Impact Analysis of Network Topology Change on Transmission Distance Relay Settings

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***Abstract*— One big challenge raised by frequent topology change in today's power system is assessing the system protection security and dependability afterwards. This paper reviews the setting algorithm for the distance relays and proposes an automated setting calculation module. The calculation procedure is broken down into blocks which could be processed in parallel in order to improve the computation speed. The module could be used to assess the system protection vulnerabilities following a topology change in instances when multiple switching actions are done in response to occurrence of cascading faults or as a result of intentional control action. The module performance is tested on New England 39-bus and IEEE 118-bus systems. A sensitivity analysis in the form of N-2 contingency impact on the network relay settings is conducted on both test systems.**

***Keywords*— Power system protection security and dependability, N-2 contingency, phase distance settings, relay ranking, topology control, vulnerability.**

NOMENCLATURE

V_{LL}	Rated line-to-line voltage.
I_{rating}	The line rating.
Z_{relay}^{30}	Relay reach in primary Ohms at a power factor angle of 30 degrees.
Z_1	Zone 1 phase reach in primary Ohms.
Z_2	Zone 2 phase reach in primary Ohms.
Z_3	Zone 3 phase reach in primary Ohms.
Z_2^l	Zone 2 phase reach based on line ohms only.
Z_2^{app}	Zone 2 phase reach based on the remote bus fault apparent impedance.
Z_3^l	Zone 3 phase reach based on line ohms only.
$Z_3^{app_{bus}}$	Zone 3 phase reach based on apparent impedance of next adjacent bus faults.
$Z_3^{app_{end}}$	Zone 3 phase reach based on apparent impedance of next adjacent line-end faults.
z_l	Impedance of zone 1 line.
$z_{l_i}^{adj}$	Impedance magnitude of the next adjacent line *i*.
$z_{p_i}^{adj}$	Line ohms path magnitude to the next adjacent bus *i*.
z_{rem}	Apparent impedance for three phase fault on remote bus.
z_i^{adj}	Apparent impedance for three phase fault on next adjacent bus *i*.
$z_{end_i}^{adj}$	Apparent impedance for three phase line-end fault on next adjacent line *i*.
N^{adj}	Number of next adjacent buses.
R_{i-j}	Distance relay looking from bus *i* to bus *j*.

I. INTRODUCTION

Incentive towards deploying the renewable distributed generation in today's power system is changing the traditional way of operation [1]-[4]. Multiple switching actions for various objectives could be considered as a big operational change which is gaining much more attention these days. The switching is mostly conducted towards reducing the system operational cost in a real time manner [5]-[8] or the load shedding recovery following a contingency [9]-[11]. Other situations of multiple switching actions may be associated with cascading failures caused by multiple faults [12], [13]. As a result, setting coordination of the distance relays may be affected due to the change of network short circuit values following a topology change [1].

There are several studies in the literature which investigate the network relays operation under abnormal conditions especially power swings [14]-[19]. Several relay ranking schemes have been proposed to identify vulnerable relays in a network. Singh *et al.* [14] have ranked the relays based on Lyapunov stability criterion in regards to the power swings severity. Relay margin concept has been used in [15] to measure the closeness of a relay from issuing a trip signal. Reference [16] has proposed a new approach to locate all the electrical centers following an unstable swing and simplify the visual monitoring of all the R-X plots. For stable swings, the concepts of branch norm, fault norm, and system norm are defined to rank the power swings, faults or contingencies, and detect an out-of-step condition respectively. Seethalekshami *et al.* [17] have used the branch loss sensitivity measure presented in [18] to propose a relay ranking index (RRI). This index is defined as the ratio of normalized apparent impedance seen by the relay to the corresponding branch loss sensitivity. The less the RRI value, the more the relay is probable to miss-operate under power swing and voltage instability conditions.

Overloaded lines, as a result of a line-tripping contingency, could also lead to relay miss-operation which is known as

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"load encroachment" in the relay operating characteristic terms. It happens when the load apparent impedance gets such small that it falls into the protection zones of a relay. Calculating the relay apparent impedance from a load flow analysis could be used to detect such a case [20], [21].

The above mentioned efforts have studied the miss-operation of distance relays under cases such as power swing, voltage instability, and load encroachment. However, the focus of this study is to investigate the adequacy of the network relay settings for a new (evolving) network topology. The zone reach of some relays might change as they have been set for a base network topology. In this paper, by topology change we mean multiple switching actions for corrective purposes alleviating the consequences of contingencies. This is done to initiate the load shedding or reduce operation cost while maintaining the stability, reliability, voltage limits, and line flow margins in the power system. An example of such a Robust Adaptive Topology Control (RATC) and its implementation issues are discussed in [1].

To determine whether the relay settings are affected by the switching action, we propose an automatic approach which detects the change in the topology and identifies the relays which have inadequate settings as a result. Utilities, all over the world, follow different rules in setting calculation of the distance relays depending on their approach to operating network. A basic phase distance setting calculation routine [22] is surveyed in this study, which focuses only on the apparent impedance reach in different zones. Then, a setting calculation module with a parallel architecture is proposed. The parallel architecture helps to improve the calculation speed. The proposed module could provide the supplementary information on how a network topology change would affect the distance relay settings. The switching candidates resulting from the optimization analysis could be ranked according to their impact on the relay settings and help network operator in the decision making process. It should be noted that the automatic coordination of the relays [23], [24] is out of scope of this paper.

The rest of the paper is organized as follows. Section II describes a short circuit database necessary for the phase distance setting calculations. Furthermore, basic rules for calculating zones 1, 2 and 3 of a distance relay are discussed in this Section. The general procedure for the proposed setting calculation is presented in Section III. Section IV illustrates the simulation results along with sensitivity analysis. Concluding remarks are summarized in Section V.

II. PHASE DISTANCE SETTING RULES

A modern distance relay has several elements which provide many protection functions in a single package. In this study, the focus is on the phase distance elements and mho settings of different zones. There are two ways to calculate the zone settings: one is based on the line ohms only, which is not so practical, and the other, which is used here, is to consider both the line Ohms and the apparent impedance of different fault types seen by the relay.

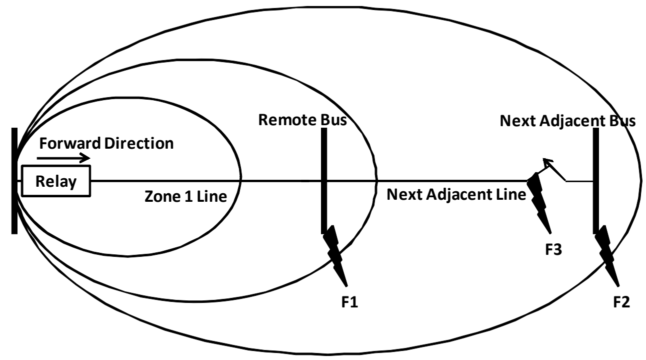

Figure 1. Fault types used for phase distance setting calculation: remote bus fault (F1), next adjacent bus fault (F2), and line-end fault (F3).

To obtain the initial mho settings, in regards to the apparent impedances, three types of fault calculation, as shown in Fig. 1, are implemented: a) three-phase fault on remote bus, b) three-phase fault on next adjacent bus, and c) three-phase line-end fault. The maximum torque angle (MTA) is considered the same as the zone 1 line angle, i.e., $\mathrm{MTA} = \measuredangle \mathrm{Z}_l$.

The apparent impedances are checked as follows to make sure they are valid to be considered during the setting procedure:

$$z_{rem} = \begin{cases} z_{rem} & \begin{array}{l} |z_{rem}| \le 10 \times |Z_l| \ \& \\ |\measuredangle z_{rem} - \mathrm{MTA}| \le \dfrac{\pi}{4} \end{array} \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

$$z_i^{adj}\Big|_{i\in N^{adj}} = \begin{cases} z_i^{adj} & \begin{array}{l} |z_i^{adj}| \le 10 \times |Z_l| \ \& \\ |\measuredangle z_i^{adj} - \mathrm{MTA}| \le \dfrac{\pi}{4} \end{array} \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

$$z_{end_i}^{adj}\Big|_{i\in N^{adj}} = \begin{cases} z_{end_i}^{adj} & \begin{array}{l} |z_{end_i}^{adj}| \le 10 \times |Z_l| \ \& \\ |\measuredangle z_{end_i}^{adj} - \mathrm{MTA}| \le \dfrac{\pi}{4} \end{array} \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

The phase distance setting rules are as follow:

A. Zone 1 Setting Rule

$$Z_1 = 0.8 \times \mathrm{Z}_l \tag{4}$$

B. Zone 2 Setting Rule

$$Z_2^l = \max\left\{1.2 \times |Z_l|, |Z_l| + 0.2 \times \left|\min\left(z_{l_i}^{adj}\right)\right|_{i\in N^{adj}}\right\} \tag{5}$$

$$Z_2^{app} = 1.2 \times |z_{rem}| \tag{6}$$

$$Z_2 = \max\left\{Z_2^l, Z_2^{app}\right\} \measuredangle \,\mathrm{MTA} \tag{7}$$

C. Zone 3 Setting Rule

$$Z_3^{l} = 1.2 \times \max\left(z_{p_i}^{adj}\right)_{i \in N^{adj}} \tag{8}$$

$$Z_3^{app_{bus}} = 1.1 \times \left|\max\left(z_i^{adj}\right)\right|_{i \in N^{adj}} \tag{9}$$

$$Z_3^{app_{end}} = 1.1 \times \left|\max\left(z_{end_i}^{adj}\right)\right|_{i \in N^{adj}} \tag{10}$$

$$Z_3 = \max\left\{Z_3^{l}, Z_3^{app_{bus}}, Z_3^{app_{end}}\right\} \measuredangle \text{MTA} \tag{11}$$

Then, the load encroachment is evaluated for all zones to prevent phase protective relay settings from limiting the transmission system loading capacity while maintaining dependability of the network protection. According to NERC [25], the relay performance should be checked for 150% of the highest seasonal rating of the lines at 0.85 per unit voltage and a power factor angle of 30 degrees:

$$Z_{relay}^{30} = \frac{0.85 \times V_{LL}}{\sqrt{3} \times 1.5 \times I_{rating}} \tag{4}$$

III. Proposed Relay Setting Calculation Module

The proposed setting calculation module contains algorithms which check the adequacy of the existing relay settings for the new system topology after switching. It performs fast relay setting calculation for the new topology and compares the new setting values with the current settings.

Figure 2 shows a general flowchart of the proposed setting calculation module. The input data for this module includes: 1) Short circuit model data such as: bus data, branch data, generator data, power flow data, and the default relay settings and 2) The list of network topology changes.

Having recognized the network topology, the module builds up the Z_{bus} for the whole network which is used in fault calculations. During the fault calculations several updates to Z_{bus} are required depending on the fault type. This magnifies the urge of preventing repetitive and excessive Z_{bus} calculation if not necessary. The sparsity oriented compensation methods are used to perform updates to Z_{bus} [26].

The algorithm computation burden mostly relates to the creation of different fault type databases, three blocks highlighted in green shown in Fig. 2. The power system Z_{bus} is a big order sparse matrix for which operations such as inversion and multiplication require more computation efforts from the processor. Each of the fault databases contains the bus voltage and branch current values for the corresponding type of fault. The voltage and current values are then used to calculate the associate apparent impedances.

To improve the calculation speed, parallel computation could be performed on the three fault types calculation independently. In other words, a separate processor could be assigned to each task. The network Z_{bus} is the only common data fed into the three blocks.

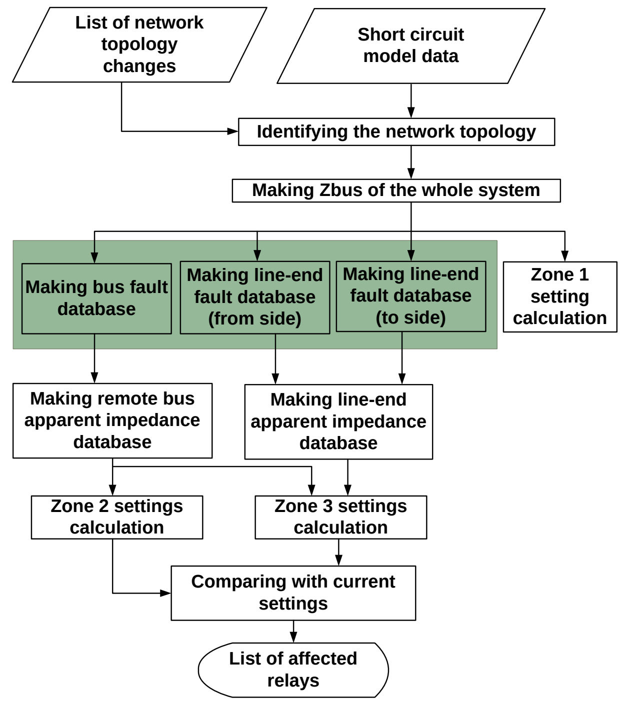

Figure 2. General flowchart of the relay setting calculation module.

The proposed module could be put into practice to assess multiple switching impacts on the network relay settings. To restore the system, the corrective switching actions are suggested by an optimization process and could be ranked in regards to their probable impact on the network relay settings. The settings are calculated for the new system topology and compared with the previous ones to identify the affected relays. The module output contains the list of the relays for which the settings change beyond an acceptable margin. It provides the network operator with an extra decision making tool to deal with the interference of switching actions with the security and dependability of power system protection.

IV. Simulation Results

The performance of the proposed module is tested on New England 39-bus and IEEE 118-bus systems [27]. The relays are assumed to be set only in forward direction as shown in Fig. 1. The transmission lines do not have mutual coupling and transformer protection is neglected for the sake of simplicity.

A sensitivity analysis to investigate the impact of N-2 contingency cases, 2 lines switched out, on the network relay settings has been done. The N-2 contingencies are chosen to be studied because of two reasons: 1) the number of cases to be investigated and 2) they are practical in regards to switching scenarios in today's power systems. The simulations have been conducted by MATLAB on a PC with an Intel Xeon W3530 C 2.8 GHz CPU.

All the N-2 contingencies for which the power flow solution converges have been considered. The number of

Table I. The number of N-2 contingency cases and their corresponding simulation time.

Test System	Number of N-2 Contingencies	Simulation Time (s)
39-bus	495	72.43
118-bus	13945	16734.23

contingency cases along with the simulation time for both test systems are shown in Table I. The simulation time considering the number of cases is promising. Depending on the processor features used to perform the calculations, the simulation time could be improved significantly.

Tables II and III, present top 10 N-2 contingency cases according to their impacts on the network relay settings for New England 39-bus and IEEE 118-bus systems respectively. A relay is considered affected if its zone 2 or zone 3 reach changes beyond 5% of the base network settings. Zone 1 is not a concern as it is only based on the line impedance.

Results in Table II and III imply that the number of affected relays reduces drastically as the size of the system grows big. The reason is that the more interconnected the system is the less the short circuit values change following a topology change.

The lines participating in the majority of the N-2 contingency cases with significant impacts on relay settings could also be identified from the sensitivity analysis. Table IV shows top 10 of such lines considered as critical lines.

Furthermore, the results of such a sensitivity analysis could be used to detect and rank the probable system protection vulnerabilities following a network topology change, i.e., N-2 contingency. The relays which settings change for a greater number of N-2 contingencies are identified as vulnerable points in the network protection. Table IV and V shows such vulnerable points in 39-bus and 118 bus system respectively. In these Tables, Participation ratio for a relay means the ratio of the number of N-2 contingency cases which have affected the relay to the total number of contingency cases.

V. Conclusion

The following conclusions were reached:

- The simulation time to run all the N-2 contingency cases could be improved depending on the number of processing cores and their features.
- The impact of topology change on relay settings was more significant in the smaller system as the network short circuit values change drastically.
- The top 10 most critical network topology changes, in the form of N-2 contingency cases, were identified along with the number of relays affected in each one of the contingency categories.
- The top 10 lines which were repeated the most in the contingency cases with significant impacts on relay settings were identified as critical lines.
- Finally, the relay settings vulnerable to network topology change were identified. Top 10 relays affected by a greater number of N-2 contingency cases were ranked.

The output of the proposed module could provide the network operator with the supplemental information about whether to proceed with the proposed switching scenario, e.g. the action to reduce the operation cost would affect the network relay settings. The vulnerable points in the power system protection following a network topology change would be detected. This information could help the operator also in decision making when choosing between the switching actions.

Table II. Critical N-2 contingencies and their number of affected relays (39-bus system).

Rank	Lines Switched Out (From-To)	No. of Affected Relays
1	8-9 & 17-27	29
2	9-39 & 17-27	28
3	8-9 & 26-27	28
4	6-11 & 17-27	28
5	10-13 & 17-27	27
6	9-39 & 26-27	27
7	6-11 & 26-27	27
8	4-14 & 16-17	27
9	4-5 & 17-27	27
10	13-14 & 17-27	26

Table III. Critical N-2 contingency cases and their number of affected relays (118-bus system).

Rank	Lines Switched Out (From-To)	No. of Affected Relays
1	65-68 & 77-80	7
2	65-68 & 89-92	7
3	65-68 & 82-96	7
4	65-68 & 94-100	6
5	77-80 & 89-92	6
6	77-80 & 82-96	6
7	77-80 & 94-100	6
8	89-92 & 82-96	5
9	89-92 & 94-100	5
10	82-96 & 94-100	5

Table IV. Critical switching actions which affect the relay settings significantly.

Critical Lines (From-To)	
118-bus System	39-bus System
61-62	26-27
66-67	17-27
65-68	8-9
77-80	16-17
89-92	13-14
82-96	6-11
94-100	9-39
54-56	10-11
55-56	10-13
60-61	4-5

Table V. The relays most vulnerable to network topology change (N-2 contingencies in 39-bus system).

Rank	Relay (Looking at From-To)	Participation Ratio (%)
1	R_{3-2}	62.02
2	R_{14-4}	59.394
3	R_{4-14}	57.37
4	R_{8-5}	56.1
5	R_{18-3}	56.1
6	R_{25-2}	53.7
7	R_{13-14}	52.6
8	R_{18-17}	52.1
9	R_{11-6}	50.12
10	R_{4-5}	49.1

Table VI. The relays most vulnerable to network topology change (N-2 contingencies in 118-bus system).

Rank	Relay (Looking at From-To)	Participation Ratio (%)
1	R_{116-68}	1.42
2	R_{114-32}	1.37
3	$R_{106-105}$	1.31
4	$R_{103-100}$	1.29
5	R_{102-92}	1.24
6	R_{95-94}	1.21
7	R_{78-77}	1.09
8	R_{61-59}	1.09
9	R_{60-59}	1.06
10	R_{56-54}	1.02

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