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A New Application of Graph Theory for Coordination of Protective Relays

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Abstract: The coordination of protective relays of multi-loop networks is a tedious and time consuming process. The complicated part of this process is the determination of a set of relays referred to as the break-point set (BPS), with a minimal size to start the coordination procedure. This letter introduces a new graph-theoretical approach to determine the BPS. This method reduces the complexity of the problem, by exploiting the available sparsity of the dependencies among relays in protection systems.

Introduction: The relays of a protection system must be set in coordination with their primary relays, to ensure selective operation. In multiloop networks each relay may belong to different loops, and its setting must be coordinated simultaneously with the settings of a number of primary relays. This is a complicating process.

To visualize the problem, the coordination of protection system $P_1$ in Figure 1 is taken as an example. In this system, the primary relays of each relay $r_i$ are located at the remote bus of $r_i$ with the exception of its adjacent relay. The adjacent relay of $r_i$ is the one that is located at the opposite end of the same line of $r_i$. As an example, $r_i$ is the adjacent relay of $r_k$. Thus, $r_i$ and $r_k$ are the primary relays of $r_i$, which are represented by primary-backup pairs $(r_k, r_i)$ and $(r_i, r_k)$ respectively.

In each loop of the network of Figure 1, the settings of each relay depends on the settings of another relay of that loop. As an example, in the loop containing relays $r_r$, $r_s$, and $r_t$, the settings of relay $r_t$ must be made based on the settings of $r_r$ according to the primary-backup pair $(r_r, r_t)$. In the same way, the settings of $r_r$ and $r_s$ must be made based on the primary-backup pairs $(r_s, r_r)$ and $(r_t, r_s)$. Then, if the setting of $r_t$ is changed, $r_r$ has to be reset for proper coordination with $r_t$ and another iteration must be done. In a multiloop network, there are many of these loops adjacent to one another, hence, a large number of iterative calculations must be performed to achieve system-wide coordination.

A recently proposed solution is to determine a proper set of relays as a starting point for the coordination procedure [1]. This starting set is called a break point set (BPS), each member of which is called a break point (BP). The main property of a BPS is: if the settings of its relays are known, coordinated setting of the rest of the relays can be determined successively. Starting coordination with a BPS relays ensures
that each relay’s settings is calculated only once at each iteration. Since the computation time for a coordination procedure increases with the size of its corresponding BPS, a BPS with a minimum size is desirable.

The proposed method converts determining the BPS into a graph-theoretical problem, allowing use of effective tools of graph theory to reduce the complexity of the problem. The method approaches to a BPS step by step, choosing an appropriate relay as a BP in each step. This approach results in a near-to-minimum or a minimum number of BPS.

Graph-Theoretical Representation of the Problem: To illustrate this method, coordinating protection system $P,$ (Figure 1) is considered. The primary-backup relations of this protection system are displayed in Figure 2 by a directed graph, referred to as a dependency diagram, $D_p.$

In a dependency-diagram each vertex (node) represents a relay, and each arc (directed branch) indicates the primary-backup relation between two relays. For example, arc $v_{3}v_{4}$ (the arc from vertex 3 to 4) represents that $r_{3}$ is a primary of $r_{4}$ (or equally, $r_{4}$ is a backup of $r_{3}$).

If a dependency-diagram has no cycle (directed loop), its vertices can be ordered in a sequence of sets in which the vertices of each set have incoming arcs only from the vertices of the previous sets, implying that the corresponding relays can be coordinated set by set consecutively. Accordingly, a minimum BPS is a minimum set of vertices which, if they are removed, all cycles of the dependency-diagram will be opened. Therefore, the determination of a minimum BPS is in fact a problem in graph theory known as Feedback Vertex Set (FVS). The problem was shown to be an NP-complete problem which can not be carried out in a polynomial time period.

Reduction Rules for Determination of a Minimum BPS (or FVS): These rules identify the vertices which have to be members of every minimum BPS, and also the vertices which need not to be members of every minimum BPS.

- Rule 1: If vertex $v$ of a dependency-diagram $D$ has no outgoing arc, $v$ is not a BP and can be deleted from $D$ (Figure 3). In the same way, if vertex $w$ of a dependency-diagram $D$ has no incoming arc, $w$ can be deleted from $D.$
- Rule 2: If vertex $v$ has only one outgoing arc $a$ which goes to vertex $w,$ $v$ is not an essential BP. So, join $v$ to $w$ and remove the connecting arc $a.$
- Rule 3: If vertex $v$ has a self-cycle (having arc from $v$ to $v$), $v$ is a member of every minimum BPS. So, remove $v$ from the dependency-diagram and consider it as a new BP.
- Rule 4: If vertex $v$ is a self-cycle of every minimum BPS, and also the vertices which need not to be members of every minimum BPS.

The proof of these rules can be found in [2].

New algorithm: The new algorithm results in a near-to-minimum or a minimum BPS (or FVS), $B,$ and consists of the following steps:

1. Create the dependency-diagram $D$ of the protection system. Initiate $B$ as an empty set: $B=\emptyset.$
2. Apply rules 1 to 3 to all vertices of $D.$ Applying Rule 3 may add a new member to $B.$
3. If step 2 changed $D,$ go back to Step 2.
4. If $D$ is empty, stop.
5. Choose an arbitrary vertex $v$ as a new BP. Remove $v$ from $D,$ add $v$ to $B,$ and go to Step 2.

Illustrative Example: To illustrate the algorithm, determining a BPS for protection system $P,$ (Figure 1) is considered as an example. The procedure is as follows, and the dependency-diagram $D_p$ of this protection scheme is shown in Figure 2:

- Initiate $B=\{\}.$ In dependency-diagram $D_1$ Rules 1 to 3 can not be applied to any of vertices in order to reduce the dependency-diagram.
- Choose one of the vertices, say $v_1,$ as a BP. Remove $v_1$ from $D_1.$ Add $v_1$ to $B: B=\{v_1\}.$
- Join $v_2$ to $v_1$ and remove arc $v_1v_2,$ applying Rule 2.
- Join $v_3$ to $v_2$ and remove arc $v_2v_3,$ applying Rule 2.
- Join $v_4$ to $v_3$ and remove arc $v_3v_4,$ applying Rule 2.

The final result is: $FVS=\{v_1, v_2, v_3, v_4\}$ which corresponds to $BPS=\{r_1, r_2, r_3, r_4\}.$

Further Improvement: The method can be improved by partitioning the dependency-diagram into its maximal strongly connected components (MSCC) [2]. In each MSCC, for every pair of vertices, there exist a cycle which contains both of those vertices. Moreover, there exist no cycle between two vertices of different MSCCs. Partitioning a dependency-diagram into its MSCCs decomposes the BPS determination into some similar subproblems. The method to decompose a directed-graph into its MSCCs can be found in [3].

Conclusion: A new graph theoretical approach is presented to determine a BPS relays as a starting set of relays for protection-coordination procedures. The rules of the method identify the essential and nonessential BP relays at each step. These identifications speed up the BPS determination resulting in a minimum or a near-to-minimum

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BPS. Owing to the flexibility of this approach, it can be easily applied to special protection schemes (e.g., protection systems with non-directional relays) and network configurations (e.g., radial networks and networks containing multiterminal lines). The method has been applied on a PENTIUM (75 MHz, 8 MB RAM) to a 400-line/200-bus network, and achieves an near-to-minimum BPS within 2.0 seconds.

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References

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Effects of FACTS Controller Line Compensation on Power System Stability

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Abstract: In this letter, the effects of line compensation of an SMIB power system using FC-TCR type TCSC or SVC for transient stability enhancement are analyzed. In particular, a novel method for analysis of line compensation by an SVC is presented. The maximum power transfer for line compensation by FACTS controllers can be written in the form $T = (1 - k)$, where is the maximum power transfer for the uncompensated line and $k$ is the degree of compensation. The analysis revealed that the effectiveness of the SVC for stability enhancement is increased if the degree of compensation of the line is increased.

Keywords: FACTS, TCSC, SVC, stability.

Introduction: Transient stabilization is important in the control of power systems. Any power utility suffers from the regimes in which power swings take place, the so-called transient regimes. It is important to be able to prevent generators from losing synchronism and damp subsequent oscillations quickly. In this letter, we discuss the effects of line compensation of a single-machine, infinite-bus (SMIB) power system by a fixed-capacitor thyristor-controlled reactor (FC-TCR) type of thyristor-controlled series capacitor (TCSC) or static var compensator (SVC) for transient stability enhancement.

Line Compensation for Stability Enhancement: It is accepted that FACTS technology will increase power transfers through power delivery systems that are presently constrained, providing power at lower cost to a greater number of customers. One of the basic concepts for mitigating the huge power imbalance between the generator mechanical power and the electrical load during a disturbance is based on the ability of FACTS controllers to rapidly vary the parameters affecting power flow such as line reactance [1, 2]. To investigate the role of line compensation by FACTS controllers in the transient regimes of the power system, an SMIB power system model is considered [3]. A number of simplifying assumptions are made to clearly illustrate the relative performance of the FACTS controllers. In particular the effects of line capacitance and resistance are ignored. The system analyzed (see Figure 1) contains an equivalent generator with direct axis reactance $x_r$, with constant mechanical input, neglecting the effect of the governor. There is a single-circuit transmission line of reactance $x_l$ and a step-up transformer of reactance $x$. There is a FACTS controller at the mid-point of the transmission line. The infinite bus, is represented by constant voltage, and frequency $f$. To appreciate the effects of adding FACTS controllers to enhance transient stability, the equal area criterion is usually used to assess the effect of compensation methods on transient stability following a fault to the SMIB power system. Despite the simplistic approach, this will allow us to gain a qualitative assessment of the stability improvement by FACTS controllers. For comparison purposes, we assume that both the prefault power flow and the duration of the fault are the same in

Figure 1. A SMIB power system model with FACTS controller connected in (a) series, and (b) shunt

45

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