

Article

Protection Coordination Index Assessment Using Fuzzy Logic Controller

Choong-Koo Chang *  and Ahmed Mohamed Elmashtoly

Department of Nuclear Power Plant Engineering, KEPCO International Nuclear Graduate School (KINGS), 658-91 Haemaji-ro, Seosang-myeon, Ulju-gun, Ulsan 45014, Korea; ahmed_mashtoly@hotmail.com

* Correspondence: ckchang@kings.ac.kr; Tel.: +82-52-712-7303

Abstract: This paper proposes the assessment method of the protection coordination index (PCI) for overcurrent protection relay and upstream relay. The protection coordination index is an indicator of how properly the equipment is protected by protective relay. The PCI is used to check the appropriateness of the protection coordination for both the component-wise and pair-wise. The protection index of each protection component of the integrated digital relay is assessed by a fuzzy logic controller. Then the device-level protection index and the composite protection coordination index between up and downstream relays are also assessed. Since the setting criteria of the overcurrent relays are given in a certain range rather than a crisp value, it is difficult to indicate the protection level of the protective system as an index. Currently, there is no way of knowing how well the overcurrent relay setting is. Thus, a method was proposed to evaluate the protection index of overcurrent systems using fuzzy logic. This is the unique research result of this paper.

Keywords: fuzzy logic controller; overcurrent relay; protection index; protection coordination index; protection level assessment



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1. Introduction

In generating stations, the auxiliary power system is subdivided into a medium voltage system and a low voltage system. The vacuum circuit breakers and related protective relays are installed for circuit protection in the medium voltage power distribution networks. The air circuit breakers with direct trip devices are used for the protection of low voltage networks. Protective relays and direct trip devices have multiple protection functions required for the protection of equipment and feeders. Among them, overcurrent relays are a major component of protective relays. The overcurrent relay monitors and protects the protected equipment and cables to operate normally within the rated current range.

Therefore, the overcurrent relay is set considering the rating and operation range of the equipment. In that case, relay setting criteria is given by linguistic value rather than crisp value. This makes it hard to assess the protection level of the overcurrent relay. In many cases, a relay unit has both time-overcurrent relay and instant overcurrent relay and, a relay unit must coordinate with upstream relay and downstream relay. Relay setting is made by component-wise and a coordination check is conducted. However, the component-wise protection level, device-wise and pair-wise protection coordination levels are not known to the system operators. Where component-wise protection means protection by each relay element of the integrated protection relay. The device-wise protection means combined protection by all overcurrent relays of the integrated protection relay. The pair-wise protection coordination means cooperative protection by downstream protection relay and upstream protection relay. Currently, it is common to set the relays after completing the electrical facility construction and check the relay setting status based on the setting calculation after one to two years of operation. This means that the electrical system operator does not know the overcurrent relay protection level as the setting calculations do not provide a protection level by crisp index.

This paper proposes the method of assessing and utilizing the protection level of the overcurrent relay of the power distribution system in a nuclear power plant. For the overcurrent relay protection level assessment is realized in the digital protective relays with the fuzzy logic controller [1]. Section 2 introduces the results of literature reviews. Sections 3 and 4 introduce a PCI evaluation method. Section 5 is dedicated to the verification of the methodology introduced in Sections 3 and 4. Section 6 describes the results of research and discussions. Finally, Section 7 describes the effectiveness of the PCI evaluation method proposed in this paper as the conclusion of this research.

2. Literature Review for Fuzzy Logic Controller Based Overcurrent Protection

In general, electric motors are protected by a motor protection relay (MPR). If the MPR detect failures or faults in the system, it trips the motor after the preset delay time. If it immediately stops a motor as soon as the system detects an error, then the production line is disrupted. On the contrary, waiting too long without stopping the motor, even when the system is critically faulty, can cause serious faults. In this regard, the results of a recently published study to improve the function and performance of overcurrent relays using the Fuzzy logic controller are described below.

References [2,3] suggest using fuzzy logic to put a delay between 0 and 4.5 s depending on the error type. If the fault is not recovered after this waiting time, stopping of the motor should be considered. In reference [4], a fuzzy logic-based condition monitoring system to detect the condition of an induction motor was proposed. The overvoltage, overcurrent, temperature, voltage unbalance, current unbalance and undervoltage conditions of the induction motor were modeled using the Simulink program. Stress factor of ac induction motor was introduced as a factor for the status of the motor, which can be used by less experienced engineers and for multiple customer processes. Reference [5] used fuzzy tool box in MATLAB to create a fuzzy inference system for detecting motor failure, and observe the data set to construct fuzzy rules and membership functions. As more insight is required into the data regarding stator current measurements, a membership functions were created with the currents in each phase (negative large zero, positive large). The output variables generated for the motor state are normal, average, and abnormal. A membership function is created by observing the data set and the behavior of the stator currents that are likely to cause the motor to faults.

Reference [6] proposed a fuzzy logic-based overcurrent protection system for low voltage induction motor protection. Current sensors, timers, current limiters and contactors are used in this system. A current sensor is used to detect overcurrent and provide a signal to the timer. If the current is not too high or at a level that allows continuous operation, the microcontroller signals the current limiter to limit the current. The contactor functions to disconnect the circuit from the mains when the current is high enough to damage the circuit. Reference [7] proposed a method of applying fuzzy logic to automate the pickup current (I_p) setting of the inverse overcurrent relay. The fuzzy system uses the measured current to determine the optimal pick-up current value. The algorithm of the fuzzy system estimates the output (I_p) using two input variables: the pre-fault current (I_{pre}) and the current variation (ΔI). I_p , which was initially a static value, becomes a dynamic variable and is updated periodically. The second harmonic restraint stabilization method used in the existing transformer differential protection relay may cause malfunctions under internal faults and misoperation during transformer energization. Therefore, recently, new technologies to improve security and reliability have been reported mainly based on fuzzy logic [8].

As discussed above, in terms of the implementation of artificial intelligence technology, most studies on overcurrent protection focused on fault determination algorithms by fuzzy logic. On the other hand, this paper deals with the evaluation of the protection level of overcurrent relays. The protection level means the level of setting an overcurrent relay compared to the optimum setting to protect the protected equipment to operate within its maximum capacity range and not operate beyond its operational range.

3. Fuzzification of Overcurrent Relay Setting Rule

The scope of this study is the medium voltage network of a nuclear power plant. The medium voltage switchgears are divided into 13.8 kV and 4.16 kV switchgears. The medium voltage switchgears are composed of redundant incoming feeders, motor feeders and transformer feeders. This first defines the overcurrent relay setting criteria with linguistic data and then perform fuzzification of the setting rules.

3.1. Overcurrent Relay Setting Criteria Subsection

The overcurrent relay consists of an overcurrent element and a high dropout instantaneous element. Figure 1 shows the relaying diagram of the condensate pump motor for the Korean standard nuclear power plant. The condensate pump motor protection system was used for the case study of the relay protection index assessment. Tables 1 and 2 show the ratings and setting data of the condensate pump motor.

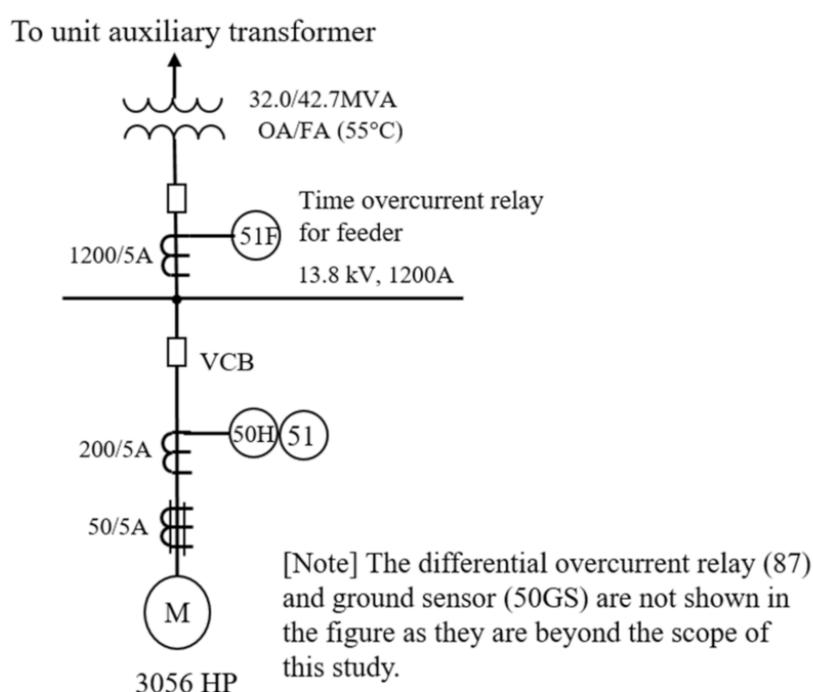


Figure 1. Relaying diagram of the condensate pump motor.

Table 1. Condensate pump motor data.

Description	Rating
Motor Name	Condensate pump
Rated Capacity	3056 Hp
Rated Current (AF)	118.7 A
Locked Rotor Ampere	735.9 A
CT Rating for OCR	200/5 A
CT Rating for Differential	50/5 A

Table 2. Condensate pump motor relay setting data.

Relay	Relay Setting
Time Overcurrent (51)	140 A
High Drop Off (50H)	240 A
Differential OC (87)	12.5 A
Ground Sensor (50 GS)	30 A

Time overcurrent relay (TOC; 51) is set at 115% of the full load current (FLC) for smaller than 1500 Hp motors of 4.16 kV switchgear and smaller than 5000 Hp motors of 13.8 kV switchgear, and, it is set at 120~140% of FLC for equal or greater than 1500 Hp motors of 4.16 kV switchgear and equal or greater than 5000 Hp motors of 13.8 kV switchgear [9]. TOC is used for the alarm only.

High dropout (HDO; 50H) element is set at 200% of the full load current (FLC) for smaller than 1500 Hp motors of 4.16 kV switchgear and smaller than 5000 Hp motors of 13.8 kV switchgear, and, it is set at 125% of locked rotor current (LRC) for equal or greater than 1500 Hp motors of 4.16 kV switchgear and equal or greater than 5000 Hp motors of 13.8 kV switchgear. HDO permits tripping when the TOC contacts are closed and the current is above the set value. Instantaneous trip (IT) element is set at the next calibration mark above 200% LRC and trip on short circuit only [9]. In the above example circuit, a differential current relay is used instead of an IT element.

Transformer protection has primary side and secondary side protection. The secondary should be set to approximately 125–200% of its oil-immersed self-cooled (OA) rating and not exceed ANSI points and thermal limit points. And the secondary protection relay setting value should be decided in consideration of protection coordination with downstream relays, inrush current and acceleration time, and constant load current. The setting current of the transformer primary protective relay is set to 200–300% of the transformer OA rating. The instantaneous overcurrent (IOC, 50) relay on the primary side of the transformer is set at the next calibration mark above 175% of the let through fault current [10].

3.2. Fuzzy Membership Functions of Overcurrent Relays

The overcurrent relay protection index is classified into seven fuzzy sets. Optimal (OPT) denotes that the overcurrent relay is set optimally according to the relay setting criteria. OPT is a single set. Normal (NOR) denotes that the overcurrent relay is set within the acceptable range according to the relay setting criteria. Alert (ALT) denotes that the over-current relay is set at a level just before it deviates from the relay setting criteria. Violation (VIO) denotes that the overcurrent relay is set to deviate from the relay setting criteria. Normal (NOR), alert (ALRT), and violation (VIO) sets are divided into a low set and high set as shown in Figure 2.

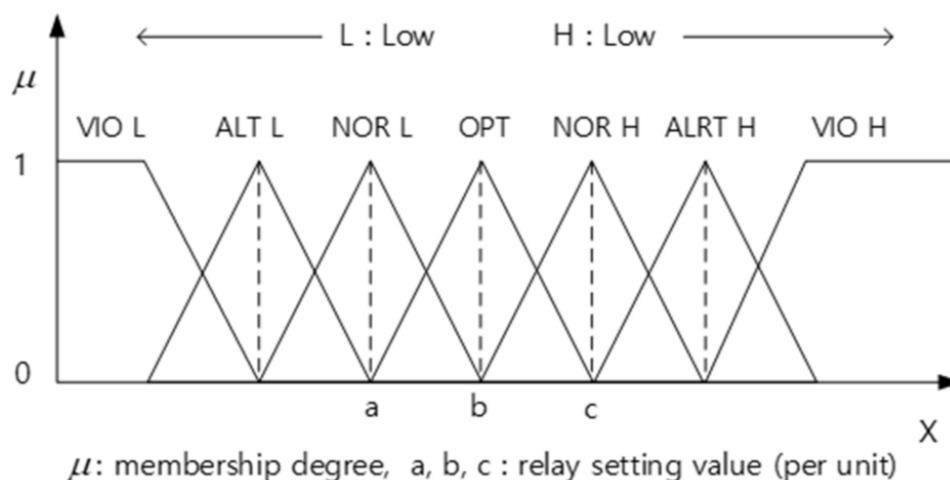


Figure 2. Fuzzy sets of overcurrent relay protection index.

According to the setting criteria in Section 3.1, fuzzy membership functions of overcurrent relays were defined as Figures 2–5. The value of the abscissa in Figures 3–5 were defined according to the setting criteria in Section 3.1. In Figure 3, the optimal setting level of time overcurrent relay (TOC; 51) is 115% of the full load current (FLC). It is 1.15 pu of FLC. Then normal low level is 1.1 pu and normal high level is 1.2 pu. If setting level is

lower than 1 pu or higher than 3 pu then it is a violation of the setting criteria. The value of the abscissa in Figures 3–5 were defined in the same manner as Figure 2.

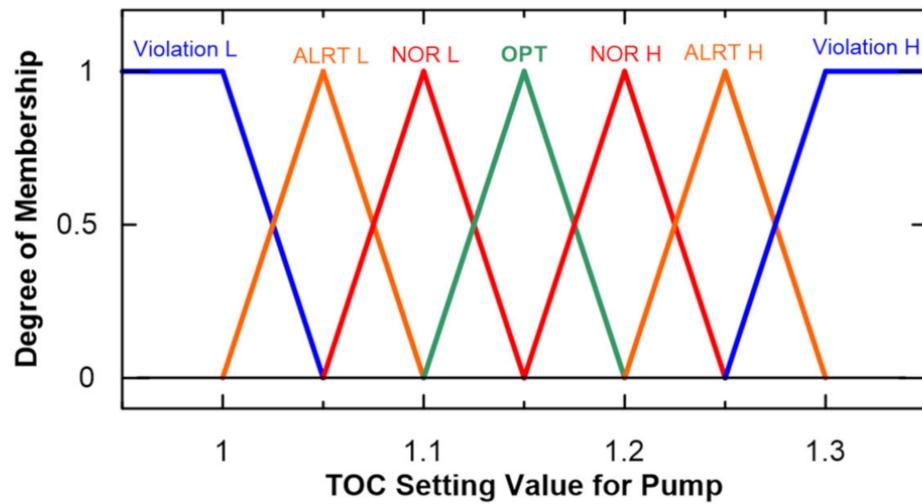


Figure 3. Membership function of time overcurrent relay (51) for motor.

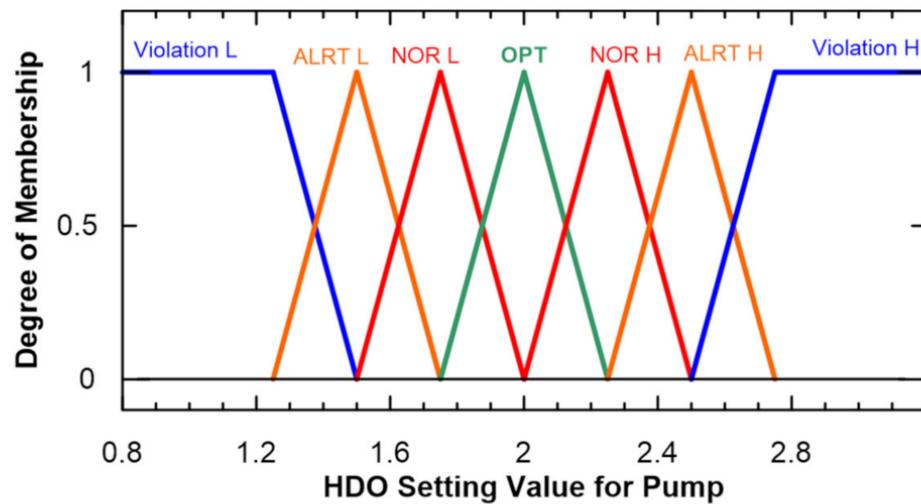


Figure 4. Membership function of high dropout overcurrent (HDO) relay for motor.

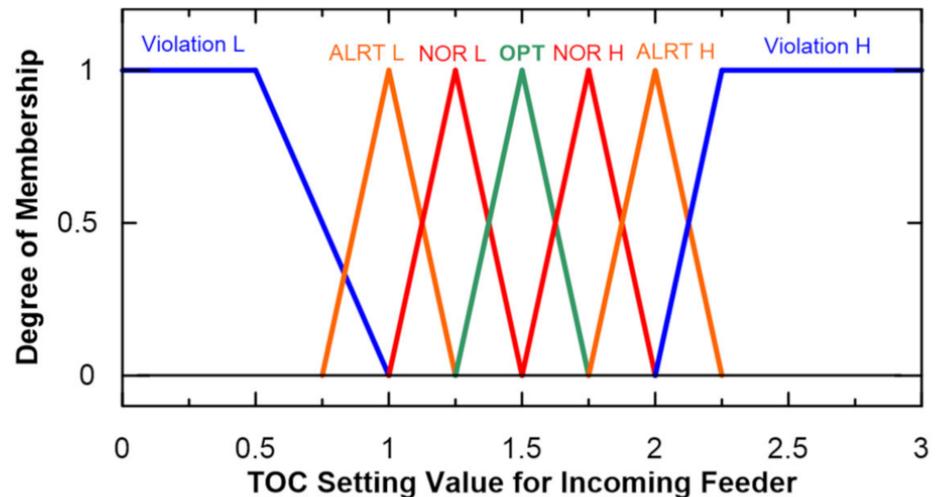


Figure 5. Membership function of time overcurrent relay (51) for incoming feeder.

3.3. Membership Degree

The degree of membership, $\mu(x)$ in each of the fuzzy sets (violation, alert, normal, and optimum) was calculated with fuzzy membership functions and relay setting data.

Membership degree of the fuzzy sets, optimal (OPT), normal (NOR) and alert (ALRT) are calculated using Equation (1) [11]:

$$\mu(x) = \max \left\{ \min \left(\frac{x-a}{b-a}, \frac{c-x}{c-b} \right), 0 \right\} \quad (1)$$

Membership degree of the fuzzy sets, low violation (VIO_L), and high violation (VIO_H) are calculated with Equations (2) and (3).

$$\mu(x) = \max \left\{ \min \left(\frac{x-a}{b-a}, 1 \right), 0 \right\} \quad (2)$$

$$\mu(x) = \max \left\{ \min \left(\frac{b-x}{b-a}, 1 \right), 0 \right\} \quad (3)$$

Accordingly, when the overcurrent relay (51) is set at 1.18 pu of the motor FLC, membership degrees of the time overcurrent relay (51) for condensate pump motor are as follows:

$$\begin{aligned} \mu_{opt}^{(1.18)} &= \max \left\{ \min \left(\frac{x-a}{b-a}, \frac{c-x}{c-b} \right), 0 \right\} \\ &= \max \left\{ \min \left(\frac{1.18-1.10}{1.15-1.10}, \frac{1.2-1.18}{1.20-1.15} \right), 0 \right\} \\ &= 0.4 \\ \mu_{nor_h}^{(1.18)} &= \max \left\{ \min \left(\frac{1.18-1.15}{1.20-1.15}, \frac{1.25-1.18}{1.25-1.20} \right), 0 \right\} \\ &= 0.6 \\ \mu_{alt}^{(1.18)} &= 0 \\ \mu_{vio}^{(1.18)} &= 0 \end{aligned}$$

When the high dropout relay (50H) is set at 2.02 pu of the motor FLC, membership degree of the high dropout relay (50H) are as follows:

$$\begin{aligned} \mu_{opt}^{(2.02)} &= \max \left\{ \min \left(\frac{2.02-1.75}{2.0-1.175}, \frac{2.25-2.02}{2.25-2.0} \right), 0 \right\} \\ &= 0.92 \\ \mu_{nor_h}^{(2.02)} &= \max \left\{ \min \left(\frac{2.02-2.0}{2.25-2.0}, \frac{2.5-2.02}{2.5-2.25} \right), 0 \right\} \\ &= 0.08 \\ \mu_{alt}^{(2.02)} &= 0 \\ \mu_{vio}^{(2.02)} &= 0 \end{aligned}$$

In the same manner, if the 13.8 kV switchgear incoming feeder protection relay (51) is set at 150% of full load current, the degree of membership are as follows:

$$\begin{aligned} \mu_{opt}^{(1.5)} &= \max \left\{ \min \left(\frac{1.5-1.25}{1.5-1.25}, \frac{1.75-1.5}{1.75-1.5} \right), 0 \right\} \\ &= 1 \end{aligned}$$

Therefore $\mu_{nor}^{(1.5)}$, $\mu_{alt}^{(1.5)}$ and $\mu_{vio}^{(1.5)}$ are all zero (0).

4. Fuzzy Operation

4.1. Fuzzy Operation Rules for Device-Wise Protection

Fuzzy rules were defined as follows for the evaluation of device-wise fuzzy memberships. There are a total of 49 rules and the fuzzy associative memory matrix (FAMM) is as shown in Table 3. The condensate pump motor feeder is provided with HDO and TOC as two protective elements. The device-wise protection of the motor feeder is achieved by

a combination of the HDO and TOC relays. HDO and TOC relays have seven fuzzy sets each. So there are 49 combinations and 49 fuzzy rules.

Table 3. Fuzzy rule table for the medium voltage motors protection.

Description		High Dropout Relay (50H)						
		OPT	NOR L	NOR H	ALRT L	ALRT H	VIO L	VIO H
TOC Relay (51)	OPT	O	N	N	A	A	V	V
	NOR L	N	N	N	A	A	V	V
	NORH	N	N	N	A	A	V	V
	ALRT L	A	A	A	A	A	V	V
	ALRT H	A	A	A	A	A	V	V
	VIO L	V	V	V	V	V	V	V
	VIO H	V	V	V	V	V	V	V

The first 10 rules among them are as follows:

Rule 1 if (TOC is optimal) and (HDO is optimal) then (Fuzzy output is optimal);

Rule 2 if (TOC is optimal) and (HDO is normal_L) then (Fuzzy output is normal);

Rule 3 if (TOC is optimal) and (HDO is normal_H) then (Fuzzy output is normal);

Rule 4 if (TOC is optimal) and (HDO is alert_L) then (Fuzzy output is alert);

Rule 5 if (TOC is optimal) and (HDO is alert_H) then (Fuzzy output is alert);

Rule 6 if (TOC is optimal) and (HDO is violation_L) then (Fuzzy output is violation);

Rule 7 if (TOC is optimal) and (HDO is violation_H) then (Fuzzy output is violation);

Rule 8 if (TOC is normal_L) and (HDO is optimal) then (Fuzzy output is normal);

Rule 9 if (TOC is normal_L) and (HDO is normal_L) then (Fuzzy output is normal);

Rule 10 if (TOC is normal_L) and (HDO is normal_H) then (Fuzzy output is normal).

The above fuzzy operation result can be summarized as Table 3: Fuzzy rule table for the medium voltage motor protection.

In the process of defuzzification, fuzzy membership sets should be converted to crisp quantity. Therefore, weighting factors in Table 4 were provided for the fuzzy membership sets in Table 3, where weighting factors are defined as; optimal is 1, normal is 0.66, alert is 0.33 and violation is 0.0. This means that the optimal setting condition of the relay is considered as unit (1) and the violation is considered as zero (0) condition.

Table 4. Weighting table for the 13.8 kV motor's protection.

Description	OPT	NOR L	NOR H	ALRT L	ALRT H	VIO L	VIO H
OPT	1	0.66	0.66	0.33	0.33	0	0
NOR L	0.66	0.66	0.66	0.33	0.33	0	0
NOR H	0.66	0.66	0.66	0.33	0.33	0	0
ALRT L	0.33	0.33	0.33	0.33	0.33	0	0
ALRT H	0.33	0.33	0.33	0.33	0.33	0	0
VIO L	0	0	0	0	0	0	0
VIO H	0	0	0	0	0	0	0

4.2. Fuzzy Operation Rules for Pair-Wise Protection Coordination

Pair-wise protection coordination means the protection coordination between the downstream motor protection and the upstream switchgear incoming feeder protection as shown Figure 1. There are a total of 28 rules and FAMM is shown in Table 5. As shown in Table 5, the branch feeder have four (4) device-wise fuzzy sets and the incoming feeder have seven (7) device-wise fuzzy sets. The incoming feeder has only one protective element. The combinations of pair-wise fuzzy sets between the branch feeder and incoming feeder are 28, as shown in Table 6.

Table 5. Fuzzy rule table for the pair-wise protection coordination.

	Description	OPT	NOR L	NOR H	ALRT L	ALRT H	VIO L	VIO H
Device Wise Protection	OPT	O	N	N	A	A	V	V
	NOR	N	N	N	A	A	V	V
	ALRT	A	A	A	A	A	V	V
	VIO	V	V	V	V	V	V	V

Table 6. Weighting table for the pair-wise protection.

Incoming Feeder Protection Relay (51 F)								
	Description	OPT	NOR L	NOR H	ALRT L	ALRT H	VIO L	VIO H
Device Wise Protection	OPT	1	0.66	0.66	0.33	0.33	0	0
	NOR	0.66	0.66	0.66	0.33	0.33	0	0
	ALRT	0.33	0.33	0.33	0.33	0.33	0	0
	VIO	0	0	0	0	0	0	0

The first 10 rules of them are as follows:

Rule 1 if (TOC_feeder is optimal) and (Device-wise is optimal) then (Pair-wise is optimal);

Rule 2 if (TOC_feeder is normal_L) and (Device-wise is optimal) then (Pair-wise is normal);

Rule 3 if (TOC_feeder is normal_H) and (Device-wise is optimal) then (Pair-wise is normal);

Rule 4 if (TOC_feeder is alert_L) and (Device-wise is optimal) then (Pair-wise is alert);

Rule 5 if (TOC_feeder is alert_H) and (Device-wise is optimal) then (Pair-wise is alert);

Rule 6 if (TOC_feeder is violation_L) and (Device-wise is optimal) then (Pair-wise is violation);

Rule 7 if (TOC_feeder is violation_H) and (Device-wise is optimal) then (Pair-wise is violation);

Rule 8 if (TOC_feeder is optimal) and (Device-wise is normal) then (Pair-wise is normal);

Rule 9 if (TOC_feeder is normal_L) and (Device-wise is normal) then (Pair-wise is normal);

Rule 10 if (TOC_feeder is normal_H) and (Device-wise is normal) then (Pair-wise is normal).

The weighting factors in Table 6 are applied to the fuzzy outputs in the process of defuzzification.

4.3. Device-Wise Fuzzy Logic Operation and Defuzzification

Form the calculation result of Section 3.2, the membership degree of each relay element are as follows:

$$\mu_{51} = \{\mu_O \ \mu_N \ \mu_A \ \mu_V\} = \{0.4 \ 0.6 \ 0 \ 0\}$$

$$\mu_{50H} = \{\mu_O \ \mu_N \ \mu_A \ \mu_V\} = \{0.92 \ 0.08 \ 0 \ 0\}$$

To find the device-wise fuzzy membership degree fuzzy intersection operation was performed.

Then,

$$\mu_{oo} = \min \{\mu_{51_o} (1.18), \mu_{50H_o} (2.02)\} = \min (0.40, 0.92) = 0.40$$

$$\mu_{no} = \min \{\mu_{51_n} (1.18), \mu_{50H_o} (2.02)\} = \min (0.60, 0.92) = 0.60$$

$$\mu_{on} = \min \{\mu_{51_o} (1.18), \mu_{50H_n} (2.02)\} = \min (0.40, 0.08) = 0.08$$

$$\mu_{nn} = \min \{\mu_{51_n} (1.18), \mu_{50H_n} (2.02)\} = \min (0.60, 0.08) = 0.08$$

where μ_{oo} is membership degree of optimal and optimal,

μ_{no} is membership degree of normal and optimal,

μ_{on} is membership degree of optimal and normal, and
 μ_{nn} is membership degree of normal and normal pair.

By the defuzzification of the fuzzy outputs convert the fuzzy quantities into crisp quantities. The center of mass defuzzification method of Equation (4) was used:

$$P = \frac{\sum \mu(x)x}{\sum \mu(x)} \tag{4}$$

where P is defuzzified crisp quantity,
 μ_x is membership degree for point x ,
 x is weight of membership set.

Based on the center of mass defuzzification method (Equation (4)) device-wise protection index (P_d) is calculated as below:

$$P_d = \frac{\{(0.4 \times 1.0) + (0.6 \times 0.66) + (0.08 \times 0.66) + (0.08 \times 0.66)\}}{(0.4 + 0.6 + 0.08 + 0.08)} = 0.78$$

The protection index 0.78 indicates that the motor protection relay setting level is 0.78 pu compared to the Optimal (51)–Optimal (50H) condition of 1 pu. (See Figure 6) This is also a slightly better condition than the Normal (51)–Normal (50H) protection index of 0.66.

Again, the P_d was converted into a membership degree of each protection condition. Then, the membership degree of device-wise protection relay is:

$$\begin{aligned} \mu_{D_opt}^{(0.78)} &= \max \left\{ \min \left(\frac{x - a}{b - a}, 1 \right), 0 \right\} = 0.35 \\ \mu_{D_nor}^{(0.78)} &= \max \left\{ \min \left(\frac{0.78 - 0.33}{0.66 - 0.33}, \frac{1 - 0.78}{1 - 0.66} \right), 0 \right\} = 0.65 \\ \mu_{D_alt}^{(0.78)} &= 0 \\ \mu_{D_alt}^{(0.78)} &= 0 \end{aligned}$$

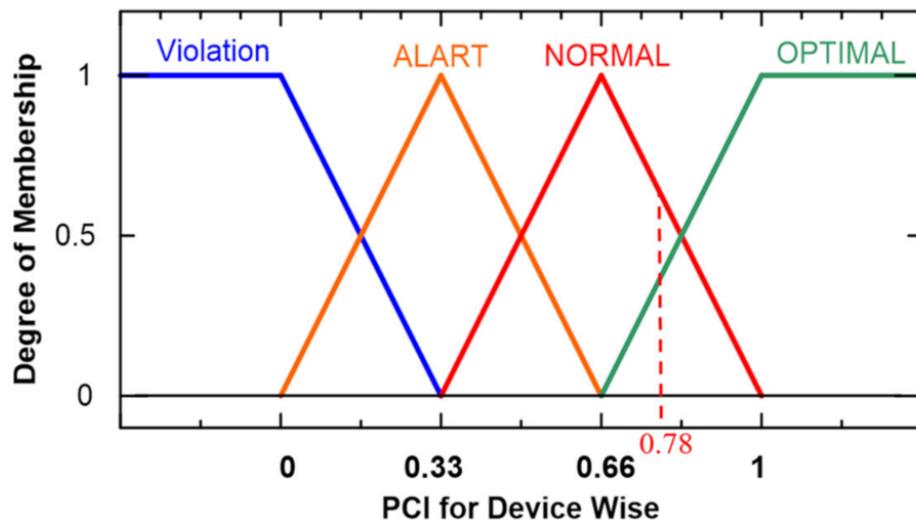


Figure 6. Membership functions of device-wise protection.

4.4. Pair-Wise Fuzzy Logic Operation and Defuzzification

According to the above calculation result, the membership degree of device-wise protection relay and switchgear incoming feeder protection relay are as below.

$$\begin{aligned} \mu_D &= \{ \mu_O \ \mu_N \ \mu_A \ \mu_V \} = \{ 0.35 \ 0.65 \ 0 \ 0 \} && \text{motor protection relay} \\ \mu_{51F} &= \{ \mu_O \ \mu_N \ \mu_A \ \mu_V \} = \{ 1 \ 0 \ 0 \ 0 \} && \text{switchgear incoming feeder relay} \end{aligned}$$

Then, by the fuzzy intersection operation pair-wise fuzzy membership were calculated.

$$\begin{aligned}\mu_{P_{oo}} &= \min \left\{ \mu_{D_{opt}}^{(0.78)}, \mu_{51F_{opt}}^{(1.5)} \right\} = \min \{0.35, 1.0\} = 0.35 \\ \mu_{P_{no}} &= \min \left\{ \mu_{D_{nor}}^{(0.78)}, \mu_{51F_{opt}}^{(1.5)} \right\} = \min \{0.35, 1.0\} = 0.35 \\ \mu_{P_{on}} &= \min \left\{ \mu_{D_{opt}}^{(0.78)}, \mu_{51F_{nor}}^{(1.5)} \right\} = \min \{0.35, 0.0\} = 0.00 \\ \mu_{P_{nn}} &= \min \left\{ \mu_{D_{nor}}^{(0.78)}, \mu_{51F_{nor}}^{(1.5)} \right\} = \min \{0.65, 0.0\} = 0.00\end{aligned}$$

Based on Equation (4) pair-wise protection coordination index (P_p) was calculated as below:

$$P_p = \frac{\{(0.35 \times 1.0) + (0.65 \times 0.66) + (0.00 \times 0.66) + (0.00 \times 0.66)\}}{(0.35 + 0.65)} = 0.78$$

Pair-wise protection coordination index (PCI) is also 0.78. It means that the protection coordination level is in between the normal state and the optimal state as shown in below Figure 7.

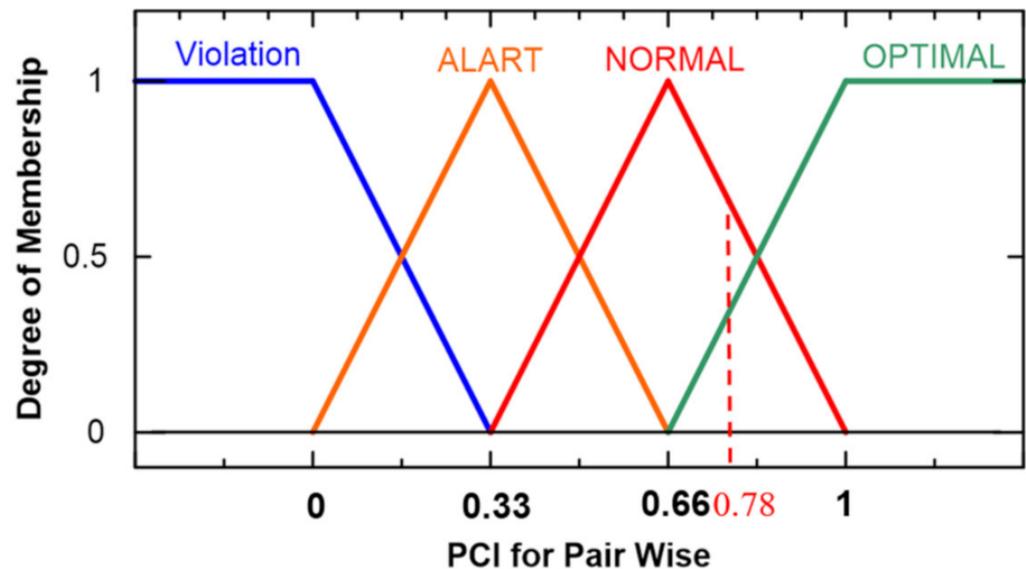


Figure 7. Membership functions of Pair-wise protection coordination.

5. Verification by MATLAB Simulation

5.1. Modeling Fuzzy Logic Controller

Fuzzy logic controllers were modeled using the MATLAB Simulink program as shown in Figure 8 [12].

Device-wise fuzzy logic controller was modelled with the membership functions shown in Figures 3 and 4, and the operational rules defined in Section 4.1. Using the membership functions of the switchgear input feeder's time overcurrent relay, the output of the device-wise fuzzy controller and the operation rules defined in Section 4.2, the pair-wise fuzzy logic controller was modeled.

The output of the pair-wise fuzzy logic controller is the pair-wise protection coordination index. After implementing the fuzzy logic controller in MATLAB, it was used to verify the PCI evaluation results of the manual calculation, which was carried out in Sections 3 and 4. It was also used to verify the behavior of the fuzzy logic controller under the same relay setting levels and different system operation conditions. When the setting levels of the TOC and HDO relays for the pump are set at 1.18 pu and 2.02 pu of FLC, respectively, the output (device-wise PCI) was 0.78, as shown in Figure 9.

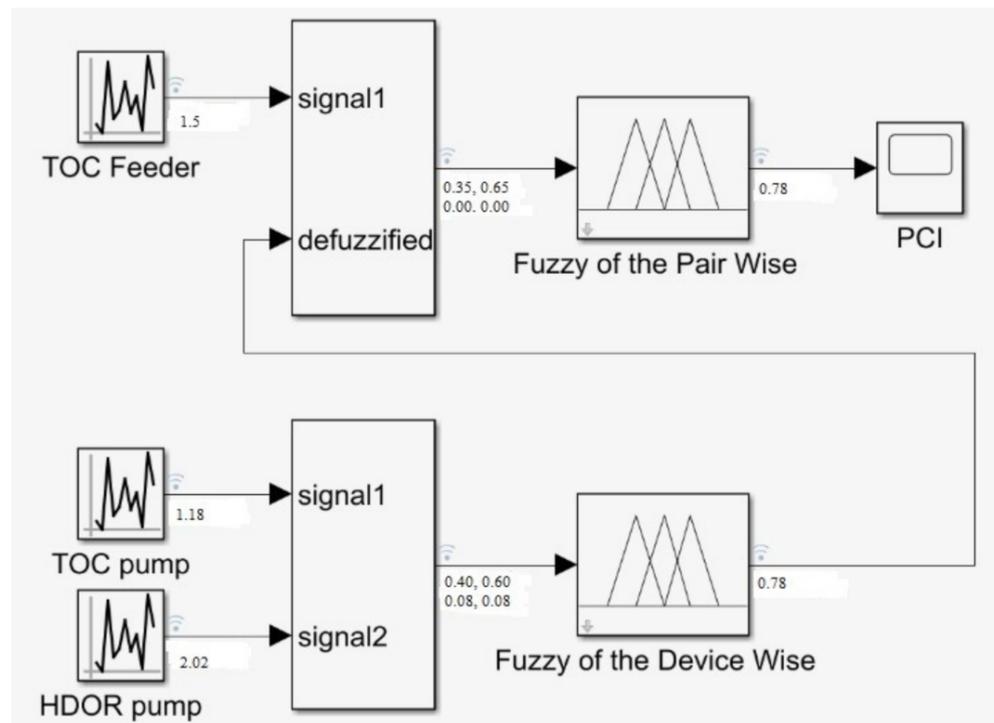


Figure 8. Simulation model in MATLAB Simulink.

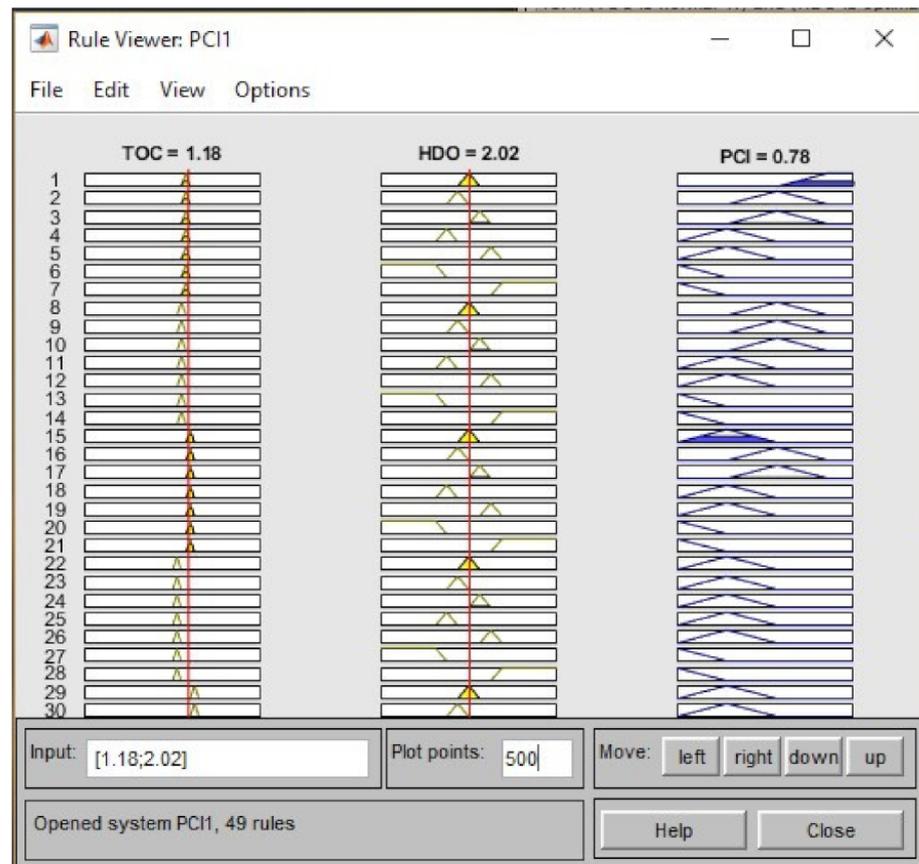


Figure 9. Rule viewer for Device-Wise Protection Coordination Index.

It is the same as the result of the hand calculation. The second fuzzy logic controller that is for the TOC of the incoming feeder was set to 1.5 pu, and, the output of the first

fuzzy logic controller is 0.78. As a result the pair wise protection coordination index is 0.78 as shown in Figure 10. The pair wise protection coordination index is also the same as the result of the manual calculation.

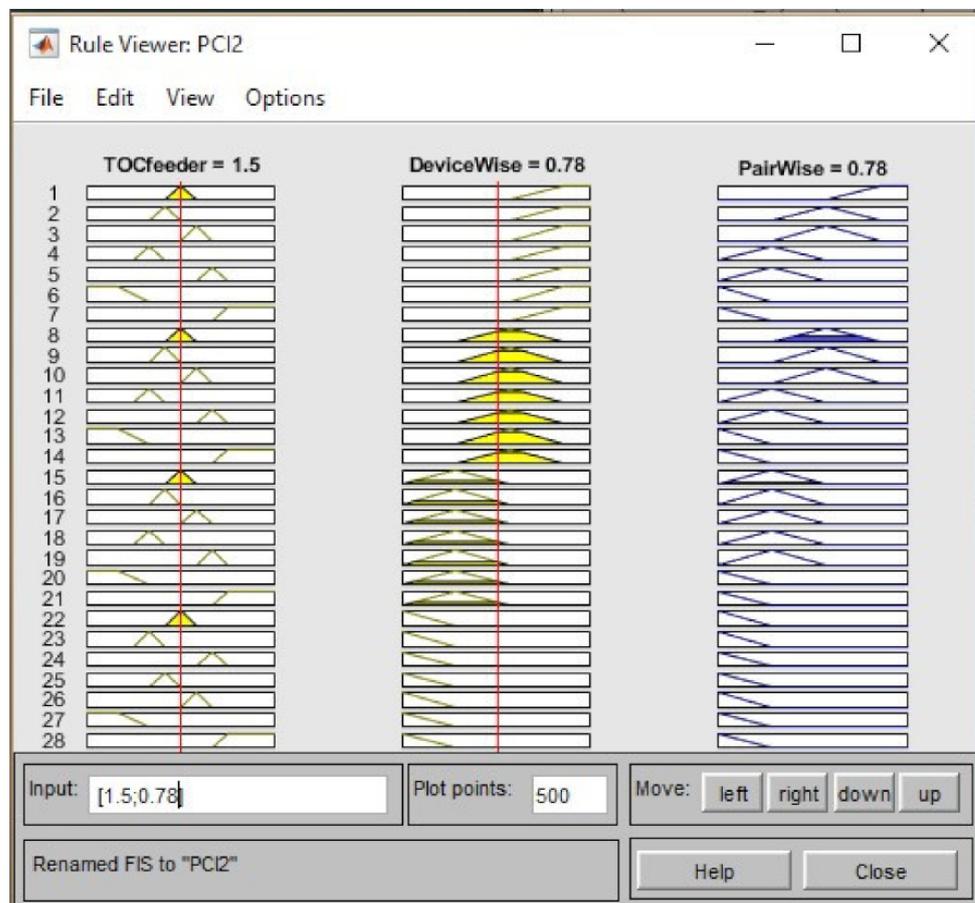


Figure 10. Rule viewer for Pair-Wise Protection Coordination Index.

5.2. Case Study for Different System Operation Condition

Depending on the transformer operating conditions, the cooling mode and temperature rise limit may change. In other words, the allowable capacity of the transformer depends on the operating conditions. So when the cooling mode or temperature rise limit changes, the FLC of the transformer changes. In the study case, the time overcurrent relay installed in the transformer secondary side was set at 1912.5 A. As specified in Section 3.1, the recommended setting level of the time overcurrent relay is 1.25 to 2.0 pu of the full load current at OA mode. Table 7 shows the pu of the relay setting current based on the FLC at each operation condition.

Table 7. Switchgear transformer secondary TOC setting current and per unit current at different operation condition.

Cooling Mode	55 °C Rise	TR FLC [A]	Relay Setting [A]	PU (Setting/FLC)	65 °C Rise	TR FLC [A]	Relay Setting [A]	PU (Setting/FLC)
OA	32 MVA	1275.0	1912.5 A	1.50	35.8 MVA	1426.4	1912.5 A	1.34
FA	42.7 MVA	1701.3	1912.5 A	1.12	47.8 MVA	1904.5	1912.5 A	1.00

[Note] Rated voltage of transformer secondary winding is 14.47 kV.

When the transformer is operating at OA mode and the temperature rise condition is 55 °C, the relay setting level is 1.5 pu of the FLC. This means, according to Figure 5, the relay protection index is 'Optimal (1.5)'.

6. Results and Discussion

The current electrical protection system is operated regardless of the operation conditions of the electrical system after setting the relay once. In some cases, this may result in the relay set value falling outside the appropriate level [13]. This paper proposed a method to evaluate device-wise protection index (PI) and pair-wise protection coordination index (PCI) using a fuzzy logic controller. The PI indicates how accurately the overcurrent relay has been set and the PCI indicates how optimally relays have been coordinated according to the relay setup guidelines. In other words, this research proposed a method for the operator to check the protection level of the overcurrent relays as needed. Overcurrent relays require protection cooperation between downstream and upstream relays. The downstream relay for the protection of the condensate pump motor, is a combination of high dropout overcurrent relay (50H) component and time overcurrent relay (51) component. Device-wise PI was obtained using the component level's fuzzy membership degrees and fuzzy rules. The device-wise protection index (PI) of the motor overcurrent relay in Figure 1 is 0.78. According to Figure 7, 0.78 is the higher value than Normal (0.66) and lower value than Optimal (1). It is not the optimum level, however, it is pretty good level and obtains PCI for each pair by performing fuzzy operations once again with PI for each device and PI for upstream relay. Figure 11 shows the fuzzy inference process used in this study.

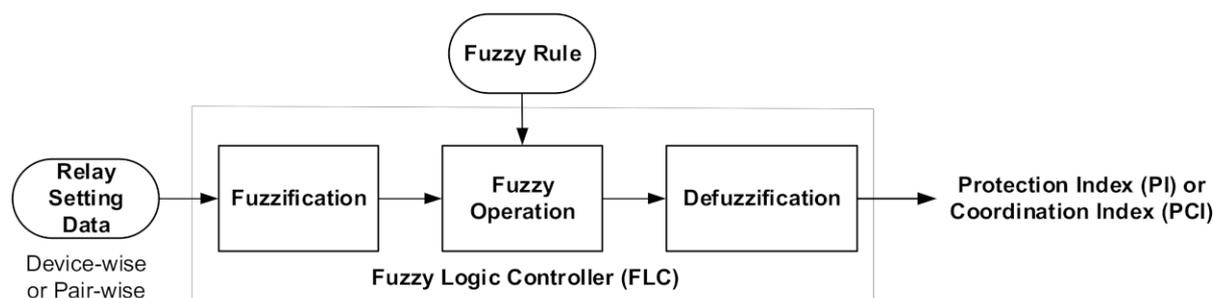


Figure 11. Fuzzy Inference Process.

By the above method, it is possible to evaluate the PCI variation in the overcurrent relay when the operation mode of the auxiliary transformer of the power plant is changed. According to the result, it may be possible to provide an alarm for the operator when the relay protection index is alert level. It is also possible to adjust the overcurrent relay's setting level using protection coordination index if required due to the change of system configuration or equipment capacity. In Section 5, the calculation processes of Sections 3 and 4 were verified using MATLAB. The verification results were consistent.

The main purpose of this paper is to propose a PCI evaluation algorithm. In this paper, the basic principles are presented. In practical systems, the system configuration of the power distribution system is larger and more complex than Figure 1. However any power distribution switchgear or distribution panel can also be decomposed into device-wise and pair-wise components. Thus, protection zone is divided into two categories; device-wise and pair-wise. The pair-wise protection means coordination between upstream relay and downstream relay.

7. Conclusions

Currently, there is no way to know how well the overcurrent relay is set. This paper proposed a PCI evaluation method for overcurrent relays using the fuzzy logic controller, which converts linguistic language to crisp language. This is a completely new and unique idea. PCI provides electrical system operators with the appropriateness of overcurrent

relay setting levels and adjustment results. Therefore, PCI helps electrical engineers operate distribution systems safely and reliably.

As the unit capacity of the plant grows, the capacity of the electric power system continues to increase, as well as the complexity of the electric power system. In particular, the introduction of distributed power will further increase the complexity of the power system. Therefore, it is sometimes necessary to adjust the set value of the over-current system according to the various operation modes. Due to the advancement of digital protection relay, the setting of the protective relay can be implemented remotely.

The assessment of PCI discussed and proposed in this paper is the core part required to make the autonomous protection and coordination system for overcurrent protection relays. If the algorithm introduced in this paper is included in the digital relay, autonomous relay setting and adjustment will also be made. Following this study, research will be conducted on how to implement a reliable high-speed autonomous relay setting and adjustment system for the auxiliary power systems of power generating stations.

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Abbreviations

ALRT	Alternative
CT	Current Transformer
FLC	Full Load Current
HDO	High Dropout
IT	Instantaneous Trip
IOC	Instantaneous Overcurrent
LRC	Locked Load Current
MPR	Motor Protection Relay
NOR	Normal
OA	Oil-immersed self-cooled
OCR	Overcurrent Relay
OPT	Optimal
PCI	Protection Coordination Index
PU	Per Unit
TOC	Time Overcurrent Relay
VIO	Violation

References

1. Chen, G.; Pham, T.T. *Introduction to Fuzzy Sets, Fuzzy Logic, and Fuzzy Control Systems*; CRC Press: New York, NY, USA, 2001; pp. 139–170.
2. Uyar, O.; Çunkaş, M. Fuzzy logic-based induction motor protection system. *Neural Comput. Appl.* **2013**, *23*, 31–40. [[CrossRef](#)]
3. Dudhat, N.M.; Pandya, A.A. Induction Motor Protection System Using Fuzzy Logic. *Int. J. Sci. Eng. Technol.* **2017**, *6*, 134–136.
4. Talaat, H.; Ezzat, M.; Saleh, A. Fuzzy Logic Based Induction Motor Condition Monitoring. *Int. Conf. Electr. Eng.* **2014**, *9*, 1–6. [[CrossRef](#)]
5. Narwade, S.; Kulkarni, P.; Patil, C.Y. Fault detection of Induction Motor using Envelope Analysis. *Int. J. Adv. Comput. Res.* **2013**, *2*, 258–262.

6. Nath, P.; Das, J.; Rohman, A.; Das, T. A fuzzy logic based overcurrent protection system for induction motor. In Proceedings of the 2016 International Conference on Communication and Signal Processing (ICCSP), Melmaruvathur, India, 6–8 April 2016; pp. 755–759. [[CrossRef](#)]
7. Momesso, A.E.C.; Bernardes, W.M.S.; Asada, E.N. Fuzzy-based Non-communicating Adaptive Overcurrent Relay. *IFAC PapersOn-Line* **2018**, *51*, 315–320. [[CrossRef](#)]
8. Bejmert, D.; Rebizant, W.; Schiel, L. Transformer differential protection with fuzzy logic based inrush stabilization. *Int. J. Electr. Power Energy Syst.* **2014**, *63*, 51–63. [[CrossRef](#)]
9. IEEE C37.96; IEEE Guide for AC Motor Protection. IEEE: Piscataway, NJ, USA, 2000; 82–87.
10. IEEE C37.91; IEEE Guide for Protective Relay Applications to Power Transformers. IEEE: Piscataway, NJ, USA, 2011; 18–20.
11. Ross, T.J. *Fuzzy Logic with Engineering Applications*, 3rd ed.; Wiley: West Sussex, UK, 2010; p. 72.
12. Uyar, O.; Çunkaş, M. Design of Fuzzy Logic Based Motor Protection System. In Proceedings of the International Advanced Technology Symposium, Elazig, Turkey, 16–18 May 2011.
13. Momesso, A.E.C.; Bernardes, W.M.S.; Asada, E.N. Fuzzy adaptive setting for time-current-voltage based overcurrent relays in distribution systems. *Int. J. Electr. Power Energy Syst.* **2019**, *108*, 135–144. [[CrossRef](#)]