SELECTION OF INSULATING MATERIAL FOR POWER CABLES USING FUZZY LOGIC CLASSIFICATION

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ABSTRACT

Insulating material is very important for design and operation of electrical cables due to safety and reliability. In this study, the fuzzy logic is used to the choosing the appropriate electrical insulating material consideration their electrical properties and costs for electrical cables. Using a fuzzy system, the solution can be obtained by a very simple application in a very fast computation time.

INTRODUCTION

Power cables have been used in transmission and distribution networks since the early days of the electrical power industry. Generally, long-distance power transmission is carried out through overhead lines. However, transmission and distribution in densely populated urban areas mostly uses underground cables. Although significantly more expensive than the overhead lines, the cables preferred in urban areas due to safety, reliability and esthetical considerations.

As a result of developments in insulating materials and manufacturing techniques, high voltage cable technology has improved significantly over years. With a continuous increase in the overall length of cable networks, questions regarding reliability, failure modes and diagnostics of such cables have assumed greater significance.

Cables are constructed using different materials for conductors, insulation, screening and armoring. Electrical insulation materials are employed over the metallic conductors of underground cables at all voltage ratings. The cable insulation usually consists of impregnated paper, synthetic polymers and compressed gases. Early cables mostly used impregnated paper insulation. At present, polymers are widely used. The polymers most often used are polyvinyl chloride (PVC) and silicon rubber (SIR) for low-voltage cables; polyethylene (PE), cross-linked polyethylene (XLPE), ethylene propylene rubber (EPR) for medium-voltage cables. Each insulation type has certain advantages and disadvantages. To choose the appropriate dielectric material for the related application, the properties of insulating materials must be known. An insulating material can be identified with its properties declared below [1-3].

- Electrical properties
- Physical & chemical characteristics
- Fire and explosion hazard data
- Reactivity data
- Health hazard data
- Cost

This paper presents selection of main solid insulation materials for power cables by using a fuzzy system with decision making algorithm considering some properties above.

ELECTRICAL INSULATING MATERIALS

The most important material used in a high voltage apparatus is the insulation material. These materials provide insulation between conductors as well as insulation between earth and conductors. Cables and insulated wires are insulated with synthetic materials [4, 5] or natural rubber, power cables also with mass-impregnated paper [6]. Some insulating materials used in cables are:

PVC : Polyvinyl chloride
PE : Polyethylene
XLPE : Cross linked polyethylene
SiR : Silicon rubber
PA : Polyamide
EPR : Ethylene-propylene rubber
EPDM: Ethylene - propylene terpolymer rubber
EP : Epoxy resin
EVA : Ethylene-vinyl acetate
Paper: Craft Paper

During the last decades insulation materials have been developed, whose electrical, thermal and mechanical characteristics render them particularly suitable for the purposes they are to be employed for. It has become possible to manufacture cables, insulated wires for use under special conditions and in difficult locations. Consequently, number of insulating material to be used for power cables has increased alternatively.

Basic Electrical Properties of Solid Insulating Materials

1. Dielectric Strength: Dielectric strength is a measure of the electrical strength of a material as an insulator. It can be defined as the maximum dielectric stress, which the material can withstand. It depends on the different parameters, such as temperature, humidity, type of applied voltage, field configurations, imperfections in dielectric materials, material of conductor, and surface conditions of conductors, etc. A material having a high dielectric strength is a better insulator for safety and reliability of an electric system.

2. Dielectric Constant: Dielectric constant is the property of a material that determines capacity and dielectric loss of electrical cables, and the relative speed of an electrical signal will travel in the material. The dielectric materials have the different dielectric constant (or permittivity) values. While the gas and liquid dielectric materials have the strict values of the constant, solid dielectrics have the large range of dielectric constant values. Therefore, there is several alternatives to select the insulation material via their dielectric constants.

3. Cost Constant: The cost of the insulating material is very important factor for the power cable engineering. The less cost of material, the more preferable it is. The cost constants of the materials have been determined by investigating the power cable manufacturers' price list. In this study, a number is assigned to the each price, in order to use these prices in fuzzy logic algorithm

Some of the other properties of the electrical insulating materials are, surface resistivity, volume resistivity, electronegativity, electrical and thermal conductivity, arc resistance, water absorption and maximum operating temperature [1-3].

FUZZY MODELLING

Fuzzy sets were first subjected in 1965 by Lotfi A. Zadeh of the University of California, Berkeley. He published a paper titled 'Fuzzy Sets' in the journal on information and control [7].

For the last couple of years, fuzzy logic theory has been used large spread areas of the science and the literature on fuzzy logic has growth very rapidly. Fuzzy logic control has been the focus of interest in applications of fuzzy set theory. Management systems, pattern classification, electrostatics, power systems and reliability problems could be solved by fuzzy logic theory.

Logic can be a means to compel us to infer correct answers, but it cannot by itself be responsible for our creativity or for our ability to remember. Fuzzy logic is a method to formalize the human capacity of imprecise reasoning or approximate reasoning. In fuzzy logic all truths are partial or approximate [8, 9].

Fuzzy sets

Fuzzy Logic is a very powerful tool that can be used to deal with imprecise data. The data of a system examined is determined by the experts. Fuzzy sets have no sharp boundaries (Fig. 1a - 1b) unlike crisp sets. Fuzzy sets are represented by membership functions. An element's position within a fuzzy set is determined by the degree of belief that the element belongs to that set. Thus, a fuzzy set is uniquely characterized by a membership function expressing this support between 0 and 1. As an example in the figure 1a, the membership value of the elements x_1, x_2, x_3, x_4 of a crisp set are as the follows;

$$\mu(x_1) = \mu(x_2) = \mu(x_3) = 1, \ \mu(x_4) = 0 \quad (1)$$

In the fuzzy sets, all of the elements of the set does not have the same degree of membership value 1 like the crisp sets (Fig 1b). For example, in Fig 1, membership values of a fuzzy set can be as follows:

$$\mu(x_1) > \mu(x_2) > \mu(x_3), \quad \mu(x_1) = 1, \ \mu(x_4)=0 \quad (2)$$

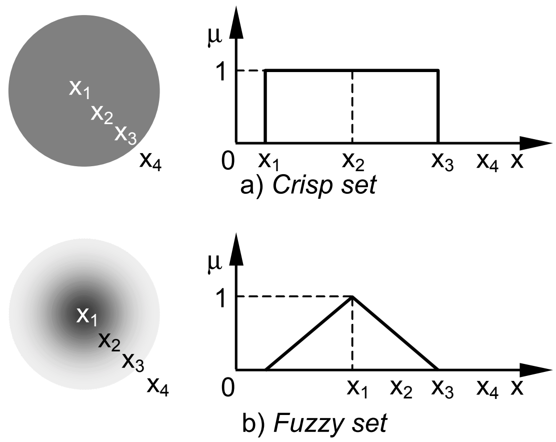

Figure 1. Representation of crisp and fuzzy sets

The membership function type is chosen by designer depending on its experience and the structure of the modeled system. There are several types of membership functions, some of them are shown in figure 2.

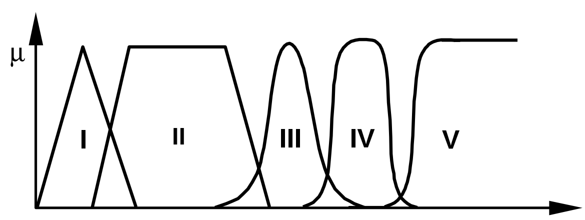

Figure 2. Types of the membership functions
I: Triangular; II: Trapezoidal; III: Gaussian; IV: Gaussian bell; V: Sigmoid.

Fuzzy modeling has some basic steps which are fuzzification of inputs, applying fuzzy operators, implication, aggregation and defuzzification. Fuzzification is the process of turning a crisp quantity into a fuzzy quantity, which is made by taking the inputs and determine the degree to which they belong to each of the appropriate fuzzy sets via membership functions. The inputs are always a crisp numerical value limited to the universe of discourse of the input variable and the output is a fuzzy degree of membership in the qualifying linguistic set (always the interval between 0 and 1). Once the inputs have been fuzzified, the degree to which each part of the antecedent has been satisfied for each rule. If the antecedent of a given rule has more than one part, the fuzzy operator is applied to obtain one number that represents the result of the antecedent for that rule. This number will then be applied to the output function. The input to the fuzzy operator is two or more membership values from fuzzified input variables. However, the aggregate of a fuzzy set encompasses a range of output values, and so must be defuzzified in order to resolve a single output value from the set.

Defuzzification is the conversion of a precise quantity to a fuzzy quantity. The output of fuzzy process can be the logical union of two or more fuzzy membership functions defined on the universe of discourse of the output variable. In the literature, many defuzzification methods are used to fuzzy modeling [8]. These are; max-membership principle, centroid method, weighted average method, mean-max membership, center of sums, center of largest area and first (or last) of maxima. In this study, weighted average method is used to defuzzification.

The underlying power of fuzzy set theory is that it uses linguistic variables, rather than quantitative variables to represent imprecise concepts. In linguistics, fundamental atomic terms are often modified with adjectives or adverbs like, very, small, big, almost, fairly, and so many more. These modifiers are called linguistic hedges [8]. Using fuzzy sets, the calculus is modified to the membership function for a basic atomic term.

FUZZY MODEL FOR CLASSIFICATION

Fuzzy logic can improve classification and decision support systems by using fuzzy sets to define overlapping class definitions. The application of fuzzy if-then rules also improves the interpretability of the results and provides more insight into classifier structure and decision making process. The fuzzy system used in this study is for classification tasks consists of the unit fuzzifications, rules base, rule composition, and defuzzification. The fuzzifications unit contains a number of membership functions for each input variable. Only conjunctive rules are used in this study.

After obtaining the fuzzy rules that can represent the set of available data, the next step is to build the hierarchy levels in the hierarchical fuzzy system [10]. Rule-based expert systems are often applied to classification problems in various application fields, like engineering, fault detection, biology and medicine.

The rule composition block uses the output of the rule base block and creates a vector of class membership values by a weighted combination of the single rule outputs. Classification rules are applied that each describes one of the N_c classes in the data set. The rule antecedent is a fuzzy description in the n-dimensional feature space and rule consequent is a crisp (non-fuzzy) class label from the set $\{1, 2, \ldots, N_c\}$

$$R_i: \text{IF } x_1 \text{ is } A_{i1} \text{ AND } \ldots\ x_n \text{ is } A_{in} \text{ THEN } g_i = p_i, \quad i = 1, 2, \ldots, M. \tag{3}$$

In equation (3), n denotes the number of features, $\vec{x} = [x_1, x_2, \ldots, x_n]^T$ is the input vector, g_i is the output of the i_{th} rule and $A_{i1}, A_{i2}, \ldots, A_{in}$ are the antecedent fuzzy sets. The AND connective is modeled by the product operator, allowing for interaction between the propositions in the antecedent. The degree of activation of the i_{th} rule is calculated as:

$$\beta_i(\vec{x}) = \prod_{j=1}^{n} \mu_{A_{ij}}(x_j) \qquad i = 1, 2, \ldots, M \tag{4}$$

where, μ_{Aij} ε [0, 1] is the membership degree of the j_{th} feature of the data pair x to A_{ij}. The certainty degree of the decision is given by the normalized degree of firing of the rule [11]:

$$z = \frac{\sum_{i=1}^{r} \beta_i(\vec{x}) g_i}{\sum_{i=1}^{r} \beta_i(\vec{x})} \tag{5}$$

APPLICATION

The properties of the power cables differs from a manufacturer from the other, therefore the cable properties are not crisp, they are fuzzy data. The fuzzy inputs are properties of materials, and the output is the type of insulating material.

In this paper, the application has been carried out with three different properties of ten insulating materials. Three properties are dielectric strength E_d, relative dielectric constant ε_r and cost constant CC. Examined ten materials are PVC, PE, XLPE, SiR, PA, EPR, EPDM, EP, EVA and paper. Properties of these materials are shown in Table 1.

TABLE - 1. The properties of the insulating materials used in cables [1, 2].

	Material	E_d (kV/cm)	ε_r	Cost Constant
1	*PVC*	110-130	8-10	3-4
2	*PE*	197-216	2.3-3	8-9
3	*XLPE*	200-250	2.1-2.6	9-10
4	*SiR*	200-250	3-6	5-6
5	*PA*	130-170	3-4	7-8
6	*EPR*	150-200	2.5-3.5	4-5
7	*EPDM*	197-315	2.5-3.5	5-6
8	*EP*	140-160	4-7	4-5
9	*EVA*	200-210	2.3-2.8	6-7
10	*Paper*	350-440	3.3-3.9	3-4

The Rules and Algorithm

The Sugeno (Singleton) implication operation is used to write the rules, and the defuzzification method is weighted average. The rules of this problem appear in the form,

IF Ed is ... AND ε_r is ... AND CC is ...
THEN the material is '...' type'

The product composition is used for 'AND' operator. In the output, a constant number (1, 2, 3, 4, 5, 6, 7, 8, 9, 10) is appointed to each material, there is no membership function to choose the output. The materials are classified according to appointed numbers.

In order to solve the problem by fuzzy logic, ten rules are written such as:

Rule 1. If (Ed is VVS) and (Eps is PS) and (CC is VS) then (the material is PVC)

Rule 2. If (Ed is M) and (Eps is PS) and (CC is VB) then (the material is PE)

Rule 3. If (Ed is VB) and (Eps is VVS) and (CC is VVB) then (the material is XLPE)

Rule 4. If (Ed is PB) and (Eps is PB) and (CC is S) then (the material is SIR)

Rule 5. If (Ed is PS) and (Eps is M) and (CC is B) then (the material is PA)

Rule 6. If (Ed is S) and (Eps is S) and (CC is PS) then (the material is EPR)

Rule 7. If (Ed is VB) and (Eps is S) and (CC is S) then (the material is EPDM)

Rule 8. If (Ed is VS) and (Eps is VB) and (CC is PS) then (the material is EP)

Rule 9. If (Ed is B) and (Eps is VS) and (CC is M) then (the material is EVA)

Rule 10. If (Ed is VVB) and (Eps is B) and (CC is VS) then (the material is Paper)

The schema of the model is shown in the Figure 3. The output variables that is obtained after defuzzification give the best material. The insulating material that has the largest output value is selected.

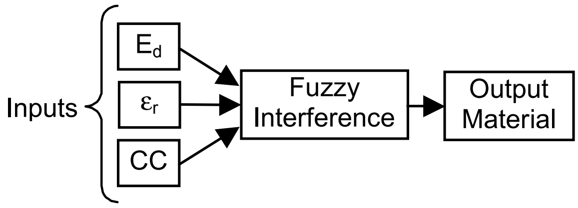

Figure 3. The fuzzy model of the problem

Membership Functions of Input and Output

The gaussian type membership functions are used for each input variables, since it is appropriate for nature of the problem. The inputs' membership functions are shown in the Fig. 4, Fig. 5 and Fig. 6, respectively. The atomic terms which are used in these figure and their analogies are as follows:

VVS : Very Very Small = $(\text{small})^4$
VS : Very Small = $(\text{small})^2$
PS : Plus Small = $(\text{small})^{1,25}$
S : Small
M : Medium
B : Big
PB : Plus Big = $(\text{big})^{1,25}$
VB : Very Big = $(\text{big})^2$
VVB : Very Very Big = $(\text{big})^4$

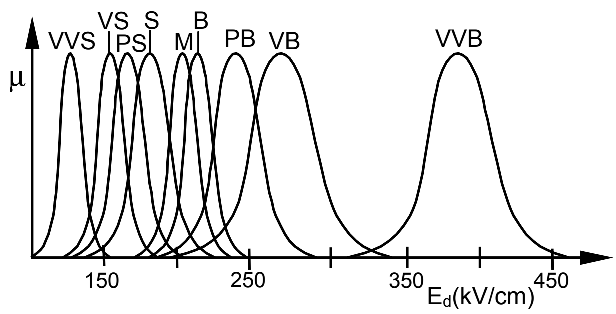

Figure 4. Membership functions of the input E_d

In the application, MATLAB fuzzy toolbox is used to solve the problem. The selection of the appropriate material is made by the fuzzy logic controller.

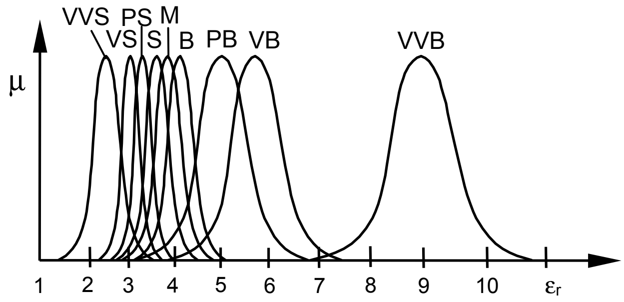

Figure 5. Membership functions of the input ε_r

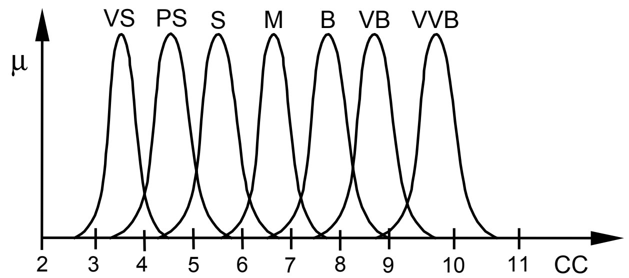

Figure 6. Membership functions of the input CC

The program could be run for different input values for choosing the appropriate insulating material. In the Table 2, examples of the program results for the different input variables are shown. These results can be expanded for different inputs.

TABLE - 2. Examples of the program results

	Ed (kV/cm)	ε_r	Cost Constant	Number	Material
1	158	9.59	3.82	1	*PVC*
2	162	5.75	4.73	8	*EP*
3	203	5.75	5.64	4	*SiR*
4	265	5.75	10	3	*XLPE*
5	186	4.33	4.27	6	*EPR*
6	381	4.33	4.27	10	*Paper*
7	144	7.77	2.36	1	*PVC*
8	189	3.32	8.55	2	*PE*
9	151	4.03	7.82	5	*PA*
10	151	4.03	4.27	8	*EP*
11	251	3.12	5.91	7	*EPDM*
12	251	5.04	5.09	4	*SiR*
13	192	2.62	6.55	9	*EVA*
14	203	3.63	7	9	*EVA*
15	374	3.63	2.64	10	*Paper*

CONCLUSION

The study shows that the material used for insulation in an electrical cable can be determined by a fuzzy system, when necessary properties of the materials are known. Fuzzy system is very efficient method for choosing insulating material and it eliminates the difficulties of decision studies. An advantage of the fuzzy system is its flexibility.

The study can be expanded to more complex problems by using different parameters. Fuzzy system can be easily applied to different problems in different areas. Simplicity of the application, consumption of significantly less computation time and highly efficient output generation makes fuzzy systems superior solution for the problems and much more preferable than the other methods for classification.

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