Application of a Simulation-based Protection Operation Audit for Identifying Prospective Weak Points in a Protection Scheme

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ABSTRACT

A method is presented for the fast and effective identification of weak points in a network's protection settings. The paper focuses firstly on the description of an automated tool which runs short-circuit sweeps across a network in order to evaluate the relay tripping times, fault clearing times and device coordination for different fault types. The second part of the paper describes a study using the tool in collaboration with Chiang Mai University (CMU) in Thailand as part of a "Wide Area Protection and Coordination Study" for the network operator Provincial Electricity Authority (PEA).

The presented evaluation process enables protection engineers to quickly evaluate the protection scheme of any protected network. The evaluation process is automated using a tool, included in the software PowerFactory, to audit all protection devices implemented in a network. A topological search categorises for each protected element which protecting devices provide primary, secondary or tertiary protection functionality. Afterwards, short-circuit sweeps are carried out across the network for different fault cases and the tripping times are stored. The analysis is done via colour coded table reports which highlight prospective weak points in the protection scheme. The evaluation process was successfully applied to one part of the 115-kV network model of PEA. It is shown how weak points of the primary protection are identified. The devices do not clear certain single phase to ground faults with fault impedance in accordance with expectation. By observing the network situation in more detail, the failures of two devices, intended to protect numerous lines, could be identified.

INTRODUCTION

Protection devices which do not operate reliably, according to their objective, for all kinds of faults and for every feasible system condition can instigate unintentional outages in the electrical grid. If the grid is highly meshed or has multiple intermediate infeeds the complexity of the setting process is increased. A simulation-based audit of the protection settings can be enormously beneficial in order to efficiently verify a multitude of possible scenarios. Furthermore, an effective analysis can only be done, if all coordinating relays are audited altogether to evaluate the coordination between main (primary) and backup (secondary and tertiary) devices.

If the audit of the protection devices is not automated, then this can take an enormous amount of time. Given the complication that every time the system changes, the devices should be audited again, this is especially problematic. Therefore, a process is introduced which enables the protection engineer to easily identify prospective weak points in the protection scheme. The process includes an automated tool which runs short-circuit sweeps across the whole network and analyses for each protected element, the coordination, tripping and fault clearing times of the associated protection devices. Further analysis of the identified weak points will depend on the specific protection philosophy applied and is therefore not automated.

EVALUATION PROCESS

To evaluate the protection scheme in a large grid, the process shown in Figure 1 is introduced. It starts with the *Network Model* which already includes the protection devices and their simulation relevant settings. The next step is to execute the *Protection Audit* tool which automatically runs short-circuit sweeps throughout the network and stores the tripping times of every protection device in relation to each fault applied. After the calculation, the analysis is carried out. The protection scheme is verified considering tripping times, fault clearing times and the coordination time between main and backup devices.

Identifying the reason for failure in the protection scheme is a manual process. In the application example numerous categories of failure are defined and each observed failure is assigned to an appropriate category. Each category tends to have a similar solution method and therefore after classification settings can be adapted accordingly. With the new settings, the protection audit has to be run again to verify that the changes made have been successful.

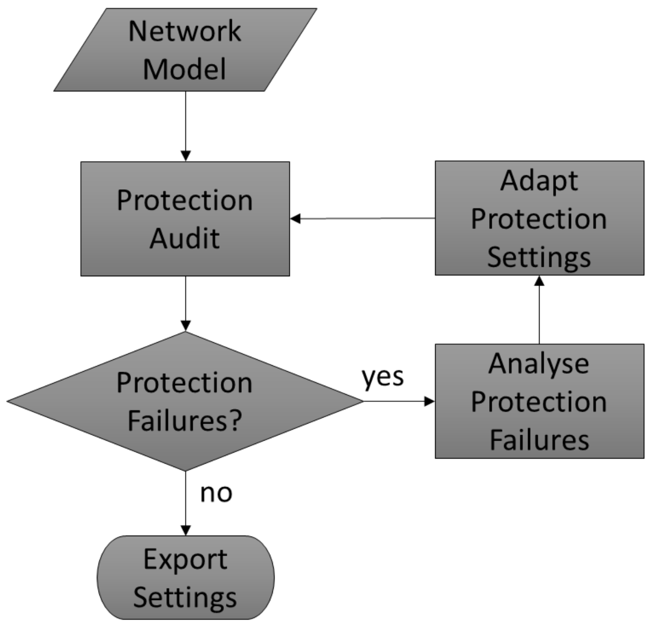

Figure 1: Protection evaluation process diagram.

PROTECTION AUDIT

The tool included in the evaluation process to audit all protection devices is based on two main functions: firstly a topological search of the grid or protection area in order to identify the dependencies between protection devices and with respect to the network elements that they protect; secondly the ability to run sweeps of multiple user-defined faults throughout the grid. The operation of the relays for each calculated fault is afterwards evaluated according to user-defined criteria such as device tripping thresholds and minimum coordination margins.

Based on Figure 2 the topological search to categorise the protection devices as main (primary) and backup (secondary and tertiary) devices is shown. The search is carried out, under the assumption that in Figure 2 there are protection devices implemented in every bay. For each protected element, in this example case the line element *lneCD*, the associated primary (main) protection devices are identified. Since the line has only two connection points, the two primary protection devices are easily located at either end of the line. In the next step the topological search continues, moving away from the protected element in two directions at the *busD* end of the line and in one direction at the *busC* end of the line. This leads to the identification of three secondary protection devices. At the *busD* end of the line, there are two secondary devices found at *busE* and *busG*, which look in the forward direction toward the protected element *lneCD*. Although not illustrated for simplicity in Figure 2, the search also categorises reverse oriented devices and will find in this example two devices located at *busD* which will be assigned a secondary reverse categorisation. In the same manner tertiary (secondary backup) devices are located.

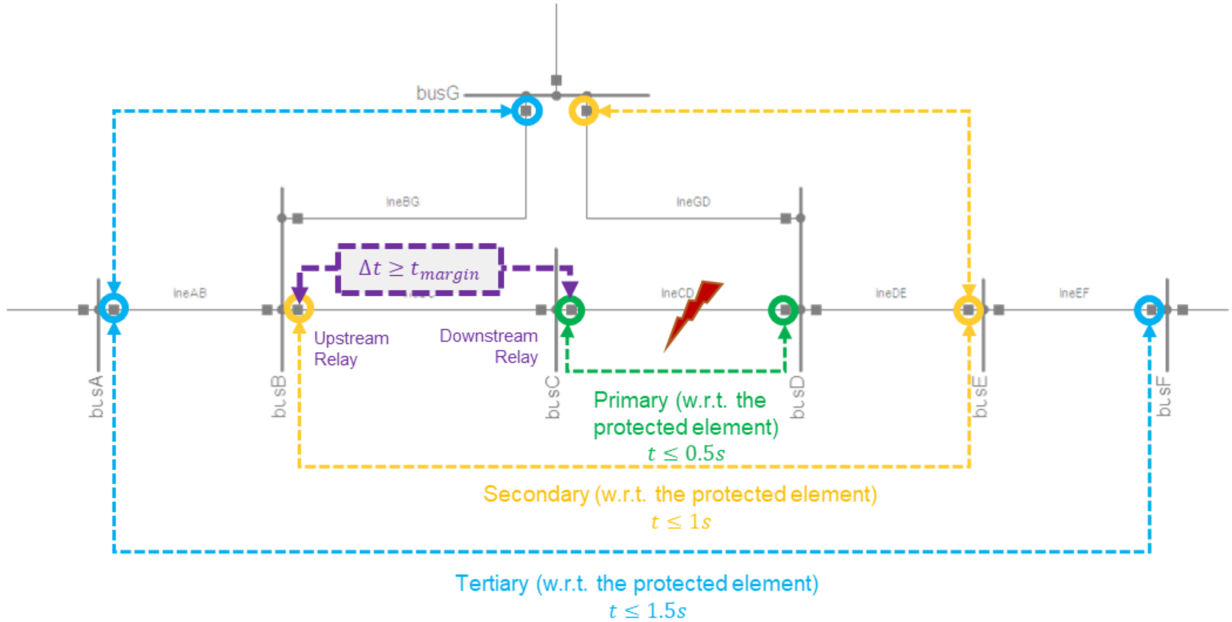

Figure 2: Protection audit concept visualising topological search and result analysis.

Once the topological search is finished, short-circuit sweeps are calculated across a specified network area for line and busbar elements. Depending on the level of detail, the short-circuit sweep's step size along line elements is user-configurable. For a complete protection scheme analysis, multiple fault cases have to be considered such as three-phase, two-phase and single phase to ground faults with and without fault impedance. For every short-circuit calculation, the tripping times of every relay are stored.

The following result analysis is divided into three areas:

1. Analysis of the relay's *tripping times* against thresholds for primary, secondary and tertiary protection.
2. Calculation of the *coordination* margin between primary and secondary as well as secondary and tertiary categorised devices.
3. Comparison of *fault clearing times* against thresholds for primary, secondary and tertiary devices.

Since the relays are categorised with respect to each protected element, the tripping times are compared to different thresholds. As shown in Figure 2 the green coloured primary devices should trip for faults across the protected line element *lneCD* below a user-specified threshold (in this case 0.5 s). If the secondary and tertiary devices are also evaluated, different thresholds are applied. The coordination margin is determined based on the stored tripping times by subtracting the tripping time of the upstream device from the downstream device. In Figure 2 (purple colour) the coordination margin is shown between one primary and secondary device. The margin is also verified against a user-specified threshold. If different switch opening times have to be taken into account, the fault clearing time analysis can be used to consider this aspect. Similar to the tripping time analysis, the fault clearing times are compared to different user-specified thresholds.

For every of the three areas of the result analysis, a colour coded table report is available. An example of the tripping times report is shown in Figure 4. Colour bars represent the line element and are coloured red if the threshold is violated and green if the tripping time is below the threshold in case of a fault on the line. Since the fault is calculated in a certain step size along the line, the colour bars are also subdivided according to this step size. The reports have an overview which is shown in Figure 4 with all calculated fault types. If the fault type has multiple fault resistances, there is a second report level available (Figure 5). These tables will highlight weak points in the protection scheme as described in the study case Thailand.

STUDY CASE THAILAND

The Provincial Electricity Authority (PEA) operates the distribution networks up to 115-kV of all geographical regions in Thailand, except the metropolitan area (Bangkok Nonthaburi and Samut Prakarn). PEA is working with the Chiang Mai University (CMU) on the topic “Wide Area Protection and Coordination of the Electrical Grid of PEA”. In this context, the above described evaluation process was applied on the 115-kV network located around Bangkok to identify prospective weak points in the protection scheme and adapt the settings accordingly.

In order to evaluate the weak points in the 115-kV network of PEA, 150 relays were audited. The study focused on the distance protection devices. The evaluation process started with the execution of the protection audit tool. Weak points in the protection settings were quickly identified using the coloured table reports. Afterwards the protection operation failures were categorised and further analysed using conventional techniques such as R-X plots. Corrective measures were applied and a new set of protection settings implemented. In critical cases an alternative starting method was selected where appropriate. To evaluate the new protection scheme, the protection audit was again executed. The resulting enhancement to the operation of the distance protection in response to the examined faults on the transmission lines is shown in [1].

The network area provided, contains the 115-kV transmission lines of the PEA Area 1 (Central) Phra Nakhon Si Ayutthaya which is shown in Figure 3. The total line length is about 2133 km. Based on the switching status 16 regions could be identified, each supplied by the transmission grid of EGAT (Electricity Generating Authority of Thailand). For the consideration of intermediate infeeds, the medium voltage level with synchronous generators is also modelled with an overall capacity of about 4319 MVA. Additionally 150 distance protection devices (21) were also implemented and set according to the situation in the field. This represents the starting point of the evaluation process.

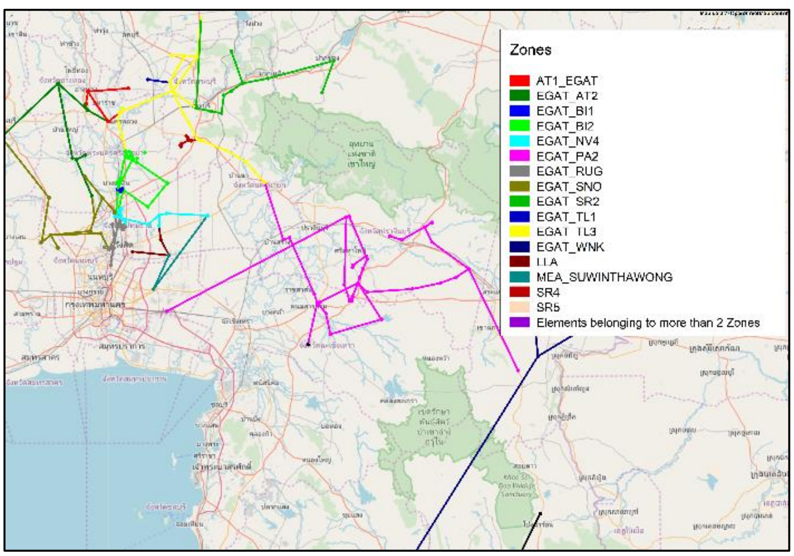

Figure 3: Geographical map containing the locations of substation and transmission lines.

IDENTIFICATION OF PROSPECTIVE WEAK POINTS

The protection settings were analysed using the evaluation process. To carry out short-circuit calculations along each line in the selected regions, the protection audit tool. In order to handle the result analysis in a manageable way, each region was analysed separately. The following settings were applied for the protection audit:

1. *Short circuit calculation method:*

   Short-circuits are calculated using the IEC60909 standard.

2. *Fault case definitions:*

a. 3-phase short-circuit with no fault resistance (R_f =0 Ohm)

b. 2-phase short-circuit (phases a-b) with R_f =0 Ohm

c. Single phase to ground fault (phase a) with R_f = 0 Ohm

d. Single phase to ground fault (phase a) with R_f = 30 Ohm (assumed value under consideration of the original settings for resistive zone reach of 40 Ohms)

3. *Considered network equipment:*

Faults are only calculated on branches. A step size of 10 % in considered for the short circuit sweep.

As a first approach, only the tripping times were evaluated by the Protection Audit of the primary protection. This means that no secondary or tertiary protection was evaluated in the first step. The threshold was set to 0.65 s which is the tripping time of the third zone. If the threshold was violated, the line element was analysed in detail using R-X or time-distance diagrams.

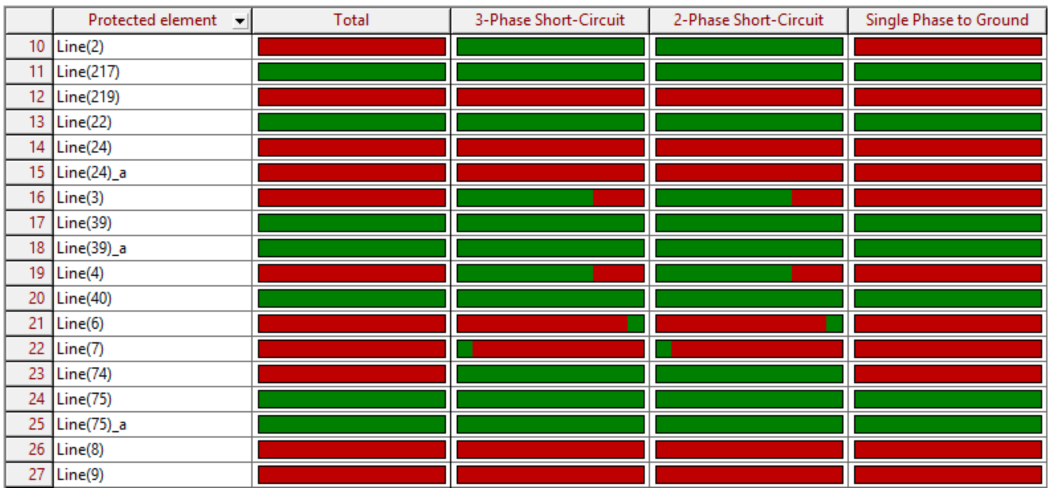

Figure 4: Evaluation of tripping times of primary protection according to line elements on zone EGAT BI2.

Figure 4 shows the results of the tripping time analysis for the relays of zone EGAT BI2 with the original settings. Only a selection of lines is displayed here. The columns represent the considered fault cases, the colour green indicates that the tripping time is below the defined threshold of 0.65 s and the line sections where the tripping time is above the threshold or where the relay does not trip are coloured red. In each case where results are marked red, it is necessary to analyse the protection failure in detail.

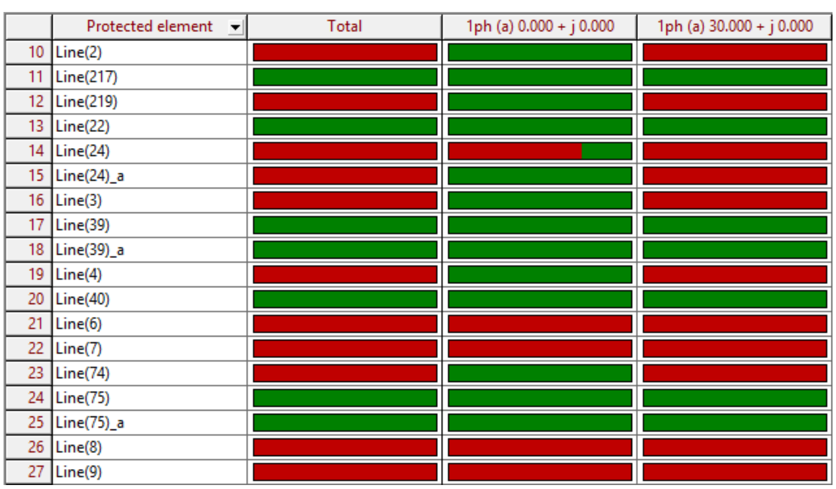

Figure 5: Evaluation of tripping times of primary protection according to line elements of zone EGAT BI2 for single phase to ground faults only.

In this selection of results it can be observed from the first column *Total*, that more than 50 % of the lines are not protected in the case of one of the calculated fault types. It is also apparent that the majority of these lines are completely or partly protected for 3- and 2-phase faults but not for single phase to ground faults e.g. *Line(2)* and *Line(74)*. This provokes further analysis of the failure of the primary protection for the single phase to ground fault cases. By expanding this fault type, the two specified fault cases (with and without 30 Ohms fault resistance) can be displayed as shown in Figure 5.

From this result overview it can be seen that it is mostly the single phase to ground fault with fault resistance cases which result in the primary protection failing to trip in less than the user-specified threshold of 0.65 s. In these cases, the primary protection devices do not recognise the fault, meaning the tripping time is indefinite. At this point the protection failure is identified and should then be analysed further looking at the specific network setup and using conventional tools and methods.

In Figure 6 the single line graphic including Line(2) is shown on the left hand side. Two distance protection devices SEL311L are located at busbars RCN and WAA. Not only is Line(2) protected by these two devices but also Line(3), Line(4), Line(24)_a, Line(219) and Line(24). The results in Figure 4 showing the violation of the tripping times threshold, indicate that all these lines are not protected in the case of single phase to ground faults. Subsequently two suboptimally configured devices have been identified leading to a prospective protection failure for faults in six lines.

For this case, a single phase to ground fault with 30 Ohms resistance is calculated on 50 % of Line(2) and the result is shown in Figure 6 on the right hand side. Neither of these devices will trip for this fault case. Two reasons were identified for this behaviour:

1. The overcurrent starting was set too high for the fault current and therefore the devices did not start.
2. As can be observed from the RX plot, the devices are underreaching.

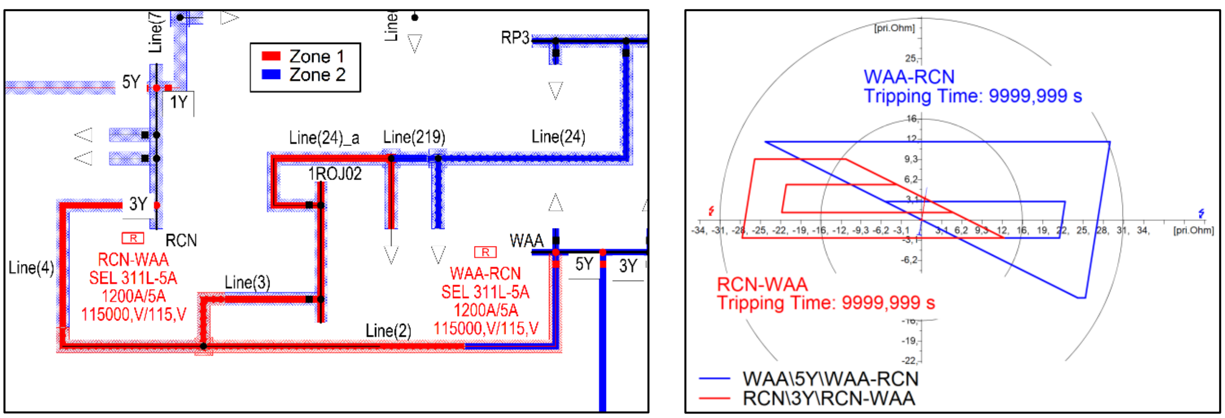

Figure 6: Protected area around Line(2); single line representation on the left side, R-X plot in case of a single phase fault at 50 % of Line(2) on the right side.

Similar steps were undertaken for every failure indicated by the protection audit tool. After the failures were identified, typical failure categories could be defined and the setting improvement started. The improved settings were afterwards, according to the evaluation process, verified using the protection audit tool.

CONCLUSION

In order to evaluate the protection settings for any kind of protection function such as distance or overcurrent protection, the evaluation process outlined in this paper utilising the automated protection audit tool can be applied. A detailed network model including the protection devices and their settings is required in order to gain reliable results. Additionally different operation points should be setup to simulate worst case conditions for the protection devices.

Using the protection audit tool, weak points can be identified efficiently. As it has been seen in the study case Thailand, the single phase to ground fault with fault impedance was identified as a possible weak point and led to two protection devices which covered multiple lines. The protection audit facilitates an overview of tripping and coordination performance, but this should be complimented by detailed manual investigations into the problematic cases identified.

REFERENCES

[1] M. Castillo, D. Gmeiner, S. Premrudeepreechacharn and N. Tantichayakorn, "Development of an Approach to Verify, Calculate and Optimise Protection Settings in a DSO Electrical Network," in *IEEE PES GTD* , Bangkok, 2019.