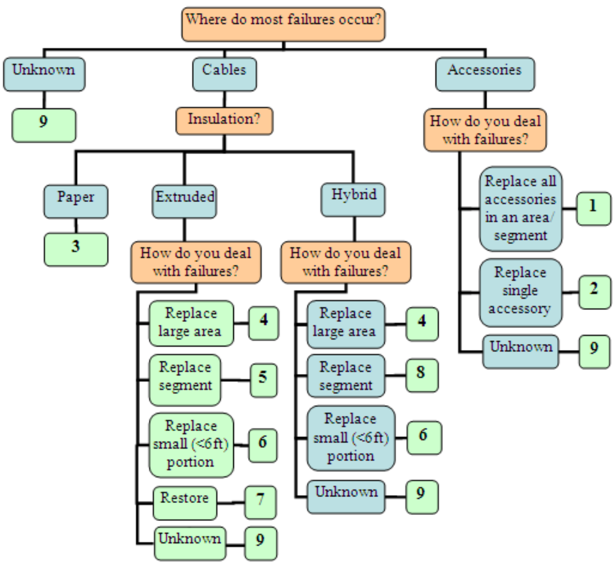

Figure 1: Example of a simplified Asset Management flowchart for selection of Diagnostic Techniques

At first sight the selection is straightforward as flow charts (Figure 1) or selection matrices (**Error! Not a valid bookmark self-reference.**) or a combination thereof could be used. However these approaches require a high level of consensus between the engineers / experts developing these representations. When attempting this route (Figure 1 and **Error! Not a valid bookmark self-reference.**) it rapidly becomes clear that the magnitude of the issues listed above (plethora of techniques & multiple dimensions for assessment) means that it is not possible to reach the requisite level of consensus. Alternatively consensus may be achieved if the classifications are extremely broad. Unfortunately these classifications are too broad to be useful.

Table 2: Potentially applicable Diagnostic Techniques for different scenarios (extract of full table)

	1	2	..	9
High Relevance	Failure History, Failure Location & Component Identification			
	VLF Withstand	Presence of PD	..	TDR for neutrals
	Monitored Withstand	PD presence	..	VLF Withstand

		& location		
Low Relevance	Presence of PD	VLF Withstand	..	

An alternate approach which is often favoured by potential users is to contact existing diagnostic users to leverage their experience. Although quite attractive this approach has a number of drawbacks:

- Existing users are often committed to single diagnostic techniques due to custom and practice issues rather than effectiveness.
- The cable system architecture and failure distribution is likely to be quite different between utilities. A recent study in the US showed that the median percentage of failures that could be ascribed to accessories is 37%; however the individual submissions ranged from 5% to 80%.
- Existing users generally have limited recent experience of the whole range of diagnostic techniques available.

To effectively compensate a user will need to contact a sufficiently diverse population of users to develop an appropriate recommendation.

As a consequence of all these issues it was decided that the most effective solution to this issue was to adopt an approach which collects a number of diverse expert inputs and then collates these such that these experiences are available to a user on demand.

ARTIFICIAL INTELLIGENCE TOOLS

Artificial Intelligence (AI) is a term that covers a wide range of techniques that attempt to mimic the human cognitive processes. The techniques that are encompassed by AI include, Neural Networks, Expert Systems, Fuzzy Logic, etc [1], [3].

When attempting to construct flowcharts for the selection of appropriate diagnostics it became clear that unanimity could not be attained but that is the vast number of cases a majority would evolve. This finding showed that the opinions of the experts working in the field did contain enough knowledge to develop a useful tool. Consequently it was determined that Fuzzy Logic would be used as the underlying technology. Expert System architectures were discounted as the input opinion data would not be sufficiently "crisp" or precise to enable this technology.
Neural Networks were also considered and it was determined that the data were amenable to the use of Neural Networks. However this approach was rejected as the authors preferred to maintain the visibility of the "knowledge" or the "rules" embedded in the expert opinions. These rules are not accessible in the Neural Network approach.

Fuzzy Logic uses inputs that are not exact but are approximate. An example of Fuzzy Logic is the classification of an acceptable room temperature. Figure 2 shows the classifications (Cold – blue, Acceptable – green, Hot – red) of four responders in the topmost portion. These responses may be considered "crisp" for temperatures in excess of 20°C as all responders considered these Hot. If the problem was formulated to determine conditions that are Hot or Not Hot, then these cases are "crisp" (complete agreement) and thus are amenable to Expert System approaches. However if higher levels of detail are required in the region below 20°C then the Fuzzy Logic approach becomes necessary. In these regions the responders' opinions on room temperature may be converted to Fuzzy Logic Membership Functions as seen in the lowermost portion.

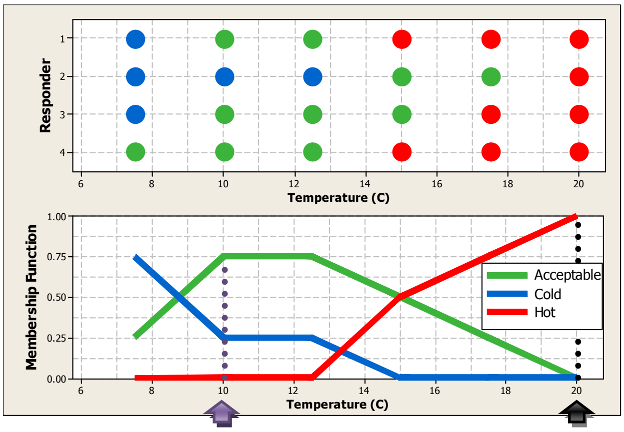

Figure 2: Example conversion of diverse responder input to Fuzzy Logic Membership Functions

The membership functions provide membership values, between 0 and 1, to each Fuzzy set (Cold, Acceptable, and Hot) and quantify the overlap between them (process known as fuzzification). Then, the membership values are applied as weighting factors to a given set of rules to compute an output response (defuzzification) [4], [5].

For example, if the following rules are considered:

If room temperature ***is*** cold ***then*** adjust thermostat by +8°C
If room temperature ***is*** acceptable ***then*** adjust thermostat by 0°C
If room temperature ***is*** hot ***then*** adjust thermostat by -8°C

The case of a room temperature equal to 10°C will trigger the first and second rules but not the third since none of the responders consider this temperature as Hot. To determine the firing strength of the first and second rules, the membership functions are used giving membership values of 0.25 and 0.75 for the Cold and Acceptable sets respectively. The output of the decision process (the adjustment in the thermostat temperature) is calculated using a weighted average approach, leading to an adjustment of +2°C (0.25·8°C + 0.75·0°C).

In the case of the selection of diagnostic techniques, Fuzzy Logic may be applied to determine the level of recommendation of a range of experts to defined scenarios. Thus the output would not be a single recommendation but a graduated scale showing the agreement between the experts; i.e. for as given scenario 80% of experts recommend diagnostic 3, whilst 65% recommend diagnostics 1 & 9.

ACQUIRING EXPERT OPINION

The process of acquiring expert opinion requires a definition of the remediation scenarios and diagnostics techniques (Table 3). These scenarios were communicated to a diverse panel of experts who responded by classifying each diagnostic technique as either: Not Recommended, Recommended, or Highly Recommended.

In addition, the experts were asked to provide their recommendation according to the configuration of the system, considering the type of insulation, age of the cable systems, and whether these were jacketed or unjacketed systems.

These findings were collated as matrices to enable efficient calculations (Table 4).

Table 3: Techniques & Remediation Scenarios

Diagnostic Techniques	DC Hipot VLF Hipot 15 minutes VLF Hipot 30 minutes VLF Hipot 60 minutes DC Withstand and Monitor VLF Withstand and Monitor Tan Delta Offline PD Online PD No Additional Diagnostic (analysis of failure history and TDR for neutrals)
Remediation Options	Replace large area Replace cable segment Replace small section (>6 ft length) Replace accessories only Liquid rejuvenation Unknown

Table 4: Example of an expert opinion matrix

Insulation	**PE-Based** (HMWPE, XLPE, WTR XLPE)					
Jacketed?	**NO**			**YES**		
Age	**Old**	**Ave**	**New**	**Old**	**Ave**	**New**
Diagnostic 1	1	2	2	3	3	1
Diagnostic 2	2	2	3	1	1	1
Diagnostic 3	1	1	3	3	3	2
…						
Diagnostic 10	2	2	2	1	3	3

* Level of recommendation: No Recommended=1, Recommended=2, or Highly Recommended=3.

Expert opinion was also collated to define the basis for the Fuzzy Logic membership functions. In this case, the age of the cable (New, Average, and Old), and the rankings for evaluating each technique in terms of total cost (Low, Medium, and High), time to perform the diagnostic test in the field, and time for results to be available (last two rankings defined in 10 discrete steps from 1: longest time, to 10: shortest time.)

The experience database has been developed from 35 separate contributors and the inputs have the following distribution:

- 29% members of Working Group IEEE ICC WGF01
- 43% from utilities
- 31% from diagnostic equipment or service providers
- 26% from other experts

The breakdown of expertise within the diagnostic equipment or service provider group (31% of the total) is:

- Dielectric Response Techniques 18%
- Partial Discharge Techniques 47%
- Withstand Techniques 35%

The contributing experts acknowledge experience of diagnostic tests on cable systems from countries that are included, but not limited to: Austria, Belgium, Canada, Germany, Luxemburg, Malaysia, Netherlands, South Africa and USA.

KBS IMPLEMENTATION

The KBS combines an Expert System and a Fuzzy Logic Analyser to interrogate the database of collated experience explained in the previous section. The output is based on the cable system information entered by the user:

- Approximate age of the cable system to be tested: 0-10, 10-20, 20-30, 30-40, 40-50, or >50 years.
- The type of insulation: PE (XLPE, PE, WTR XLPE, Paper, EPR, or Hybrid (any combination of PE, Paper, or EPR).
- Cable jacketing (jacketed or unjacketed).
- User's planned / preferred approach to remediation Replace large area, Replace cable segment, Replace small section (> 6 ft length), Replace accessories only, Liquid rejuvenation, or Unknown.

Single Cable Technology

Once the data are input to the KBS, the KBS outputs a graph showing the collated recommendations from the expert base. Figure 3 shows an example of KBS output for a 10 – 20 year old EPR Jacketed cable system where the preferred remediation approach would be to replace the accessories.

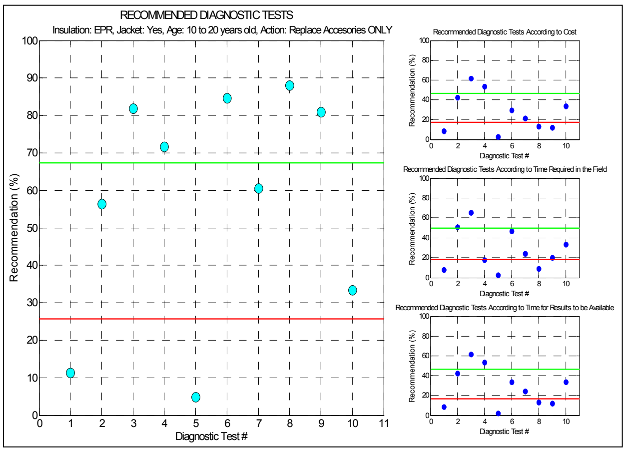

Figure 3: Example of KBS Output for Single Cable Technology

The output shows four different graphs, each of which shows the recommendations considering different constraints: purely technical (main plot), total cost (top right), time required to test in the field (center right), and time for results to be available to the user (bottom right). The data on each of these graphs show the percent of experts who recommend that the user consider each of the diagnostics considering the corresponding criterion. This case may be interpreted as; overall diagnostics 3, 6, 8 & 9 are recommended by between 70% and 80% of the experts, whereas when the constraints of cost and time are added diagnostic 3 gains the highest level of recommendation.

For simplicity, the diagnostic technologies are represented with generic designations of 1 – 10 (a reference key is provided in Table 5). This architecture makes it very straightforward to append or modify any of the techniques used. The red and green lines are statistical measures of the recommendation level and degree of agreement between diagnostics. The techniques that are above the green line are those that have strong consensus from the experts as being good choices to consider. On the other hand, techniques that are below the red line have a weak consensus and the experts do not recommend them for this application. The recommendation levels are adjusted for each scenario as the consensus between experts is not constant.

Table 5: Diagnostic Technique's Reference Key

#	Diagnostic Technique
1	DC Withstand
2	VLF Withstand – 15 Minutes
3	VLF Withstand – 30 Minutes
4	VLF Withstand – 60 Minutes
5	DC Withstand & Monitor
6	VLF Withstand & Monitor
7	Tan δ
8	PD Online
9	PD Offline
10	No Additional Diagnostic

Hybrid Cable Technology

As cable systems age it becomes very common for additional cable system technologies to be introduced; these situations are commonly described as Hybrid Systems. The most common Hybrid Systems are Paper (PILC) / EPR or Paper (PILC) / XLPE or XLPE / EPR / Paper. These situations present a dilemma for selection of diagnostics as it is not clear which of the cable technologies determines the correct diagnostic; for example DC Hipots have been used effectively for the commissioning of paper cables, however they have been proven to be detrimental to XLPE cables.

There are many solutions to this issue within a KBS framework the two that were considered in this work were:

- Resurvey experts for specific hybrid scenarios – this was not chosen as it would require a very extensive matrix of scenarios
- Use the separate insulation expert inputs and weight the expert recommendations by the size and age of the component parts – this solution was selected as it offered a very flexible arrangement for many diverse hybrid scenarios and context could be retained by comparison to the individual insulation recommendations.

To generate the hybrid cable system recommendations, the KBS requires additional information on the system in the form of:

- Percentage of each type of insulation (0-99 %).
- Approximate age of cable system for each insulation class (0-10, 10-20, 20-30, 30-40, 40-50, or >50 years).
- Failure rate for each insulation class (Low, Medium, High, or Unknown).

In this example the hybrid system composition is shown in Table 6. All the cables were jacketed. The provisional

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remedial action is to replace a whole segment. Once the required information is entered into the KBS, the first step is to generate recommendations for each individual insulation type. For each of these outputs, the KBS utilizes the type of insulation, age, jacket, and remedial action to compute the expert recommendations for the diagnostic tests.

Table 6: Hybrid Cable System Composition

Component Insulations	Composition (%)	Age	Failure Rate
EPR	25	Less than 10 years old	Low
Paper	50	More than 50 years old	High
XLPE	25	30-40 years old	Medium

The next step is to combine the outputs for each insulation type into the hybrid case. For this case, the KBS considers the percentage of each insulation type and the failure rate. The goal is to give priority to the type of insulation that makes up the largest portion of the cable system while also to taking into account its weakest link – the part of the system that is more critical and prone to fail.

The final output of the hybrid module is the weighted sum of expert opinions for all diagnostic tests (Figure 4). The individual recommendations for the component cable system designs are computed and displayed as the three side graphs: PE (top right), EPR (center right), and Paper (bottom right). The main recommendation (large figure) is estimated using a weighted contribution from these side graphs. In this case diagnostics 6 & 7 are recommended by between 85% and 95% of experts.

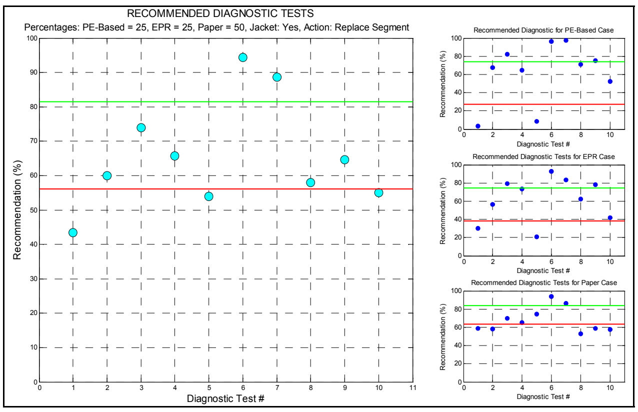

Figure 4: Example of KBS Output for Hybrid Cable Technology

CASE STUDY

A portion of a feeder cable circuit consisting of 25 kV XLPE jacketed cable, installed in the early 1980's, experienced a higher-than-normal failure rate in a six month period. These recent failures all occurred in accessories – heat-shrink joints that were likely not installed properly. The utility involved was considering either complete replacement or replacement of accessories if it could be assured that the cables were in a reasonable health.

The KBS system was utilized to determine the most appropriate diagnostic techniques; the main features of this circuit, from where the KBS inputs were extracted are:

- 1980 vintage XLPE feeder cable
- 1000 kcmil, 260 mils wall, jacketed
- Recently experienced high failure rates of splices on this section: 32 fails / 100 miles / yr
- Overall there have been 10 -15 failures of these
- Splice replacement <u>may</u> be accepted if there is a technical basis
- Test time (determined by switching) 4 - 5 Days
- Retest required after remediation to assure work had been completed satisfactorily - 1 Day

Using the Knowledge-Based System (KBS) and an Economic Model (outside the scope of this paper), the situation was analyzed to determine what routes to pursue. The KBS was used to generate a list of diagnostic tests for three corrective action scenarios. These scenarios were:

- Replace a small portion (< 6 ft)
- Replace segment
- Replace accessories only

Table 7: Summary of KBS recommendations by action scenario

Actions	Diagnostic Techniques								
	DC Withstand	VLF 15 Mins	VLF 30 Mins	VLF 60 Mins	DC Withstand and Monitor	VLF Withstand and Monitor	Tan Delta	PD Online	PD Offline
Replace Small Portion	NR	R	R	R	NR	R			R
Replace Segment	NR		R		NR	R	R		R
Replace Accessories	NR		R	R	NR	R		R	R

A summary of the KBS outputs is shown in Table 7. The colors indicate the recommendation level computed by the KBS:

- Highest recommendation level (R) – Green
- Middle recommendation level – Yellow
- Low recommendation level (NR) – Red

Based on the outputs, three diagnostic techniques received the highest recommendation level for all three of the proposed corrective action scenario:

- Very Low Frequency (VLF) Withstand - 30 Min
- Monitored VLF Withstand
- PD Offline

An economic assessment showed that all three of the above diagnostic tests could generate a benefit for the utility over the alternative of wholesale replacement.

Considering both the recommendations of the KBS and the economic analysis it was decided to use a monitored VLF withstand technique as the initial approach. The monitoring was performed using the Tan δ technique as the monitor. Subsequently a smaller portion (approx 30%) was selected to be sufficiently interesting from a Monitored Withstand point of view for PD testing. The multiple PD tests confirmed that this smaller section was worthy of remediation.

It is worthy of note that the ultimate remediation that was selected by the utility was quite different to those considered in the initial phase and its choice was influenced by the outcome of the diagnostic tests. This finding is not unusual and is not a concern for the whole process as it is valuable to have a plan when initiating a test program even if this changes at a later date. The savings of the complete program, when compared to the initially favoured utility solution, were of the order of 40%; which is approximately 8 times the cost of the complete diagnostic program (including the utility switching costs).

FUTURE CHALLENGES

The KBS described in this paper was developed to address tests as applied to aged Medium Voltage cable systems. As a consequence use over the last two years a number of challenges may be identified:

- Extension to High Voltage (HV) cable systems
- Extension to commissioning tests in addition to maintenance testing
- Incorporation of current diagnostic knowledge / experience
- Editing of the available diagnostic techniques to account for newly developed approaches and those that have fallen into disuse.

CONCLUSIONS

This paper has described how Cable System Management processes can be supported by an improved way to select the appropriate cable system diagnostic. The decision making is aided by a Knowledge Based System (KBS) that takes the knowledge of many diverse experts and delivers a robust framework by which rational, reproducible and transparent choices may be made.

The approaches for Knowledge Capture and Knowledge Management have been discussed. Examples of Single Cable Insulation and Hybrid Cable Systems are presented to demonstrate the practical implementation of this approach.

The benefits of using the KBS system are discussed in a case study of a utility experiencing a higher failure rate in a portion of a feeder cable circuit. The proposed KBS is utilized to select a short list of appropriated diagnostic techniques according to the characteristics of the cable and the possible remediation scenarios. After the suggested diagnostic tests were performed, the utility was able to select the best remediation approach for the system. This remediation approach was different from the utility's initial preferred course of action, and represented a total savings of 40% in the cost of the complete diagnostic program.

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GLOSSARY

DC: Direct Current
EPR: Ethylene Propylene Rubber
HV: High Voltage
KBS: Knowledge Based System
MV: Medium Voltage
PD: Partial Discharge
PE: Polyethylene
VLF: Very Low Frequency
XLPE: Crosslinked PE
WTR-XLPE: Water Tree Retardant XLPE

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