A Probabilistic Method Based Protectability Evaluation of Distance Relay in Transmission Networks

Wen-Hao Zhang†, Myeon-Song Choi*, Seung-Jae Lee*, Il-Hyung Lim* and Seong-Jeong Rim*

Abstract – This paper defines the concept of "protectability" for the performance evaluation of distance relay considering its sensitivity and selectivity. The paper starts from the probabilistic modeling of the errors, and based on this model, a detailed explanation of protectability calculation for each zone of the distance relay is presented. An effect of the Weighting Rate and the Measurement Deviation on the protectability evaluation is also given. By considering this effect, the optimization of relay setting can be realized. The proposed method is applied to a typical model system to show its effectiveness

Keywords: Distance relay, Protectability evaluation, Selectivity, Sensitivity

1. Introduction

The operation of power systems highly depends on the performance of relays. However, protective relaying performance is not easily quantified. Numerous works were done on the performance evaluation of system relaying. Security, dependability, and availability were defined as performance indicators in [1] and [2], a reliability index was proposed in [3] and [4], and sensitivity in [5]. Due to a lack of relay information, evaluation could not be performed in a combined manner to pinpoint the causes of malfunction. The level ranking using fuzzy methods was proposed in [6] and [7], in which the author also agreed on the arbitrary selection for parameters.

For the transmission system, distance relay is essential. Reports on the blackout showed that because of the hidden failure of the relay system, backup distance relay mis-operation was one of the main causes [8], [9]. Many works on the adaptive distance relay setting were presented to meet the practical needs [10], [11].

"Protectability" is not a new concept. It was proposed to indicate the protection level of the system or how good the protection system is, given a certain set of settings [7], [12]. In this paper, the basic concept of protectability proposed in [7] and [13] was adopted, which is defined from totally different content by considering the measurement errors. The evaluation of the protection ability was proposed based on a probabilistic method for the distance relay. Definition and the probabilistic modeling are presented in the following Section II. A detailed illustration of the protectability calculation for each zone of distance relay is provided in Section III. Case study and relationship between protectability evaluation and optimization are addressed in Section IV. And, finally, conclusive remarks are given.

† Corresponding Author: Dept. of Electrical Engineering, Myongji University, Korea. (xiwen_ren@hotmail.com)

* Dept. of Electrical Engineering, Myongji University, Korea. (mschoi@mju.ac.kr, sjlee@mju.ac.kr, sojoo2jan@mju.ac.kr, rimsj@dreamwiz.com)

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2. Protectability Definition and Probabilistic Modeling

2.1 Protectability Definition

Protectability is an index to denote the protection level of both a single element and the whole system under current relay setting and variable system conditions. In this paper, we only consider the protectability evaluation of each zone for distance relay.

Protectability is defined including two parameters:

1) Sensitivity: the ability to operate for the fault within its protection zone. Here, we take it to describe the probability to trip correctly for the fault within its zone.
2) Selectivity: the ability not to operate for the fault without its protection zone. Here this index is considered to describe the coordination of relays.

2.2 Probabilistic Modeling

There are errors in the measurement of the apparent fault distances. These errors are a consequence of a relay's own imperfection, CT and VT inaccuracy, and line constants from imperfect modeling.

A probabilistic model for these inaccuracies was presented in [13], [14], where they were modeled by uniform probability distributions. This is a good working hypothesis, because it overweighs the errors in the extremes and the combination of a number of distributions always yields an approximate Gaussian function that is particularly good for uniform densities. The range assumed for these errors can be based on typical data.

For each zone, there is a setting distance L_S. Because of the errors, L_S has an effective reach L_R which accords with a Gaussian Probability Distribution.

$$f(L_R)=\frac{1}{\sqrt{2\pi}\sigma}\exp\left[-\frac{(L_R-L_S)^2}{2\sigma^2}\right] \tag{1}$$

where, $f(L_R)$ is the Gaussian distribution density with variable L_R, mean L_S and a deviation σ which is decided by the system condition and the measurement devices.

3. Probability Based Protectability Evaluation Method

In this section, the protectability of three zones of distance relay is evaluated individually.

3.1 Protectability Evaluation of Zone1

A. The Aim of Zone1 and Setting Rule

Zone1 of distance relay is aimed to protect its own line, and not overreach the faults beyond the ending bus.

The traditional setting adopts 80% of the line considering the measurement errors. This setting is based on the engineering experience, so a more reasonable method to obtain the setting is needed [15].

B. Sensitivity of Zone1

Sensitivity of Zone1 is defined as the correct operating degree of tripping the fault within its line.

Seen from Fig. 1, Zone1 of R1 has a setting $L1_{1S}$. Effective reach is $L1_{1R}$ according to (1), with a deviation σ_1, its probability density is:

$$f(L1_{1R})=\frac{1}{\sqrt{2\pi}\sigma_1}\exp\left[-\frac{(L1_{1R}-L1_{1S})^2}{2\sigma_1^{\,2}}\right] \tag{2}$$

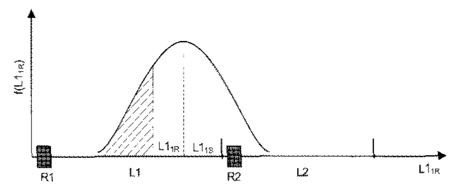

Fig. 1. Correct Trip Probability for Fault in $L1$

For an effective reach $L1_{1R}$, the fault located at $l<L1_{1R}$ (shaded area) can be tripped correctly, so the conditional probability of correct fault tripping at l can be defined by:

$$P(l\,|\,l<L1_{1R})=\int_l^{+\infty} f(L1_{1R})dL1_{1R} \tag{3}$$

Zone1 aims for correct fault tripping in $L1$, assuming that fault occurs in $L1$ with a uniform probability density. As such, fault location l is itself a random variable with probability density function $P(l)=1/L1$, whereby Zone1's sensitivity can be defined as:

$$F_1(L1_{1S})=\frac{1}{L1}\int_0^{L1} P(l\,|\,l<L1_{1R})dl \tag{4}$$

Fig. 2 represents the sensitivity changes according to setting $L1_{1S}$. With an increasing setting, the probability of all faults being tripped in $L1$ would also increase. If the setting is large enough, it tends to trip the fault at any location on $L1$. When σ_1 increases, the tendency delay increases. Here, $L1$=10km, σ_1=20%*$L1$.

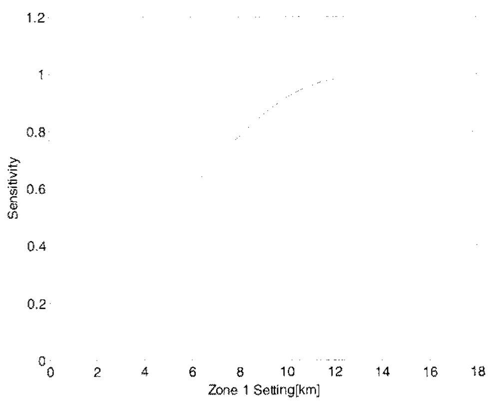

Fig. 2. Sensitivity of Zone1 with Varied Setting

C. Selectivity of Zone1

Selectivity of Zone1 is defined to denote the correct operating degree of un-tripping the fault in the neighboring lines.

For Zone1, it should not trip the fault in the neighboring lines. With setting $L1_{1S}$, for the fault at length l, Zone1 could not trip the fault when effective reach $L1_{1S} < l$. So the conditional probability of un-tripping a fault in $L2$ is:

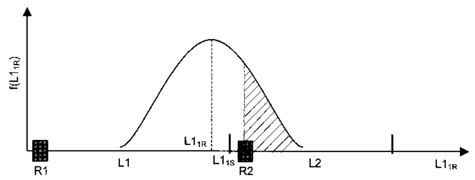

Fig. 3. Correct Un-Trip Probability for Fault in $L2$

$$P(l \mid l > L1_{1R}) = \int_0^l f(L1_{1R}) dL1_{1R} \tag{5}$$

Similarly, considering the probability of un-trip of fault in $L2$, selectivity of Zone1 is shown as:

$$F_2(L1_{1S}) = \frac{1}{L2}\int_{L1}^{L1+L2} P(l \mid l > L1_{1R}) dl \tag{6}$$

Selectivity also changes corresponding to setting, as shown in Fig. 4. With the increase of setting, selectivity would decrease to 0, which means that the probability of mis-tripping the fault in the next lines would increase. The longer the setting is, the bigger the probability of mis-tripping is. And at some length, it would totally lose its selectivity. Similarly, if σ_1 increases, the selectivity would decrease from a shorter length according to (2).

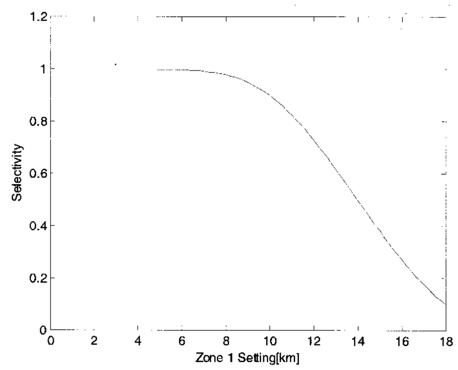

Fig. 4. Selectivity of Zone1 with Varied Setting

D. Protectability of Zone1

As explained in Section II, the objective function of protectability is given as follows:

$$F(L1_{1S}) = \omega_1 F_1(L1_{1S}) + \omega_2 F_2(L1_{1S}) \tag{7}$$

Where, $F_1(L1_{1S})$ is the sensitivity and $F_2(L1_{1S})$ is the selectivity defined by (4) and (6), respectively. In (7), ω_1 and ω_2 are the weighting factors, $\omega_1 + \omega_2 = 1$ and $K = \omega_2/\omega_1$ is defined as weighting rate. Zone2 and Zone3 also follow this definition.

Protectability $F(L1_{1S})$ is shown in Fig. 5 adopting K=4 attaching more importance to selectivity. There is a maximum protectability corresponding to an optimal setting.

According to the characteristics of sensitivity and selectivity in Figs. 2 and 4, if weighting rate K increases with fixed σ, the length with maximum protectability would move to the left since selectivity plays a greater part with a descending attribute. Fig. 6 shows the length with maximum protectability changes in accordance with weighting rate K.

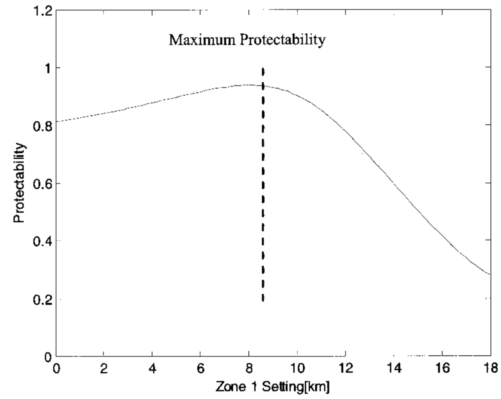

Fig. 5. Protectability of Zone1 with Varied Setting

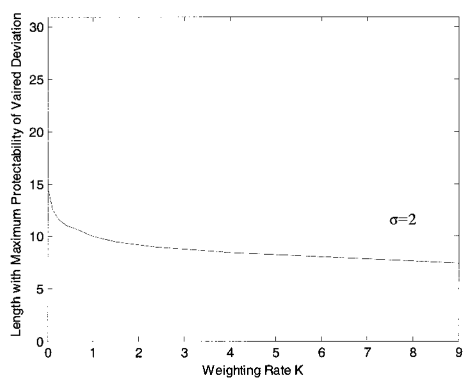

Fig. 6. Length with Maximum Protectability of Varied Weighting Rate

Furthermore, if deviation σ increases, sensitivity would increase to saturation at a longer length, and selectivity would decrease from a shorter length. In Fig. 7, K=4 indicating the need to attach more importance to the selectivity which has a descending attribute, so the length with maximum protectability would decrease.

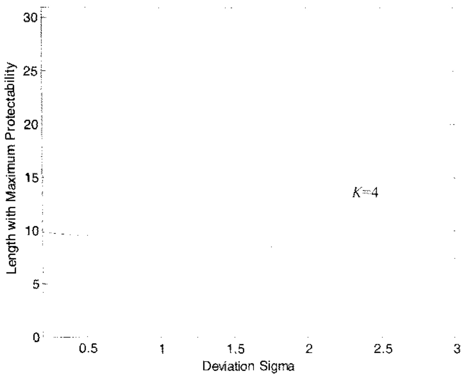

Fig. 7. Length with Maximum Protectability of Varied Deviation

3.2 Protectability Evaluation of Zone2

A. The Aim of Zone2 and Setting Rule

Zone2 has two requirements to fulfill: 1) to guarantee the protection of its own line beyond the setting of Zone1, and 2) to provide the quickest and greatest backup for the neighboring lines starting at the end bus, without superposing Zones2 of their own primary relays [16].

Requirement 1) is mandatory and requirement 2) aims at another goal in addition to backup: to ease the coordination of Zones3 of the relays behind, allowing their extension while keeping selectivity. Traditionally, Zone2 is set as 120% of its line by considering the measurement errors.

B. Sensitivity of Zone2

The sensitivity of Zone2 shares the same meaning with Zone1, indicating the performance for the fault in line1.

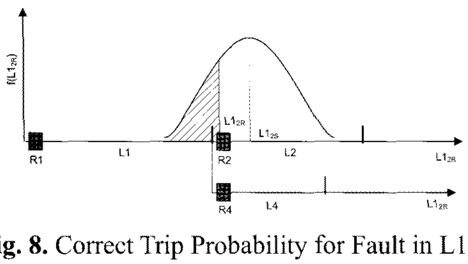

Fig. 8. Correct Trip Probability for Fault in L1

The approach for Zone2 is similar to Zone1:

$$P(l \mid l < L1_{2R}) = \int_{l}^{+\infty} f(L1_{2R}) dL1_{2R} \tag{8}$$

$$F_1(L1_{2S}) = \frac{1}{L1} \int_{0}^{L1} P(l \mid l < L1_{2R}) dl \tag{9}$$

where, $F_1(L1_{2S})$ is the sensitivity of Zone2, $L1_{2S}$ is the setting of Zone2, and $L1_{2R}$ is its effective reach.

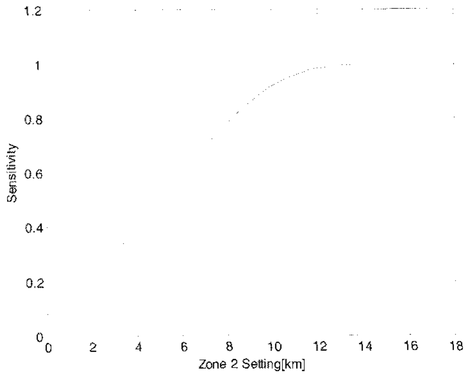

Fig. 9. Sensitivity of Zone2 with Varied Setting

C. Selectivity of Zone2

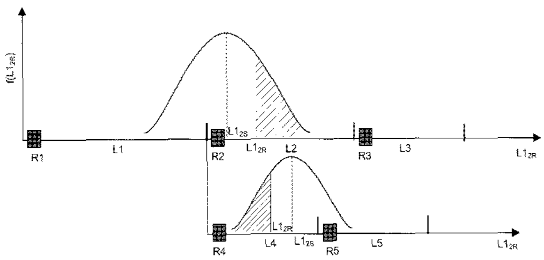

Fig. 10. Mis-Trip Probability of R1 and Un-Trip Probability of R2

As to the selectivity of Zone2, it refers to the faults that overreach $L1_{2S}$ but that are within reach of Zone1 in the next line. Seen from Fig. 10, Zone2 of R1 should not mis-trip the fault which Zone1 of R2 and R4 un-tripped. As such, two parts would be included:

(1) The mis-trip conditional probability of Zone2 of R1.

$$P(l \mid l < L1_{2R}) = \int_{l}^{+\infty} f(L1_{2R}) dL1_{2R} \tag{10}$$

(2) The un-trip conditional probability of Zone1 of neighboring R2 and R4.

$$P(l \mid l > L2_{1R}) = \int_{0}^{l} f(L2_{1R}) dL2_{1R} \tag{11}$$

$$P(l \mid l > L4_{1R}) = \int_{0}^{l} f(L4_{1R}) dL4_{1R} \tag{12}$$

So the incorrect probability is:

$$P_{In} = P(l \mid l < L1_{2R}) * (K_1 * P(l \mid l > L2_{1R}) + K_2 * P(l \mid l > L4_{1R})) \tag{13}$$

Here the coefficients are set as un-trip rate corresponding to the line length. $K_1 = L2/(L2 + L4)$, $K_2 = L4/(L2 + L4)$.

$L2$=8km, $L4$=6km.

The correct trip probability and selectivity of Zone2 are:

$$P = 1 - P_{In} \tag{14}$$

$$F_2(L1_{2S}) = \frac{1}{L2}\int_{L1}^{L1+L2} P dl \tag{15}$$

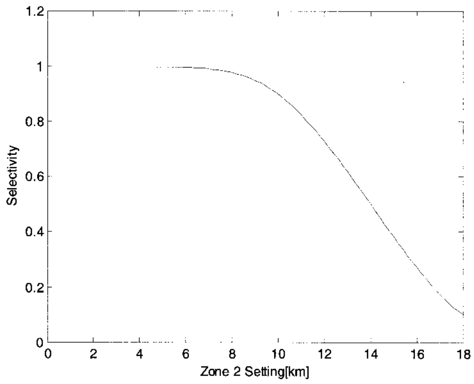

Fig. 11. Selectivity of Zone2 with Varied Setting

D. Protectability of Zone2

The same function for protectability is adopted:

$$F(L1_{2S}) = \omega_1 F_1(L1_{2S}) + \omega_2 F_2(L1_{2S}) \tag{16}$$

in which $F_1(L1_{2S})$ is sensitivity and $F_2(L1_{2S})$ is sensitivity. The protectability of Zone2 is shown in Fig. 12 with ω_1=0.8 and ω_2=0.2.

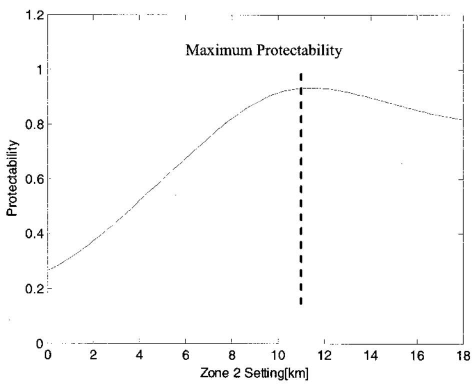

Fig. 12. Protectability of Zone2 with Varied Setting

3.3 Protectability Evaluation of Zone3

A. The Aim of Zone3 and the Setting Rule

Traditionally, Zone3 has provided the maximum backup to the neighboring lines, but without intersecting Zone3s of their own primary relays. To have a full guaranty that this backup is indeed provided, the neighboring line with the maximum apparent distance has to be covered. Zone3 is set as 120% of the longest neighboring line.

B. Sensitivity of Zone3

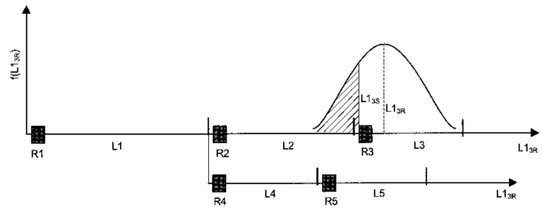

Fig. 13. Correct Trip Probability for Fault in L3

The sensitivity of Zone3 shares the same meaning with other zones, so it is calculated by:

$$P(l \mid l < L1_{3R}) = \int_{l}^{+\infty} f(L1_{3R}) dL1_{3R} \tag{17}$$

$$F_1(L1_{3S}) = \frac{1}{L1+L2}\int_{0}^{L1+L2} P(l \mid l < L1_{3R}) dl \tag{18}$$

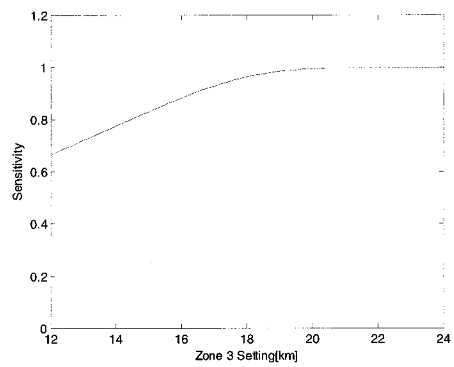

Fig. 14. Sensitivity of Zone3 with Varied Setting

C. Selectivity of Zone3

For Zone3, considering the selectivity, it means for the faults to overreach the setting of $L1_{3S}$, Zone3 of R1 would not mis-trip the fault which the Zone3 of R2 and R4 un-tripped.

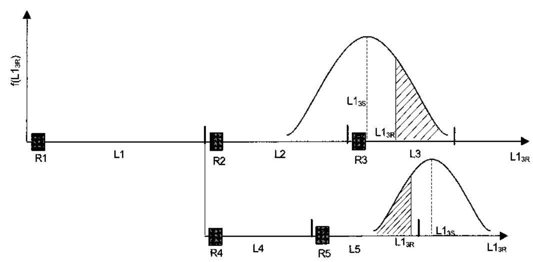

Fig. 15. Probability of Mis-trip of R1 and Un-trip of R2, 4

The selectivity calculation of Zone3 is similar to what was done for Zone2, but with a larger computation set.

(1) The mis-trip probability of zone 3 of R1:

$$P(l \mid l < L1_{3R}) = \int_{l}^{+\infty} f(L1_{3R}) dL1_{3R} \tag{19}$$

(2) The un-trip probability of Zone 3 of neighboring relays:

$$P(l \mid l > L2_{3R}) = \int_{0}^{l} f(L2_{3R}) dL2_{3R} \tag{20}$$

$$P(l \mid l > L4_{3R}) = \int_{0}^{l} f(L4_{3R}) dL4_{3R} \tag{21}$$

Therefore, the incorrectly and correctly tripped probabilities are:

$$P_{In} = P(l \mid l < L1_{3R}) * (K_1 * P(l \mid l > L2_{3R}) + K_2 * P(l \mid l > L4_{3R})) \tag{22}$$

$$P = 1 - P_{In} \tag{23}$$

in which $K_1 = \frac{L2+L3}{L2+L3+L4+L5}$, $K_2 = \frac{L4+L5}{L2+L3+L4+L5}$, L3=6km, L5=6km.

Selectivity is shown as:

$$F_2(L1_{3S}) = \frac{1}{L3} \int_{L1+L2}^{L1+L2+L3} P dl \tag{24}$$

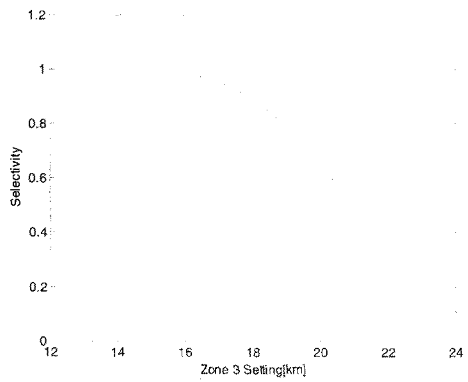

Fig. 16. Selectivity of Zone3 with Varied Setting

D. Protectability of Zone3

Protectability of Zone3 can also be expressed as:

$$F(L1_{3S}) = \omega_1 F_1(L1_{3S}) + \omega_1 F_2(L1_{3S}) \tag{25}$$

where, $F_1(L1_{3S})$ is the sensitivity of Zone3. $F_2(L1_{3S})$ is the sensitivity of Zone3. Here, ω_1 =0.8 and ω_2 =0.2, shown in Fig. 17.

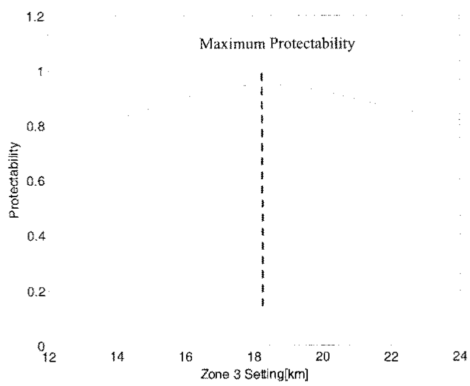

Fig. 17. Protectability of Zone3 with Varied Setting

4. Case Study

4.1. Protectability Evaluation for Model System

The proposed evaluation method is applied to a model system as given in Fig. 18.

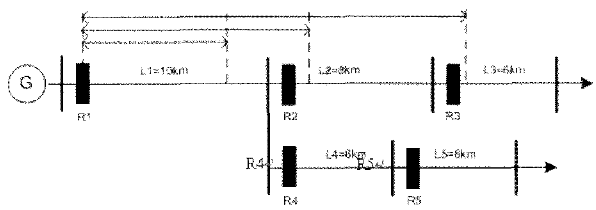

Fig. 18. Model System

Setting data and evaluation results for R1 are shown in Table 1. L_{AVE} means the traditional setting length, L_{MAX} denotes the length with maximum protectability, L_{MIN} signifies the length with minimum protectability, and L_{MIS} refers to the mis-setting length. And σ =20 %*(Line Length). P means the protectablility corresponding to setting length, *k* is defined as normalized protection factor, calculated by:

$$k = \frac{P - P_{MIN}}{P_{MAX} - P_{MIN}} \tag{26}$$

4.2. Protectability Evaluation and Optimization

The setting is a key factor of the relay protection, directly related to relay performance. The presented evaluation techniques enable for measuring the "goodness" of a given setting of the distance relay protection in a

Table 1. Evaluation Results for Model System

R1	Setting	Length	P	k
Zone1	L_{MAX}	8	0.9400	1
	L_{MIN}	0	0.8160	0
	L_{AVE}	8	0.940	1
	L_{MIS}	7	0.9304	0.9226
	L_{MIS}	9	0.9325	0.9395
Zone2	L_{MAX}	11.4	0.9351	1
	L_{MIN}	18	0.8200	0
	L_{AVE}	12	0.9326	0.9783
	L_{MIS}	11	0.9335	0.9861
	L_{MIS}	12	0.9190	0.8527
Zone3	L_{MAX}	18.2	0.9511	1
	L_{MIN}	24	0.8213	0
	L_{AVE}	19.6	0.9364	0.8867
	L_{MIS}	18.8	0.9489	0.9831
	L_{MIS}	20.4	0.9166	0.7342

power system. For a given system, its deviation σ can be known by considering the system conditions, and each zone's sensitivity and selectivity can also be calculated based on the presented method. Specified weighting rate can be adopted to meet special needs pertaining to sensitivity and selectivity.

Using Table 1, assume "average" settings and mis-setting for the given model system, and evaluate their protectability applying a set of weighting rates. However, it is found that these settings cannot meet the maximum protection of the system, and settings corresponding to maximum protectability can be gleaned in the evaluation process. Consequently, the system can obtain its optimization by adopting these optimized settings.

5. Conclusion

In this paper, a probabilistic model for the errors in the distance relay setting is presented, and a concept of "protectability" which indicates the protection degree of each element of the relay is proposed. A full description of the developed procedures and the analysis of their results are also given.

Protectability is composed of sensitivity and selectivity. Sensitivity is defined as the ability to operate for the fault within its protection zone, which means for the protection ability of the line itself, and selectivity is to describe the ability not to operate for the fault without its protection zone, which aims for coordination of relays. Each zone of distance relay is evaluated by these two indexes, and then its protectability is attained through an objective function with given weighting rate by considering the practical need of sensitivity and selectivity.

The concept of "protectability" can be used not only for checking the protection degree of the current setting but also for the system setting optimization. This method would provide a good reference to the system setting optimization.

Acknowledgements

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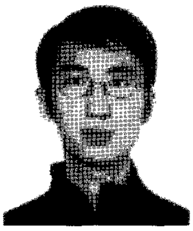
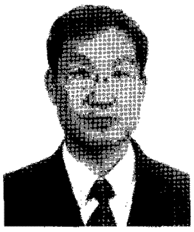
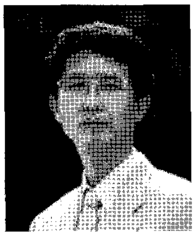


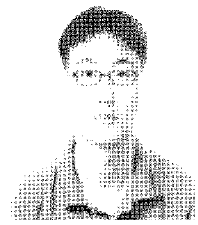
Wen-Hao Zhang
He was born in Shanxi, China, in 1982. He received his B.E. degree in Electrical .Engineering from the Harbin Institute of Technology, Harbin, China in 2003. He received his M.S. degree in Electrical Engineering from Xi'an Jiao Tong University, Xi'an, China in 2006. He is now working towards his Ph.D. at Myongji University. His research interests are power system protection and control and power system automation.



Myeon-Song Choi
He was born in Chungju, Korea, in 1967. 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 a Professor at Myongji University. His major research fields are power system control and protection, including artificial intelligence application



Seung-Jae Lee
He was born in Seoul, Korea, in 1955. 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. in Electrical Engineering from the University of Washington, Seattle, USA in 1988. Currently, he is a Professor at Myongji University and a Director at NPTC (Next-Generation Power Technology Center). His major research fields are protective relaying, distribution automation, and AI applications to power systems.



Il Hyung Lim
He was born in Seoul, Korea, in 1979. He received his B.E. and M.S. degrees in Electrical Engineering from Myongji University, Yongin, Korea in 2007. He is now working towards his Ph.D. at Myongji University. His research interests are power system control and protective relaying, including artificial intelligence application.

Seong-Jeong Rim
He received a B.S. from Seoul National University of Technology in 1991 and his M.S and Ph.D. degrees from Soongsil University in 1993 and 1998, respectively. He has worked for the Electro-mechanical Research Institute of Hyundai Heavy Industries. Currently, he is a Research Professor at the New-generation Power Technology Center in Myongji University, Yongin, Korea. His research fields are protective relaying, substation automation, and reliability assessment.