Hybrid Fuzzy Evaluation Algorithm for Power System Protection Security Assessment

Georg Janick Meyer
Tobias Lorz, Rene Wehner
Johann Jaeger
Friedrich-Alexander Universität Erlangen-Nürnberg
Erlangen, Germany
janick.meyer@fau.de

Maximilian Dauer
Rainer Krebs

Siemens AG
Erlangen, Germany
max.dauer@siemens.com

***Abstract*—System Protection Security Assessment is an important task in modern energy grids to ensure system security at all. The assessment system is particularly challenged by multivariate grid structures caused by volatile renewable infeeds.**

This paper presents an innovative strategy to evaluate the protection relay coordination of system-wide power grids. A way to calculate the quality of all protection relays based on realistic simulation data and independent of the protection method was sought. The hybrid algorithm consists of two major steps. First, a systematic analysis with various fault simulations is performed and the measurement results of all relays of all simulations are used as database. Subsequently, the use of fuzzy sets allows to express the quality of each relay setting regardless of its type.

Specifically developed for the use of an optimization algorithm, finally, a new protection coordination is determined for an adapted version of the IEEE 9 bus grid. The results are validated, discussed and the effectiveness of the methodology compared to conventional setting rules.

***Index Terms*—Fuzzy Evaluation, Relay Settings, Optimization Algorithm, Protection Coordination, Protection Security Assessment**

I. BACKGROUND

Protection relays have been developed over 100 years ago and are crucial for system security: They limit the impact of faults and can be seen as the last line of defense for the power system. [1]

Distribution grids worldwide are confronted with higher enforcement of power electronics, shorter time constants and an increasing number of prosumers participating in the market. Volatile sources and the increasing use of flexible AC transmission systems (FACTS) lead to changing load flows and thus to different and time-dependent fault situations. Especially, protection relays are disregarded in this times, even though incorrect settings of not adapted relays have led to numerous blackouts in recent years. [2]

A necessary step would be frequent and quick reviews of the protection system coordination after major changes to ensure correct functionality. However, the review is a complex and time-consuming task that is still mainly carried out by experts today. In addition, conventional protection coordination approaches and tools reach their limits of practical applicability. In [3], [4] the authors introduce a fully automated Protection Security Assessment (PSA) tool for main and backup protection. The system response is simulated, rated and visualized, so weak points can be identified. However the information is missing, why the settings lead to the respective results and which settings would be better. Several other methods have been published to find optimal settings locally and to coordinate distance (DI) and overcurrent (OC) protection relays, but no system-wide approach was investigated. [5], [6]

A method to evaluate protection relay settings based on fuzzification was firstly introduced here [7]. The authors describe there idea to make a statement on the quality of a protection system without simulations.

II. CHALLENGE

Power system protection relays are currently the only controllers in the grid that are allowed to automatically trigger a topology change of themselves. Their goal is to keep the whole system stable and to minimize the impact of faults on the transmission system as well as to protect humans and nature. Therefore, protection areas define related sections that are isolated coherently during a fault. The coordination of all relays and types in a system-wide grid is a difficult task. The challenge is to develop an adaptive, automated and clear evaluation system for protection coordination in multivariate grids. It should function fast and reliably and be designed for the use of a heuristic optimization algorithm to improve the coordination of all relays to the same time.

A. Protection Principals & Coordination

In the following the two most common types of protection relays with backup function are introduced: DI and OC protection. Subsequently, it is explained why protection relays often have difficulties in measuring accuracy.

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1) DI (21): The distance or impedance protection principle is based on the evaluation of voltage and current and calculates the resulting fault resistance and reactance X_F locally at the point of installation. Based on the known reactance $X_L^{'}$ of the surrounding equipment the distance l_F from the relay to the fault location can be determined by formula (1) and (2). If the fault occurs in the own protection area the relay should trip immediately. Otherwise it can work as a time delayed backup for following relays in the surrounded protection areas. External influences on the measurement distorting the calculated impedance can lead to a wrong fault location determination and would thus cause a gross violation of selectivity. The facts are explained in detail in section II-B. Therefore, most protective methods use time grading at the borders of the protective areas. Safety margins are usually considered of 10 % to 20 % to the end of the next protection area. The resulting first distance zone is to clear faults within its own area with no intentional time delay. The second zone is to cover the borders of the protective area securely. Time delays are in the order of 15 to 30 cycles of the fundamental frequency. Following zones are used as backup and should be coordinated with zone 1 and zone 2 of subsequent relays.

High voltage grids are designed primarily meshed, so that there are usually several subsequent lines from the protection relay's point of view. For the protection engineer it is difficult to coordinate all relays properly. Various protection coordination philosophies exist and depend on the respective grid situation. The IEEE Guide for Protective Relay Applications to Transmission Lines (C37.113) suggests settings based on formula (3). [8]

Figure 1 demonstrates the grading for such a complex structure based on formula (3). Following the time grading path of relay R1, it is obvious that the zone reach of X_3(R1) is overlapping X_3(R2). This could cause an over-function. Whereas, X_2(R4) has no backup protection of X_3(R1) at the end of line L_{BE}. This circumstance could lead to an under-function and fault clearing problems. Those are typical challenges for DI relays that are installed on a line with a short and long line following.

$$\underline{X}_F = Img\left\{\frac{\underline{U}_k}{\underline{I}_k}\right\} \tag{1}$$

$$l_F = \frac{X_F}{X_L^{'}} \tag{2}$$

$$\begin{aligned} X_1 &= 0.8 \cdot X_{L_{AB}} \\ X_2 &= 1.2 \cdot X_{L_{AB}} \\ X_3 &= X_{L_AB} + X_{max,next} \end{aligned} \tag{3}$$

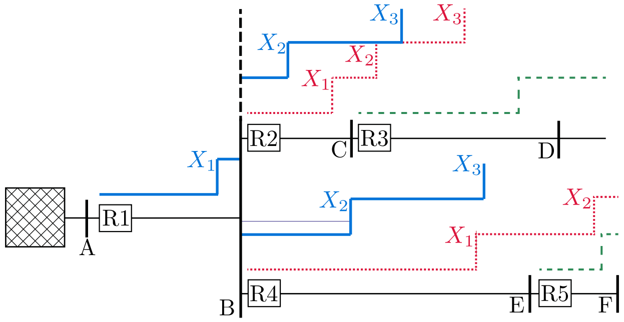


Fig. 1. Distance protection: Grading chart for a radial network

2) OC (50/51/67): OC relays are the most commonly used protection relay type. They can be used as main and backup protection in transmission and distribution systems. They are available with various timing characteristics to coordinate with other protection relays and to protect specific equipment. The most important difference in function lies whether the command time depends on the amount of short-circuit current (51) or not (50). If the relay uses in addition to the magnitude the direction of current for the tripping decision, it has the code designation 67. Figure 2 shows the tripping characteristic of an independent OC relay with two tripping stages. The high current stage $I_{>>}$ has to trip short-circuits without delay time. The overcurrent stage $I_{>}$ is used as backup and overload stage. Typical setting rules can be seen in formula (4).

To prevent unselective tripping during normal operation the overload stage must be higher than the highest load current that can occur. The short-circuit stage depends on the short-circuit level and must be coordinated with subsequent relays.

$$\begin{aligned} I_{>>} &= (1.5...4.0) \cdot I_r \\ I_{>} &= (1.1...1.5) \cdot I_r \end{aligned} \tag{4}$$

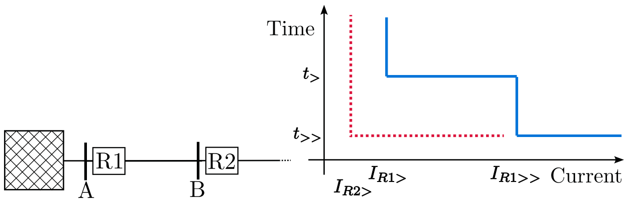


Fig. 2. Overcurrent protection: Grading chart for a stub line

B. Adverse Effects for Measuring Accuracy

Especially in the practical use of DI relays, a number of influencing factors that adulterate the measurement results must be taken into account. The greatest inaccuracies are caused by phase shift due to long lines, size of the fault impedance, zero sequence mutual coupling, intermidiate infeed and impedance change through parallel lines. The last two effects show how strongly the result of the impedance measurement can be influenced and are explained in the following.

1) Parallel Lines: in Figure 3 a simple grid model can be seen. If all three switches are open the relay R1 measures the correct distance to the fault, which can be calculated based on formula (5). Under the condition that $X'_{L,AB}$ equals $X'_{L,BC}$ the result is a straight line (1-black).

If the switch S2 is closed, the upper and lower line between node B and C form a parallel line, which reduces the fault reactance seen by the relay R1 (2-green) and can be calculated based on formula (6). If the fault is directly at node C ($y = 1$) the measured reactance of line L_{BC} is halfed and the relay just measures $X_{L,AB} + 0.5 \cdot X_{L,BC}$. Should this not be taken into account, unselective tripping would be the result.

$$X_{meas.}(R1) = \begin{cases} x \cdot X'_{L,AB} & \text{fault on } L_{AB} \\ X_{L,AB} + y \cdot X'_{L,BC} & \text{fault on } L_{BC} \end{cases} \tag{5}$$

$$X_{meas.}(R1) = X_{L,AB} + y \cdot (1 - \frac{y}{2}) \cdot X_{L,BC} \tag{6}$$

2) Intermediate Infeed: An increasingly common problem of decentralized renewable energies is the intermediate infeed. An example can be seen in Figure 3 (3-red line). Switch S1 is closed and S2 and S3 are open. During a fault on line L_{BC} relay R1 measures just half of the short-circuit current ($I_{A1} = 0.5 \cdot I_A$) supplied by the source connected to node A. The current I_{A2} flows from the node B in addition to the fault location and thereby causes an additional voltage drop from node B to the fault, which also increases the voltage at the location of relay R1. Measuring a higher voltage but not the total short-circuit current leads to a higher reactance measurement. In this case relay R1 measures $X_{L,AB} + 2.0 \cdot X_{L,BC}$, which means that the relay assumes the fault to be much further away than it is. The measuring error is greater, the stronger the intermediate infeed is.

The last two cases (blue) show both effects combined. Especially the course of the dark blue line, which is caused by the additional infeed from node C, is sophisticated. The maximum measured impedance is on the line L_{BC} and not at the end as in all other cases.

The overall coordination of all protection relays and types including all possible effects that lead to erroneous measurements in all possible grid situations is a highly complex question. That is why there is usually not the one perfect setting. The main goal of this paper is to provide a robust solution with minimal complexity, which is able to evaluate all protection relay settings easily and clearly. This is presented in the next section.

III. EVALUATION ALGORITHM FOR SETTING OPTIMIZATION

A. Underlying Simulation Data

Traditional approaches are using the resistance and reactance of the connected equipment as reference data to calculate the individual settings for each relay (e.g. equation (3)). As in section II-B explained, various effects are influencing the measurement results. In order to take all possible eventualities into account, a systematic fault analysis is done in advance

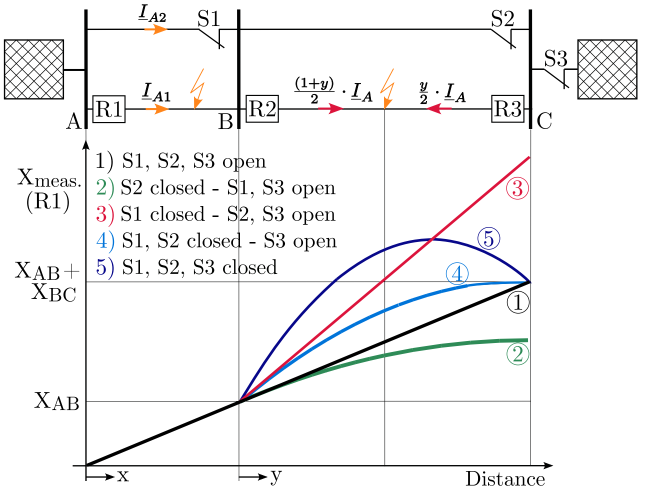


Fig. 3. Influence of various effects caused by different switching states of S1, S2 and S3 on the measured reactance of relay R1

to generate realistic and reliable reference data based on simulations. Depending on the required attention to detail, every X% of every line of the grid a short-circuit fault simulations is carried out.

For each individual simulated fault, all measured fault impedances of all DI relays and all fault currents of all OC relays are recorded. The measurement result of each relay is then assigned to the respective protection area (1 to 3) of the relay according to the responsibility for the fault. Therefore, for every fault simulation is stored, what each relay measures and to which protection area the result values belong. Figure 4 shows the procedure with an example. A short-circuit is simulated on line L_{DE}. The protection relays R5 and R6 are connected directly to that line and thus provide the main protection. Their measurement values are assigned to their individual ProtArea1. The relays R3 and R7 see the fault in forward direction and provide the first backup. Their result values are assigned to their ProtArea2. The relays R1 and R9 provide backup protection for R3 and R7 and add the measurement results to ProtArea3.

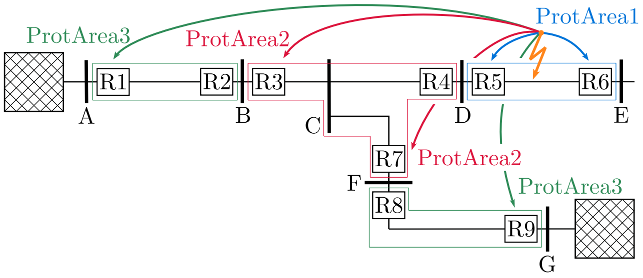


Fig. 4. Allocation of individual measurement values of every relay during the fault to the respective protection area 1, 2 or 3

This process is repeated for all topologies and possible states of the grid. Thus all eventualities and electrotechnical phenomena can be taken into account automatically. At the end all results are merged and form the underlying reference data for the following evaluation strategy.

B. Evaluation Criteria

Two of the most important criteria when assessing power system protection are **dependability** and **security**.

Dependability is defined as the degree of certainty that a protection relay or a system of protection relays operates correctly. In contrast, the definition of security is that a protection relay or a system of protection relays does not operate incorrectly. Specifically, this means that dependability indicates whether a protection relay trips when its necessary. Security, on the other hand, is the ability to avoid unnecessary tripping behaviour in all operating conditions, as well as short-circuits and faults outside of the relevant zones, and is therefore closely linked to the notion of selectivity. The edge between dependability and security of a protection system is usually narrow, especially since both criteria make conflicting demands on the setting values. [9], [10]

The new evaluation strategy bases on the fuzzification of the criteria dependability and security using two different membership functions. The principle is the same for any protection method and allows a quick and clear assignment of the setting values to both criteria.

C. Membership Function

Precision is crucial in technical systems, although goals, limits and consequences are not always precisely defined in the practical implementation. They move in a certain frame and are therefore inaccurate or out of focus. By contrast, organic systems are inherently imprecise. Be it movements of an animal, the growth direction of a plant or even the human mind. These systems are powerful as well as highly complex and, despite or perhaps because of their blurring, superior to the technical systems. In 1965, Prof. Lofti A. Zadeh of Berkley University published his work on fuzzy sets that forms the basis of today's fuzzy logic. Fuzzy sets extend the assessment of membership of elements to a set from bivalent to gradual. Therefore, the membership is described not only by ”0” for not belonging and ”1” for belonging, but it is any number as a degree of affiliation possible.[11]

This kind of consideration is now applied to the setting elements X_1, X_2 and X_3 of DI relays and $I_{>>}$ and $I_{>}$ of OC relays. They are assigned to the membership functions *m_dependability* and *m_security*. The process is called fuzzification. This makes it possible to express independently the quality of each setting over a degree of belonging to both criteria. The graphs of the membership functions are sigmoid functions, which are subject to the following criteria and can be seen in Figure 5:

- The slope at the inflection point is 0.5.
- Both sigmoid functions are defined by two points: **bad** and **good**. Bad is the point at which the graph continues to be 0 and good is the point at which it continues to be 1. The sigmoid function runs between the two points.
- The functions can only accept values in the range [0, 1].
- Both function graphs are opposite to each other but usually not symmetrical.
- The optimal point of both functions is between good of dependability and good of security. The points are marked with dashed lines in Figure 5.

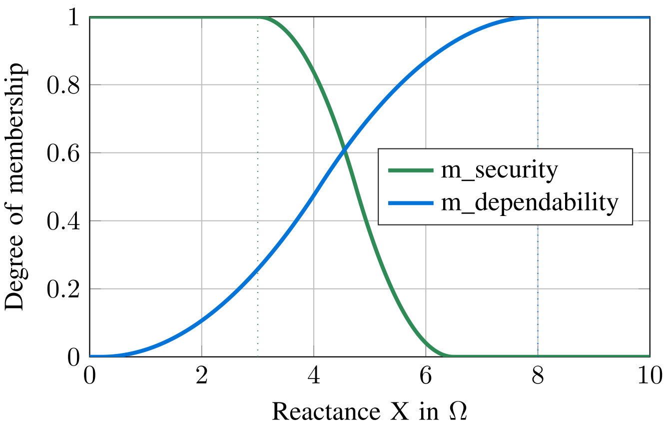


Fig. 5. Qualitative course of the membership functions security and dependability for DI protection relays

The calculation of the points good and bad for security and dependability of all settings of all relays bases on the previously generated underlying simulation data. In addition, the setting values of the following protection relays with the same direction of view are used for some points. The measured impedance up to the following relay is added to the actual setting value of it. Those points mark a direct violation of selectivity. Formula (7) and (8) give an example of the calculation principle.

m_security:

$$\begin{aligned} X1_{bad} &= X_{ProtArea1,\ max} \\ X1_{good} &= 0.7 \cdot X_{ProtArea1,\ min} \\ I_{>>_{bad}} &= I_{ProtArea1,\ min} \\ I_{>>_{good}} &= I_{ProtArea1,\ max} \end{aligned} \tag{7}$$

m_dependability:

$$\begin{aligned} X1_{bad} &= 0.7 \cdot X_{ProtArea1,\ min} \\ X1_{good} &= X_{ProtArea1,\ max} \\ I_{>>_{bad}} &= I_{ProtArea1,\ max} \\ I_{>>_{good}} &= I_{max,\ operation} \end{aligned} \tag{8}$$

For a good rating of dependability a DI relay needs a high setting value, so it can clear faults far away and work as a backup relay. To get sure not to trip unselective, a shorter range is advantageous. Tripping at a high current is a more secure setup for OC relays, whereas tripping at lower current ensures tripping for complex fault scenarios.

Through the fuzzy sets, it is now possible to formulate this kind of evaluation mathematically, which is why it can be perfectly combined with a heuristic optimization algorithm.

D. Optimization

Optimization is the process of finding values for different variables x_i of a system out of the set $\mathbb{X}$ in a fraction of time, with which the system is best designed. It means that the evaluation function f of the system is under the conditions $F = \{f1, f2, ..., fn\}$ with the determined values in the global maximum or minimum. Such evaluation functions are also called goal or fitness functions.

Each optimization algorithm is based on different basic techniques and methods for determining the individual solutions to an optimization problem. The most simple way would be to calculate all possible solutions and compare them, which is not feasible for real problems with reasonable resources.

The fuzzy evaluation strategy is a multi-criteria optimization problem, since two membership functions (*m_dependability*) and (*m_security*) for each setting $(X_1, X_2, I_>, ..)$ of every relay must be maximized simultaneously. In addition, the defining points (bad and good) of some membership functions are depending on the actual setting values of following relays. That means a change of the setting values of one relay will therefore also lead to new membership functions of other relays, which in turn will lead to a new overall evaluation. This circumstance makes the optimization problem NP-hard. By combining all membership functions of all settings of all relays, it is possible to calculate by the mean of all fuzzy sets one quality index for the whole protection system. This type of construction thus represents a fitness function to be maximized, the functionality of which is new and well suited for use with an optimization algorithm.

Proven to be efficient in the respect of multi-criteria problems, we suggest to use the $EPSO_{DE}$ particle swarm algorithm, which was firstly introduced here [12]. It is a hybrid, heuristic, optimization algorithm combining the advantages of EA (Evolutionary Algorithm), DE (Differential Evolution) and PSO (Particle Swarm Opimization).

In the following case study we show, how the new methodology leads to the best compromise between dependability and security and therefore to an efficient coordination of all relays.

IV. CASE STUDY

In this section the hybrid fuzzy evaluation strategy is used with the $EPSO_{DE}$ optimization algorithm to find the best settings of all protection relays of the power grid model shown in Figure 6.

A. Test Grid: Adapted IEEE9 Bus Grid

The power grid model is an extended and adapted version of the IEEE 9 Bus grid. It is adapted to have more realistic influences on the protection system through the added parallel line and changed length of the transmission lines. In addition, two stub lines are added and the loads distributed. All transmission lines are protected by two DI relays at the beginning and end of each line. Just the stub lines are only protected by one OC relay at the beginning of the line. The generators get protected by an own OC relay. The line data of the test grid is presented in Table I and the transformer data in Table II. Various grid states the protection system should be able to handle are also shown in Figure 6 in blue, red and green and explained in Table III.

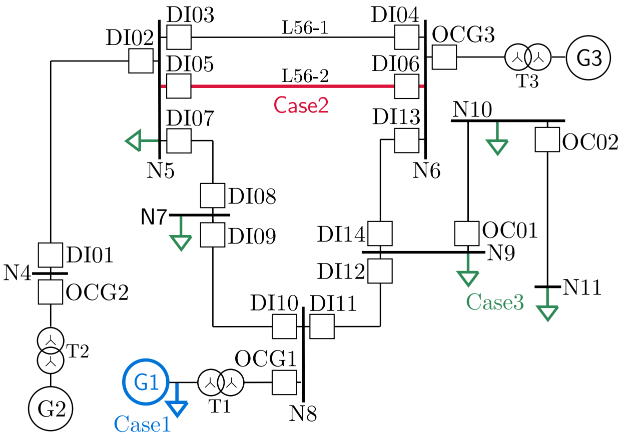


Fig. 6. Test Case: Modified IEEE9Bus grid model

TABLE I
TEST GRID: LINE DATA. NAMING DEPENDS ON NODES THAT ARE CONNECTED.

Name	From Node	To Node	Length l in km	ReactanceX' in Ω/km	Reactance X in Ω
L45	N4	N5	40	0.4	16.0
L56-1	N5	N6	30	0.4	12.0
L56-2	N5	N6	30	0.4	12.0
L57	N5	N7	10	0.4	4.0
L69	N6	N9	25	0.4	10.0
L78	N7	N8	25	0.4	10.0
L89	N8	N9	25	0.4	10.0
L910	N9	N10	20	0.4	8.0
L1011	N10	N11	10	0.4	4.0

TABLE II
TEST GRID: TRANSFORMER DATA

Name	Prim. Vol. U_{pri} in V	Sec. Vol. U_{sec} in V	Power S_n in MVA	Reac. x_d in %
T1	110	16.5	50.0	8.0
T2	110	18.0	72.0	8.0
T3	110	13.8	120.0	8.0

B. Setting Calculation

In order to be able to classify the optimized values later on, all settings of all relays are calculated based on formulas (3) and (4). As a database for the formulas the grid data of the base grid is taken. The result of the calculation is shown in Table IV for all DI relays and in Table V for the OC relays. The settings of the three OC relays protecting the generators are kept the same for the calculation and optimization case and can be seen in Table VI.

C. Setting Optimization

The test grid contains of 14 DI and 2 OC relays. That makes 46 fuzzy sets as shown in Figure 5, which need to be optimized simultaneously by the used $EPSO_{DE}$ algorithm.

TABLE III
TEST GRID: VARIOUS STATES OF THE IEEE 9 BUS BASE GRID TO BE HANDLED BY THE PROTECTION SYSTEM

Name	Pumped storage power plant G1 (blue)	Parallel Line L56 (red)	Loads (green)
Base grid	generator operation	in operation	100 %
Case 1	pump operation	in operation	100 %
Case 2	generator operation	single line	100 %
Case 3	generator operation	in operation	50 %

As underlying reference data for the evaluation all grid states as described in Table III are used. On every 10 % of each line a 3-phase fault is simulated dynamically with the network planing tool, PSS©Netomac, and the measured values of all relays assigned to the corresponding protection areas. Figure 7 shows the minimum and maximum measured impedances of protection relay DI08 for all three protection areas of the base grid. Figure 8 shows those aspects for all grid states (base grid + case 1 to 3) combined. It is easy to see, that the measured fault impedances of protection area two and three are extensive and in both cases strongly overlapping. For all grid states combined it is even worse. That means that both protection areas make different demands on the setting values in terms of security and dependability. The resulting setting values can be seen in Table IV and V.

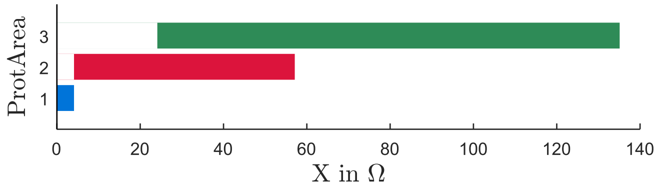


Fig. 7. DI08: Minimum and maximum measured impedances in the base grid according Table III for protection areas 1 to 3

D. Result

To validate and compare both protection setting setups, the PSA methodology within the system analysis software, PSS©Sincal, is used. It simulates a "running" fault on all lines and evaluates the protection relay behavior in terms of

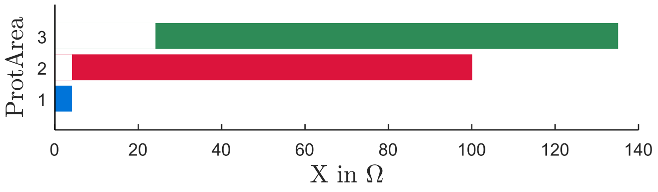


Fig. 8. DI08: Minimum and maximum measured impedances for all grid states according Table III for protection areas 1 to 3

TABLE IV
TEST CASE: CALCULATED SETTING VALUES FOR ALL DI RELAYS BASED ON FORMULA (3) ON THE LEFT SIDE AND OPTIMIZED VALUES ON THE RIGHT SIDE IN Ω

DI-Relay	X_1 10 ms	X_2 250 ms	X_3 500 ms	X_1 10 ms	X_2 250 ms	X_3 500 ms
		calculated			optimized	
DI01	12.8	19.2	28.0	13.5	18.9	29.8
DI02	12.8	19.2	25.6	13.5	20.9	30.5
DI03	9.6	14.4	24.0	10.1	20.2	171.1
DI04	9.6	14.4	28.0	10.0	15.5	56.7
DI05	9.6	14.4	24.0	10.1	13.6	171.2
DI06	9.6	14.4	28.0	10.1	15.5	56.8
DI07	3.2	4.8	14.0	3.4	9.0	15.6
DI08	3.2	4.8	20.0	3.4	11.4	36.2
DI09	8.0	12.0	20.0	8.5	18.6	30.7
DI10	8.0	12.0	14.0	8.4	11.6	19.1
DI11	8.0	12.0	20.0	8.4	13.6	28.6
DI12	8.0	12.0	29.4	8.5	18.6	39.6
DI13	8.0	12.0	20.0	8.4	13.6	25.4
DI14	8.0	12.0	22.0	8.5	20.9	160.1

TABLE V
TEST CASE: CALCULATED SETTING VALUES FOR THE OC RELAYS OF THE STUB LINES BASED ON FORMULA (4) ON THE LEFT SIDE AND OPTIMIZED VALUES ON THE RIGHT SIDE IN I_r

OC-Relay	$I_{>>}$ 10 ms	$I_{>}$ 250 ms	$I_{>>}$ 10 ms	$I_{>}$ 250 ms
	calculated		optimized	
OC01	4.0	1.2	4.65	1.15
OC02	4.0	1.1	3.12	1.05

TABLE VI
TEST CASE: USED SETTING VALUES FOR THE OC PROTECTION RELAYS OF THE GENERATORS IN I_r

OC-Relay	$I_{>>}$ 10 ms	$I_{>}$ 2 s
OCG1 OCG2 OCG2	1.1 forward direction	1.1 both directions

selectivity and fault clearing time. It also considers the failure of the main protection to analyze the tripping behavior of the backup relays. The mechanical delay time of all circuit breaker is $40\,\mathrm{ms}$. Because the calculated values base on the base grid, it was taken to be evaluated with both setups. The results can be seen in Figure 9 for the calculated values and in Figure 10 for the optimized values. For all other cases the calculated values achieved similar or worse results, whereas the optimized values were just as good or even better. The ranking and meaning of the colours is as following:

- **Selective (green):** Protection system acted correctly.
- **Over-function (yellow):** In addition to the responsible relays, at least one additional relay tripped.
- **Under-function (orange):** Some of the responsible relays did not trip, but the fault was cleared by other relays.
- **No fault clearing (red):** Fault was not tripped till the end of the simulation.

Using the calculated values, the PSA analysis shows that in 16 out of 32 investigated situations the protection system does not work as intended. In a large number of cases, faults are tripped with under- or over-function and the fault clearing times are relatively high. The result clearly shows the negative effects on the measurement due to the intermediate infeed and the parallel line effects.

For the optimized values, the PSA analysis finds 3 situations for improvement and all concern just the backup protection. On some sections of the relevant lines the fault is cleared with an over-function (zone 3). This is because all protection relays are using the same delay time for all tripping zones. A minimal adjustment of the delay time to improve the protection coordination would solve the problem. In the future, the delay time could be added to the evaluation algorithm as a further variable to be optimized. Last but not least, it is noticeable that the fault clearing times are on average significantly shorter.

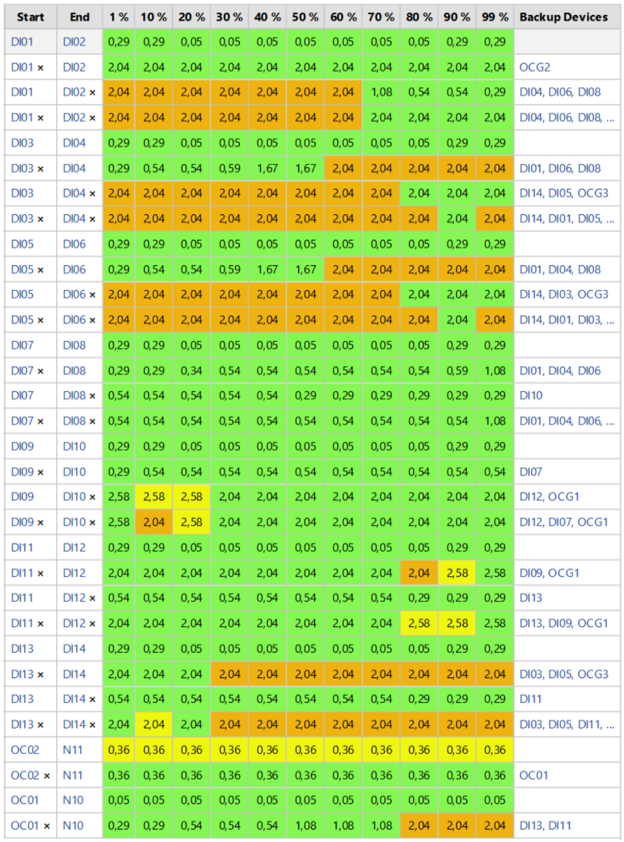
The new hybrid evaluation strategy combining fuzzy sets with a new way to assign simulation values to protection areas in cooperation with a search/optimization algorithm proves to be flexible applicable and produces reliable setting values.

V. SUMMARY

We presented an innovative strategy that is able to find new protection relay settings for DI and OC protecion relays to the same time. It is able to find the best compromise in complex grid structures in terms of security and dependability. It can be applied for any grid size and considers various grid variations to act correctly even in unusual and emergency situations.

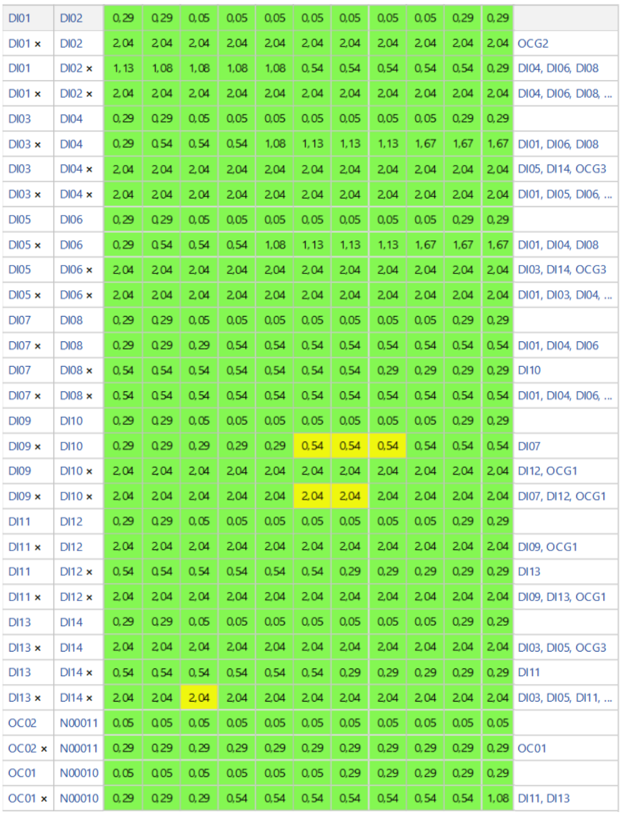
Todays power grids need new methods for assessing and optimizing their protection systems. A promising approach should be generic, flexible and easy to reconstruct. We proposed a modular concept of grid models, a fuzzy evaluation strategy and optimization algorithm.

We compared protection system settings calculated by adjustment rules based on equipment data with a new way to use simulation data to compensate for any negative effects on



Start	End	1 %	10 %	20 %	30 %	40 %	50 %	60 %	70 %	80 %	90 %	99 %	Backup Devices
DI01	DI02	0,29	0,29	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,29	0,29	
DI01 ×	DI02	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	OCG2
DI01	DI02 ×	2,04	2,04	2,04	2,04	2,04	2,04	2,04	1,08	0,54	0,54	0,29	DI04, DI06, DI08
DI01 ×	DI02 ×	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	DI04, DI06, DI08, ...
DI03	DI04	0,29	0,29	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,29	0,29	
DI03 ×	DI04	0,29	0,54	0,54	0,59	1,67	1,67	2,04	2,04	2,04	2,04	2,04	DI01, DI06, DI08
DI03	DI04 ×	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	DI14, DI05, OCG3
DI03 ×	DI04 ×	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	DI14, DI01, DI05, ...
DI05	DI06	0,29	0,29	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,29	0,29	
DI05 ×	DI06	0,29	0,54	0,54	0,59	1,67	1,67	2,04	2,04	2,04	2,04	2,04	DI01, DI04, DI08
DI05	DI06 ×	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	DI14, DI03, OCG3
DI05 ×	DI06 ×	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	DI14, DI01, DI03, ...
DI07	DI08	0,29	0,29	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,29	0,29	
DI07 ×	DI08	0,29	0,29	0,34	0,54	0,54	0,54	0,54	0,54	0,54	0,59	1,08	DI01, DI04, DI06
DI07	DI08 ×	0,54	0,54	0,54	0,54	0,54	0,29	0,29	0,29	0,29	0,29	0,29	DI10
DI07 ×	DI08 ×	0,54	0,54	0,54	0,54	0,54	0,54	0,54	0,54	0,54	0,54	1,08	DI01, DI04, DI06, ...
DI09	DI10	0,29	0,29	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,29	0,29	
DI09 ×	DI10	0,29	0,54	0,54	0,54	0,54	0,54	0,54	0,54	0,54	0,54	0,54	DI07
DI09	DI10 ×	2,58	2,58	2,58	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	DI12, OCG1
DI09 ×	DI10 ×	2,58	2,04	2,58	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	DI12, DI07, OCG1
DI11	DI12	0,29	0,29	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,29	0,29	
DI11 ×	DI12	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,58	2,58	DI09, OCG1
DI11	DI12 ×	0,54	0,54	0,54	0,54	0,54	0,54	0,54	0,54	0,29	0,29	0,29	DI13
DI11 ×	DI12 ×	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,58	2,58	2,58	DI13, DI09, OCG1
DI13	DI14	0,29	0,29	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,29	0,29	
DI13 ×	DI14	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	DI03, DI05, OCG3
DI13	DI14 ×	0,54	0,54	0,54	0,54	0,54	0,54	0,54	0,54	0,29	0,29	0,29	DI11
DI13 ×	DI14 ×	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	DI03, DI05, DI11, ...
OC02	N11	0,36	0,36	0,36	0,36	0,36	0,36	0,36	0,36	0,36	0,36	0,36	
OC02 ×	N11	0,36	0,36	0,36	0,36	0,36	0,36	0,36	0,36	0,36	0,36	0,36	OC01
OC01	N10	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	
OC01 ×	N10	0,29	0,29	0,54	0,54	0,54	1,08	1,08	1,08	2,04	2,04	2,04	DI13, DI11

Fig. 9. Test case: Result of PSA analysis for the calculated setting values



DI01	DI02	0,29	0,29	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,29	0,29	
DI01 ×	DI02	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	OCG2
DI01	DI02 ×	1,13	1,08	1,08	1,08	1,08	0,54	0,54	0,54	0,54	0,54	0,29	DI04, DI06, DI08
DI01 ×	DI02 ×	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	DI04, DI06, DI08, ...
DI03	DI04	0,29	0,29	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,29	0,29	
DI03 ×	DI04	0,29	0,54	0,54	0,54	1,08	1,13	1,13	1,13	1,67	1,67	1,67	DI01, DI06, DI08
DI03	DI04 ×	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	DI05, DI14, OCG3
DI03 ×	DI04 ×	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	DI01, DI05, DI06, ...
DI05	DI06	0,29	0,29	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,29	0,29	
DI05 ×	DI06	0,29	0,54	0,54	0,54	1,08	1,13	1,13	1,13	1,67	1,67	1,67	DI01, DI04, DI08
DI05	DI06 ×	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	DI03, DI14, OCG3
DI05 ×	DI06 ×	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	DI01, DI03, DI04, ...
DI07	DI08	0,29	0,29	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,29	0,29	
DI07 ×	DI08	0,29	0,29	0,29	0,54	0,54	0,54	0,54	0,54	0,54	0,54	0,54	DI01, DI04, DI06
DI07	DI08 ×	0,54	0,54	0,54	0,54	0,54	0,54	0,54	0,29	0,29	0,29	0,29	DI10
DI07 ×	DI08 ×	0,54	0,54	0,54	0,54	0,54	0,54	0,54	0,54	0,54	0,54	0,54	DI01, DI04, DI06, ...
DI09	DI10	0,29	0,29	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,29	0,29	
DI09 ×	DI10	0,29	0,29	0,29	0,29	0,29	0,54	0,54	0,54	0,54	0,54	0,54	DI07
DI09	DI10 ×	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	DI12, OCG1
DI09 ×	DI10 ×	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	DI07, DI12, OCG1
DI11	DI12	0,29	0,29	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,29	0,29	
DI11 ×	DI12	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	DI09, OCG1
DI11	DI12 ×	0,54	0,54	0,54	0,54	0,54	0,54	0,29	0,29	0,29	0,29	0,29	DI13
DI11 ×	DI12 ×	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	DI09, DI13, OCG1
DI13	DI14	0,29	0,29	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,29	0,29	
DI13 ×	DI14	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	DI03, DI05, OCG3
DI13	DI14 ×	0,54	0,54	0,54	0,54	0,54	0,54	0,29	0,29	0,29	0,29	0,29	DI11
DI13 ×	DI14 ×	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	2,04	DI03, DI05, DI11, ...
OC02	N00011	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	
OC02 ×	N00011	0,29	0,29	0,29	0,29	0,29	0,29	0,29	0,29	0,29	0,29	0,29	OC01
OC01	N00010	0,05	0,05	0,05	0,05	0,05	0,05	0,29	0,29	0,29	0,29	0,29	
OC01 ×	N00010	0,29	0,29	0,29	0,54	0,54	0,54	0,54	0,54	0,54	0,54	1,08	DI11, DI13

Fig. 10. Test case: Result of PSA analysis for the optimized setting values

the measurement accuracy. Especially in future and rapidly changing grids, this will provide an advantage.

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