論 文
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경험적 탐색에 의한 배전계통 보호 기기 정정협조

Heuristic Search in Overcurrent Protection Coordination of Power Distribution Systems

李 承 宰* · 朴 永 文** · 李 正 元***
(Seung-Jae Lee · Young-Moon Park · Jeong-Won Lee)

요 약

배전선로 보호기기 정정은 시스템의 신뢰도를 제고하는 적절한 정정치를 구하기위하여 많은 시행착오를 거쳐야하는 조합적 탐색 문제이다.

본 논문은 이 문제의 성격과 보호 기기의 주보호-후비보호 기기의 패턴을 이용한 경험적 규칙을 적용하여 탐색 공간을 효율적 탐색으로 축소하는 방법을 제시한다. 이의 유용성은 실계통에서의 적용으로 입증하였다.

Abstract - The setting problem of protective devices in power distribution systems is a combinatorial search problem involving a lot of trial & errors to search for a proper solution which has a great impact for the system reliability. This paper discusses the nature of the problem and proposes a scheme to prune the decision tree achieving the efficient search for a setting solution by applying heuristic rules which utilize pattern informations of backup and primary devices. Its effectiveness is demonstrated through many tests on real systems.

1. Introduction

The protective devices applied to primary feeders of the electric power distribution systems include overcurrent relays, reclosers, sectionalizers, fuses, etc. Those protective devices ought to be carefully selected and set to achieve the best security and setting job in a downstream fashion starting from the substation level due to higher importance of the transmission systems and a radial structure of distribution systems.

During the setting process, selection and setting of a pair of the primary and backup devices are repeated until the certain coordination criteria are satisfied for all pairs. Those coordination constraints vary depending on the pattern of the

*正 會 員 : 明知大 工大 電氣工學科 助教授 · 工博
**正 會 員 : 서울大 工大 電氣工學科 教授 · 工博
***正 會 員 : 三星電子 研究所 研究員
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primary-backup pair such as recloser-recloser, recloser-fuse, recloser-scctionalizer-fuse, etc. and they usually contain the inequality constraints yielding multiple solutions. Engineers usually have to go through the candidate generation and test' process in order to find a good solution, suffering from a lot of failed attempts and time-consumption in case of a large system.

Since setting parameters take discrete values, this setting problem has a combinatorial nature and thus heuristic search techniques[1] should be adopted. Mathematical optimization techniques such as integer programming can hardly be used for this problem due to following reasons: 1) no exact mathematical formulation of the T/C curves of the protective devices exist 2) most constraints are non-linear 3) no clear objective function can be defined. There have been some computer programs to automatize this tedious process[2, 3, 4]. But they are not capable enough to handle various protective devices and they have not paid attention to "how to reduce the number of failed attempts" or efficiency of the algorithms.

In this paper, an issue of "how to reduce the search space?" is discussed and the heuristic method to set the protective devices in primary distribution systems is proposed. The proposed scheme utilizes information on patterns of backup-primary devices to reduce the number of failed constraint checking by guiding the search and reduce the number of alternatives to be tested.

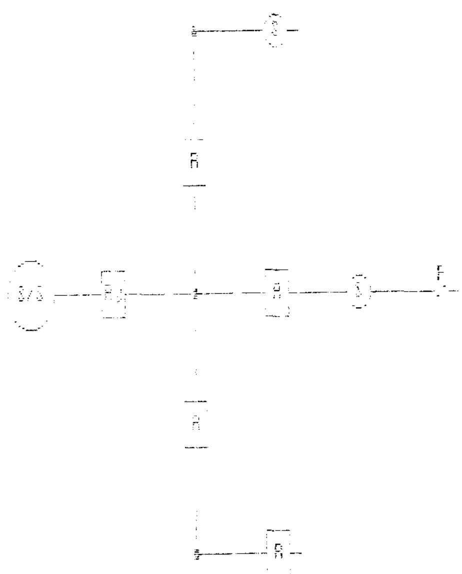

Fig. 1 Typical Feeder Configuration

Fig. 1 shows the configuration of a general primary distribution system. Usually feeders from a substation are protected by various devices such as relays, reclosers, sectionalizers and fuses against the overcurrent. Each device has setting parameters which determine its operating characteristic and they ought to be selected to achieve the proper functional requirements, i.e., selectivity, sensitivity and speed[5]. Selection problem of proper settings for protective devices in the primary distribution system can be stated as follows:

Problem:

Find a set $S=\{s_1, s_2, \cdots, s_n\}$

subject to:

$C_1(S)=1$ (device constraints)

$C_2(S)=1$ (coordination constraints)

where

n : number of protective devices

s_i : settings of device i

1 : state of satisfied constraints

Setting parameters vary depending on the type of devices, i.e., {tap, lever} if i=relay, {minimum trip rating, sequence} if i=recloser, {minimum actuating current, memory time, counts to trip} if i=sectionalizer, {continuous current rating} if i=fuse. Since in this study, types of devices are assumed known, selection of other ratings such as voltage rating, interrupting rating, maximum continuous current rating, etc. are not dealt with. C_1 represents a set of constraints specified by system

Table 1 Device-wise Constraints C_1

Device	Rule
Ry	$1.5\times I_L < TAP < I_{Mf}/1.5$
Rec	$1.4\times I_L < MT < I_{Mf}$
Sec	$I_L < MA < I_{Mf}$
F	$I_L < CC < I_{Mf}$

conditions such as system loading, fault currents, as summarized in Table 1 and it is used to determine ratings of a device disregarding coordination with other devices. Usually these constraints are given in inequality form and thus define the range of possible ratings.

The second constraint set C_2 contains constraints imposed by following coordination principles for a pair of devices connected in series[8]. (This pair will be referred to as B-P pair hereafter)

Principle 1 : The primary (or protecting or load-side) device must clear a fault before the back-up (or protected or source-side) device interrupts the circuit or operates to lockout.
Principle 2 : Outages caused by permanent faults must be restricted to the smallest section of the system for the shortest time.

Combination patterns of devices of B-P pairs include Ry-Rec, Rec-F, Rec-Rec, Rec-Sec, etc. and application of coordination principles to each pattern results in coordination constraints of C_2 shown in Table 2. Note that inequality constraints constitute the major part as is the case in C_1, which causes a non-unique solution.

Table 2 Coordination Constraints C_2

Pattern	Coordination Constraints
Ry-Rec	$OT_{Ry}(I_{Mf}) > TAT(I_{Mf}) + 10\text{cycles}$
Rec-Rec	$OT(B, F, I_{Mf}) > OT(P, F, I_{Mf})$ $OT(B, D, I_{Mf}) > OT(P, D, I_{Mf}) + \Delta t$ $LO(B, P) = P$
Rec-F	$OT(B, D, I_{mf}) > MCT(P, I_{mf})$ $OT(B, F, I_{Mf}) \times Kf < MMT(P, I_{Mf})$ $SEQ(F) >= 1$ $SEQ(D) >= 1$
Rec-Sec	$LOT(I_{mf}) < MEM$ $MTR_{sec} = 0.8 \times MTR_{Rec}$ $\text{COUNT} = SEQ(F) + SEQ(D) - 1$ $FOT < 0.7$ $SEQ(F) + SEQ(D) >= 2$
Rec-Sec-F	Rec-Sec conditions & Rec-F conditions $SEQ(F) = 1$ $SEQ(D) = 3$
F-F	$MCT(P, I_{Mf}) / MMT(B, I_{Mf}) \Leftarrow 0.75$

3. Nature of Problem

A feeder in distribution systems has basically a tree structure due to the radial operation. A corresponding tree graph showing the connectivity of protective devices in the feeder system in Fig. 1 can be drawn as Fig. 2.

In this graph, a node represents a protective devece and a branch denotes the B-P relationship of two nodes it connects. The tree graph starts from a root node which is a relay (Ry) usually followed by reclosers. Since settings of the relay are assumed known in this study and all reclosers are to coordinate with this relay, as far as setting is concerned, paths beyond the root node can be considered independent.

As discussed in the previous section, the basic unit in the setting process is the B-P pair for which the following operation is applied:

"given settings of the backup device, determine settings of the primary device to satisfy certain constraints specified by the device type"

In this operation, the designer usually first finds some candidate setting values satisfying corresponding constraints of C_1 and since not all values meet coordination constraints, he then tries to determine the most suitable one which not only satisfies coordination constraints but also fits well other practical considerations. The whole setting process consists of the repeated use of above

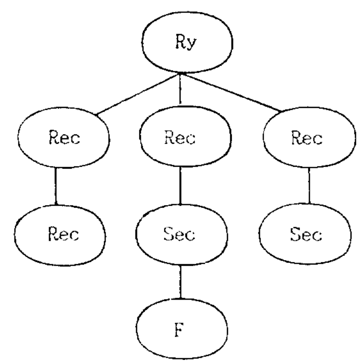

Fig. 2 Graph Representation of Protection System

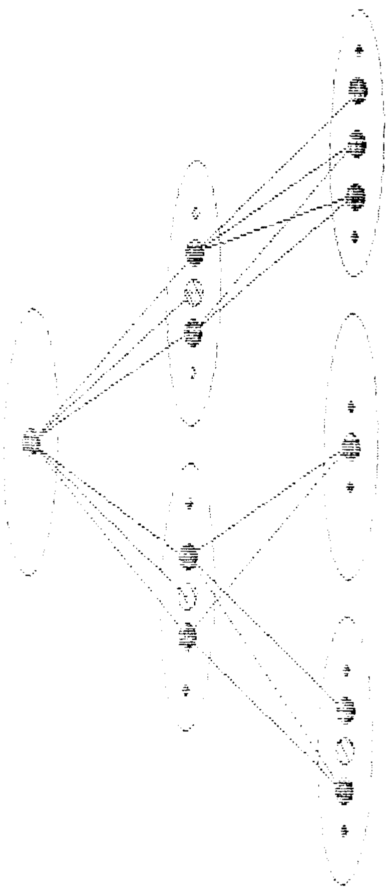

Fig. 3 Solution Search Space

operation following through the graph and would generate the search space as shown in Fig. 3. In this figure, each node contains a set of elements or alternatives which represent candidate setting values and a link connecting e_i and e_j represents a coordinated pair of node i and j.

Note that a solution is given as a set of connected elements visiting all nodes, which due to the multiple elements in each node, falls in the combinatorial search problems, that is, problems in which finding a solution normally involves the analysis of the exponentially increasing number of alternatives. For such combinatorial problems, heuristic programming techniques are generally used to cut down the number of alternatives to be evaluated to a manageable number by utilizing the problem-specific heuristics. However, to our knowledge, as far as the setting problem in feeder systems is concerned, so far neither systematic method nor clear heuristics to prune the decision tree or the search space has been reported. In practice, the heuristic 'trial & error' method which repeats 'candidate generation and test' process is generally adopted until certain conditions are met and its efficiency is heavily dependent on the engineer's empirical knowledge. Since for a large system, great effort and time have to be spent, it is desirable to have a guided search which can reduce such effort and can be applied to the general system. In the following section, a heuristic method adopting the device-pattern-guided search and some heuristic rules to prune the decision tree, developed based on following observations on the primary feeder systems is presented.

Observations :

1) A different pattern of a B-P pair has a differnet level of stringency in coordination constraints.

2) Due to the limitation in the number of devices connected in series, each path from a root to an end node has almost the same depth.

4. Heuristic Search

From Fig. 3, one can easily see that the number of elements (or alternatives) in a node and the order of nodes to visit have a strong influence on the size of the decision tree. The proposed method has adopted heuristic rules to reduce the number of elements in each node and to decide the order of nodes to proceed the setting process. It consists of four major steps-node ordering, candidate set generation, candidate selection and coordination checking-as shown in Fig. 4.

1) Node Ordering

This step determines the order of search based on the device pattern of B-P pairs. To be more specific, given nodes visited (intially, this is a root node), next node to visit is selected among the set of their childern nodes which form the B-P relation, applying the following pattern-based priority order : *Rec-Sec-F*, *Rec-F*, *Rec-Rec*, *F-F*, *Rec-*

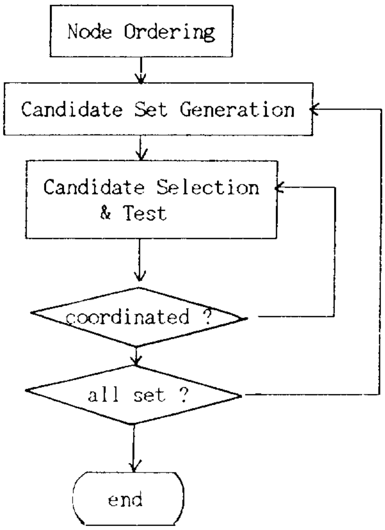

Fig. 4 Flowchart of Setting Process

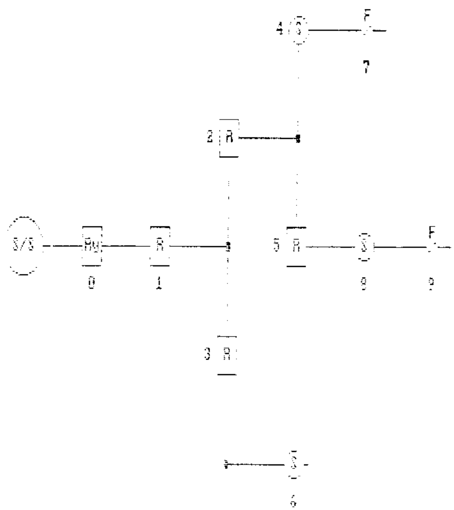

Fig. 5 Node Ordering for System

Sec-Sec, *Rec-Sec*. This priority order has been determined based on the following heuristic rules:

HR1 : if coordination constraints of certain $B\text{-}P_i$ pair are satified then those for other $B\text{-}P_j (j \neq i)$ pairs with less stringency are likely to be satisfied.

HR2 : coordination constraints of a pattern with different types of devices are more stringent than the one with the same type.

HR3 : coordination constarints of a pattern containing more devices are more stringent than the one with less devices.

If more than one same *B-P* pattern having the highest priority exist, then strongest patterns of *B-P* pairs consisting of their children nodes and grandchildren nodes are compared in the same manner. Here, this procedure is illustrated for the system in Fig. 5. Starting from the root node (*Ry*), the first node to visit is obviously one with a recloser. Then next patterns are taken into consideration. Since node 2 has two pattens, *Rec-Sec-F* and *Rec-Sec* the stronger one, *Rec-Sec-F*is compared with node 3's *Rec-Sec* pattern. Consequently node 2 is selected according to the pattern priority. In the next step, selection is made among a set of candidate nodes {3, 4(7), 5}which form patterns of *Ry-Rec*, *Rec-Sec-F*, *Rec-Rec*, respectively. thus node 4 becomes the next node since it makes the strongest pattern together with the fuselink at node 7. in a similar manner, the process continues to result in the sequence of {1, 2, 4(7), 5, 8(9), 3, 6} as indicated in Fig. 5.

2) Candidate Set Generation

This step generates the possible set of elements for a primary node given a specific element of the backup node (two nodes making *B-P* relation will be referred to as backup node and primary node, respectively). The possible set can be identified by applying the corresponding selection criteria in C_1. Note that the possible set may contain infeasible elements which do not satisfy coordination constraints C_2. The reduced set which contains a fewer infeasible elements can be constructed by utilizing information on types of adjacent nodes, which are summarized in the following rules:

CR1 : for a given node, if its backup node has the same type of device, then its rating may not be bigger than its backup's.

CR2 : if a given node is a recloser and its backup node is also a recloser, then it must have the equal or more fast operations than its backup.

CR3 : if a given node is a recloser and its backup node is also a recloser, then it must have the euqal or smaller number of total operations than its backup.

CR4 : if a given node is a recloser and any childeren node is a fuselink then its sequence must have at least one delay and one fast operations.

CR5 : if a given node is a recloser and any children node is a sectionalizer followed by a fuselink (*Rec-Sec-F* pattern) then its sequence need be 1F3D.

3) Candidate Selection & Test

This step is in charge of selecting one candidate from a set of candidates and checking its feasibility, i.e., coordination constraints. In practice, it requires the engineer's empirical knowledge in order to select the one with the most desirable features. However, in this paper, the operating speed of the device is taken as a selection criteria and thus, element of a node is selected and tested using following rules until the feasible one is found.

CR1 : if the device is a recloser and the setting parameter is rating then select the smallest rating

CR2 : if the device is a recloser and

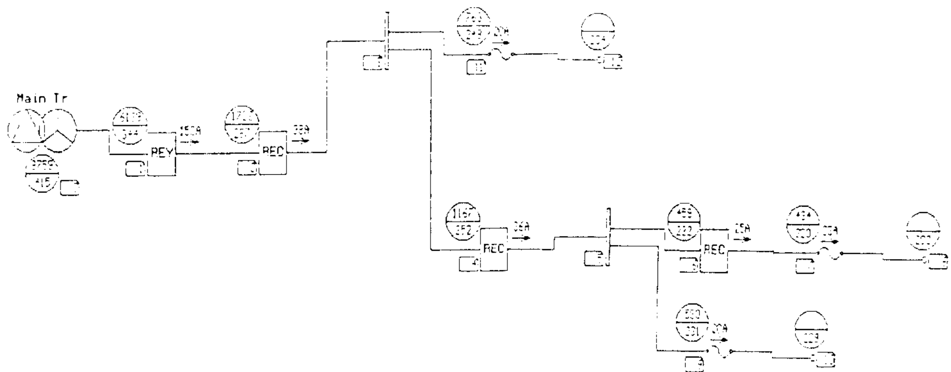

Fig. 6 Test System 1

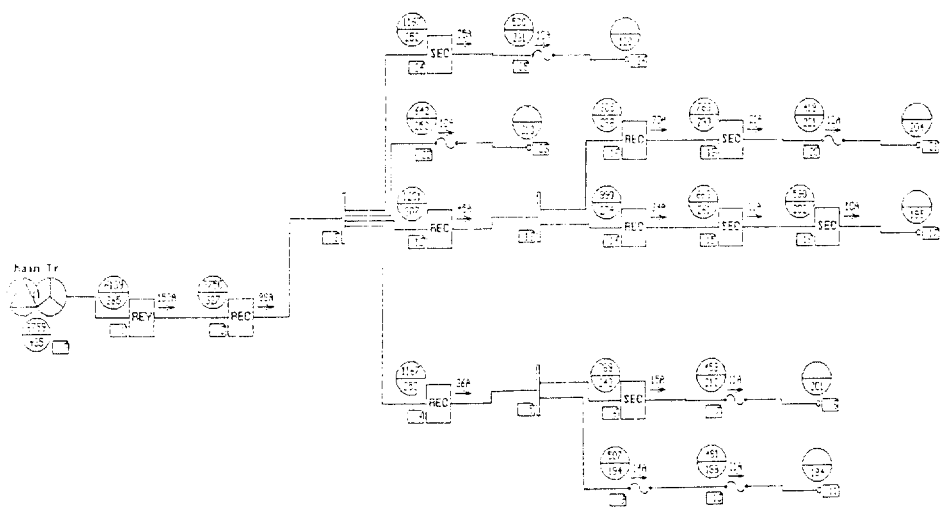

Fig. 7 Test System 2

the setting parameter is sequence
then select one with a smallest number of delay operation and a smallest number of total operations.

CR3 : if the device is fuselink
then select the smallest rating

5. Test Examples

In order to verify effectiveness of the proposed level of scheme, tests on two sample systems with different complexity have been carried out. The system shown in Fig. 6 is relatively a simple one that has seven protective devices on two branches, while the system in Fig. 7 is a fairly complex one that contains seventeen devices on six branches. The nominal voltage of 22.9KV is assumed for both systems. Necessary data such as fault currents and load currents are also indicated on the same diagrams. Types of devices in both systems are assumed as *CO*-9 for relay, *VWVE* for recloser, *GV* for sectionalizer, and *K* for fuselink.

In the following, two comparisons are performed to show the efficiency of the proposed pattern-based ordering and reduction rules in candidate set generation. First, the total number of condition checkings involved in the search for all possible solutions adopting four different search strategies-Depth First Search (DFS), Breadth First Search(BFS), Longest Path First Search (LPS) and the proposed scheme, Pattern-Based Search(PBS), -are compared and the result is summarized in Table 4. In this process, reduction rules for candidate set generation were not applied. Corresponding search ordering is shown in Table 3.

In this table, numbers in parenthesis denote the ratio of the checking number to that of PBS. Note

Table 3 Node Ordering

	Strategy	Node Ordering
system 1	BFS	1-2, 2-4, 2-11, 4-6, 4-9, 6-7
	DES	1-2, 2-4, 4-9, 4-6, 6-7, 2-11
	LPS	1-2, 2-4, 4-6, 6-7, 4-9, 2-11
	BPS	1-2, 2-11, 2-4, 4-9, 4-6, 6-7
system 2	BFS	1-2, 2-4, 2-12, 2-24-25, 12-18, 12-14, 4-9, 4-6-7, 14,15, 9-10, 18-19-20, 15-16
	DFS	1-2, 2-12, 12-14, 14-15, 15-16, 12-18, 18-19-20, 2-4, 4-9, 9-10, 4-6-7, 2-22, 2-24-25
	LPS	1-2, 2-12, 12-14, 14-15, 15-16, 12-18, 18-19-20, 2-4, 4-9, 9-10, 4-6-7, 2-24-25, 2-22
	PBS	1-2, 2-24, 2-22, 2-4, 4-6-7, 4-9, 2-12, 12-18, 18-19-20, 9-10, 12-14, 14-15, 15-16

Table 5 Efficiency of Reduction Rules

system	without rdduction		with reduction	
	(A)	(S)	(A)	(S)
1	12.58 (1.8)	681 (1.8)	688 (1.0)	373 (1.0)
2	2950 (5.2)	1754 (4.6)	572 (1.0)	384 (1.0)

Table 4 Comparison of Different Search Schemes

System	BFS		DFS		LFS		PBS	
	(A)	(S)	(A)	(S)	(A)	(S)	(A)	(S)
1	4394 (3.5)	2710 (4.0)	4881 (3.9)	3288 (4.8)	6619 (5.3)	4231 (6.2)	1258 (1.0)	681 (1.0)
2	8913 (3.0)	5927 (7.9)	8353 (2.8)	5760 (7.6)	8353 (2.8)	5760 (7.6)	2950 (1.0)	754 (1.0)

(A) : total number of attempted condition checking
(S) : total number of succeeded condition checking

Table 6 Setting Soultion for System 1

Position	Device	Rating	Sequence
2	Rec	140.0	1F2D
4	Rec	100.0	1F2D
6	Rec	100.0	2F1D
7	F	38.0	
9	F	45.0	
11	F	60.0	

Table 7 Setting Soulution for System 2

Position	Device	Rating	Sequence /Count	Memory Time (Sec)
2	Rec	200.0	1F3D	
4	Rec	100.0	1F3D	
6	Sec	80.0	3	9.57
7	F	38.0		
9	F	45.0		
10	F	12.0		
12	Rec	140.0	1F3D	
14	Rec	100.0	3F0D	
15	Sec	80.0	2	4.09
16	Sec	80.0	1	4.09
18	Rec	100.0	1F3D	
19	Sec	80.0	3	9.60
20	F	38.0		
22	F	60.0		
24	Sec	160.0	3	9.80
25	F	45.0		

that by following orders generated by the pattern-based search (PBS), remarkably high efficiency in total number of condition checkings has been obtained during the search for the whole setting solutions in PBS, that is only 29% of BFS (4394), 26% of DFS (4881) and 19% of LPS (6619). Similarly, for System 2, about 65% efforts in condition checkings were saved. System 1 and 2 have been found to have 37 and 720 setting solutions respectively.

Next, two cases-whole solution space search with and without rduction rules applied, in the pattern-based search are tested and the results are illustrated in Table 5. For System 1, about 45% of condition checking effort is saved while the bigger saving (81%) is observed for System 2 which shows that the more complex the system is, the bigger the effect of the reduction rules is. Among 37 and 720 possible solutions for two sample systems, application of selection rules has yielded setting solutions Shown in Table 6 and 7.

6. Conclusion

In this paper, a heuristio search to determine setting parameters of various proteotive devioes used in the primary distribution systems has been proposed. The proposed soheme consists of three parts-node ordering, range generation, candidate selection & test and each part utilizes some heuristics developed in this study to reduce the number of failed checking of coordination constraints. Test results on many actual systems have shown its high efficiency. Although this study takes the speed as the only criterion in selecting the candidate, further work to take other practical factors into consideration needs to be pursued.

Notations

Ry : relay
Rec : recloser
Sec : sectionalizer
F : fuselink
B : backup
P : primary
F : fast operation
D : delay operation
MT : minimum trip rating
CC : continuous current rating
MA : miinimum actuating current
I_L : maximum load current
I_{Mf} : maximum fault current
I_{mf} : minimum fault current
OT_{RY} : operating time of relay
OT : operating time of recloser
TAT : total accumulated time of relay
LOT : lock-out time
LO : recloser to lock-out
SEQ : number of sequence
MEM : memory time

$MCT(I_f)$: maximum clearing time at fault current

$MMT(I_f)$: maximum melting time at fault current

FOT : fault on time

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