Dempster-Shafer 추론을 이용한 보호방식 선택

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Dempster-Shafer Reasoning in Protection Scheme Selection

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Abstract

This paper presents a preliminary study of introduction of the Dempster-Shafer inexact reasoning method to the expert system for the power system design problem. A brief review of *Dempster-Shafer theory of evidence is presented* and development of an inference engine adopting the Dempster-Shafer theory is reported. Developed inference engine has a ability of handling both the confirming and disconfirming knowledge represented in the production rule, and has a general purpose application in the design and diagnosis problems. Its applicability has been tested on *the problem of the protection scheme* selection, one of the typical design problem and we believe, it has shown the feasibility of adoption of the inexact reasoning methodology into the design problem.

I. INTRODUCTION

The design process is the recursive interaction of the activities of analysis, synthesis and evaluation. Most design problems in engineering contain multiple objectives and multiple constraints which are often conflicting and sometimes lack the well-defined goal. The designer frequently has to deal with desgins not meeting all constraints and objectives and thus often has to make the trade-off between conflicting objectives. In this decision-making process, designers' experience, engineering judgement, special knowledge on the problem domain play a major role and its computerization can benefit from the expert system approach [1,2,3].

Human expert's knowledge may be uncertain, imprecise or even vague and incomplete and thus the expert system to perform such design tasks should be able to handle the uncertain knowledge. Inexact reasoning deals with representation and manipulation of such incomplete and imperfect information. One of the major inexact reasoning *methods is the Dempster-Shafer Reasoning which is* considered a good modelling for the human cognitive process in decision making with multiple evidences [4-8].

In this paper, an inference engine adopting the Dempster-Shafer reasoning is developed and the pertinent knowledge representation to differentiate the confirming and disconfirming statements si established. Its application is illustrated through the test expert system which deals with selection of the protection scheme in transmission systems.

II. Dempster-Shafer Theory of Evidence

Dempster-Shafer theory of evidence deals with weights of evidence and numerical degrees of support based upon evidence. Its ability to model the narrowing the hypothesis set with accumulation of evidence, that characterizes the diagnostic reasoning process of human experts is well suited for the expert system requiring an *inexact reasoning.*

Let H be a set of propositions which are mutually exclusive and exhaustive in a problem domain, and P(H) be the set of all possible subsets of H. H is called the frame of discernment and elements of P(H), i.e., subsets of H, are the class of general propositions in the domain. One element subset in P(H) is called *'singleton' while a subset with more than two* elements is called compound. Note that in general the proposition or hypothesis supported by evidence could be either a singleton or a compound.

A function m:P(H) -> [0,1] is called a basic probability assignment (bpa) if it satisfies m(0) = 0 and m(A) = 1. m(A) is called A's basic probability *number which represents* the degree to which the evidence supports the hypothesis. Thus m assigns a number in the range [0,1] to every subset of H such that the numbers sum to 1. A bpa is a generalization of the traditional probability density function. The remaining belief 1-m(A) is assigned to H, representing one's ignorance.

The belief function Bel *assigns to each* subset of H a measure of a total belief in the proposition represented by the subset. The relation between two functions Bel and m can be represented by

$$Bel(A) = \sum_{B \subseteq A} m(B) \quad \text{for all } A \subseteq H$$

or

$$m(A) = \sum_{B \subseteq A} (-1)^{|A-B|} Bel(B)$$

Since m(B) is part of the measure Bel(A), but *not conversely, it follows that the total* belief in A is the sum of the exact belief in all propositions that imply A plus the exact belief in A itself. For example, when A = {h1,h2}, the corresponding total belief for A can be given as the sum of m({h1}), m({h2}) and m({h1,h2}).

Additional information can be extracted from the belief function Bel(A), namely, the plausibility denoted Pl(A) which is defined as 1 - Bel(A^c). Pl(A) represents the extent to which the evidence allows one to fail to doubt A and it is given by eq.(4)

$$Pl(A) = \sum_{A \cap B \neq 0} m(B)$$

The interval specified by [Bel(A),Pl(A)] is called 'belief interval' and its width represents a measure of the belief that is committed to neither A nor A^c, i.e., amount of uncertainty.

Consider bpa's, m1 and m2 defined on the same frame of discernment H, and their respective belief functions, Bel1 and Bel2. Then a new bpa, denoted m1*m2, which represents the combined effect of m1 and m2 is computed in the following formulation called Dempster's rule of combination.

when A ≠ 0:

$$m(A) = K^{-1} \sum_{X \cap Y = A} m_1(X)\, m_2(Y)$$

$$K = 1 - \sum_{X \cap Y = 0} m_1(X) m_2(Y) = \sum_{X \cap Y = 0} m_1(X) m_2(Y)$$

and A(0) = 0.

From eq. (5) and eq.(6), it is easy to show the following properties:

Property 1 (Commutativeness):
m1*m2 = m2*m1
Property 2 (Associativeness):
(m1*m2)*m3 = m1*(m2*m3)

These properties ensure that the rule yields the same value regardless of the order in which the functions are combined. Therefore order and grouping of combinations is immaterial. This is an important property since evidence aggregation should be independent of its gathering.

III. Protection System Design Problem

In this section, the Dempster-Shafer reasoning approach to the design problem is illustrated by taking the example from the selection problem of the protection scheme in the power systems.

1. Selection of Protection Scheme

As expansion of the power system and introduction of the ultra-high voltage, various protection schemes have been developed. As a consequence, one of the problems encountered in the power system design is the selection of the appropriate protection scheme. In practice, several fundamental factors influence the final choice. General main considerations in protection system design include [9,10]

a) Function and importance of line: effect on service continuity, realistic and practical time requirements to isolate the fault from the rest of the system.
b) Operating conditions: voltage, ampacity, fault current distribution, reclosing scheme, strength of the source, etc.
c) Type of circuit: cable, overhead, single line, parallel lines, multi-terminal, line length, etc.
d) Coordination and matching requirements: compatibility with equipment on the associated lines and systems.
e) Economic conditions: installation cost, maintenance efficiency, reliability, etc.

Because of these many considerations, it is not possible to establish firm rules or mathematical formulation for selection of the ideal scheme. In practice, it is the engineer's knowledge which plays the major role. This knowledge-based nature of the process suggests the expert system approach. As will be discussed in the following sections, this problem domain, we believe, is a good application area for Dempster-Shafer theory.

2. Reasoning Process in Selection

The first inference step in this selection problem is to construct a set of candidate schemes, which is performed based on conditions of large categories (such as transmission or distribution systems) by the experienced designers without difficulty. Then each scheme is evaluated considering various design factors and this process involves the subjective inference using the judgemental knowledge, which usually utilizes the design factors as conditions. However each piece of knowledge might suggest a different scheme with different degree of preference. Taking design factors into consideration or applying the judgemental knowldege consecutively, the designer continuously builds up his over-all relative supporting degree for each scheme. The final decision usually comes after combining the effects of all factors. Note that this process is very similar to the Dempster-Shafer inexact reasoning process. To be more specific, the process of considering design factors can be viewed as the evidence pooling process and the designer's preference on the specific scheme can be treated as his belief. Dempster's combination rule, then provides a very effective tool to combine all the effects of various design factors in a very similar way that the human expert proceeds.

3. Design Knowledge

Human expert's knowledge can generally be extracted in the form of the production rule which has a condition part and the conclusion part, and so is the knowledge involved in the selection problem of the protection scheme. The condition part consists of design factors illustrated in the previous section and the conclusion part contains the supported protection scheme. Each knowledge has its own degree of belief (or support or preference) which can be represented by a real number in the range [0,1]. Through discussions with the relay engineers and investigation of the literatures, the knowledge for the ground protection system design have been acquired and some of them are shown in the following.

R1: If the system is a subtransmission system and the required maximum fault clearing time is smaller than 20 Hz
Then the suggestion is
- distance relaying (0.6)
- definite time overcurrent relaying (0.15)

- power balancing relaying (0.15)

R2: If the system is a subtransmission system and the required maximum fault clearing time is larger than 20 Hz
Then the suggestion is
- not (distance relaying) (0.6)
- not (power balancing relaying) (0.15)

R3: If the system is a subtransmission system and it adopts a resistance grounding,
Then the suggestion is
- definite overcurrent relaying (0.6)

R4: If the system is a subtransmission system and it adopts a solid grounding and it has a loop structure
Then the suggestion is
- definite overcurrent relaying (0.35)
- distance relaying (0.4)

R5: If the system is a subtransmission system and the line is parallel circuits
Then the suggestion is
- power balancing relaying (0.8)

R6: If the system is a subtransmission system and it has a radial structure,
Then the suggestion is
- overcurrent relaying (0.8)

Following remarks can be made regarding the above rules:
1) Uncertainty associated with each piece of knowledge corresponds to a basic probability assignment in the Dempster-Shafer theory of evidence if their total sum is 1.
2) General form of the condition part is a conjunctive of multiple (usually 1 to 3) conditions.
3) Conclusion part contains multiple (usually 1 to 3) conclusions, each of which is a confirming statement or disconfirming statement.
4) Statement in the conclusion may contain the compound hypothesis as seen in rule R6.

4. Implementation

4.1 Knowledge Representation

Considering the characteristics of the design knowledge discussed in the previous section, the following PROLOG representation of a production rule has been established:

```
RULE("Ref",conditions([C1,...,Cm]),
          conclusions([pro(H1,p1),
                       against(H2,p2),
                       .....
                       pro(Hn,pn)])).
```

Here, the rule is specified using the rule head 'RULE' and similarly, the condition part by 'conditions' and the conclusion part by 'conclusions' respectively. "Ref" denotes the rule reference which is introduced for tracing of fired rules during the reasoning process. The condition part contains a list of multiple conditions, i.e., design factors. In conclusion part, in order to differentiate the confirming statement from the disconfirming statement, different representations of pro(H,p) and against(H,p), respectively are introduced, where H denotes the hypothesis, i.e., protection scheme supported by the condition part and p represents the basic probability assignment, i.e., the uncertainty level which has a value of 0 to 1. Since H can be a compound hypothesis, H has a list data structure. For example, PROLOG representation of rules R2 and R3 is as follows:

```
RULE("R2", conditions([subtransmission_system,
       maximum_clearing_time_smaller_than_20Hz]),
     conclusions([against(distance_relaying,0.6),
       against(power_balancing_relaying,0.15)])).
RULE("R3",conditions([subtransmission_system,
                       resistance_grounding]),
     conclusions([pro(definite_time_overcurrent_
            relaying,0.6)])).
```

4.2 Inference Engine

Main functions of the inference engine include selection and execution of the rule and induction of the conclusion by processing uncertainties associated with the rules. Since the final decision is made after pooling all evidence (i.e., design factors) based on the resultant total belief, the inference engine is designed to have a forward chaining control. The flowchart which illustrates the inference procedure is shown in Fig. 4. Three parts constitute the main body of the inference engine - rule selection, rule execution and conclusion induction, and each part is briefly discussed in the following.

<u>Rule Selection</u>

The inference engine has been designed in such a way that it processes the rule in a sequential order appearing in the rulebase. To be more specific, the inference engine searches a rule from the top of the rulebase in a sequential order and select one which has not been executed and whose condition part is satisfied.

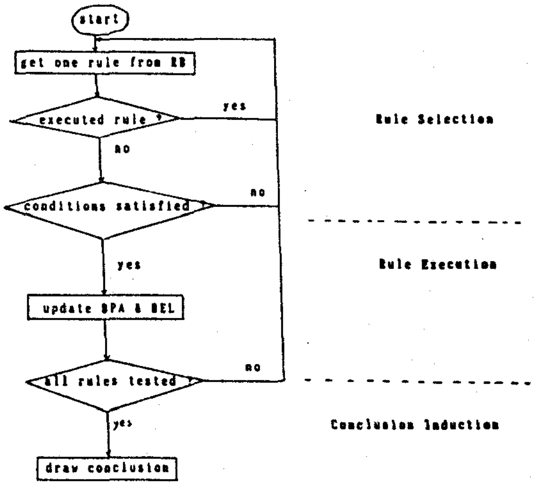

Fig.4 Inference procedure

<u>Rule Execution</u>

Main function of this part is to calculate the new belief on various hypotheses due to the evidential information identified in the rule selection stage. Computation is performed by applying the Dempster's combination rule. Rule execution consists of four parts:
a) transformation of hypothesis
b) calculation of combined bpa (BPA)
c) normalization
d) calculation of total belief (BEL)

In the Dempster-Shafer theory, if the premise disconfirms the conclusion with degree p, then it is considered as confirmation of the subset corresponding to the negation of the conclusion with the same degree in the frame of discernment. This is performed in step (a). Steps (b)-(d) implement the Dempster's combination rule explained in Sec. II. In calculating BPAs and total BELs, when the size of the frame of discernment is big, the computational burden will be quite heavy [Barnett]. Reduction of computation has been achieved in this inference engine by limiting the calculation on only those hypotheses that appear as focal elements. This is ascribed to the fact that the number of hypotheses supported by the rules is usually much smaller than the number of total elements in the hypothesis space.

Conclusion Induction

Upon completion of processing all rules based on the available evidential information, belief is distributed over all hypotheses consisting the hypothesis space and each hypothesis may be either a singleton or compound. However the general task of interest is to determine "which singleton hypothesis (e.g., protection scheme) is the most appropriate one ?". Therefore, it is needed to somehow interpret the belief distribution over the hypothesis space. The Dempster-Shafer theory does not provide any way of such interpretation. In this study, in order to derive a practical conclusion, belief assigned to a compound is assumed to be uniformly distributed over its element hypotheses (i.e., singletons). Thus by adding all beliefs assigned to the same singleton and ordering them, the singleton conclusion can be presented in an ordered fashion.

5. Test Results

A small knowledge-base containing the protection scheme selection knowledge has been constructed and the developed inference engine has been tested to determine the ground protection scheme among four different schemes - definite time overcurrent relaying, inverse time overcurrent relaying, distance relaying, power balancing relaying. The test results are given in the following.

```
< CASE 1 >

Conditions
   - solid grounding
   - loop structure
   - maximum fault clearing time < 20 Hz
   - parallel circuits

User Dialogue and Reasoning Process
Q> Is it direct_grounding ? y
   Is it loop_structure ? y
["definite_time_overcurrent_relaying"]
                    BPA = 0.35 BEL = 0.35
["distance_relaying"]
                    BPA = 0.4  BEL = 0.4
Q>Is                                        it
maximum_fault_clearing_time_smaller_than_20hz ? y
["power_balance_relaying"]          BPA  =  0.060
BEL = 0.060
["definite_time_overcurrent_relaying"]
                                    BPA  =  0.202
BEL = 0.202
["distance_relaying"]                  BPA = 0.700
BEL = 0.700
Q>                    Is                    it
maximum_fault_clearing_time_larger_than_20hz ? n
Q> Is it resistor_grounding ? n
Q> Is it radial_structure ? n
Q> Is it parallel_circuits ? y
["definite_time_overcurrent_relaying"]
                                    BPA  =  0.144
BEL = 0.144
["distance_relaying"]                  BPA = 0.500
BEL = 0.500
["power_balance_relaying"]             BPA = 0.331
BEL = 0.331
!> No more rules
```

```
 Conclusions:
  1. "distance_relaying"                          BEL =
 0.500
  2. "power_balance_relaying"                     BEL =
 0.331
  3. "definite_time_overcurrent_relaying"         BEL =
 0.144
```

V. Conclusions

A design problem is a good area for application of expert systems to which however, not much research attention has been paid because of its complexity and uncertainty involved in the design knowledge. In this paper, the inexact reasoning method in the expert system is briefly reviewed and development of the inference engine adopting the Dempster-Shafer theory of evidence is reported. Established representation for the uncertain knowledge has an ability to differentiate the confirming and disconfirming statements. Developed inference engine can be utilized for to the general design problems as well as the diagnosis problems.

This paper is believed to have shown the applicability of the inexact reasoning methodology in the design problem through the test expert system dealing with the protection scheme selection problem. Further works to extend the current test system to the practical level is expected to unveil more aspects of the proposed methodology. Among them are the problem of how to get the meaningful certainty factor (or bpa) and how to handle the impreciseness or ambiguity of the condition part, i.e., design factors. Although there are many such potential difficulties, we strongly believe that the design problem can greatly benefit the expert system approach adopting the inexact reasoning method.

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IV. References

[1] J. McDermott, "R1:a rule-based configurer of computer systems", Artificial Intelligence, 19,1982,pp.135-173.

[2] J.J. Jansen et al. "ASDEP:An Expert System for Electric Power Power Plant Design", IEEE expert, Spring, 1987,pp.56-66.

[3] Seung Jae Lee and et al. "An Expert System for Setting Relays of Transmission Systems", IEEE Proc. Power Industry Computer Applications Conference, May, 1989, Seattle, U.S.A., pp. 296-302.

[4] R.R. Yager, "Reasoning with Uncertainty for Expert Systems", IJCAI, 1985, pp. 1295-1297.

[5] P.L. Bogler, "Shafer-Dempster Reasoning with Applications to Multisensor Target Identification Systems", IEEE Tr. SMC-17, No. 6, 1987, pp. 968-977.

[6] J.A. Barnett, "Computational Methods for A Mathematical Theory of Evidence", IJCAI, 1981, pp. 868-875.

[7] B.G. Buchanan, E.H. Shortliffe, Rule-Based Expert Systems, Addison Wesley, 1984.

[8] H. Prade, "A Synthetic View of Approximate Reasoning Techniques", Proc. IJCAI, 1983, pp. 130-136.

[9] Protective Relaying for Power Systems, edited by S. H. Horowitz, IEEE Press, 1980.

[10] C.R. Mason, The Art and Science of Protective Relaying, John Wiley and Sons, Inc., New York, 1956.