Protection coordination: Determination of break point set

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Protection co-ordination: determination of the break point set

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Abstract: Modern power system networks are often multiloop structured. Co-ordinated setting of overcurrent and distance protective relays in such networks is tedious and time consuming. The complicated part of this problem is the determination of a proper minimum set of relays, the so-called minimum break-point set (BPS), to start the co-ordination procedure. The paper presents a new graph-theoretical method to determine a near-to-minimum or a minimum BPS. Using the lemmas of this method, the determination of a minimum BPS can be reduced and decomposed into subproblems. Owing to the efficiency of these lemmas, the presented method quickly achieves the result, even for large networks. Moreover, due to the simplicity of the method, it can be manually applied to the graph of each network. Since the presented lemmas are general, they can be applied to improve any method dealing with BPS determination.

1 Introduction

The basic task of a protection system is to detect faults in system components, and to rapidly isolate them by opening all incoming current paths. On the other hand, in the case of any fault, the protection system should disconnect only a minimum number of components, to minimise interruptions to consumers. Therefore, relays of a protection system should be adjusted for the minimum possible operation time, while maintaining co-ordination among all relays.

In recent years, efforts have been made to develop a systematic algorithm for co-ordination of directional overcurrent and distance relays. Earlier works in this field used a graph-theoretical scheme [1–3]. The basic idea of these methods is to determine a proper set of relays to start the co-ordination procedure. Such a set of relays is termed a break point set (BPS), and each relay in a BPS is termed a break point (BP). The main

property of a BPS is, if settings of its relays are known, co-ordinated settings of the rest of the relays can be determined successively. The main advantage of this co-ordination approach is that it exploits the sparsity of the dependencies among the relays of the protection system. Since the computation time for a co-ordination procedure increases with the size of the BPS, a *minimum* BPS having a minimum number of relays is desirable. Although the earlier methods can determine a minimum BPS, their computation times increase exponentially with the number of relays. This computation problem is quite prohibitive when the number of relays is large.

Another method in this field is based on the functional dependencies [4]. This method obtains a *minimal* BPS, in a time period which is a polynomial function of the number of relays. A *minimal* BPS is defined as a BPS in which all of its members are essential. As a result, a minimal BPS can be different from a minimum BPS, and even its size is not necessarily near to the size of a minimum BPS. Therefore, the result of this method cannot guarantee a fast co-ordination procedure.

This paper presents a new graph-theoretical approach to determine a minimum and a near-to-minimum BPS. The next Section introduces the concept of BPS and represents it using graph theory. In this representation, each BP relay is replaced by a diode, and a BPS represents a set of diodes, which open all loop-paths of the network. Based on the methods of graph theory, some efficient lemmas have been developed. By applying these lemmas, the proposed method reduces the complexity of the BPS determination, and decomposes it into subproblems. A fast algorithm to find a near-to-minimum BPS is presented. For illustration, this algorithm is applied to a 11-bus/19-line network. Unlike the algorithm proposed in [4], this algorithm always results in a minimal BPS of a size near to the minimum. Due to its simplicity, the algorithm can also be applied manually on the graph of each network. Moreover, owing to the efficient lemmas of the method, this algorithm is much faster than other algorithms proposed in [2, 3]. To have generality, in all networks of this paper, each busbar is considered as an infeeding point. The proof of the theorem and the lemmas of the method can be found in [5].

2 Concept of BPS and its representation

To illustrate the concept of BPS, co-ordination of protection system P_1 in Fig. 1 is taken as an example. In this single-loop network, each directional relay takes

over the function of backup for the relay at its remote bus (e.g. a_1 is a backup of a_2, or equally a_2 is a primary for a_1). To achieve a co-ordinated protection, each relay must be set based on the settings of its primaries. Therefore, the setting of a_1 depends on the setting of a_2. Similarly, the settings of a_2, a_3, ..., a_n, a_1 are consecutively dependent on each other, based on the primary-backup dependencies among them. In the same way, the settings of b_n, b_{n-1}, ..., b_1, b_n are consecutively dependent on each other.
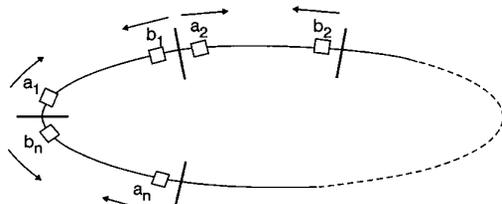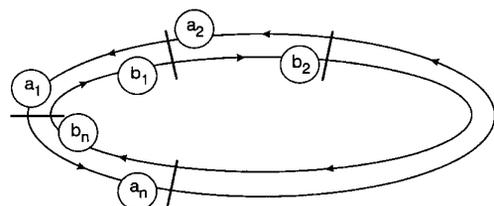

Fig. 1   Protection system P_1

Fig.2   Dependency diagram D_1

These dependencies among the relays can be displayed by the diagram shown in Fig. 2, the so-called dependency diagram [6]. In this diagram, *directed edges* (directed lines) denote the primary-backup relations between the relays. As an example, the directed edge from a_2 to a_1 denotes that a_2 is a primary of a_1.

To co-ordinate this protection, a proper set of relays, known as a break point set (BPS), must be determined as the starting point of the procedure. As mentioned in [1–3], a *minimum* BPS is a minimum set of relays, containing at least one relay in each clockwise and counterclockwise loop. According to the dependency diagram in Fig. 2, a minimum BPS for protection system P_1 must include one relay from a_i and another one from b_i, e.g. $\{a_1, b_2\}$.
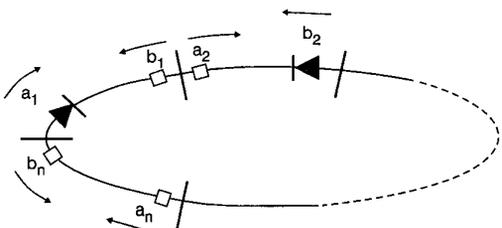

Fig.3   Representation of a_1 and b_2 as break points

The effect of choosing a relay as a starting point (BP) can be shown on the dependency diagram, by removing all of the edges which come to that relay. For example, the effect of choosing a_1 as a BP can be applied on dependency diagram D_1 in Fig. 2, by removing edge a_2a_1. This effect can be represented by replacing a_1 with a diode on the network's graph. The direction of this diode is from the local bus towards the remote bus of a_1. The same procedure must also be applied for relay b_2 as a BP. As a result, BPS $\{a_1, b_2\}$ is shown in Fig. 3 by two diodes.

In general, determination of a minimum BPS in a multiloop network is allocating a minimum number of diodes on the network's lines. Such a set of diodes must open all the loop-paths in both clockwise and counterclockwise directions.
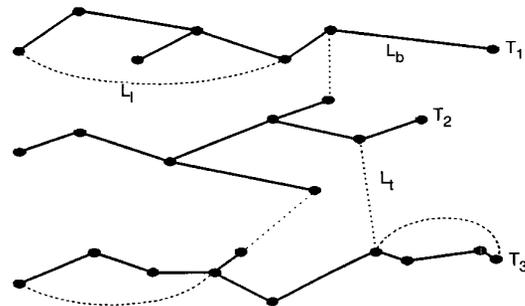

Fig.4   Illustrations of tree T_1, branch L_b, link L_l and tie L_t lines

3   New approach to BPS determination

To present the new graph-theoretical approach, the following definitions are made and illustrated in Fig. 4:

Tree: a connected network without any loop-path (e.g. T_1, T_2, T_3)

Branch: a line which belongs to a tree (e.g. L_b).

Link: a line of the network which connects two different nodes of a tree. A link does not belong to any tree (e.g. L_l).

Tie: a line which connects two different trees in the network (e.g. L_t)

Link-less tree: a tree which has no link in its network (e.g. T_2).

As mentioned earlier, to determine a minimum BPS, a method to allocate a minimum set of diodes such that they open all loops of the network is developed. This method will be called the *PIF* method, and contains the following steps:

(i) partitioning the given network into a minimum number of link-less trees;

(ii) numbering the trees, using integer numbers from 1 to t;

(iii) putting a diode on each tie line, in the direction from the tree with lower number to the tree with higher number.

By allocating such a set of diodes, there exist only upward routes among the link-less trees of the network. As a result, all loop-paths of the network are opened. After allocating all diodes, each diode from bus B_i on line L_k denotes that the relay located at the incidence of bus B_i and line L_k is a BP.

The network partitioning of step-1 is known as partitioning into forest (PIF), and has been proved to be a *NP-complete* problem [7]. As a consequence, any exact solution method very likely needs a computation time which increases exponentially with the size of the network. However, for this particular problem there is not yet an efficient exact or approximate solution method. In this paper, an exact and an approximate solution method is proposed. For every network, there may exist several minimum BPS. The following theorem proves that the PIF method is always capable of achieving some of the minimum BPSs.

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3.1 Main Theorem

For every protection system there exists at least one minimum BPS, which can be derived by the PIF method.

4 Lemmas to reduce the BPS problem

Six lemmas based on the mentioned theorem are presented. The lemmas reduce the BPS determination and decompose it into subproblems.

4.1 Lemma 1 (network reduction)

(i) If a bus in a network has only one line, that bus can join to its adjacent bus without any effect on any minimal or minimum BPS.

(ii) If a bus of a network has only two nonparallel lines, that bus can join to one of its adjacent buses. This change does not affect the size of any minimum BPS.

4.2 Lemma 2 (network decomposition)

Let a subnetwork S_1 of network N have connections to the rest of the network S_2, only through some sets of parallel lines. Then, a minimum BPS for network N can be determined as follows.

(i) Remove all sets of parallel lines. This removal may reduce network N to some disconnected subnetworks $S_1, S_2, ..., S_m$.

(ii) Return each set of parallel lines which does not connect two different subnetworks.

(iii) Specify the lines between two different subnetworks as tie lines. On each tie line, choose the relay next to the subnetwork with the lower number as a BP.

(iv) Continue the minimum BPS determination for every subnetwork, separately.

This lemma is illustrated in Fig. 5. Accordingly, the network of Fig. 5 is broken into two subnetworks, and relays r_1, r_2, r_5, r_6 are chosen as BP relays.
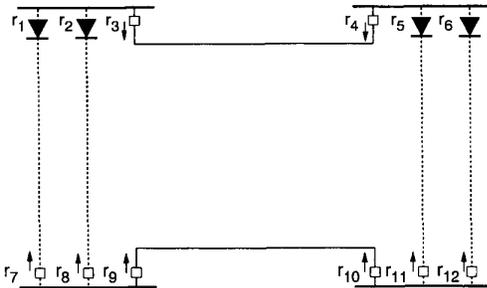

Fig.5 Illustration of Lemma 2

To present the next decomposition lemma, the following definitions have to be made.

Cut-bus: a bus of a network N is called cut-bus, if its removal splits network N into two or more subnetworks. Each network may contain more than one cut-bus.

Block: a connected network that does not have any cut-buses is termed a block. To determine the blocks of network N, assume bus C is a cut-bus of N such that its removal cuts N into disjointed subnetworks $S_1, S_2, ..., S_m$. The blocks of N can be obtained by adding the cut-bus C to each of these sub-networks, i.e. $B_i = S_i \cup \{C\}$. If a network has more than one cut-bus, this procedure must be repeated for all cut-buses one by one.

4.3 Lemma 3 (network splitting)

Every minimum BPS of a network N is a combination of minimum BPS of its blocks.

This lemma is illustrated in Fig. 6. In this Figure, bus C is the cut-bus therefore, the BPS determination can be divided into BPS determination for blocks S_1 and S_2.
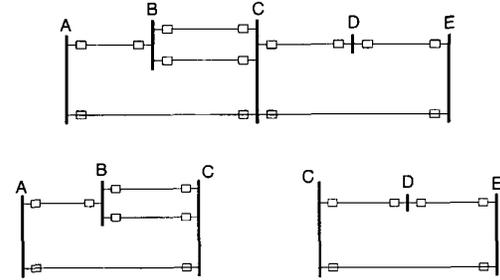

Fig.6 Illustration of Lemma 3
Network N_4 and blocks S_1, S_2

The application of lemmas 2 and 3 may break the BPS determination of a large network into similar subproblems. Since the complexity of the minimum BPS determination increases exponentially with the size of the networks, these decompositions highly reduce the computation time.

4.4 Lemma 4: (lower and upper bounds)

For each nonradial network, the size of each minimum BPS is:

$$l - b + 2 \leq \text{size of minimum BPS} \leq l,$$

where l and b are the number of lines and buses of the network, respectively.

4.5 Lemma 5 (disregarding adjacent relay)

If a relay is considered as a BP, its adjacent relay (which is located at the opposite end of the same line) can be marked as a non-BP during the rest of the BPS determination.

4.6 Lemma 6 (unification of symmetrical relays)

Let R_A and R_B be the two sets of relays located at the opposite ends of a set of parallel lines. Then, the relays of R_A must be considered as BPs, while the relays of R_B can be marked as non-BPs, or vice versa.
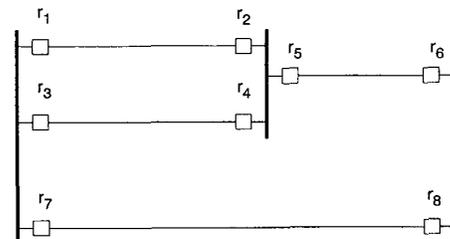

Fig.7 Illustration of Lemma 6

To illustrate this lemma, the network of Fig. 7 is taken as an example. Accordingly, there are some minimum BPS that include relays $\{r_1, r_3\}$ and not $\{r_2, r_4\}$; or include relays $\{r_2, r_4\}$ and not $\{r_1, r_3\}$.

5 Algorithm for near-to-minimum BPS

An algorithm is presented which is based on the presented method and lemmas. The algorithm determines a minimal BPS with a size near to the minimum and consists of the following steps:

(i) Input the topology of the given network N, set $i = 1$.

(ii) Decompose network N into its irreducible subnetworks S_1, S_2, ..., S_m. This is done by applying Lemmas 1, 2 and 3 repeatedly, and is terminated when no further decomposition or reduction would be possible. Note that the application of Lemma 2 may result in some BP relays.

(iii) Reduce subnetwork S_i, by applying Lemma 1.

(iv) Initiate tree T by an arbitrary bus of subnetwork S_i.

(v) If there exist a bus B such that:

    (a) bus B has only a single connection to tree T,
    (b) the removal of bus B and tree T does not cut subnetwork S_i,

then join B to T and go to step (v).

(vi) Determine the lines with only one end in tree T. Then on each of these lines, choose the relay next to tree T as a BP.

(vii) Remove tree T from subnetwork S_i (i.e. $S_i = S_i - T$).

(viii) If S_i is not empty, go to step (iii).

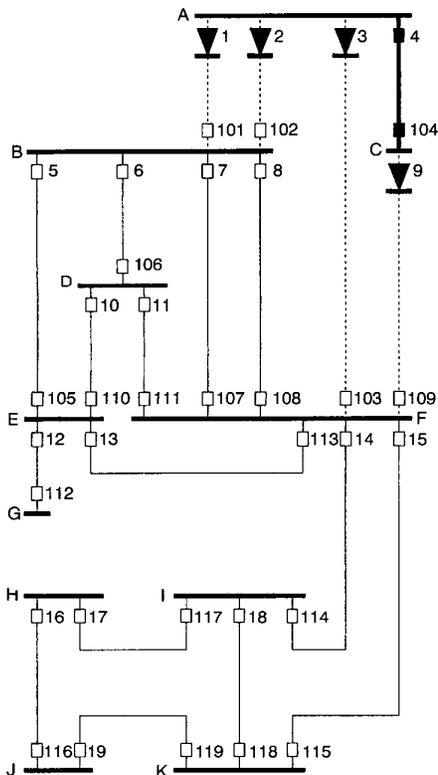(ix) If $i < m$, set $i = i + 1$ and go to step (iii).

(x) Stop.

Fig. 8 *Illustrative network N_1*

6 Illustrative example

To illustrate this algorithm, the determination of a near-to-minimum BPS for network N_1 in Fig. 8 is taken as an example. The procedure is as follows:

(i) Join bus C to bus A, by applying Lemma 1.

(ii) Apply lemma 2 to isolate bus A (and C), which results in r_1, r_2, r_3, r_9 as BPs.

(iii) Apply lemma 3 to split the network at bus F into two subnetworks S_1 and S_2, (Figs. 9 and 10).
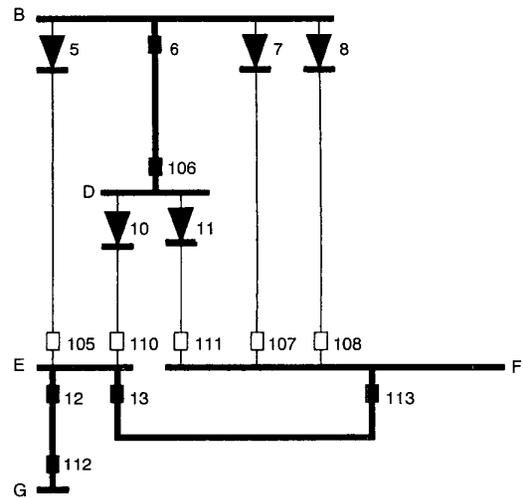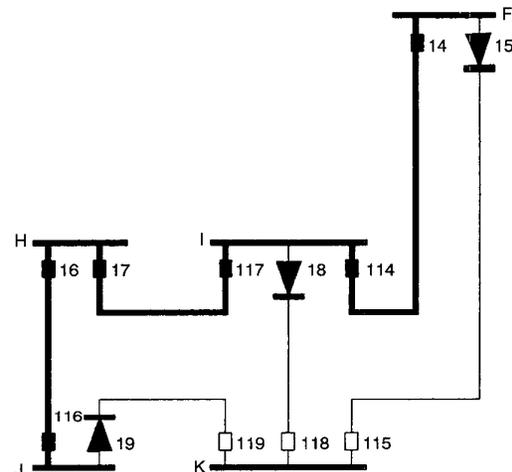

Fig. 9 *Subnetwork, S_1, of N_1*

Fig. 10 *Subnetwork, S_2, of N_1*

6.1 BPS determination of subnetwork S_1

(i) Joining bus G to bus E, by applying Lemma 1.

(ii) Initiate a new tree T from bus B.

(iii) Join bus D to tree T.

(iv) Remove T from S_1 and choose r_5, r_7, r_8, r_{10}, r_{11} as BPs. The rest of subnetwork S_1 is a tree which contains no BP.

6.2 BPS determination of subnetwork S_2

(i) Join bus J to bus H, H to I and F to I.

(ii) Initiate a new tree T from bus I.

(iii) Remove T from S_2, and choose r_{15}, r_{18}, r_{19} as BPs. The rest of the subnetwork S_2 is a single bus K which does not contain any BP.

(iv) The final BPS will be obtained by combining its parts as follows:

$$\{r_1, r_2, r_3, r_5, r_7, r_8, r_9, r_{10}, r_{11}, r_{15}, r_{18}, r_{19}\}.$$

Since both subnetworks S_1 and S_2 are partitioned into two trees, the resulting BPS is a minimum one.

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7 Conclusion

A novel graph-theoretical approach has been presented to determine a minimum or a near-to-minimum BPS for protection coordination. Based on the representation of this method, efficient lemmas have been developed. The application of these lemmas reduces the complexity of the BPS determination, and decomposes it into subproblems. Owing to the efficiency of these lemmas, the presented method quickly leads to an optimal result, even for quite large networks. Based on the method and its lemmas, an algorithm to determine a near-to-minimum BPS has been presented. Due to the simplicity of the method, this algorithm can be manually applied to the graph of each network. Since the presented lemmas are general, they can be applied to improve *any* method dealing with BPS determination.

8 Acknowledgment

9 References

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