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Zero-one Integer Programming Approach to Determine the Minimum Break Point Set in Multi-loop and Parallel Networks

Joymala Moirangthem†, S. S. Dash* and Ramas Ramaswami*

Abstract – The current study presents a zero-one integer programming approach to determine the minimum break point set for the coordination of directional relays. First, the network is reduced if there are any parallel lines or three-end nodes. Second, all the directed loops are enumerated to reduce the iteration. Finally, the problem is formulated as a set-covering problem, and the break point set is determined using the zero-one integer programming technique. Arbitrary starting relay locations and the arbitrary consideration of relay sequence to set and coordinate relays result in navigating the loops many times and futile attempts to achieve system-wide relay coordination. These algorithms are compared with the existing methods, and the results are presented. The problem is formulated as a set-covering problem solved by the zero-one integer programming approach using LINGO 12, an optimization modeling software.

Keywords: Minimum Break Point Set (MBPS), Looped system, Relay coordination, Relay settings, 0-1 integer programming, N-P complete problem

1. Introduction

When a fault occurs on transmission lines or at substations, the transmission protection system senses the faults and rapidly isolates these faults by opening all incoming current paths. The term "coordination" means there should be a sufficient time delay between the primary and backup relay operations in which primary relay should operate first for any fault. With the increase in system size, the number of the primary/backup relay pairs that have to be coordinated for any fault grows dramatically.

The process of coordinating a system of directional relays involves setting the relays one by one until the relay being set coordinates with all its primary relays. Difficulty in setting relays appears when the last relay is set in a sequence that closes a loop. It must coordinate initially with one set in that loop, or else it must recoordinate relays in sequence. Further, the coordination process is also affected by relays in the adjacent loops. Therefore, this traversal of loops for coordination is a highly iterative and complex process. To overcome and identify efficient ways of addressing this problem, Break Point Relays, which are a minimum set of relays that can break all the loops in the system in both directions, are suggested. The idea of break point sets (BPS) to reduce the complexity in relay coordination was first introduced by Knable in [1]. An efficient sequence of all the other relays will be determined to reduce the number of iterations and to accelerate the convergence of the coordination process. The sequence for setting the relays is displayed by a relative sequence matrix (RSM) [2]. In setting a relay, determining which relays will be backed up by this relay is necessary. The set of all primary and backup relays sorted by the backup relays is the set of sequential pairs (SSP) [2-4]. The simple and straightforward methods are those based on the graph theory, as in [5, 6]. Finding a break point relay in a small network with a limited number of buses and loops is not too complex. However, with the increase in the number of buses and loops in the system, the problem of finding the suitable BPS is practically complicated [7]. The depth-first search can enhance the efficiency of finding all the loops [2]. In [8], the methodology developed does not require the generation of all the directed loops. As in [9-11], the proposed approaches are based on functional dependency, which applies heuristic method for selecting BPS. As in [12], an improved algorithm has been applied by partitioning graphs into forests. Sastry in [13] tried a heuristic approach in which a bus with the highest degree of relays is chosen, and all the relays on that bus are removed. The process is carried out until no loops are left in the system. The BPS in polynomial time was determined in [14]. A novel approach based on two dynamic matrices of node-relay matrix and relay incidence matrix was introduced in [15] to find the minimum break point set (MBPS).

† Corresponding Author: Dept. of Electrical and Electronic Engineering, SRM University, India. (joy.mala@gmail.com)
* Dept. of Electrical and Electronic Engineering, SRM University, India. (munu_dash_2k@yahoo.com, r.ramaswami@ieee.org)
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2. Topological Analysis

For a given network configuration, identifying all the primary/backup relay pairs before starting the actual coordination is necessary. The coordination process is complex because of the large number of loops present in the typical transmission network.

To illustrate the coordination problem, consider the six-bus test system in Fig. 1. Let us start with Relay 13 for the backup coordination process. Relay 13 is initially set as a backup to coordinate with Relay 1.

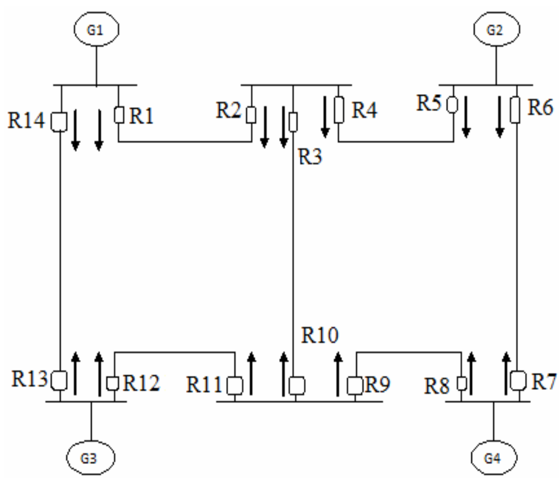

Fig. 1. Six-bus test system

Relay 11 is set as a backup to coordinate with Relay 13, whereas Relay 3 is set as a backup to coordinate with Relays 11 and 9. Relay 1 is set as backup to coordinate with Relays 3 and 4, thus closing the loop. This newly changed setting value of Relay 1 necessitates recomputing the already set values of our initial Relay 13. This new setting value of Relay 13 is then propagated to all other relays in that loop for proper coordination of the relays in the same loop. The coordination process is affected by relays in the adjacent loops, making this traversal of loops for coordination a highly iterative and complex process. Therefore, identifying the minimum number of initiating relays is important to minimize the number of iterations. The minimum set of relays is referred to as break point relays. Once the BPS is found, all other relays are arranged such that whenever any relay beyond the BPS is to be arranged, all of its primary relays have already been set in a previous step. This step ensures that a relay can be set to coordinate with all of its primary relays. Setting relays in sequence ensures that each relay is visited only once during an iteration through all the relays. The absence of such a sequence may require visiting each relay more than once per iteration. Using this sequence, the coordination process converges very rapidly. The sequence for setting the relays is displayed by the RSM. For setting a relay, determining which relays will be backed up by this relay is necessary. The set of all primary and backup relays sorted by the backup relays is the SSP [2].

The algorithm for the topological analysis of any system is described in Fig. 2.

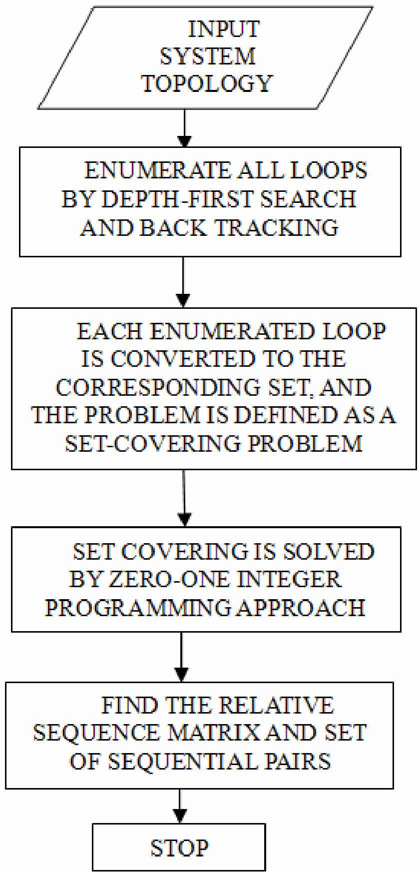

Fig. 2. Algorithm for the topological analysis

2.1 System description

2.1.1 Treatment of the three-end node

In Fig. 3, a network with a three-terminal line junction point is indicated as a bus, which is called "phantom bus." The relays are called "phantom relays" in Fig. 4.

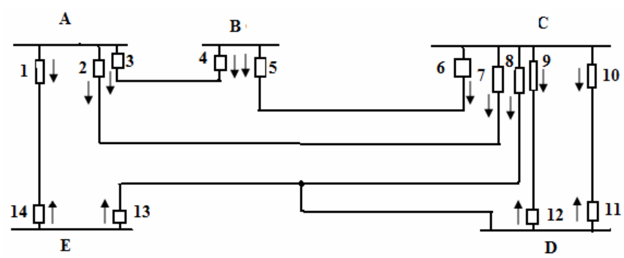

Fig. 3. System with a three-end node

While formulating the problem, the phantom relays looking away from the phantom bus should be excluded because phantom relays cannot become break point relays. The inclusion of phantom relays in the MBPS causes a problem in setting the sequential pairs. To avoid this, after generating all the possible combination of loops, all the entries corresponding to phantom relays are set to zero or removed to reflect the actual coordination. Each loop should be broken by virtue of having at least one real relay

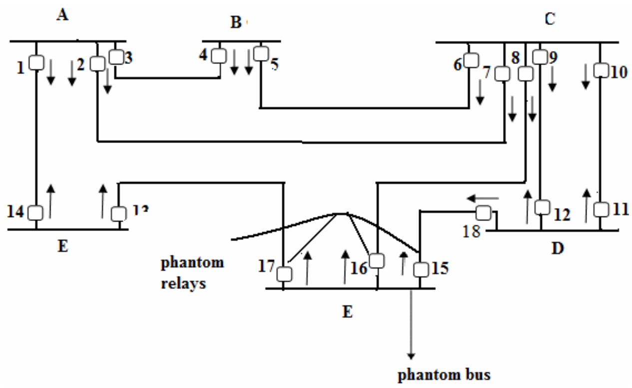

Fig. 4. System with a phantom bus and phantom relays

in the MBPS.

2.1.2 Treatment of parallel lines

A system having many parallel lines can cause a steep increase in the number of loops in the system, increasing the execution time. This problem can be overcome if certain properties of parallel lines are made, e.g., removing certain parallel edges in the network and finding the solution (i.e., break point relays) for the reduced problem. Consider directional loops involving two parallel lines in Fig. 5.

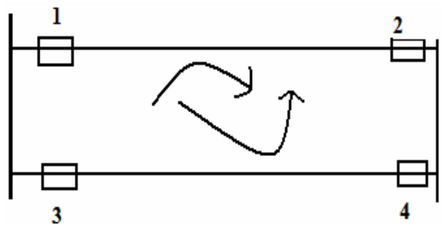

Fig. 5. Two lines in parallel

Out of the four relays, one set must be selected as a break point relay that breaks the loops in both directions. The procedures for selecting the break point relays to break the loops are as follows:

(1) Only one line for each set of parallel lines is included, and the resulting loops and corresponding break point relays are enumerated.

(2) The lines that are not included in step 1 are added. To update the break point relays for each added line, the following strategies are adopted:

  (i) If the relays included on the line in step 1 is not a break point relay, add both the relays on the line in step 2 as break point relays.

  (ii) If either one of the relays included in step 1 is a break point relay, add the corresponding relay on the line in step 2 as a break point set.

  (iii) If both relays on the line included in step 1 are break point relays, then both the relays on the line in step 2 will be break points relays.

2.2 Algorithm for loop enumeration

The identification of break points requires the enumeration of all the loops of the system in both directions and determines a minimum set of relays that will open all these loops. This loop enumeration is achieved though the Depth-First Search and Backtracking procedure. Start from a bus and travel deep into the network until one loop is found.

(1) Backtrack to the previous bus and look for other possible loops.

(2) If we have backtracked to the bus where we started, eliminate this bus from the system, consider the next bus, and look for other possible loops. This algorithm ensures a systematic and efficient procedure for enumerating each loop only once.

2.4 Computation of MBPS, RSV and SSP

Once all the directed loops of the system are found, each loop is converted to a corresponding set. At this stage, the phantom relays from the system are removed or set to zero. The problem in computing for the MBPS is converted to a set-covering problem. The zero-one integer programming approach is applied in the study.

The zero-one programming technique has been successfully applied to solve a project selection problem in which projects are mutually exclusive and/or technologically interdependent. It is used in a special case of integer programming, in which all the decision variables are integers. It can assume the values either as zero or one. Integer linear programming problems are a special class of linear programming problems, in which all or some of the variables in the optimal solution are restricted to non-negative integer values. Here, the problem of finding the break point relays is formulated as a zero-one integer programming problem. Each directed loop should have at least one break point relay that breaks the loop; the relay will take the value of 1 if it is a break point and 0 if it is not. The zero-one integer programming provides an efficient approach to the computation of optimal BPS. The problem is solved using the solver called LINGO 12. The problem can be defined as minimizing the break point relays, which can be written as follows:

$$\text{Minimize Break point set} = \sum_{j=1}^{n} C_j BP_j \tag{1}$$

Subject to the constraints

$$\sum_{j=1}^{n} L_{ij} BP_j >= 1 \tag{2}$$

Where, L is the simple loop matrix

Cj is the cost function

BP = array of break point set

n = number of breakers

BPj = {1, if breaker j is a BP; else, 0 if breaker j is not a break point}.

Once the MBPS is determined, the next step is to determine the RSM, which is an ordered sequence of all the relays in the system, such that during each setting, the given relay is visited or set only once. The sets of break point relays are the first row of the RSM, and the remaining relays are preceded in sequence. If all the primary relays of a given relay are present in the matrix, they will form an RSM.

Next, we find the SSP. The primary and backup relays of the system are ordered in sequence. The pairs are ordered so that the backup relays appear in the same sequence as the RSM. Enumeration is carried out by taking each relay from the RSV as backup and obtaining all its primary relays. SSP provides rapid convergence of the iterative coordination process.

3. Case Study

In Fig. 6, a six-bus system is taken for testing the algorithm. The relays on the line are marked as the number.

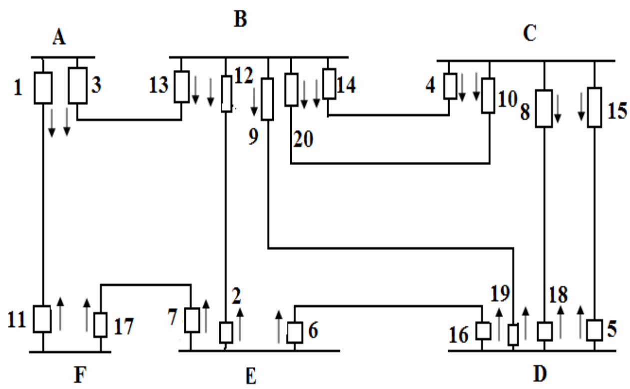

Fig. 6. Six-bus test system

Number of the line = 10
Number of the relays = 20
Total number of directed loops = 34
Possible number of break point relays = (Number of fundamental loops + 1) = 6
Break point set = {9, 12, 14, 15, 17, 20}

The RSM is given as follows:

$$\begin{bmatrix} 9 & 12 & 14 & 15 & 17 & 20 \\ 3 & 1 & & & & \\ 11 & 13 & & & & \\ 7 & 10 & 19 & 4 & 2 & \\ 16 & 18 & & & & \\ 5 & & & & & \\ 8 & 6 & & & & \end{bmatrix}$$

SSP: Primary / Backup relays [(16,15),(18,15),(19,15),(5, 9),(16,9),(18,9),,, etc.]

4. Results and Discussion

The proposed method has been tested on several networks, and the results have been compared with those of the existing methods. The comparison of study results is presented in Tables 1, 2, 3, 4, and 5.

Table 1. 5 Bus system with one phantom bus and nine lines

	Method presented by R. Ramaswami [4] *et al.*	Proposed method
No of minimum BP relays	6	5
Minimum break point relays	{6,7,9,10,11,12}	{6,7,8,9,10}

Table 2. Six bus and ten lines

	Method presented by Sastry [13]	Proposed method
No of minimum BP relays	7	6
Minimum break point relays	{8,9,10,12,13,15,20}	{9,12,14,15,17,20}

Table 3. Seven bus and twelve lines

	Method presented by Hossein [17]	Proposed method
No of minimum BP relays	8	7
Minimum break point relays	{7,9,10,14,15,18,19,23}	{5,6,10,15,16,20,21}

Table 4. IEEE 14 bus system

	Method presented by Hossein[19] *et al.*	Proposed Method
No of minimum BP relays	12	10
Minimum break point relays	{2,3,9,10,11,16,18, 19,27,28,37,38}	{4,5,6,7,10,23,31,32, 35,40}

Table 5. Indian utility system

	Method Proposed by Rajeev [18]	Proposed Method
No. of loops	1190	12
No of minimum BP relays	19	19
Minimum break point relays		{3,15,28,22,25,26,30,42,34,39, 38,37,36,35,34,33,31,32}

The proposed method is found to be efficient in minimizing the break point relays compared with the method proposed by other authors.

5. Conclusion

The current study has found zero-one integer programming to be an efficient approach for computing minimum break point relays. The technique has been applied to typical structures associated with transmission network, such as two-and-three lines, parallel lines, loop, and radial lines. This zero-one integer programming approach has been implemented using LINGO 12. The tool solves various optimization problems, such as linear, nonlinear, and integer programming. Comparison with other methods demonstrates the efficiency of the proposed method.

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Joymala Moirangthem received her Bachelor of Engineering in Electrical and Electronics Engineering from Thiagarajar College of Engineering in Madurai, India, and her Master of Engineering in Power System Engineering from Velammal Engineering College in Chennai, India. Having obtained the first rank in M.E. program under Anna University in India, she received the Michael Faraday Medal from Velammal Engineering College. She is currently pursuing her Ph.D in the EEE Department of SRM University, India. Her area of interest includes power system protection and FACTS.

Subhransu Sekhar Dash is a professor and head of the Department of EEE at SRM University, Chennai in Tamil nadu, India. He has guided more than 20 PG Students and continues to guide 15 research scholars. His areas of interest are power system operation, control and stability, power quality, and FACTS.

R. Ramaswami is currently a Professor of the EEE Department at the SRM University in Chennai, India. He was originally involved in the concepts, detailed design, and engineering of the CAPE system during his employment with Electrocon International, Inc. from 1986 to 1996. He received his B.Tech. from the Indian Institute of Technology in Madras, India, M.S. from North Dakota State University, USA, and Ph.D from the University of Washington, USA, all in Power Engineering. He is actively involved with IEEE, having served as chair of a Working Group, and is a member of various WGs and Standard Committees. He has published more than 40 papers and reports, mostly in IEEE, to his credit. He has been awarded Best Student Prize Paper, PSRC Prize Paper Award, and Chapter Outstanding Engineer Award, all from IEEE.