論 文
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A New Evaluation Methodology for Protection Systems of Primary Distribution Systems Considering Multi-Factors Based on Dempster's Combination Rule

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Abstract - In this paper, a conceptual framework of a new concept of protectability is proposed, which indicates the protection level of the system. Evaluation attributes have been identified and a hierarchical evaluation model has been established. Dempster-Shafer Theory of Evidence is applied in combining multiple uncertain judgements to produce an aggregated evaluation.

Key Words : Power System Protection, Distribution System, Evidential Reasoning, Protective Relaying

1. Introduction

In the primary distribution systems, various protective devices such as overcurrent relay (OCR), recloser, sectionalizer and fuse are applied. The operating parameters of those devices ought to be carefully selected to best satisfy the required protection functions according to the setting rules. The setting rules generally have an inequality expression like smaller than or larger than. For example, one rule for the recloser said that the minimum trip rating should be larger than 1.4 times the maximum loading and smaller than the minimum fault current. Therefore there are multiple feasible setting values and since there is no clear criteria to select the best or the most desirable one, a setting is determined relying on the protection engineers intuition and empirical knowledge [1,2].

Generally the setting job assumes a fixed configuration and loading condition, which however, inevitably change due to the system operation such as service restoration and load balancing. A serious change might cause the protective devices not to be able to perform the required protection function like losing selectivity or sensitivity. Therefore it is strongly needed to have a means to evaluate the protection level [3,4].

In this paper, a conceptual framework of a new concept of protectability is proposed, which indicates the protection level of the system or how good the protection system is, given a certain set of settings. Evaluation attributes have been identified and a hierarchical evaluation model has been established. Dempster's Rule of Combination is used in combining multiple uncertain judgements to produce an aggregated evaluation.[5,6]

2. Protection Level

In the protection point of view, the power system may have one of four levels Optimal, Normal, Alert, Violation that represents how well the system is protected by the protective devices. Usually the setting rule used in the distribution system has an inequality expression like bigger than, smaller than and therefore, there are more than one setting values that satisfy the setting rules. When all the setting values of the protective devices installed in the system, the system is said to have Normal level. Among the feasible setting values, the best setting can be defined based as far as certain criteria are concerned and when the system has these settings, it is said to be in the Optimal level. Some of the settings may have values close to the boundary values of the setting rules that provides some doubt on the devices normal operation. In this case, the system is said to be in the Alert level. When the settings are well outside the range defined by the setting rules, the system is said to have Violation level.

Usually the setting and coordination of the protective

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device aims at achieving the optimal or at least normal protection level. However since the system will inevitably experience the change of the configuration, source impedance, loading, etc., the protection level of the system will make a transition from one level to another as depicted in Fig.1

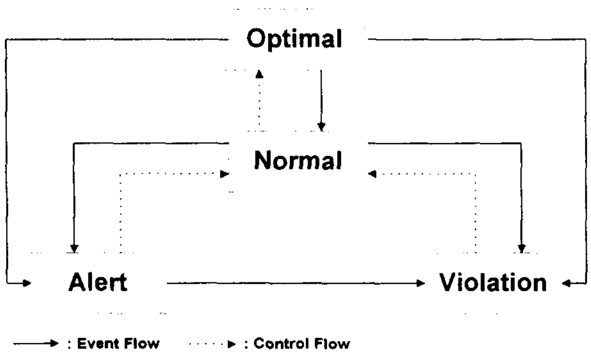


Fig. 1 Protection level transition diagram

3. Evaluation of Protection Level

3.1. Evaluation Methodology

Evaluation of the current systems protection level is a subjective judgement problem to determine which level the current system belongs to as far as the protection capability is concerned. It involves multiple qualitative evaluation attributes that need to be considered simultaneously and contains uncertainty. The methodology adopted in this study is based on the Dempster-Shafer's Theory of Evidence (simply D-S theory). D-S theory of evidence is well suited for handling uncertain subjective judgement when multiple factors need to be considered simultaneously. It provides a powerful and convenient means to combine multiple uncertain judgements to produce an aggregated evaluation [5,6]. For the problem on hand, the qualitative evaluation attribute is treated as a piece of evidence and the evaluation grade i.e., protection level is treated as a basic hypothesis in the D-S theory.

3.2. Dempsters Rule of Combination

In the D-S Theory of Evidence, a sample space is called a frame of discernment defined as H which consists of possible hypothesis (four protection levels in our problem). To every subset A of H, a probability mass denoted by $m(A)$ can be assigned and satisfies the following conditions:

$$\sum_{A \subseteq B = C} m(A) = 1, m(\Phi) = 0$$

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

$m(A)$ called the basic probability assignment (bpa), indicates that portion of the total belief exactly committed to a hypothesis A given a piece of evidence, or the degree to which the evidence supports the hypothesis. When there are two pieces of evidence with m_1 and m_2 as their bpas respectively, a combined bpa m_{12} can be obtained from the Dempsters Rule of Combination defined below:

$$m_{12}(S) = \sum_{A \cap B = C} m_1(A) m_2(B) / (1 - K), \quad m_{12}(\Phi) = 0$$

$$\text{where} \quad K = \sum_{A \cap B = \Phi} m_1(A) m_2(B), \quad A, B \subseteq H$$

If one more evidence provides a bpa m_3, then the combination rule is applied again to produce the combined bpa m_{123}.

3.3 Evaluation Attributes

Qualitative attributes required in the protection level evaluation can be categorized into two groups: Device-wise group and Coordination-wise group. The former defines those attributes that each device should satisfy and the latter defines those that each pair of primary and backup devices should satisfy. Since distinction between protection levels can not be clearly made, they are defined as fuzzy sets and so the fuzzy membership as a function of an evaluation attribute is defined for each attribute. The membership degree is then used as a bpa that denotes the support to the hypothesis or the protection level. Below, evaluation attributes are enumerated together with its associated fuzzy membership function. The fuzzy membership functions have been developed for the overcurrent relay, recloser, sectionalizer and fuse based on their setting rules [7]. The parameters appearing in the setting rule determine a few values F defined in the base membership function in Fig. 2 and by equally dividing the interval specified by the known values, the rest values are defined. Below only the part of the membership functions are shown.

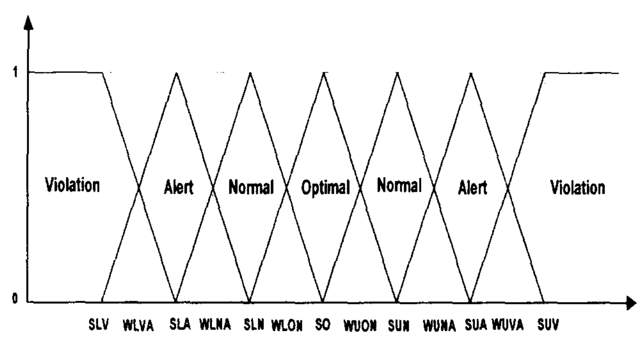


Fig. 2 Base membership function

Each letter constituting the boundary definition term in Fig.2 can be read as follows:

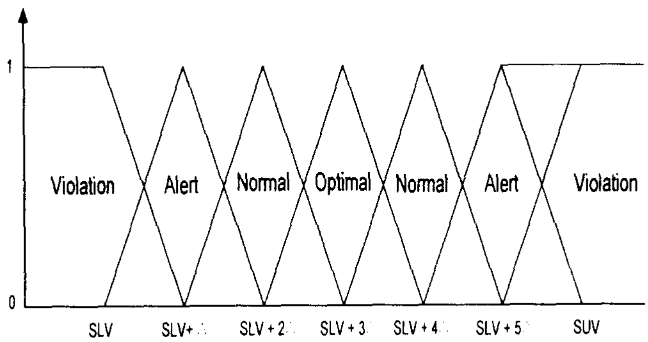
S: strong W: weak L: lower U:upper

V:violation A:alert O:optimal N:normal

According to this, SLA represents Strong lower (boundary for) Alert.

3.3.1. Device-wise attributes

(1) Sensitivity : the capability to detect any faults in the primarily assigned line section.

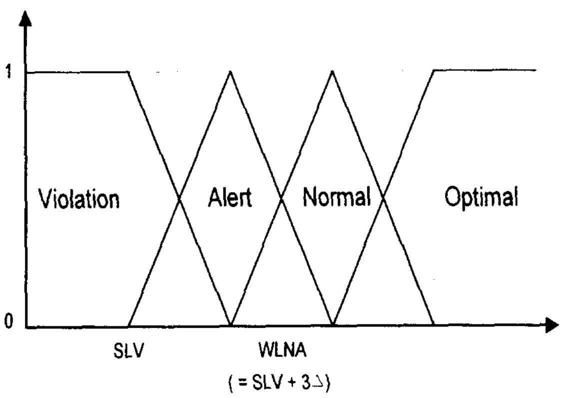


△=(SUV-SLV)/6

<Time Overcurrent Element>

Where, SLV : Current loading

SUV : Minimum fault current



△=(WLNA-SLV)/3

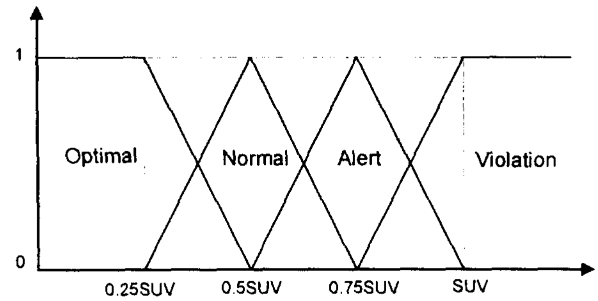
<Instantaneous Trip Element>

Where, WLNA = 1.5 * IMf

(IMf=Maximum fault current)

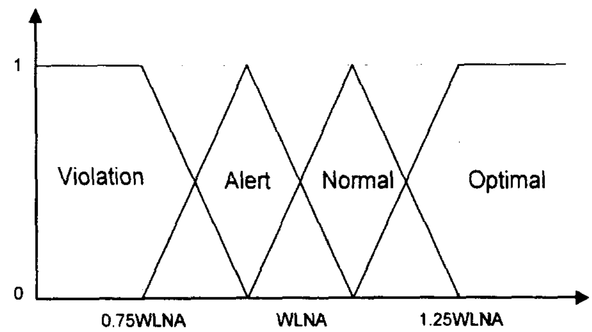
SLV = IMf

(2) Line protection : the capability to protect the primarily assigned line section. It can be evaluated by the ratio of the operating time of the protective device over the short circuit duration time of the line at the fault current.



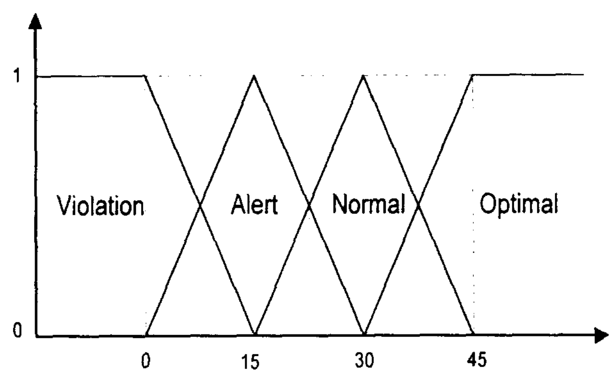
Where SUV is given by the ratio of operating time of the device over the short circuit duration time at 1.5 times the operating pickup current and maximum fault current.

(3) Detection of high impedance fault: the detecting capability of the high impedance fault.



Normal ground fault resistance is 30[Ω] when a single phase ground fault is occurred.

(4) Cold load pickup: the capability not to operate due to the cold load.



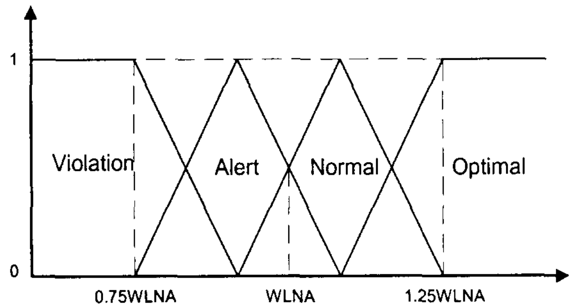
Where, WLNA = 2.5[sec] for 1.7×Tap current or 6×IML (IML=Maximum Load Current)

(5) Singular rule : the capability to satisfy the singular rule that can not be covered by criteria.

3.3.2. Coordination-wise attributes

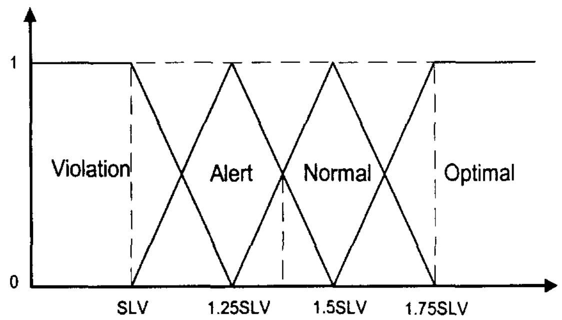
(1) Coordination time interval: operating time difference between primary and backup devices

a) OCR - Recloser

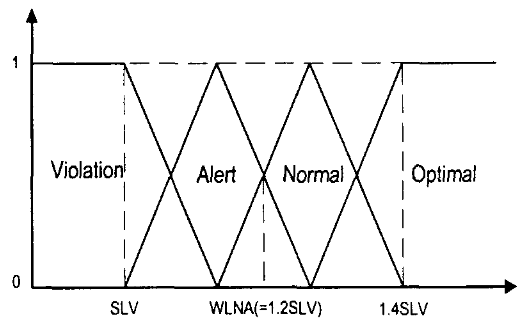


Where, WLNA = 10 cycle

b) Recloser-Recloser (Fast operation)



c) Recloser-Recloser(Delay operation)



Where, SLV is given by the ratio of backup recloser operating time over the primary recloser operating time.

(2) Backup reach: the capability of the backup device to detect the fault in the line section assigned to the primary device.

(3) Primary line protection: the capability to protect the line section assigned to the primary device.

(4) Singular coordination rule: the capability to satisfy the singular coordination rule that can not be covered by criteria (1),(2),(3).

4. Hierarchical Evaluation Model

An evaluation model proposed in this study has a hierarchical structure composed of four levels evidence level, device level, triple level and system level as depicted in Fig.3.

In the attribute level, evaluation of each qualitative attribute for a protective device and a pair of primary-backup devices, is to be carried out and the resultant evaluation grade will be protection levels with associated the bpa. In each level of the model except for the attribute level, combination of evaluation results obtained from the lower level is performed using Dempster's Rule of Combination.

The device level deals with evaluation of a device and a pair, and the triple level evaluates all possible sets of a pair and associated two devices for a system. Finally, the system evaluation is to be done at the system level. Note that at each level, evaluation is made on one of the protection levels with associated bpa. In order to consider the different significance of evaluation attributes, the weight factor is introduce in combining effects of multiple attributes at each level.

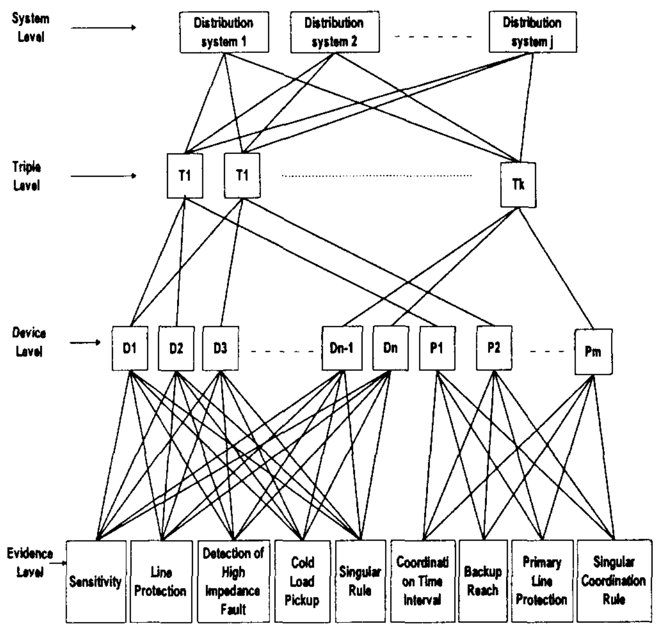


Fig. 3 A Hierarchical evaluation model

The final evaluation grade obtained from the system level may not be able to give an idea on how good the protection system is because of its fuzzy representation. The numerical index called Protectability is introduced to quantify these evaluation grades and eventually to quantify subjective judgements with uncertainty. It is obtained by calculating the weighted sum of the fuzzy evaluation grade with weights of 1, 0.5, -0.5, -1 assigned to O,N,A,V respectively.

5. Examples

The proposed evaluation method is applied to two example systems with different complexity. Each system is given two settings which were generated from the setting program DISCO [7]. Evaluation program has been developed in C is used to calculate the protecability.

5.1 System 1

The system as shown in Fig.4 has four devices OCR, recloser, sectionalizer and fuse using real system data. The minimum and maximum fault currents are also shown on the system Two sets of setting data are listed in Table 1.

For each set of settings, according to the model, evaluation of the evidence level is performed and its results are summarized in Table 2.

Here for each evaluation criterion and for each device, the evaluation results at the evidence level are given. For example, for recloser R1 and for sensitivity criterion, $0.016/H_O$, $0.984/H_N$ can be seen and it represents that the setting of recloser R1 belongs to the optimal state with a supporting degree of 0.016 and the normal state with a supporting degree of 0.984.

Applying Dempster's combination rule repeatedly at each level with associated weights, the final evaluation results are obtained and summarized in Table 3, which indicates that the second setting is better than the first one. The protectability of Setting 1 and 2 are 0.5 and 0.522 which are calculated from the weighted sum of each state's supporting degree.

Table 1. Setting data

	OCR (OCR1)	Recloser (R1)	Sectionalizer (S1)	Fuse (F1)
Type	CO-9M	VWVE	GH	T Type
Setting 1	Tap : 1.0 [A] Lever : 3 Pickup 180 [A]	MTR : 140 [A] Sequence : 1F3D X multiple : 8	MAC : 112 [A] Count : 2	MR : 60 [A]
Setting 2	Tap : 1.5 [A] Lever : 4 Pickup : 240 [A]	MTR : 200 [A] Sequence : 1F3D X multiple : 6	MAC : 160 [A] Count : 2	MR : 60 [A]

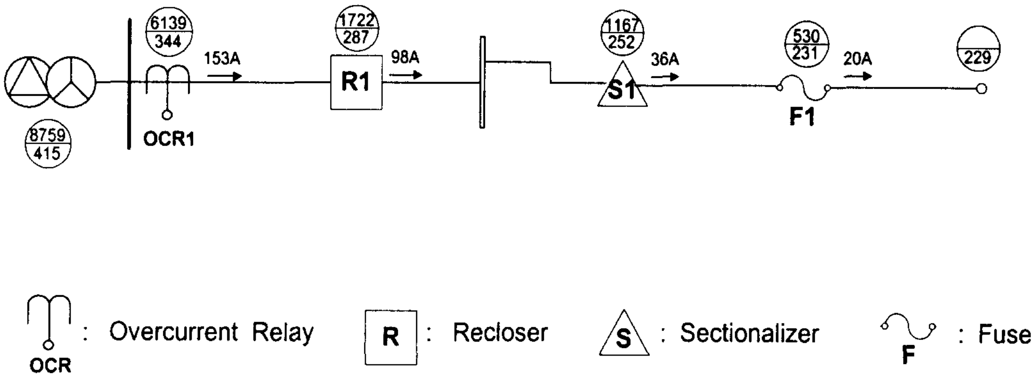


Fig. 4 Example system

Table 2. Evaluation results for evidence level

(a) Setting 1

Device-wise	Sensitivity		Lime Protection		Cold Load Pickup		Singular Rule	
OCR1	0.214/H_N	0.786/H_A	0.500/H_O	0.500/H_N	0.699/H_N	0.301/H_A	1.000/H_O	0.000/H_N
R1	0.641/H_N	0.359/H_A	0.500/H_O	0.500/H_N	0.341/H_O	0.659/H_N	1.000/H_O	0.000/H_N
S1	0.338/H_O	0.662/H_N	0.500/H_O	0.500/H_N				
F1	0.149/H_N	0.851/H_A	0.500/H_O	0.500/H_N				
Pair-wise	**Coordination Time Interval**		**Backup Reach**		**Primary Line Protection**		**Singular Coodination Rule**	
OCR1-R1	0.980/H_N	0.020/H_A	0.602/H_N	0.398/H_A	0.500/H_O	0.500/H_N		
R1-S1			0.600/H_N	0.400/H_A	0.500/H_O	0.500/H_N	0.000/H_O	1.000/H_N
R1-F1	1.000/H_O	0.000/H_N	0.724/H_N	0.276/H_A	0.500/H_O	0.500/H_N	0.000/H_O	1.000/H_N

(b) Setting 2

Device-wise	Sensitivity		Line Protection		Cold Load Pickup		Singular Rule	
OCR1	0.100/H_O	0.000/H_N	0.500/H_O	0.500/H_N	0.699/H_N	0.301/H_A	1.000/H_O	0.000/H_N
R1	0.016/H_O	0.984/H_N	0.500/H_O	0.500/H_N	0.845/H_O	0.155/H_N	1.000/H_O	0.000/H_N
S1	0.185/H_O	0.815/H_N	0.500/H_O	0.500/H_N				
F1	0.149/H_N	0.851/H_A	0.500/H_O	0.500/H_N				
Pair-wise	**Coordination Time Interval**		**Backup Reach**		**Primary Line Protection**		**Singular Coodination Rule**	
OCR1-R1	1.000/H_O	0.000/H_N	0.768/H_O	0.232/H_N	0.500/H_O	0.500/H_N		
R1-S1			0.523/H_O	0.477/H_N	0.500/H_O	0.500/H_N	0.000/H_O	1.000/H_N
R1-F1	1.000/H_O	0.000/H_N	0.585/H_O	0.415/H_N	0.500/H_O	0.500/H_N	0.000/H_O	1.000/H_N

Table 3. Final evaluation results

	Optimal	Normal	Alert	Violation	Protectability
Setting 1	0.000	1.000	0.000	0.000	0.500
Setting 2	0.044	0.956	0.000	0.000	0.522

5.2 System 2

Another evaluation is performed for the complex system depicted in Fig.5. It has seven protective devices-one OCR, two reclosers, one sectionalizer, and three fuses. Setting data and evaluation results are shown in Table 4,5,6. It can be seen that the second setting with protectability of 0.853 gives a better protection level than the first one with protectability of 0.500.

6. Conclusion

In this paper, a new concept of protectability which indicates the protection level of the system is proposed. Evaluation attributes together with their associated fuzzy membership functions for each protective device have been identified and the three level hierarchical evaluation model has been proposed. A systematic evaluation methodology applying Dempster's combination rule has also been presented.

The concept of protectability can be used not only for checking the protection level of the current system but also for determining the best setting values. The proposed method is expected to find more application in the adaptive protection system.

Table 4. Setting data

	OCR (OCR1)	Recloser (R1)	Recloser (R2)	Sectionalizer (S1)	Fuse (F1)	Fuse (F1)	Fuse (F1)
Type	CO-9M	VWVE	VWVE	GH	T Type	T Type	T Type
Setting 1	Tap : 1.0 Lever : 3 Pickup 180	MTR : 140 Seq : 1F3D X multi : 8	MTR : 100 Seq : 1F3D X multi : 4	MAC : 80 Count : 2	MR: 60	MR: 60	MR: 60
Setting 2	Tap : 1.5 Lever : 4 Pickup : 240	MTR : 200 Seq : 1F3D X multi : 6	MTR : 140 Seq : 1F3D X multi : 4	MAC : 112 Count : 2	MR: 60	MR: 60	MR: 60

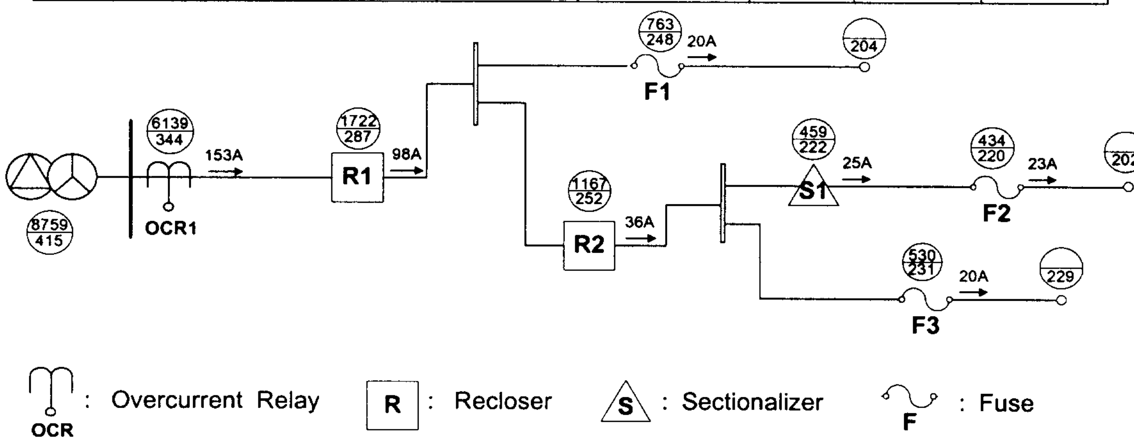


Fig 5 Example system 2

Table 5. Evaluation result for evidence level

(a) Setting 1

Device-wise	Sensitivity		Line Protection		Cold Load Pickup		Singular Rule	
OCR1	0.214/H_N	0.786/H_A	0.500/H_O	0.500/H_N	0.708/H_N	0.292/H_A	1.000/H_O	0.000/H_N
R1	0.680/H_N	0.320/H_A	0.500/H_O	0.500/H_N	0.341/H_O	0.659/H_N	1.000/H_O	0.000/H_N
R2	0.065/H_O	0.935/H_N	0.500/H_O	0.500/H_N	0.162/H_O	0.838/H_N	1.000/H_O	0.000/H_N
S1	0.692/H_N	0.308/H_A	0.500/H_O	0.500/H_N				
F1	0.307/H_N	0.693/H_A	0.500/H_O	0.500/H_N				
F2	0.242/H_N	0.758/H_A	0.500/H_O	0.500/H_N				
F3	0.149/H_N	0.851/H_A	0.500/H_O	0.500/H_N				

Pair-wise	Coordination Time Interval		Backup Reach		Primary Line Protection		Singular Coodination Rule	
OCR1-R1	0.982/H_N	0.018/H_A	0.640/H_N	0.360/H_A	0.500/H_O	0.500/H_N		
R1-R2	1.000/H_O	0.000/H_N	0.677/H_N	0.323/H_A	0.500/H_O	0.500/H_N		
R2-S1			0.154/H_N	0.846/H_A	0.500/H_O	0.500/H_N	0.000/H_O	1.000/H_N
R1-F1	1.000/H_O	0.000/H_N	0.958/H_N	0.042/H_A	0.500/H_O	0.500/H_N	0.000/H_O	1.000/H_N
R2-F2	0.143/H_N	0.857/H_A	0.292/H_N	0.708/H_A	0.500/H_O	0.500/H_N	0.000/H_O	1.000/H_N
R2-F3	0.067/H_N	0.933/H_N	0.149/H_N	0.851/H_A	0.500/H_O	0.500/H_N	0.000/H_O	1.000/H_N

(b) Setting 2

Device-wise	Sensitivity		Line Protection		Cold Load Pickup		Singular Rule	
OCR1	0.100/H_O	0.900/H_N	0.500/H_O	0.500/H_N	0.708/H_N	0.292/H_A	1.000/H_O	0.000/H_N
R1	0.920/H_N	0.080/H_A	0.500/H_O	0.500/H_N	0.847/H_O	0.153/H_N	1.000/H_O	0.000/H_N
R2	0.645/H_O	0.355/H_N	0.500/H_O	0.500/H_N	1.000/H_O	0.000/H_N	1.000/H_O	0.000/H_N
S1	0.678/H_N	0.322/H_A	0.500/H_O	0.500/H_N				
F1	0.307/H_N	0.693/H_A	0.500/H_O	0.500/H_N				
F2	0.242/H_N	0.758/H_A	0.500/H_O	0.500/H_N				
F3	0.149/H_N	0.851/H_A	0.500/H_O	0.500/H_N				
Pair-wise	**Coordination Time Interval**		**Backup Reach**		**Primary Line Protection**		**Singular Coodination Rule**	
OCR1-R1	1.000/H_N	0.000/H_A	0.840/H_N	0.160/H_A	0.500/H_O	0.500/H_N		
R1-R2	1.000/H_O	0.000/H_N	0.645/H_N	0.355/H_A	0.500/H_O	0.500/H_N		
R2-S1			0.769/H_N	0.231/H_A	0.500/H_O	0.500/H_N	0.000/H_O	1.000/H_N
R1-F1	1.000/H_O	0.000/H_N	0.935/H_O	0.065/H_N	0.500/H_O	0.500/H_N	0.000/H_O	1.000/H_N
R2-F2	1.000/H_N	0.000/H_A	0.963/H_N	0.037/H_A	0.500/H_O	0.500/H_N	0.000/H_O	1.000/H_N
R2-F3	1.000/H_N	0.000/H_N	0.724/H_N	0.276/H_A	0.500/H_O	0.500/H_N	0.000/H_O	1.000/H_N

Table 6. Final evaluation results

	Optimal	Normal	Alert	Violation	Protectability
Setting 1	0.000	1.000	0.000	0.000	0.500
Setting 2	0.706	0.594	0.000	0.000	0.853

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