배전선로 보호기기 정정에서의 경험적 탐색 방법

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Heuristic Search in Coordination of Overcurrent Protection of Power Distribution Systems

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Abstract

By the nature of distribution system, the coordination process of protection devices depends on various heuristic rules. This paper reviews the practical rules that adopted in coordination, and proposes some heuristic rules improving the coordination process.

I. 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 reliability of the system. It is the common practice to perform the 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 the pairs. Those coordination constraints vary depending on the pattern of the primary-backup pair such as recloser-recloser, recloser-fuse, recloser-sectionalizer-fuse, etc. and they usually contain the inequality constrains yielding multiple solutions. Engineers usually have to go through '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 formulations 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 protecive devices in the primary distribution systems is proposed. The proposed scheme utilize information on patterns of the backup-primary devices to reduce the number of failed checking of coordination constraints.

II. Problem Formulation

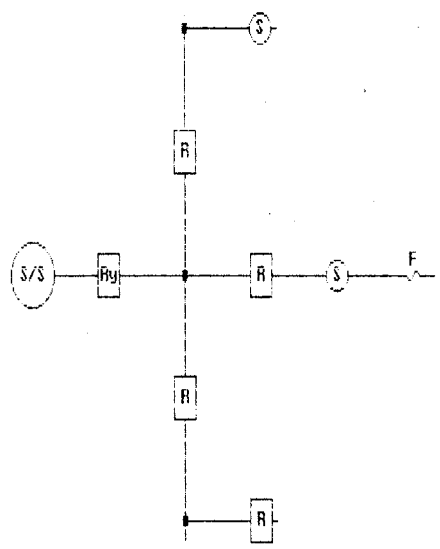

Fig. 1　Typical Feeder Configuration

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 parameters which determine its operating characteristics and they ought to be selected to achieve the proper level of selectivity and sentivity for the system security and reliability.

Selection problem of proper settings for protective devices in the primary distribution system can be stated as follows:

<u>Problem</u>

Find a set S = {s1,s2,...,sn}
subject to:
C1(S) = 1 (device-wise constraints)
C2(S) = 1 (coordination constraints)

where n : number of protecive devices
si : setting parameters 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. Ratings other than above-mentioned ones, such as voltage rating, interrrupting current rating, maximum continuous current rating, etc. are assumed to satisfy requrements since they are factors to determine types of devices which are assumed known in this study.

Constraints of Ci as summarized in Table 1 are specified by system conditions such as system loading, fault currents, which determine ratings of a device disregarding relationship with other devices. Usually these constraints are given as inequality constraints and thus define the range of possible ratings.

Table 1. Device-wise Constraints C1

Device	rule
Ry	$1.5 * I_L < TAP < I_{Mf}/1.5$
Rec	$1.4 * I_L < MT < I_{Mf}$
Sec	$I_L < MA < I_{Mf}$
F	$I_L < CC < I_{Mf}$

where Ry : relay Rec : recloser
Sec : sectionalizer F : fuse link
MT : minimum trip rating
CC : continuous current rating
MA : minimum actuating current
I_L : maximum load current
I_{Mf} : maximum fault current

The second constraint set C2 contains constraints imposed by following coordination principles between a pair of devices forming the primary and backup relation [7].

<u>Principle 1:</u> The primary device must clear a fault before the backup device interrupts the circuit or operates to lockout.
<u>Principle 2:</u> Outages caused by permanent faults must be restricted to the smallest section of the system for the shortest time.

Each B-P (backup-primary) pair may take a differnet combination of devices showing such patterns as Ry-Rec, Rec-F, Rec-Rec, Rec-Sec, etc. Application of coordination principles to each pattern results in coordination constraints, C2 shown in Table 2. Note that inequality constraints consistute the major part as is the case in C1, which cause a non-unique solution.

Table 2. Coordination Constraints C2

pattern	coordination constraints
Ry-Rec	$OT_{Ry}(I_{Mf}) > TAT(I_{Mf})$ + 10 cycles
Rec-Rec	$OT_B(F,I_{Mf}) > OT(P,F,I_{Mf})$ $OT_B(D,I_{Mf}) > OT(P,D,I_{Mf})$ + seperation time LO(B,P) = P
Rec-F	$OT(D,I_{mf}) > MCT(I_{mf})$ $OT(F,I_{Mf})*Kf < MMT(I_{Mf})$ SEQ >= 1F1D
Rec-Sec	TAT < MEM $MTR_{Sec} = 0.8 * MTR_{Rec}$ COUNT = SEQ(B,t) - 1 FOT < 0.7 SEQ(t) >= 2
Rec-Sec-F	R-S conditions & R-F conditions SEQ = 1F3D
F-F	$MCT(P,I_{Mf}) / MMT(B,I_{Mf}) <= 0.75$

where B : Backup operation P : Primary operation
F : Fast operation D : Delay operation
t : total
I_{mf} : Minimum fault current
I_{Mf} : Maximum fault current
$OT(I_f)$: Operating time in fault current I_f
$TAT(I_f)$: Total accumulated time in fault current I_f
LO : Lock-out
SEQ : Recloser sequence
MEM : Memory time
$MCT(I_f)$: Maximum clearing time in fault current I_f
$MMT(I_f)$: Maximum melting time in fault current I_f
MTR : Minimum trip rating
FOT : Fault on time

III. Nature of Problem

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

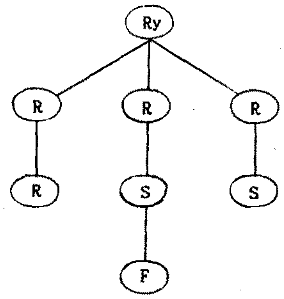

Fig. 2 Graph Representation of Protection System

In this graph, a node represents a protective deive and a branch denotes the B-P relationship between nodes it connects. The graph starts from a root node which is a D/L relay whose settings are known and so does the setting process. Thus 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
find settings of the primary device to
satisfy constraints C1, C2"

Note that it is inequality constraints of C1 and C2 that makes the solution space complex as shown in Fig. 3. Nodes corresponding to devices contains a set of elements (e_i,...) which represents a set of device's setting parameterse satisfying C1, and a link connecting e_i and e_j represent a coordinated pair of node i and j satisfying C2.

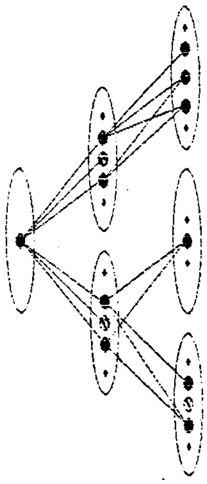

Fig. 3 Solution Space

Note that a solution is given as a set of connected elements visiting all nodes, which is so called 'a spanning tree'. Due to multiple elements for each node, to search for one solution with a certain characteristic has a combinatorial nature. Thus the setting problem is a combinatorial search problem for which so far no systematic method or no clear rule has been reported. In practice, the heuristic 'trial & error' method which repeats "candidate generation and test" process until all devices are set is generally adopted and its search 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 well-guided search method which can reduce such effort and can be applied to the general system.

For this, a heuristic method is proposed in this paper and it is developed based on following observations:

Observations:

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

2) The depth of a primary feeder or its corresponding graph is generally 2-5 levels because of limitation in the number of devices in series and thus each branch has almost the same depth level.

IV. Heuristic Search

From Fig. 3, one can easily see that the number of elements in a node and the order of nodes to visit have a strong influence on the number of tries. The proposed method tries to achieve the efficient search by adopting heuristic rules to reduce the number of elements in a node and to decide the order of the nodes to proceed the setting process. It consists of three major steps - node ordering, candidate set generation, candidate selection and test - as shown in Fig. 4.

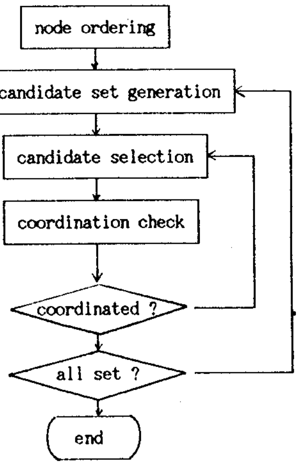

Fig. 4 Flowchart of Setting Process

1) Node Ordering

This step determines the order of search based on the pattern of the B-P pair. To be more specific, given nodes visited (initially, this is a root node), next node to visit is selected among the set of their children nodes or primary nodes which form the B-P relation, applying the following pattern-based order: R-S-F, R-F, F-F, R-R, R-S-S, R-S. However more than one same B-P pattern may exist and in this case, strongest patterns of B-P pairs consisited of children nodes and their grandchildren nodes are compared.

The oreder of B-P pattens has been determined based on the following heuristic rules:

HR1: if coordination constraints of a certin B-P_i pair are satisfied then those for other B-P_j ($j \neq i$) pairs with less stringency are likely to be satisfied.
HR2: coordination criteria of a pattern with different type is more stringent than the one with the same type.

HR3: a pattern containing more devices has more stringent coordination constraints than the one with less devices.

Here, this procedure is illustrated for the system in Fig. 5. Starting from the root node, since patterns formed by its children nodes are both Ry-Rec's, patterns of their grandchildren nodes are taken into consideration. Since node 2 has two pattens, Rec-Sec-F and Rec-Rec, the stronger one, Rec-Sec-F is compared with node 3's pattern Rec-Sec. Consequently node 2 is selected according to the pattern ordering. 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. Note that node 4 makes a pattern together with the fuselink at node 7. The most stringest pattern, Rec-Sec-F of node 4(7) is chosen. The next node to visit will be node 3 since its pattern Ry-Rec has a higher ordering than the Rec-Rec pattern of node 5. In a similar manner, the process continues resulting in the sequence of {2,4(7),3,5,6} as shown in Fig. 5.

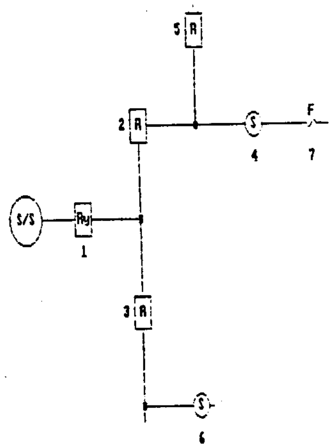

Fig. 5 Node Oredering for System

2) Candidate Set Generation

This step generates the possible set of elements for a primary node given an element of the bacup node. The possible set can be identified by applying the selection criteria C1. Note that the possible set may contain infeasible elements which do not satisfy coordination constraints C2. The reduced set which contain fewer infeasible elements can be constructed by utilizing information on types of adjacent nodes. The following rules are adopted in this process.

CR1) for a given node if its backup node has the same type of device, then its rating need be smaller 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 greater number of 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 equal or smaller number of total operations than its backup.
CR4) if a given node is a recloser and any children 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 seletion criteria and thus, elements of a node are selected and tested using following rules until the feasible one is found.

CR1 : if the device is recloser and
the setting parameter is rating
then select the smallest rating
CR2 : if the device is recloser and
the setting parameter is sequence
then select one with a smallest number of delay operation
CR3 : if the device is fuselink
then select the lowest rating

Note that coordination checking results for a certain B-P pair can also be utilized to identify some fesible elements without further checking using the following rules:

S1) if a certain element forming a pattern of Rec-Rec with its backup is tested feasible, then those elements which have following properties are also feasible:
- same sequence and smaller MTR
- same MTR and smaller number of delay operations
- same MTR, same number of delay operations and smaller number of fast operations
S2) if a certain element forming a pattern of F-F with its backup is tested feasible, then those elements which have the smaller CCR are feasible.

V. Test Examples

In order to verify effectiveness of the proposed method, test on two sample systems with different complexity has been carried out. The system shown in Fig. 6 is relativily 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 22.9 KV is assumed for both systems. Necessary data such as fault currents and load currents are also indicated on the same diagrams. Types of adopted devices are shown in Table 3.

In the following two comparisons are performed to show the efficiency of the pattern-based ordering and reduction rules in candidate set generation. First, total number of condition checkings involved in the search of all possible solutions adopting four different search strategies - Depth First Search (DFS), Breadth First Search (BFS), Longest Path First Search (LPS) and the propsed scheme, Pattern-Based Search (PBS), - is compared and the result is presented in Table 5. In this process, reduction rules for candidate set generation were not applied. Corresponding search ordering is shown in Table 4.

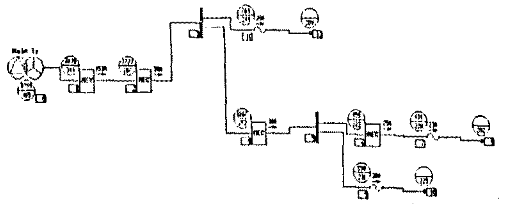

Figure 6. Test system 1

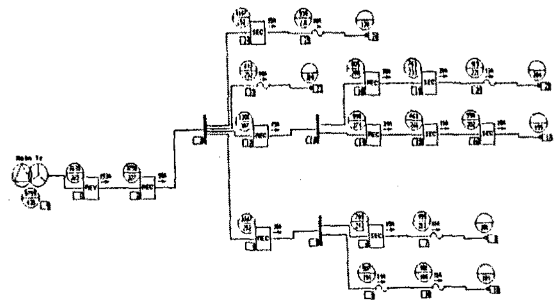

Figure 7. Test system 2

Table 3. Type of devices

Device	Type
Rey	CO-9
Rec	VWVE
Sec	GV
Fuse	K

Table 4. Node Ordering

	Stratage	Node Ordering
system 1	BFS	1-2,2-4,2-11,4-6,4-9,6-7
	DFS	1-2,2-4,4-9,4-6,6-7,2-11
	Longest Path	1-2,2-4,4-6,6-7,4-9,2-11
	Pattern	1-2,2-11,2-4,4-9,4-6,6-7
system 2	BFS	1-2,2-4,2-12,2-22,2-24-25,12-18,12-14,4-9,4-6-7,14-15,9-10,18-19-20,15-16
	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
	Longest Path	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
	Pattern	1-2,2-24-25,2-22,2-4,4-6-7,4-9,2-12,12-18,18-19-20,9-10,12-14,14-15,15-16

Table 5. 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

In this table, numbers in parenthesis denote the ratio of the checking number to that of PBS. Note that by following orders generated by the pattern-based search (PBS), remarkable efficiency in total number of condition checking has been achieved. To be more specific, for System 1, 1258 condition checkings are attempted during the search for whole setting solutions in PBS, that is only 29 % of BFS (4394), 26 % of DFS (4881) and 19 % of LFS (6619). Similarly, for System 2, about 65 % of 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 reduction rules applied, but adopting the pattern-based search are tested and the results are illustrated in Table 6. 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 impact of the reducton rules is.

Table 6. Efficiency of Reduction Rules

system	without reduction		with reduction	
	(A)	(S)	(A)	(S)
1	1258 (1.8)	681 (1.8)	688 (1.0)	373 (1.0)
2	2950 (5.2)	1754 (4.6)	572 (1.0)	384 (1.0)

Among 37 and 720 possible solutions for two sample systems, application of rules to select the fast one has yield setting solutions as shown in Table. 7, 8.

Table 7. Setting solution for System 1

Pos-ition	Device	Rating	Sequence
2	Rec	140.0	1F2D
4	Rec	100.0	1F2D
6	Rec	100.0	2F1D
7	Fuse	38.0	
9	Fuse	45.0	
11	Fuse	60.0	

Table 8. Setting solution for System 2

Pos-ition	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	Fuse	38.0		
9	Fuse	45.0		
10	Fuse	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	Fuse	38.0		
22	Fuse	60.0		
24	Sec	160.0	3	9.80
25	Fuse	45.0		

VI. Conclusion

A heuristic mehtod to search for a set of settings of protecive devices in primary deistribution systems is proposed. It consists of three major parts - node ordering, candidate set generation, candidate selection. Each part atttempts to reduce the number of failed checking of coordination constraints during the course of setting process by applying heuristic rules identified in this study.

The proposed search scheme has been tested very effective and it is expected to show a better performance as the system becomes complicated and the number of protective devices increases. The adopted selection strategy, however, does not incorporate the engineer's empirical knowledge which in practice, plays an important role to identify the most desirable one for the specific system, which is left for the future research.

VII. References

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