Automatic Tuning of Out-of-Step Relays

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***Abstract*—A method and prototype tool for tuning out-of-step relay parameters is presented. A decision making matrix is built from dynamic simulation results. Based on this matrix, an optimization problem is formulated that determines the out-of-step relay parameters that minimize the number of cases in which the relays do not operate satisfactorily. The method has been successfully tested on a simple test case with one relay to tune, and on a four zone test case where several relays are tuned for different operating scenarios.**

***Index Terms*-- Power system analysis, power system dynamics, power system protection, out-of-step relays.**

I. INTRODUCTION

Out-of-step (OOS) or loss-of-synchronism relays are used to quickly detect out-of-step conditions in a power system and send tripping signals to selected circuit breakers. The timely detection of out-of-step conditions is important to avoid unacceptably high currents that could otherwise arise. For out-of-step relays to operate correctly, they should be able to distinguish out-of-step events from other phenomena such as short-circuits. Two modes of failure are possible. A Type I error means that the relay operated when it should not have. Such an error is referred to as spurious tripping. A Type II error means that the relay failed to detect an out-of-step condition for which it should have operated. Such an error is referred to as a tripping failure. For generator out-of-step relays, it is straightforward to tune the relay parameters such that the relay operates correctly under all conditions. However, when multiple relays are installed in a power system to split the system along different locations, depending on the part of the system that loses synchronism, the tuning process turns into a very complex problem.

In this paper, a methodology for the tuning of OOS relay parameters is presented. In addition to that, a tool for automatic tuning of the parameters is proposed. The methodology and the tool have been tested on equivalent models representing the behavior of real power systems.

The organization of the paper is as follows: Section II presents the principles of OOS relays. Section III specifies the assumptions and limitations of the method. In Section IV, the methodology is explained. In Section V, the software implementation of the method is discussed and in Section VI, the method and tool is tested on two test systems.

II. OUT-OF-STEP RELAYS

Although there is wide variety of out-of-step relay designs, they are all based on the same fundamental principles [1], [2]. The relays have an outer zone, which activates the out-of-step relay when the impedance trajectory crosses it, and an inner zone, which is used to evaluate the time the impedance trajectory took to travel a certain distance in the R-X plane. The travel time is compared to the relay timer setting in order to distinguish between a power swing and other system disturbance s (i.e. fault).

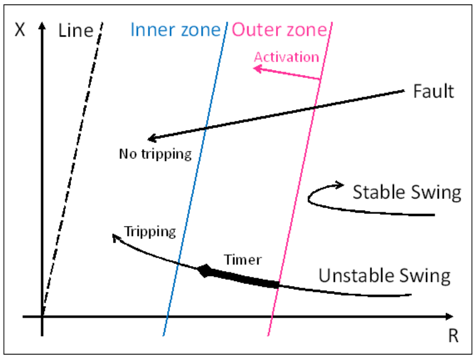

Figure 1. Operation principle of out-of-step relay.

III. ASSUMPTIONS & LIMITATIONS

The methodology and tool that are presented in this paper are restricted to the tuning of the out-of-step relays. It is therefore assumed that the location of all the out-of-step relays in the network to be tuned is known. In other words, the purpose of the function proposed here is to tune existing relays, not to propose optimal locations for new ones. The tuning of power swing blocking, to prevent unwanted distance relay element operation during power swings is not covered. It is also assumed that the characteristics of the out-of-step relays are known beforehand, and based on the following principles:

- The measured positive-sequence impedance at the relay location is used;
- To differentiate between a fault and a swing, the difference between impedance rate of change during a fault and during a power swing is used;

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- The impedance rate of change is determined by the elapsed time required by the impedance vector to pass through a zone limited by two blinders.

It is important to note that the assumptions listed here do not impose a given shape of the impedance characteristics of the relay: it can be double blinders, concentric polygons, concentric circles, etc. Similarly, the logic leading to tripping can be either "trip on-the-way-in" (TOWI) or "trip-on-the-way-out" (TOWO). The method is therefore useful for the majority of existing OOS relay configurations. Finally, it is assumed that the remedial actions triggered by each out-of-step relay when it detects an unstable power swing are known.

With this set of assumptions, the tuning of out-of-step relays is limited to:

- The settings defining the zone limited by two impedance characteristics;
- The timer setting that differentiates between a fault and a power swing.

IV. METHODOLOGY

The first step in the methodology for OOS relay tuning is a system stability analysis. From this, scenarios leading to power swings are derived. Typical scenarios are three-phase faults cleared in back-up time, where the back-up time is longer than the critical clearing time, or outages where the post contingency flows exceed the transfer capability of the transmission system. For each of these scenarios, or incidents, it should be indicated which relays should trip, and which ones should not. This information is summarized in the "target trip matrix". The target trip matrix indicates the relays that are expected to trip for each of the simulated incidents. This information is an input provided by the user for the methodology. An example is given in Table I.

TABLE I. EXAMPLE TARGET TRIP MATRIX

	INCIDENT 1	INCIDENT 2	…	INCIDENT N
RELAY 1	NOT TRIPPING	NOT TRIPPING	…	NOT TRIPPING
RELAY 2	NOT TRIPPING	NOT TRIPPING	…	TRIPPING
…	…	…	…	…
RELAY M	TRIPPING	NOT TRIPPING	…	TRIPPING

A second matrix, the "achieved trip matrix", with the same structure as the target trip matrix is now built as follows. The OOS relay logic is modelled in the simulation tool, and each incident is simulated. It is then verified which relays have tripped and which ones have not. This information, which is a direct output of the simulations, is introduced in the achieved trip matrix. When the achieved trip matrix is exactly the same as the target trip matrix, all relays behave as expected and no tuning is required. In practice, it is often impossible to achieve perfect settings that assure correct operation of the relays in all situations. The relay parameters then have to be tuned. Tuning of the parameters could be done by minimizing the following function, with A the target trip matrix, and B the achieved trip matrix.

$$\alpha \cdot \sum_{\substack{spurious \\ tripping}} \left(A_{ij} - B_{ij}\right)^2 + \beta \cdot \sum_{\substack{tripping \\ failure}} \left(A_{ij} - B_{ij}\right)^2$$

The theoretical problem with this formulation is that the objective function is constant as long as the number of spurious and failed tripping does not change. Consequently, it does not provide any indication on a "direction" which would allow minimization. This makes the task of the optimizer very difficult. Therefore, we propose to select another objective function to optimize which is continuous.

V. IMPLEMENTATION

The optimization process focuses on those cases where the relays do not behave as expected: spurious tripping and unwanted tripping.

Spurious tripping are cases of stable swings where the measured impedance enters into the outer zone when it should not, and does not quit before the timer expires. The time spent in the outer zone beyond the timer can be used as a "performance measure" in the function to optimize such cases, as follows:

$$T = T_{exit\ outer} - T_{enter\ outer} - T_{timer}$$

where:

- $T_{exit\ outer}$ is the absolute time at which the measured impedance exits the outer zone;
- $T_{enter\ outer}$ is the absolute time at which the measured impedance enters into the outer zone;
- T_{timer} is the timer delay.

Tripping failures are cases of unstable swings where the measured impedance does not enter into the outer zone when it should, or cases where the relay does not trip before the instability happens (remedial actions are not triggered or triggered too late), or cases where the measured impedance enters into the inner zone before the timer expires. For each unstable swing, the remedial actions are known, as it is the latest time at which they should be activated to regain stability. This time is a point on the impedance trajectory of the case in the plane [R, X]. Theoretically, this point must be located between the inner and the outer zones, and it must be reached after the expiration of the timer (otherwise the remedial actions are triggered too late). In other words, correct operation happens if:

$$T_{remedial\ actions} > T_{enter\ outer} + T_{timer}$$

where $T_{remedial\ actions}$ is the latest time at which the remedial actions should be implemented to regain stability. $T = T_{remedial\,actions} - T_{enter\,outer} - T_{timer}$ can be used as a "performance measure" in the function to optimise for such cases (having in mind that in the initial problem for optimisation; the time at which the measured impedance enters into the outer zone can be "after" the latest time at which the remedial actions should be implemented). Changing the inner zone, the outer zone and the timer settings, will affect continuously $T_{enter\ outer}$ and T_{timer}, and hence will allow smooth optimisation of the cases of tripping failure.

The two unwanted situations are combined in the objective function, giving a higher weight to spurious tripping than to tripping failures. The effect on the minimization process is to first remove the spurious tripping before removing the tripping failures.

$$F = F_{spurious\,tripping} + F_{tripping\,failure}$$

With

$$F_{spurious\,tripping} = -10 \cdot T + 10$$
$$F_{tripping\,failure} = -T$$

The optimization problem must respect the following constraints. For the outer zone:

- The outer zone must be greater than the impedance of the line where the relay is located (in order to avoid any interference with the operation of other relays, like distance relays for instance);
- The outer zone should not interfere with the locus of the impedance measured by the out-of-step relay when the flow or current on the branch is equal to the nominal one ("load region").

For the inner zone:

- The inner zone must be greater than the impedance of the line where the relay is located (in order to avoid any interference with the operation of other relays, like distance relays for instance);
- The inner zone must be inside the outer zone.

For the timer:

- The timer must be greater than zero.

In our prototype, those constraints turn into bound constraints on the parameters. They are easy to be taken into account by the optimization algorithm.

EUROSTAG© was used for dynamic simulations and relay modelling [3]. The optimization prototype was implemented in Python, using EUROSTAG's python API and a general framework for optimization algorithms, pyGMO [4]. Different metaheuristic methods have been tested. Simple Genetic Algorithm reveals to be the most performant on our problem.

VI. TESTS & RESULTS

A. Test 1: Single Relay

1) Problem Statement

The methodology developed above has been verified on a test case. The test network is the "Nordic 32" system. This network is a simplified representation of the transmission system of the Nordic countries. It contains 41 buses in total. Out-of-step relays are supposed to be located on the five lines connecting the northern and central parts of the system.

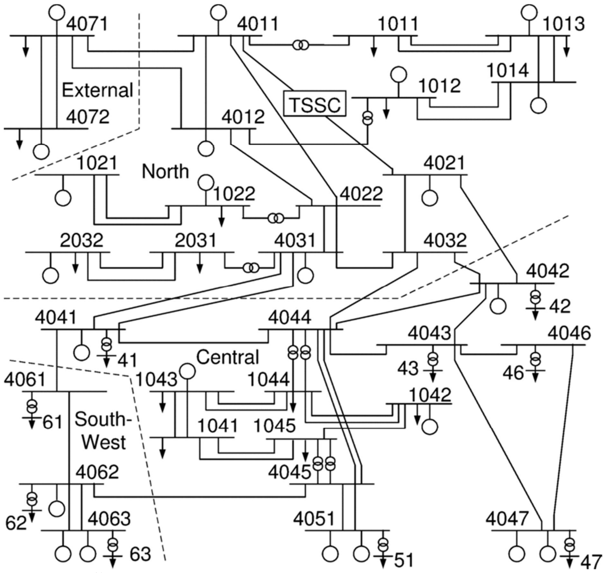


Figure 2. Nordic 32 system.

When the line NO4011-NO4021-1 in the north is lost, the transfer capability of the remaining lines is not sufficient to accommodate the large north to south power flows, which causes an angular instability between the northern and central parts of the system. This instability can be avoided if the power produced in the north is quickly reduced after the tripping of the line. This can be done by tripping out the generator connected to the bus NO1012 at the latest 0.5825 seconds after the loss of the line. The maximum angle deviation is then 155° between the machines connected to the buses CE4041 in the centre and NO1021 in the north.

As there is only one incident leading initially to an instability of the system, only one out-of-step relay is tuned in this first test system. The tuning will first be done by hand, and the result will then be compared with the automatic OOS tuning prototype output.

2) Manual Tuning of the Out-of-Step Relays

The out-of-step relay has first been tuned by hand, based on time domain simulations. It appeared that the problem is infeasible. The solution to solve this feasibility issue is to accept spurious tripping. The incident giving the lowest measured resistance is ignored. With the resulting settings, the measured impedance enters into the outer zone 0.53 seconds after the loss of the line.

3) *Final Verification*

All the incidents (including the faults) are checked with the manually-computed relay settings. As expected, the outage of the line NO4011-NO4021-1 is stabilised thanks to the action of the out-of-step relay located on the line NO4032-CE4042-1. The outage of the line NO4021-CE4042-1, or a fault on the same line, causes a spurious tripping of the out-of-step relay located on the line NO4032-CE4042-1, but this does not lead to an unstable situation. This is the price to pay to make the problem feasible and secure the critical systemic incidents. A fault on the line CE4046-CE4047-1 also causes a spurious tripping of the out-of-step relay located on the line NO4032-CE4042-1, but in this case, the measured reactance is above 0.07 p.u., which is above the reactance of the line (0.04 p.u.). This case can be easily solved by restricting the outer and inner zones along the X axis.

4) *Optimisation Results*

The same system was optimised using the prototype tool. The result of the optimisation was that there are no tripping failures, but one spurious tripping. This result is qualitatively the same as the manual calculation, which validates the tool for this problem. The final value of the objective function is slightly lower than the one manually found, which justifies the interest of automatic optimization of OOS relay settings, even for a simple system with only one relay. Indeed, the stability margins are enhanced through optimal parameterisation of the relay.

B. Test 2: Multiple Relays

1) *Introduction*

The next step in validating the prototype is to apply the optimisation method on a test case composed of multiple relays. This adds a new dimension to the tuning problem as the coordination between the different relays during the incidents becomes important (i.e. different relays are required to operate for the different cases considered). Additionally, it is for these cases that the prototype developed provides real added-value as doing the job by hand becomes very complex and time-consuming.

2) *Problem Statement*

The test system consists of four interconnected zones. The system has been configured in such a way that it is subject to loss of stability during exceptional operational conditions where the flows on the interconnection lines exceed their maximum transmittable powers. In these instances, out-of-step relays should operate and separate the zones at the right location and in sufficiently fast time in order for the system to recover a safe operating system. Therefore, the system is ideally suited for validating the relay tuning prototype that was developed on a system with multiple relays.

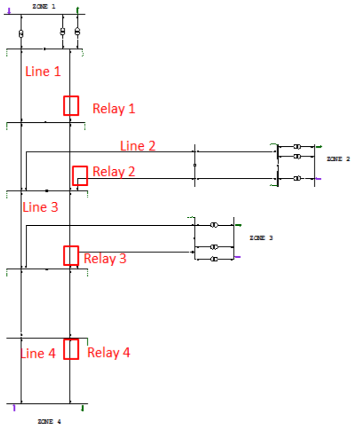


Figure 3. Four zone test system.

In Table III, a description of the relays, their purpose (when they should operate) and the corrective actions that they trigger are given:

TABLE II. RELAYS

RELAY	FUNCTION	ACTIONS
R1	SHOULD OPERATE DURING INSTANCES WHERE ZONE 1 LOSES SYNCHRONISM WITH REST OF THE SYSTEM	OPEN BOTH LINES THAT CONNECT ZONE 1 TO THE REST OF THE SYSTEM
R2	SHOULD OPERATE DURING INSTANCES WHERE ZONE 2 LOSES SYNCHRONISM WITH REST OF THE SYSTEM	OPEN BOTH LINES THAT CONNECT ZONE 2 TO THE REST OF THE SYSTEM
R3	SHOULD OPERATE DURING INSTANCES WHERE ZONE 1 AND ZONE 2 LOSE SYNCHRONISM WITH REST (ZONE 3 AND ZONE 4)	OPEN BOTH LINES THAT CONNECT ZONE 1 AND ZONE 2 TO THE REST OF THE SYSTEM
R4	SHOULD OPERATE DURING INSTANCES WHERE ZONE 4 LOSES SYNCHRONISM WITH REST OF SYSTEM	OPEN BOTH LINES THAT CONNECT ZONE 4 TO THE REST OF THE SYSTEM

3) *Tuning scenarios*

In order to tune and coordinate the parameters of the four relays, tuning scenarios are needed in which different relays are required to operate. The scenarios are built around the opening of the lines in parallel to those of the relay locations, and with two different load flows: one in which the active power through the corridor is greater than the maximum transmissible power and another where it is smaller. Therefore there are four incidents to be simulated on the system (for each relay), with two operating load flows: one which leads to loss of synchronism (termed the “unstable incident load flow”) and one which leads to a stable post-incident system state (termed the “stable incident load flow”). The two load flows are extreme for tuning the relays in the sense that they are at the boundary between stable and unstable behavior of the system.

The eight cases (load flow + incident) that will be used to tune the relays are described in Table IV which describes each of the eight cases (column 1), explains the associated simulation result if no relay action is taken and finally describes the relay that should act in order to stabilize the system.

TABLE III. DESCRIPTION OF CASES

CASE DESCRIPTION	OUTCOME (WITHOUT RELAY)	RELAY REQUIRED TO OPERATE
CASE1→ LOSS OF LINE 1 (UNSTABLE INCIDENT LOAD FLOW)	ZONE 1 LOOSES SYNCHRONISM WITH REST OF THE SYSTEM	R1
CASE1S→ LOSS OF LINE 1 (STABLE INCIDENT LOAD FLOW)	STABLE POST-INCIDENT SYSTEM STATE	/
CASE2→ LOSS OF LINE 2 (UNSTABLE INCIDENT LOAD FLOW)	ZONE 2 LOOSES SYNCHRONISM WITH REST OF THE SYSTEM	R2
CASE2S→ LOSS OF LINE 2 (STABLE INCIDENT LOAD FLOW)	STABLE POST-INCIDENT SYSTEM STATE	/
CASE3→ LOSS OF LINE 3 (UNSTABLE INCIDENT LOAD FLOW)	ZONE 1 AND ZONE 2 LOOSE SYNCHRONISM WITH REST (ZONE 3 AND ZONE 4)	R3
CASE3S→ LOSS OF LINE 3 (STABLE INCIDENT LOAD FLOW)	STABLE POST-INCIDENT SYSTEM STATE	/
CASE4→ LOSS OF LINE 4 (UNSTABLE INCIDENT LOAD FLOW)	ZONE 4 LOOSES SYNCHRONISM WITH REST OF THE SYSTEM	R4
CASE4S→ LOSS OF LINE 4 (STABLE INCIDENT LOAD FLOW)	STABLE POST-INCIDENT SYSTEM STATE	/

The results of the simulation of cases 2 and 2S are shown on Figure 4 and Figure 5 respectively (it should be noted that the line incidents occur at 10s in the simulations). Both figures show the angular positions of the four zones. Clearly, it is seen that case 2 leads to pole slipping between zone 2 and the rest of the system (initiated at around 13.5s) and eventual instability.

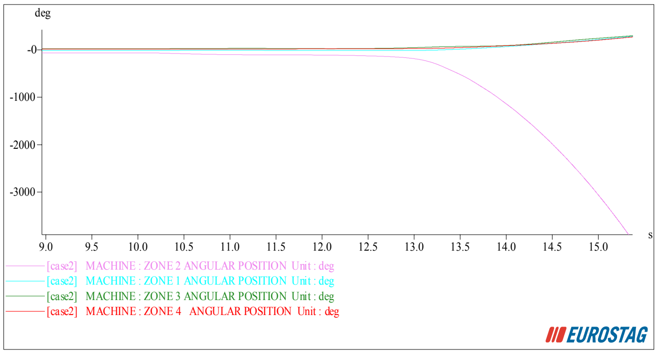


Figure 4. Simulation results: case 2.

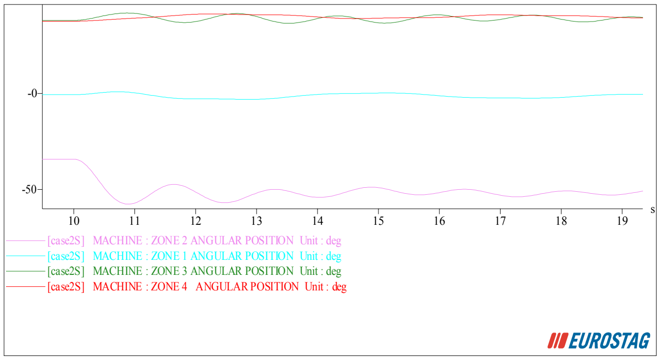


Figure 5. Simulation results: case 2S.

To avoid the resulting instability, relay 2 should separate zone 2 from the rest of the system within 3.5s following the incident before pole slipping occurs (this is the $T_{\text{remedial actions}}$ parameter mentioned above).

When the R2 relay takes action in time, the system manages to stabilize to a stable operating point, as shown on Figure 6, Figure 7 which display the machine angles, active power flows through the tie lines connecting zone 2 to the rest of the system respectively. It shows that at 10s, a line is tripped leading to increased active power flow on the remaining parallel transmission line (zone 2 is importing 3GW). The relay R2 then detects the potential instability and sends a trip command signal to the remaining line in order to separate the system and regain stability.

The same simulations were carried out for all cases. This simulation work enables to configure the optimization problem and is the starting point before running the tuning algorithm.

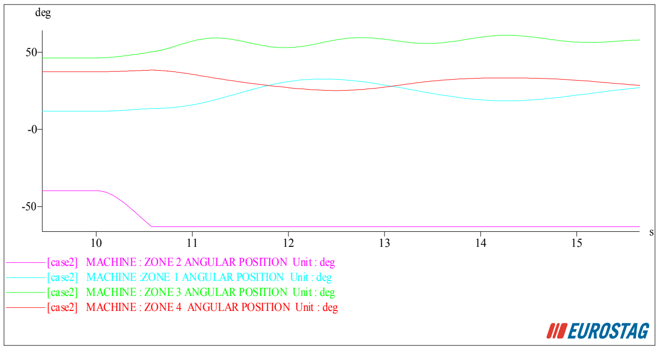


Figure 6. Case 1 simulation with action of relay R1: angular positions.

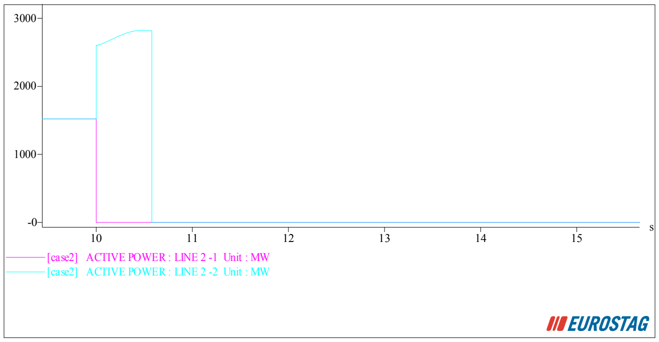
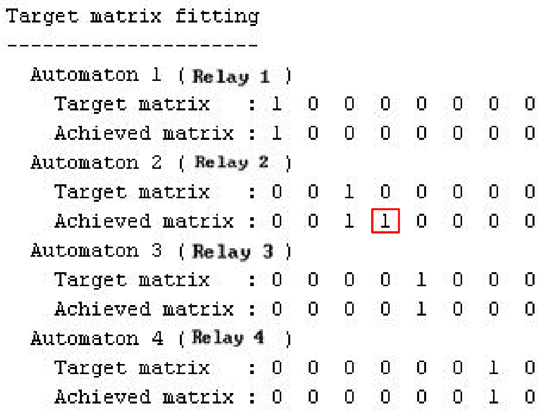


Figure 7. Case 1 simulation with action of relay R1: active power flows.

4) *Optimization results*

Figure 8 displays the comparison between target and achieved trip matrix that have been obtained after optimization.



```
Target matrix fitting
---------------------
  Automaton 1 ( Relay 1 )
    Target matrix   : 1  0  0  0  0  0  0  0
    Achieved matrix : 1  0  0  0  0  0  0  0
  Automaton 2 ( Relay 2 )
    Target matrix   : 0  0  1  0  0  0  0  0
    Achieved matrix : 0  0  1  1  0  0  0  0
  Automaton 3 ( Relay 3 )
    Target matrix   : 0  0  0  0  1  0  0  0
    Achieved matrix : 0  0  0  0  1  0  0  0
  Automaton 4 ( Relay 4  )
    Target matrix   : 0  0  0  0  0  0  1  0
    Achieved matrix : 0  0  0  0  0  0  1  0
```

Figure 8: Tuning results.

It is seen that the optimization algorithm has converged to a solution for this test system that gives no tripping failure and only one spurious tripping. Although one spurious tripping (relay 2 – incident 4) remains, it should be noticed that the tuning scenarios are extreme in the sense that they cover marginally stable/unstable cases. These scenarios are chosen specifically because they represent the toughest cases in terms of relay tuning. The rationale is that if the relays can cope with these extreme scenarios they can cope with any other stable/unstable operating scenario. However, they are also low probability scenarios and therefore the spurious tripping obtained on this extreme scenario should be put into perspective as other similar less extreme and more probable scenarios will be well handled by the relay (dependable and secure tripping).

Figure 9 displays the R-X trajectory as seen from relay 2 during the case 2 simulation along with the relay parameter settings obtained from optimization (outer and inner zone settings). As can be seen, the relay timer expires within the relay zone and this leads to operation of the relay and to stabilization of the system. Figure 10 displays the R-X trajectory seen from relay 2 for the case 2S simulation and relay parameter settings. The R-X trajectory does not enter into the relay zone with the relay parameters obtained from the optimization algorithm, as is desired.

VII. CONCLUSIONS

A methodology and prototype tool with the purpose of automatic out-of-step relay tuning has been developed. It works by solving an optimisation problem. The goal of the tool is to find the set of relay parameters that minimises the number of spurious tripping and tripping failures. Doing this manually is very time-consuming, and leads to sub-optimal results. Additionally, it can only be performed for simple cases with a low number of relays.

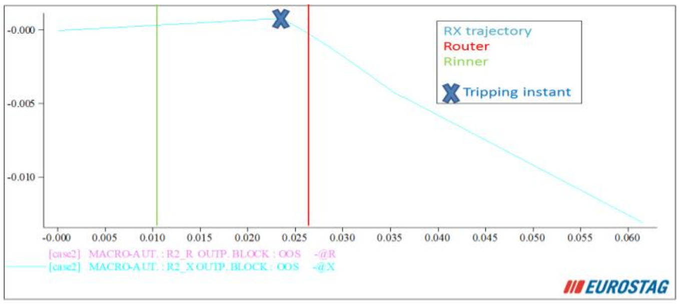


Figure 9. CASE 2: R-X profile seen from relay 2 and relay parameter settings.

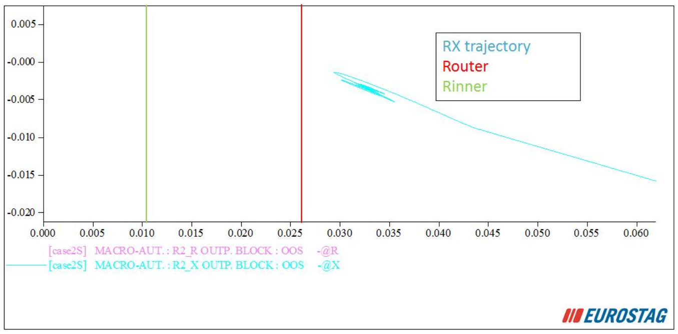


Figure 10. CASE 2S: R-X profile seen from relay 2 and relay parameter settings.

The prototype developed was first validated on the NORDIC system with one relay. A manual solution was used as benchmark to verify and assess the solution found by the OOS tuning prototype. The results on this simple 1-relay system showed that although qualitatively similar (one spurious tripping for both parameter sets), the solution derived by the prototype allowed increased stability margins compared to the manual one. Mathematically, the cost function was lower than that of the manual solution. The prototype was then validated on a 4-relay system in order to verify its ability of coordinating the different relays for each of the cases (tuning scenarios) considered. The results obtained demonstrated the correct functioning of the prototype as the optimal solution found by the algorithm resulted in zero tripping failures and one spurious tripping.

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