Protectability: An Index to Indicate Protection Level of Primary Distribution Systems

Seung-Jae Lee*, Myeon-Song Choi*, Sang-Hee Kang* and Sang-Tae Kim*

Abstract - A new method to evaluate the protection capability of distribution systems is reported in this paper. This work describes the fuzzy evaluation attributes and aggregation method of evaluation results based on a hierarchical model and the modified combination rule. An evaluation grade index called "Protectability" is proposed and is expected to be a very useful tool in defining an optimal protection and realizing the adaptive protection.

Keywords: distribution systems, power system protection, adaptive protection, protection relays, fuzzy decision making

1. Introduction

In primary distribution systems, various protective devices such as overcurrent relays, reclosers, sectionalizers, and fuses, are applied. The operating parameters of those devices ought to be carefully selected to satisfy the required protection functions, and usually setting rules acquired from years of experience are utilized. The setting rules generally have an inequality expression like "smaller than" or "larger than." For example, one setting rule for the recloser says that the minimum trip rating should be larger than 1.4 times the maximum loading and smaller than the minimum fault current. Consequently multiple feasible setting values exist, and since no clear criterion stands out for selecting the best or the most desirable one, the protection engineer relies on his intuition and empirical knowledge [1,2]. A criterion for determining which setting is better or best is strongly needed to help the relay engineers perform the setting job.

Generally the setting job assumes a fixed configuration and loading condition but, which inevitably experiences change due to the system operation such as service restoration and maintenance. A serious change might cause the protective devices to be unable to perform the required protection function. The best way to secure a high protection level is to make the protection system have an adaptive function [3]. For this adaptive function, a means to know or to evaluate the current protection capability is strongly needed. One interesting method for relay performance assessment is suggested [4]. Definition of statistical performance measures for microprocessor-based relays has been presented [5,6].

A Markov model is utilized for evaluating various elements of pilot protection schemes [7].

A number of performance indices for evaluation, design, and setting optimization for relays and protection systems have been proposed [8] that utilize multi-objective decision-making based on fuzzy logic.

Kim et al. introduce a new methodology to evaluate the protection capability and treat the problem as an evidence gathering process, taking an evaluation attribute as a piece of evidence[9].

This paper extends the work of Kim et al. All the details have been refined and completed and the modified combination rule is suggested in integrating the evaluation results. A practical application example is fully described, showing the efficiency and usefulness of the proposed method. The paper is organized as follows. Section 2 defines fuzzy evaluation levels for protection systems. In Section 3, the Dempster-Shafer (DS) Theory of Evidence is briefly reviewed and the modified Dempster's rule is proposed. Section 4 defines evaluation attributes, and Section 5 explains the hierarchical evaluation model. Finally, examples are given in Section 6.

2. Protection Level

In this study, the protection level of the power system or protection device is classified into four levels, – "Optimal", "Normal", "Alert", and "Violation" as seen in Fig. 1. Level "Normal" denotes the state that settings of a protective device are in the range that satisfies the basic protection requirements. The range is usually specified by the setting rules. Among the feasible setting values, the most desirable

---

* Next-Generation Power Technology Center Myongji University, Yongin, Korea (sjlee@mju.ac.kr, mschoi@mju.ac.kr, shkang@wh.myongji. ac.kr, jesteca@hotmail)

Received November 27, 2002 ; Accepted February 26, 2003.

settings can be defined as far as certain criteria are concerned and when the protective device has these settings, it is said to be at the "Optimal" level. If the device has settings close to the boundary values that provide some doubt of the device's protection capability, then it is said to have the "Alert" level. When the settings are far outside the normal range, so that the protection requirements can never be met, the device is said to be in the "Violation" level. As far as the protection capability of the protection system is concerned, the same four protection levels are used.

Usually the setting and coordination of the protective device attempts to achieve the "Optimal" protection level. However, since the system inevitably experiences changes in the configuration, source impedance, loading, and so on, the protection level of the system will make a transition from one level to another as depicted in Fig. 1. The protection engineers are responsible for maintaining the "Optimal" or at least "Normal" system protection level through appropriate control actions. Current development of digital computer and communication technology enables the realization of such an adaptive protection concept. To evaluate such a protection level, i.e., how well the protection requirements are satisfied, for the protective device or the protection system, evaluation criteria and evaluation methodology are required. These criteria and methodology are the main theme of this paper and are described in the following sections.

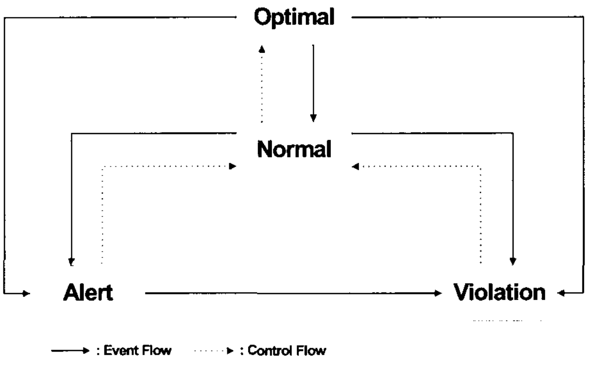


Fig. 1 Protection Level Transition Diagram

3. DS Theory-Based Evaluation

Evaluation of the protection capability involves multiple qualitative evaluation attributes that sometimes contradict each other but need to be considered simultaneously and contain uncertainty. Evaluation of the current system's or device's protection level is subjective and involves determining which level the current system belongs to as far as the protection capability is concerned and considering various evaluation factors. Therefore, this evaluation can be classified as a fuzzy measure problem that can be well handled by Dempster-Shafer's theory of evidence (simply, DS theory). DS theory mimics the human belief-building process when there are multiple pieces of evidence and each piece of evidence has its supporting degree for the different hypotheses. DS theory is well known to be suited for multi-objective decision-making problems [7].

In this study, the problem is treated as an evidence gathering process and Dempster-Shafer's theory of evidence is utilized. To be more specific, each evaluation attribute becomes a piece of evidence having a supporting degree to each protection level and each level is considered as a hypothesis. A brief explanation about DS theory is given before going into more details of the evaluation of protection capability.

3.1 Dempster-Shafer's Theory of Evidence

In the DS theory of evidence, a sample space is called a "frame of discernment," defined as ***H***, which consists of possible hypotheses. In our problem, a set of four protection levels, {Optimal (O), Normal (N), Alert (A), Violation (V)} become ***H***. To every subset *A* of ***H***, which is also a hypothesis, a probability mass or fuzzy measure denoted by m(*A*) can be assigned, which satisfies the following conditions:

$$\sum_{A \subseteq H} \mathrm{m}(A) = 1,\ \mathrm{m}(\varnothing) = 0$$

$$0 \le \mathrm{m}(A) \le 1 \text{ for all } A \subseteq \boldsymbol{H}.$$

m(*A*), called the basic probability assignment (bpa), indicates that portion of the total belief exactly committed to a hypothesis *A* given a piece of evidence (an evaluation attribute in our problem) or the degree to which the evidence supports the hypothesis. When two pieces of evidence are present, with associated bpas, m_1 and m_2, a combined bpa, $m_{1\oplus2}$, which denotes an integrated supporting degree, can be obtained by using Dempster's Rule of Combination:

$$\mathrm{m}_{1\oplus2}(C) = \sum_{A\cap B=C} \mathrm{m}_1(A)\mathrm{m}_2(B)/(1-\mathrm{K}),\ \mathrm{m}_{1\oplus2}(\varnothing) = 0 \qquad (1)$$

$$\text{where}\quad \mathrm{K} = \sum_{A\cap B=\varnothing} \mathrm{m}_1(A)\mathrm{m}_2(B), \quad \boldsymbol{A,B} \subseteq \boldsymbol{H}.$$

If another evidence provides bpa m_3, then the same combination rule is applied again to integrate $m_{1\oplus2}$ and m_3, producing a combined bpa $m_{1\oplus2\oplus3}$ that denotes the integrated supporting degree of the three pieces of evidence. The final belief or supporting degree for each hypothesis is obtained by applying this combination process until all pieces of evidence are reflected one by one.

3.2 Modified Dempster's Rule of Combination

When two pieces of evidence highly conflict with each other, Dempster's rule might generate an unreasonable result. For example, suppose two bpas are given as

$$m_1 = [0.3/H_1, 0.7/H_2, 0.0/H_3, 0.0/H_4]$$
$$m_2 = [0.0/H_1, 0.0/H_2, 0.6/H_3, 0.4/H_4].$$

In this notation, x/H_i denotes bpa x for a hypothesis H_i. Applying Dempster's rule would yield

$$m_{1\oplus2} = [0.0/H_1, 0.0/H_2, 0.0/H_3, 0.0/H_4],$$

showing no belief for any hypothesis. A modified combination rule is proposed to resolve such a problem since some evaluation attributes contradict each other in our problem. This modified combination rule first groups evidence so that each group has the same hypothesis with non-zero bpa. Then, for each group, the conventional Dempster's rule is applied. The final result is obtained using Eq. (2) instead of Eq. (1).

$$m_{1\oplus2}(Ai) = \{\, m_1(Ai) + m_2(Ai) \,\}/2 \qquad (2)$$

For the same example above, applying the modified Dempster's rule would yield

$$m_{1\oplus2} = [0.15/H1, 0.35/H2, 0.3/H3, 0.2/H4].$$

4. Evaluation Attributes

Qualitative attributes identified for the protection level evaluation can be categorized into two groups: device-wise and pair-wise. The former defines those attributes that each device should satisfy and the latter defines those that each pair of primary (or protecting) and backup (or protected) devices should satisfy for the protection coordination. The evaluation is based on the setting value, i.e., how much the setting value secures the protection function in terms of the evaluation attribute. The setting value may support more than two levels with uncertainty or fuzzy measure bpa. This fuzzy measure is determined by the fuzzy membership function associated with each evaluation attribute.

Below, evaluation attributes are enumerated together with their associated fuzzy membership function. The base membership functions for all states adopted in this study are shown in Fig. 2. Note that each one has a triangular shape where its center is named as "center(C)" and its two intersection points with neighboring functions are called "intersection (I)." Note that there are seven peak points and six intersection points in Fig. 2. The points are also called "lower (L)" or "upper (U)" depending on their position, i.e., whether they are located in the left side (L) or right side (U) of the center of the total membership function. Some points can be specified by the setting rules, some empirical knowledge, or protection and coordination principles. Setting the "center" or "intersection" point is totally subjective and requires the designer's knowledge and intuition. The rest can be determined by equally dividing the interval specified by the known values or by the designer. The fuzzy membership functions have been developed for the overcurrent relay, recloser, sectionalizer, and fuse based on their setting rules, and not all membership functions are illustrated in this paper.

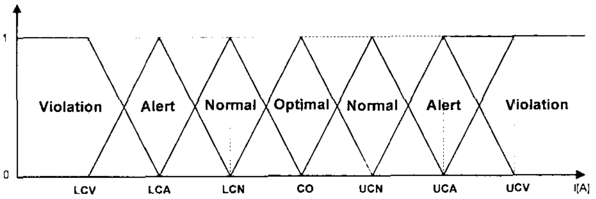


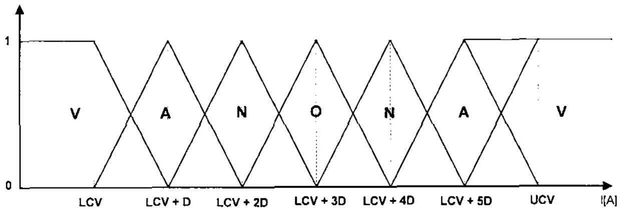
Fig. 2 Base Fuzzy Membership Functions for all States

The naming convention for each point shown in Fig. 2 is as follows. ABC(D) denotes an A (Lower or Upper) and B (Intersection or Center) point for state C (or between state C and state D). For example, UCN denotes the Upper Center point for state Normal, while LINA represents the Lower Intersection point between Normal and Alert states.

Taking the overcurrent relay case as an example, evaluation attributes and their associated fuzzy membership functions are explained in the following section.

4.1 Device-wise Attributes

Sensitivity (SEN) represents the capability of detecting any fault in the region it is supposed to protect. Its fuzzy membership function is given in Fig. 3.



D = (UCV - LCV) / 6

Fig. 3 SEN Membership Function

Since the relay should not operate due to the load current but must operate responding to the fault, its pickup current or TAP should not be smaller than the current load and not be larger than the minimum fault current (I_{mf}). Therefore, the current load becomes LPV (lower peak for violation) and the minimum fault current becomes UPV (upper peak for violation). Equal interval between the two adjacent boundaries is applied to determine other points.

High impedance fault detection (HIF) represents the capability of detecting the high impedance fault in the protection region. Since in the Korea Electric Power Corporation(KEPCO), a fault resistance of 30[Ω] is normally considered, the fuzzy membership function takes 30[Ω] as LPN is constructed as shown in Fig. 4. Other boundaries are obtained by applying the 15[Ω] step. Note that the x-axis is represented as the fault current at the corresponding fault resistance.

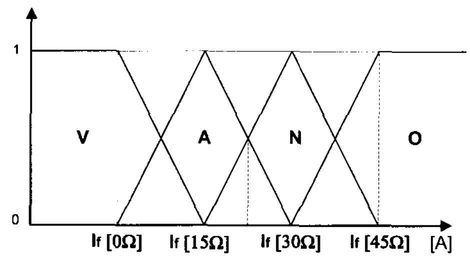


Fig. 4 HIF Membership Function

Cold load pickup (CLP) represents the capability of not operating due to the cold load and is shown in Fig. 5.

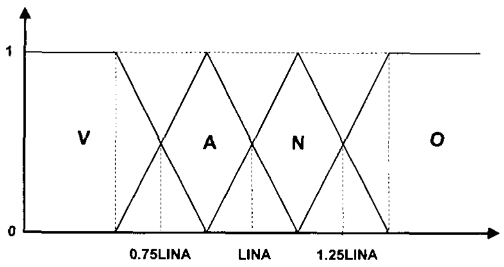


Fig. 5 CLP Membership Function

The corresponding setting rule currently used in KEPCO is that the operating time at 1.7 times TAP should be bigger than 2.5 [sec], and 2.5 seconds becomes the LINA as shown in Fig. 5. The other two extreme points are determined by taking 25% difference from this value.

Singular Device Rule (SDR) consists of the rules that are applied to a particular device or that are not included in the categories explained in the previous paragraphs. The operating time limit of an overcurrent ground relay is an example of this rule. Fig. 6 shows a membership function of the SDR for an OCGR. It has been derived from KEPCO Rule that an OCGR must operate within 2 seconds for a line-to-ground fault with fault resistance 30[Ω]. The UINA in this case becomes 2 seconds.

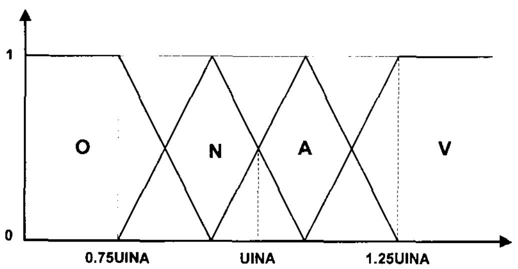


Fig. 6 SDR Membership Function for an OCGR

4.2 Pair-Wise Attributes

The coordination time interval (CTI) indicates that the primary device, D1 in Fig. 7, should interrupt the circuit before the backup device, D2 for the fault F. Based on this rule, the CTI attribute determines if enough operating time difference for coordination is secured between two adjacent devices.

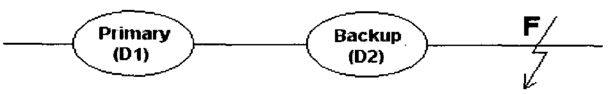


Fig. 7 Primary-Backup Pair

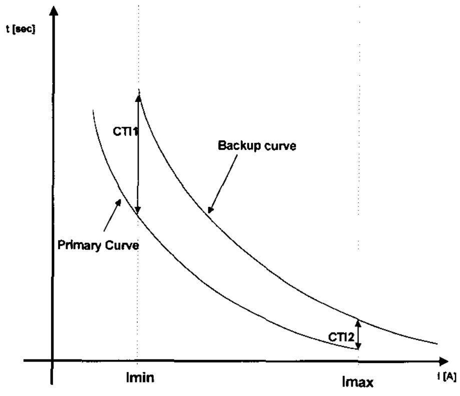


Fig. 8 Coordination Time Interval

Fig. 8 shows the coordination time interval between the primary and backup curves when a fault occurred at the primary zone. In this study, only the operating time at the maximum fault current in the primary zone is considered. Note that many combinations of devices exist in the distribution systems, and here the membership function for the relay-recloser pair is presented in Fig. 9 as an example. Its boundary is identified from the coordination rule that states

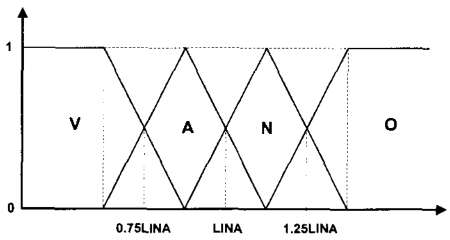


Fig. 9 The CTI Membership Function for the OCR-Recloser

that the total accumulated time of the recloser should be smaller than the relay operating time by 10 cycles, i.e., 10 cycles becomes the LINA.

Backup reach sensitivity (BRS) represents the capability of the backup device to detect the fault in the line section assigned to the primary device. In this case, the membership function is determined by the basic protection requirement that the backup device should have full coverage of the forward primary line. Consequently, the current load specifies the LPV and the minimum and maximum fault currents in the primary zone specify the PO and UPV, respectively. Fig. 10 shows the associated membership function.

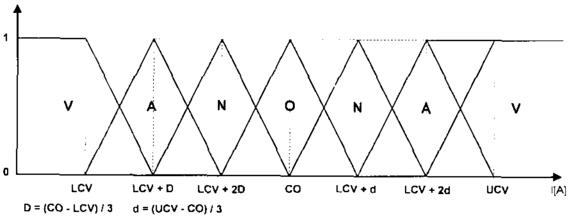
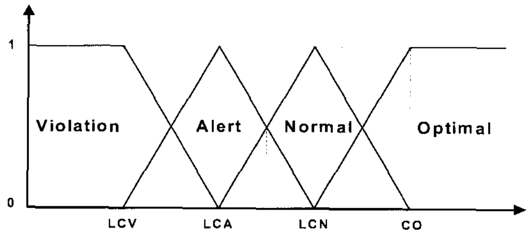


Fig. 10 Backup Reach Membership Function

The singular coordination rule (SCR) includes a rule that is the same as the one explained for the device-wise attribute case except that it is for the coordination capability. For example, in Recloser-Fuse coordination, 2F2D (2 Fast 2 Delay) is considered to be the best sequence, and 1F3D or 3F1D are the second best. Fig. 11 shows the SCR membership.



CO : 2F2D
LCA : 1F2D, 2F1D
LCN : 1F3D, 3F1D
LCV : 1F1D, 2D, 3D, 4D

Fig. 11 SCR Membership Function for Recloser-Fuse

5. Hierarchical Evaluation Model

Evaluation for the device or the system is performed according to the evaluation model established in this study as shown in Fig. 12. The evaluation model has a hierarchical structure composed of four levels: attribute, device, triple, and feeder. Evaluation starts from the attribute level and goes up to the system level, combining the evaluation results obtained from its lower level using Dempster's combination rule.

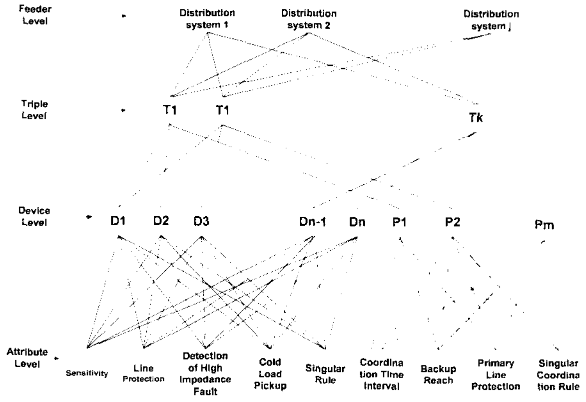


Fig. 12 Hierarchical Evaluation Model

In the attribute level, the evaluation of each qualitative attribute for a protective device and a primary-backup pair is to be carried out, and the resultant evaluation grade will be protection levels with associated bpa. Here bpa represents a supporting degree of the protection capability from the viewpoint of the single specific attribute.

Consider a feeder in Fig. 13 that has three devices (two reclosers and one relay). Note that it has two pairs: OCR-R1 and R1-R2. At the attribute level, evaluation for each device and each pair is performed, and one example is given here.

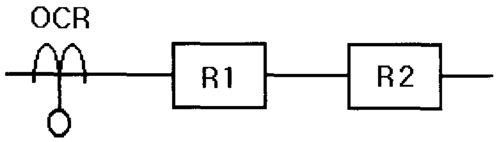


Fig. 13 A feeder with three devices

Suppose the overcurrent relay has 5 [A] TAP and 2.4 Time Dial settings. Assume that the fuzzy membership function for the sensitivity has been determined using the current load and fault current as shown in Fig. 14. Then the device can be said to have its protection capability with Normal by a degree of 0.7 and with Alert by a degree of 0.3 from the viewpoint of sensitivity. Similarly, after defining the associated fuzzy membership functions, other bpas can be obtained. Suppose they are given as follows: Normal by 0.6, Optimal by 0.4 from the HIF point of view, Normal by 0.8, and Alert by 0.2 from the CLP point of view.

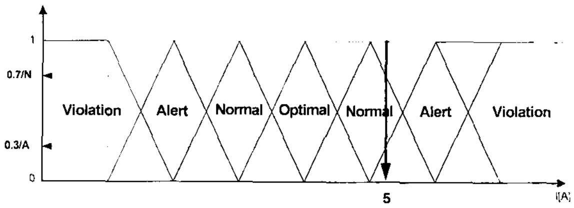


Fig. 14 SEN Membership Function for an OCR

Then evaluation result at the attribute level for an OCR can be represented as follows.

$$\begin{aligned} &A_{SEN} &&: [0.0/O,\ 0.7/N,\ 0.3/A,\ 0.0/V] \\ &A_{HIF} &&: [0.4/O,\ 0.6/N,\ 0.0/A,\ 0.0/V] \\ &A_{CLP} &&: [0.0/O,\ 0.8/N,\ 0.2/A,\ 0.0/V] \end{aligned} \tag{1}$$

Similar evaluation processes continue for other devices. Evaluation for a pair is to be performed and the evaluation result at the attribute level for an OCR-R1 pair would be given as follows.

$$\begin{aligned} &A_{CTI} &&: [0.1/O,\ 0.9/N,\ 0.0/A,\ 0.0/V] \\ &A_{BRS} &&: [0.0/O,\ 0.6/N,\ 0.4/A,\ 0.0/V] \\ &A_{SCR} &&: [0.0/O,\ 0.7/N,\ 0.3/A,\ 0.0/V] \end{aligned} \tag{2}$$

The device level deals with the evaluation of a device and a pair and involves the process of combining evaluation results given from the attribute level using the modified Dempster's Rule of Combination. One evaluation example for a device OCR is given. First, by applying Dempster's combination rule to the bpas from SEN and CLP in (1) that have the same supporting hypothesis, the combined result is given as

$$C_{SEN\oplus CLP} \quad : [0.0/O,\ 0.9/N,\ 0.1/A,\ 0.0/V].$$

Then, it is combined with the bpa of HIF, resulting in the final evaluation for OCR as

$$D_{OCR} \quad : [0.2/O,\ 0.75/N,\ 0.05/A,\ 0.0/V]. \tag{3}$$

Suppose similar processes have generated evaluation results for R1 and the pair (OCR-R1) at the device level as in (4) and (5), respectively.

$$D_{R1} \quad : [0.3/O,\ 0.7/N,\ 0.0/A,\ 0.0/V] \tag{4}$$

$$D_{OCR\text{-}R1} : [0.05/O,\ 0.84/N,\ 0.11/A,\ 0.0/V] \tag{5}$$

Now, at the triple level, a set of a pair and its comprising two devices (called "triple" in this paper) is evaluated by combining the results obtained from the device level. As an example, consider a triple of T1 that consists of two devices, OCR and R1, and a pair, OCR-R1. Its evaluation combines three evaluation results at the device level, D_{OCR}, D_{R1}, and $D_{OCR\text{-}R1}$, given in (3), (4), and (5), by applying the modified Dempster's Combination Rule and it would result in (6).

$$T_{T1} \quad : [0.01/O,\ 0.99/N,\ 0.0/A,\ 0.0/V] \tag{6}$$

Finally, evaluation for the feeder is performed at the feeder level, which is another similar process of combining evaluation results obtained from the triple level.

6. Protectability

Note that at each level, evaluation results have the same fuzzy representation, which has four fuzzy membership values for four protection levels. The numerical index called "Protectability" is introduced to defuzzify these fuzzy evaluation grades into a practical meaningful value. The defuzzication process can be carried out at each level, calculating the weighted sum of the fuzzy grades with weight of 1, 0.5, -0.5, and -1 assigned to O, N, A, and V, respectively. As an example, consider a fuzzy evaluation grade given as $E = [0.2/O,\ 0.6/N,\ 0.15/A,\ 0.05/V]$. Then its protectability is obtained by calculating $0.2\times1+0.6\times0.5+0.15\times(-0.5)+0.05\times(-1)$, which is 0.375.

7. Example

The proposed evaluation method is applied to an example system shown in Fig. 15 that has seven devices: one OCR, two reclosers, one sectionalizer, and three fuses. The maximum and minimum fault currents are circled and the load current is shown above the arrows. Two sets of setting data are shown in Table 1 and 2. Using the proposed method, we calculate the protection level of the system and determine which setting is better.

The first step of the evaluation is to identify the fuzzy membership functions based on the system data. The membership functions corresponding to R1, F1, and the R1-F1 pair are illustrated in Fig. 16 for setting data 1.

Based on these functions, the evaluation for each attribute is carried out. Since recloser R1 sees the load current of 98[A] and the minimum fault current of 287[A], its MTR setting of 140[A] would have SEN capability of 0.333 for Normal and 0.667 for Alert as can be seen in Fig.16-a. Its Tx given by (98×10)/287 or 3.414 gives X of 8, which results in 100% supporting degree for Optimal (Fig.16-b) for the CLP capability. High impedance capability is ignored for the recloser in this study because only phase elements are considered.

From Fig.16-c, fuse F1 can be seen to have SEN capability of 0.053 for Normal and 0.947 for Alert since it has a 60 A rating. For an R1,F1 pair, the coordination time of 2.15 (R1: 362 cycle, F1: 168 cycle, OT/MCT = 2.15) gives 1.0 for Optimal and zero for others (Fig.16-d). and 140 A MTR results the backup reach of 0.579 for Normal and 0.421 for Alert (Fig.16-e). Its sequence setting of 1F3D generates the singular coordination rule attribute capability

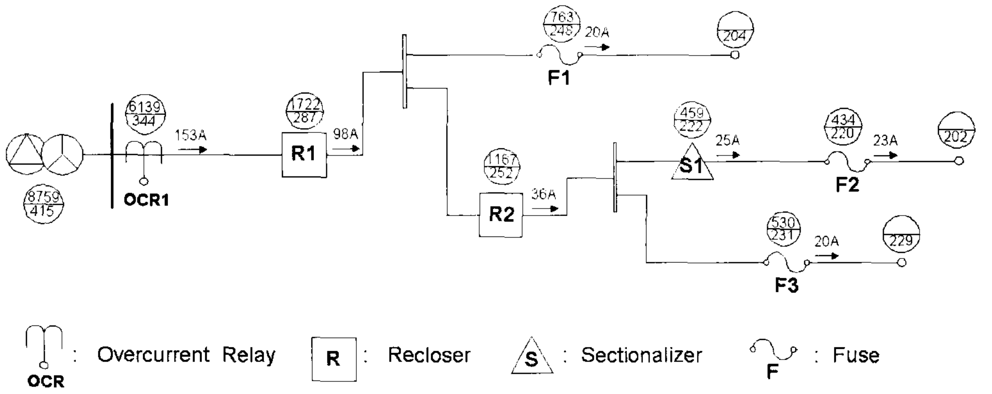


Fig. 15 Example System

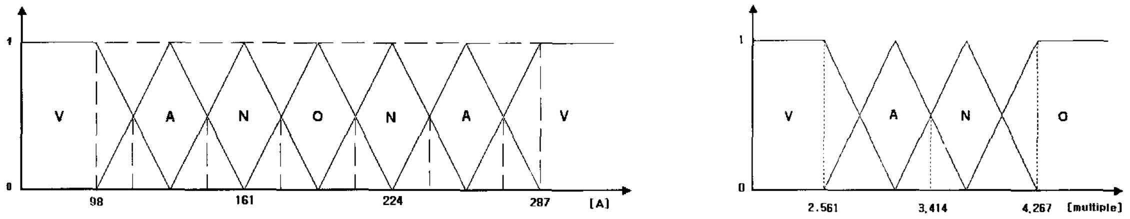
Table. 1 Setting Data: Setting 1

	OCR	R1	R2	S1	F1	F2	F3
Type	CO-9M	VWVE	VWVE	GH	T Type	T Type	T Type
Setting 1	Tap: 2.0 TD: 4 CT: 600/5	MTR: 140 Seq: 1F3D X: 8	MTR: 95 Seq: 1F3D X: 4	MAC: 76 Count: 2	MR: 60[A]	MR: 60[A]	MR: 60[A]

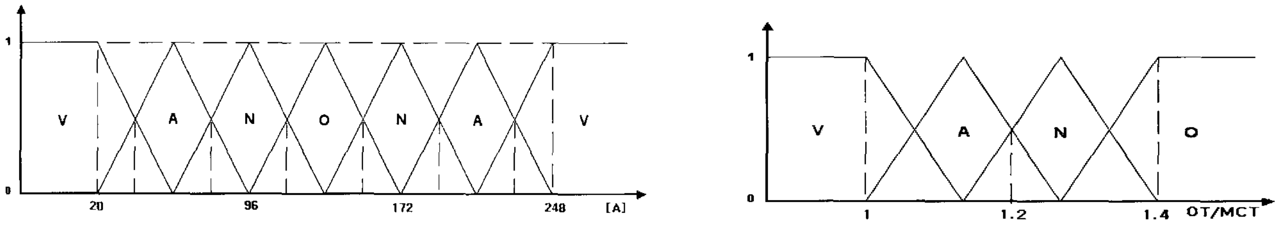
Table 2 Setting Data: Setting 2

	OCR	R1	R2	S1	F1	F2	F3
Type	CO-9M	VWVE	VWVE	GH	T Type	T Type	T Type
Setting 2	Tap: 2.0 TD: 4 CT: 600/5	MTR: 200 Seq: 1F3D X: 6	MTR: 140 Seq: 1F3D X: 4	MAC: 112 Count: 2	MR: 60[A]	MR: 60[A]	MR: 60[A]

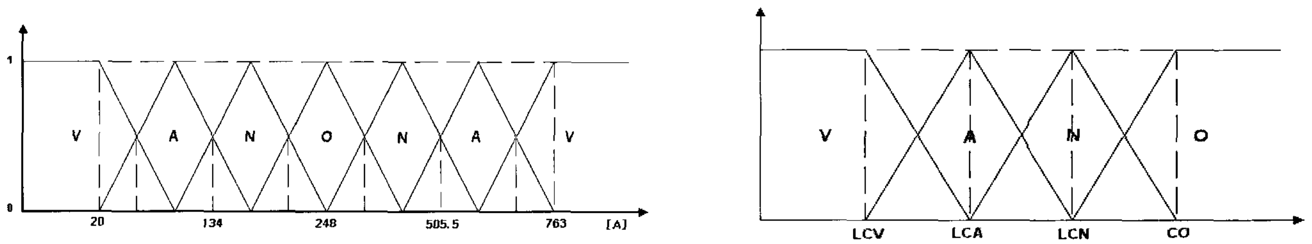
TD: time dial; MTR: minimum trip rating; MAC: minimum actuating current; MR: minimum rating; X: multiple of rated current



(a) SEN for R1 (b) CLP for R1



(c) SEN for F1 (d) CTI for R1-F1 pair



(e) BRS for R1-F1 pair (f) SCR for R1-F1 pair

Fig. 16 Membership functions for R1, F1, R1-F1 of 1.0 for Normal and zero for others. Evaluation for all attributes for all devices and pairs is carried out this way and the results are given in Table 3 for setting 1. With all these values available, the device level evaluation can now be performed. For recloser R1, the device level evaluation involves the combination of two attribute level evaluations:

SEN: [0.333/N, 0.667/A]
CLP: [1.000/O, 0.000/N].

The application of MDS would result in [0.500/O, 0.167/N, 0.334/A], which gives R1 protectability of 0.417. For fuse F1, since there is only one attribute level evaluation, illustrated in Table 5 the device level will have the same value as the attribute level. For a pair (R1-F1), the combination of three attribute level results is performed by applying MDS. Since A_{CTI}, A_{SCR}, and A_{BRS} have different supporting hypothesis, MDS results in [{1.0/3}/O, {(1.000+0.579)/3}/N, (0.421)/3]/A] or [0.333/O, 0.526/N, 0.141/A] and its protectability is given as 0.526.

Similar processes for other devices have been carried out and the evaluation results together with the corresponding protectability are summarized in Table 4. From this table, it can be said that device R2 has the best protection capability while F1 has very poor capability.

The triple level evaluation follows and results are illustrated in Table 5. Another evaluation for setting data 2 has been carried out and the results at the attribute level are given in Table 6. The other level evaluations would proceed in a same way.

Table 3 Evaluation Results for Evidence Level (Setting 1)

Device Wise	A_{SEN}	A_{CLP}	A_{SDR}
OCR	[0.733/O, 0.267/N, 0.000/A, 0.000/V]	[0.000/O, 0.020/N, 0.980/A, 0.000/V]	[1.000/O, 0.000/N, 0.000/A, 0.000/V]
R1	[0.000/O, 0.333/N, 0.667/A, 0.000/V]	[1.000/O, 0.000/N, 0.000/A, 0.000/V]	
R2	[0.639/O, 0.361/N, 0.000/A, 0.000/V]	[1.000/O, 0.000/N, 0.000/A, 0.000/V]	
S1	[0.000/O, 0.553/N, 0.447/A, 0.000/V]		
F1	[0.000/O, 0.053/N, 0.947/A, 0.000/V]		
F2	[0.000/O, 0.127/N, 0.873/A, 0.000/V]		
F3	[0.000/O, 0.137/N, 0.863/A, 0.000/V]		

Pair Wise	A_{CTI}	A_{BRS}	A_{SCR}
OCR-R1	[0.100/O, 0.900/N, 0.000/A, 0.000/V]	[0.254/O, 0.746/N, 0.000/A, 0.000/V]	
R1-R2	[0.389/O, 0.611/N, 0.000/A, 0.000/V]	[0.000/O, 0.444/N, 0.556/A, 0.000/V]	
R2-S1		[0.000/O, 0.066/N, 0.934/A, 0.000/V]	[0.000/O, 1.000/N, 0.000/A, 0.000/V]
R1-F1	[1.000/O, 0.000/N, 0.000/A, 0.000/V]	[0.000/O, 0.579/N, 0.421/A, 0.000/V]	[0.000/O, 1.000/N, 0.000/A, 0.000/V]
R2-F2	[0.000/O, 1.000/N, 0.000/A, 0.000/V]	[0.000/O, 0.096/N, 0.904/A, 0.000/V]	[0.000/O, 1.000/N, 0.000/A, 0.000/V]
R2-F3	[0.000/O, 1.000/N, 0.000/A, 0.000/V]	[0.000/O, 0.066/N, 0.934/A, 0.000/V]	[0.000/O, 1.000/N, 0.000/A, 0.000/V]

Table 4 Device Level Evaluation Results (Setting 1)

Device Wise	BPA	PI
OCR	[0.578/O, 0.096/N, 0.327/A, 0.000/V]	0.463
R1	[0.500/O, 0.167/N, 0.334/A, 0.000/V]	0.417
R2	[0.500/O, 0.320/N, 0.180/A, 0.000/V]	0.570
S1	[0.000/O, 0.553/N, 0.447/A, 0.000/V]	0.053
F1	[0.000/O, 0.053/N, 0.947/A, 0.000/V]	-0.447
F2	[0.000/O, 0.127/N, 0.873/A, 0.000/V]	-0.373
F3	[0.000/O, 0.137/N, 0.863/A, 0.000/V]	-0.363

Pair Wise	BPA	PI
OCR-R1	[0.036/O, 0.964/N, 0.000/A, 0.000/V]	0.518
R1-R2	[0.195/O, 0.528/N, 0.278/A, 0.000/V]	0.459
R2-S1	[0.000/O, 0.533/N, 0.467/A, 0.000/V]	0.033
R1-F1	[0.333/O, 0.526/N, 0.141/A, 0.000/V]	0.526
R2-F2	[0.000/O, 0.699/N, 0.301/A, 0.000/V]	0.199
R2-F3	[0.000/O, 0.689/N, 0.311/A, 0.000/V]	0.189

Table 5 Triple Level Evaluation Results (Setting 1)

Triple Set	BPA	PI
OCR, R1, OCR-R1	[0.367/HO, 0.502/HN, 0.131/HA, 0.000/V]	0.553
R1, R2, R1- R2	[0.521/HO, 0.301/HN, 0.178/HA, 0.000/V]	0.583
R2, S1, R2-S1	[0.250/HO, 0.453/HN, 0.297/HA, 0.000/V]	0.328
R1, F1, R1-F1	[0.278/HO, 0.249/HN, 0.474/HA, 0.000/V]	0.166
R2, F2, R2-F2	[0.250/HO, 0.287/HN, 0.464/HA, 0.000/V]	0.162
R2, F3, R2-F3	[0.250/HO, 0.290/HN, 0.460/HA, 0.000/V]	0.165

Table 6 Evaluation Results for Evidence Level (Setting 2)

Device Wise	A_{SS}	A_{CLP}	A_{SR}
OCR	[0.733/O, 0.267/N, 0.000/A, 0.000/V]	[0.000/O, 0.020/N, 0.980/A, 0.000/V]	[1.000O, 0.000/N, 0.000/A, 0.000/V]
R1	[0.762/O, 0.238/N, 0.000/A, 0.000/V]	[1.000/O, 0.000/N, 0.000/A, 0.000/V]	
R2	[0.556/O, 0.444/N, 0.000/A, 0.000/V]	[1.000/O, 0.000/N, 0.000/A, 0.000/V]	
S1	[0.650/O, 0.350/N, 0.000/A, 0.000/V]		
F1	[0.000/O, 0.053/N, 0.947/A, 0.000/V]		
F2	[0.000/O, 0.127/N, 0.873/A, 0.000/V]		
F3	[0.000/O, 0.137/N, 0.863/A, 0.000/V]		

Pair Wise	A_{CT}	A_{BR}	A_{SR}
OCR-R1	[1.000/O, 0.000/N, 0.000/A, 0.000/V]	[0.254/O, 0.746/N, 0.000/A, 0.000/V]	
R1-R2	[0.000/O, 0.722/N, 0.278/A, 0.000/V]	[0.278/O, 0.722/N, 0.000/A, 0.000/V]	
R2-S1		[0.056/O, 0.944/N, 0.000/A, 0.000/V]	[0.000/O, 1.000/N, 0.000/A, 0.000/V]
R1-F1	[1.000/O, 0.000/N, 0.000/A, 0.000/V]	[0.368/O, 0.632/N, 0.000/A, 0.000/V]	[0.000/O, 1.000/N, 0.000/A, 0.000/V]
R2-F2	[0.000/O, 1.000/N, 0.000/A, 0.000/V]	[0.086/O, 0.914/N, 0.000/A, 0.000/V]	[0.000/O, 1.000/N, 0.000/A, 0.000/V]
R2-F3	[0.000/O, 1.000/N, 0.000/A, 0.000/V]	[0.000/O, 0.991/N, 0.009/A, 0.000/V]	[0.000/O, 1.000/N, 0.000/A, 0.000/V]

Table 7 Final Evaluation Results

	Optimal	Normal	Alert	Violation	PI
Setting 1	0.281	0.482	0.237	0.000	0.403
Setting 2	0.286	0.712	0.002	0.000	0.641

With these results, one can get an idea of which setting gives a better protection capability for each device, pair, triple, and feeder by comparing their protectability indices. For example, since setting 1 gives R1 with protectability of 0.417 and setting 2 gives 0.941, we can say that setting 1 gives R1 better protection capability. The final feeder level evaluation results for two setting cases are shown in Table 7. The setting 2 with protectability of 0.641 gives a better overall protection capability than the setting 1 with protectability of 0.403.

8. Conclusion

This paper proposes a novel method for evaluating the protection level. Fuzzy evaluation attributes with associated fuzzy membership function have been identified and a hierachical evaluation model has been developed in this study. The basic evaluation methodology is to treat the problem as an evidence gathering process and apply Dempster's combination rule.

The proposed "Protectbility" index could be used not only for checking the capability of the protection system, but also for determining the best setting values. The authors believe that the proposed evaluation scheme will be a very useful tool in realizing adaptive protection.

Acknowledgements

The authors would like to express their sincere thanks to the Korea Ministry of Science and Technology and the Korea Science and Engineering Foundation for their support through the ERC program.

Reference

[1] S. J. Lee, Y. M. Park, J. W. Lee, "Heuristic Search in Overcurrent Protection Coordination of Power Distribution Systems," *KIEE Transaction*, Vol. 40, No. 2, Feb. 1991, pp. 135 -143.

[2] "Application and Coordination of Reclosers, Sectionalizers and Fuses," IEEE Tutorial, 1980.

[3] G. D. Rockefeller and et al., "Adaptive Transmission Relaying Concepts for Improved Performance," *IEEE Trans. on Power Delivery*, Vol. 3, No. 4, Oct. 1988, pp. 1446 -1458.

[4] F. C. Chan, "Performance Assessment and Control of Power System Relaying," *IEEE Trans. on Power Delivery*, Vol. 4, No. 2, April 1989, pp. 986 -994.

[5] E. A. Udren et al., "Proposed Statistical Performance Measures for Microprocessor-Based Transmission-Line Protective Relays. I. Explanations of the Statistics," *IEEE Trans. on Power Delivery*, Vol. 12, No. 1, Jan. 1997, pp. 134 -143.

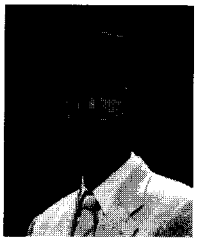
[6] E.A. Udren et al., "Proposed Statistical Performance Measures for Microprocessor-Based Transmission-Line Protective Relays. II. Collection and Uses of Data," *IEEE Trans. on Power Delivery*, Vol. 12, No. 1, Jan. 1997, pp. 144 -156.

[7] O. E. Schweitzer, III, and J. J. Kumm, "Statistical Comparison and Evaluation of Pilot Protection Schemes," *Proc.* of the 23rd Western Protective Relay Conference, 1996.

[8] M. Kezunovic and B. Kasztenny, "Design Optimization and Performance Evaluation of the Relaying Algorithms, Relays and Protective Systems Using Advanced Testing Tools," *IEEE Trans. on Power Delivery*, Vol. 15, No. 4, Oct. 2000, pp. 1129 -1135.

[9] S. T. Kim, S. J. Lee, et al., "A New Evaluation Methodology for Protection Systems of Primary Distribution Systems Considering Multi-Factors Based on Dempster's Combination Rule," *Trans. of KIEE*, Vol. 48, No. 11, 1999, pp. 1401 -1409.

[10] G. Shafer, *A Mathematical Theory of Evidence*, Princeton University Press, 1976.



Seung-Jae Lee

He received his B.E. and M.S. degrees in Electrical Engineering from Seoul National University, Korea, in 1979 and 1981, respectively. He received his Ph.D. degrees in Electrical Engineering from the University of Washington, Seattle, Washington, U.S.A., in 1988. Currently, he is a professor at Myongji University and a chief of the Next-Generation Power Technology Center (NPTC). His major research interests are protective relaying, distribution automation, and AI applications to power systems.

Tel: +82-31-330-6362, Fax: +82-31-330-6816

Myeon-Song Choi

He received his B.E., M.S., and Ph.D. degrees in Electrical Engineering from Seoul National University, Korea, in 1989, 1991, and 1996, respectively. He was a visiting scholar at the University of Pennsylvania State in 1995. Currently, he is an associate professor at Myongji University. His major research interests are power system control and protection, including artificial intelligence applications.

Tel: +82-31-330-6367, Fax: +82-31-320-6816

Sang-Hee Kang

He is an associate professor at Myongji University, Korea. He received the B.S., M.S., and Ph.D. degrees from Seoul National University, Korea, in 1985, 1987, and 1993, respectively. He was a visiting fellow and a visiting scholar at the University of Bath, UK, in 1991 and 1999. His research interest is to develop digital protection systems for power systems using digital signal processing techniques.

Tel: +82-31-330-6364, Fax: +82-31-321-0271

Sang-Tae Kim

He received his B.S. and M.S. degrees from Myongji University, Yongin, Korea, in 1996 and 1998, respectively, and he is now working toward his Ph.D. at Myongji University. His main research interest is AI applications to power transformer protection.

Tel.: +82-31-335-2068, Fax: +82-31-330-6816