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An Alternative Method for Obtaining the Optimal Directional Characteristic Angle of Directional Overcurrent Relays in Transmission Networks

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Abstract

Directional overcurrent elements, both phase and ground, are widely used as backup protection for transmission lines in interconnected power systems around the world. Traditionally, the specialized literature has focused on the determination of the time dial settings of such elements for improving selectivity, as well as the polarization method to be used, for improving security; leaving the directional characteristic settings, and more specifically, the determination of the directional characteristic angle, to the application of the so-called typical settings. This setting, most commonly known as Maximum Torque Angle (MTA) or Relay Characteristic Angle (RCA), is the basis for the direction determination algorithm. Therefore, it is of paramount importance to establish a methodology for its proper calculation. The main contribution of this paper is an alternative methodology to stablish the MTA/RCA settings of directional overcurrent relays, by using a detailed short-circuit sensitivity analysis and a non-linear optimization technique. The application of this novel approach on real complex transmission systems increases the reliability of directional overcurrent protection elements, and has shown that the values required by the actual fault conditions of the transmission system could present a large deviation from the so-called typical settings.

Keywords: Power system protection, optimization, electrical faults, polarization, directional protection relays

1 Introduction

Protection relays have always played a key role in the general performance of power systems, especially in terms of reliability. They are also intended to preserve the different elements of the power system from damage caused by abnormal conditions, such as high currents caused by the occurrence of short-circuit faults, and also, to prevent such conditions from becoming a major hazard for people, animals and the environment [3], [2]. This makes the calculation and validation of their settings very important, so that their correct operation can be ensured for the most critical abnormal conditions in the protected system.

The different types of applications, operating scenarios, contingencies, and in general, the complexity of the protected power system, pose major challenges to protection engineers. In order to deal with such challenges, the development of new tools aiming to reduce the time expended in calculations and repetitive validations, has become crucial, so that most of the time can be expended in analyzing the particularities related to a given study case.

This paper focusses on the problem related to the determination of settings for directional overcurrent protection elements (ANSI 67 and 67N) in transmission networks, and more specifically, to the determination of the directional characteristic angle, which determines the directionality frontier (Forward and Reverse) used by these elements to identify the direction in which the short-circuit occurs.

A complete review regarding different techniques used for the determination of settings related to the operating times and adequate coordination of protection systems is presented in [7]. In [16] the basis for the effective application of linear programming to solve the coordination of directional overcurrent relays problem in large-scale transmission systems, only in terms of the time dial setting, is presented. In [9] the authors present an application example of the linear programming approach to solve the same problem. In [4], the coordination problem with additional constraints, when applied to a ring fed distribution system is presented. However, the authors only consider the time dial setting as the decision variable of the optimization problem; In [8] the authors propose an optimal coordination method between distance zone 2 and overcurrent protection elements in transmission systems, but once again, the zone 2 backup protection is used as an additional constraint, and the decision variable remains the time dial setting; In [13] and [10] the same approach is used with variations of the simplex solution method for the same linear programming problem based on the determination of the time dial setting. Finally, in [5] an alternative application of the simplex solution method to the linear programming problem is presented. Such method reduces the number of calculation and memory requirements. A common feature of the aforementioned studies is that they focus on determining the settings controlling selectivity for the overall protection system, and do not consider all the other settings of directional overcurrent relays. Such settings result absolutely relevant, since they enable or block the operation of directional overcurrent relays, which is being taken as granted by the cited references. No previous work related to the problem of determination of the optimal RCA by using linear or non-linear programming techniques was found in the literature. The main contribution of this paper consists on the development of a new alternative to the determination of the RCA setting in directional overcurrent protection elements by using optimization techniques based on a detailed short-circuit sensitivity analysis of a given transmission network.

This paper is organized as follows: Section 1 presented an outline of the problem of determining the proper RCA setting as discussed in this article, Section 2 describes the main factors affecting direction determination algorithms as used in modern protection relays, and the currently used practices for the calculation of the RCA setting; Section 3 describes in detail the proposed methodology as a more solid alternative to the currently used practices; Section 4 includes a study case used to present the impact of using the proposed methodology for directional phase overcurrent elements in a complex transmission system; and Section 5 presents the main conclusions of the research work.

2 Factors affecting direction determination and current practices for determining the RCA of directional overcurrent protection elements

2.1 Main factors affecting direction determination algorithms

Different direction detection techniques have been used to determine the direction of the fault in directional overcurrent relays, as outlined in [3] and [17] for both directional phase overcurrent (ANSI 67) and directional ground overcurrent (ANSI 67N) elements. Most modern numerical protection relays use the cross-polarization technique in addition to voltage-memory for directional phase overcurrent elements; and polarization using zero-sequence or negative-sequence voltage and currents for directional ground overcurrent elements.

The cross polarization technique is based on the relationship between the faulted phase voltage and the quadrature phase-to-phase voltage related to the non-faulted phases, which is taken as reference voltage, and rotated by an angle given by the RCA setting, so that it becomes the polarization voltage Vpol, based on which the border separating the Forward and Reverse detection regions is established. For a directional relay to detect a forward fault, the operating current phasor, which will be the faulted phase current, must be within the Forward region determined from Vpol. This is illustrated in Fig. 1.

As it can be seen in Fig. 1, if, prior to the fault inception, the protected line is open at the terminal opposed to the position of the directional overcurrent relay, the angle between the faulted phase voltage VA and the quadrature voltage VB-C, used as reference, is always close to 90°. Now, the angle between the faulted phase voltage and the operating current will be close to the protected line characteristic angle plus the equivalent system impedance angle (60° to 85°) for short-circuits involving a very low fault resistance, and will reduce gradually to some value close to 0° for very high fault resistance values. Based on this, some specific relay manufacturers and studies [2] have recommended a setting of 45° for the RCA, and even state that there is no way the relay can fail to determine the correct direction of the fault with this setting.

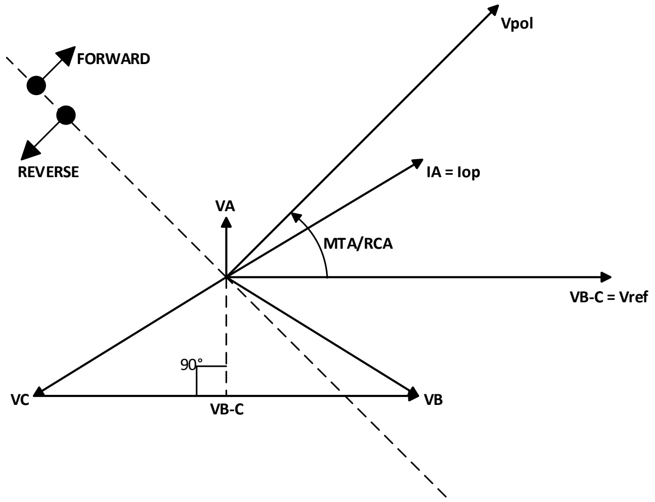
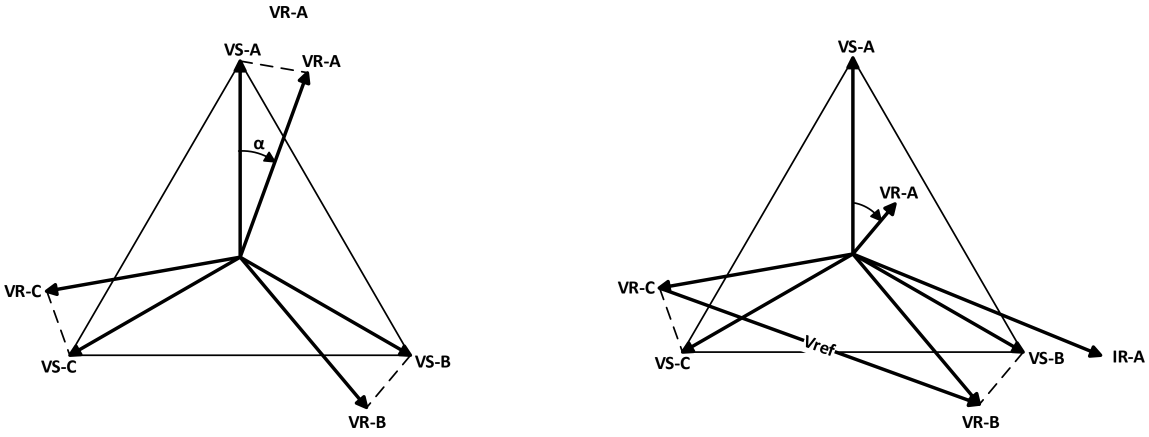


Figure 1. Direction determination characteristic using cross polarization for a single-phase ground fault

However, the possibility of incorrect direction detection is increased in the more realistic case of a loaded transmission line, as described in [20], for which there is an angular separation between the faulted phase voltage and the reference phase-to-phase voltage, as the first will change as a result of the fault condition with respect to the pre-fault state, whereas the second will remain unchanged. In order to better illustrate this, as depicted in Fig. 2, the stationary transmission angle α between the system source and the voltage at the relay location is critical for the correct determination of the RCA setting, as the border separating the Forward and Reverse regions are no longer established based on the relation of the faulted phase voltage and current, but on a pre-fault condition.

The stationary transmission angle increases with higher transmission line length, which according to [17], can be as high as 60° for long lines with heavy load. Moreover, the angle will present a completely different behaviour for forward and reverse faults, as the short-circuit contributions from the opposite ends of the protected transmission line are always different. According to this, an optimal alternative method for the determination of the RCA setting for directional overcurrent relays is required, as the typical settings recommended in the specialized literature, and widely used in the current practices, may not be enough to ensure a reliable detection of the direction of the fault, for all possible operation scenarios and fault conditions to which the protection relay will be subjected.



a) Pre-fault condition

b) During fault condition

Figure 2. Voltages at the source system and at relay location a) prior to the fault inception; b) during fault condition

The zero sequence and negative sequence polarization technique is used in directional ground overcurrent relays, given their higher sensitivity for high impedance faults. This technique is based on the angular relationship between the zero sequence current -3I0 or the negative sequence current -3I2, and the zero sequence residual voltage 3V0 or negative sequence residual voltage 3V2. For a directional relay to detect a forward fault, the operating current phasor, which will be the residual current -3I0 for zero sequence polarization, or -3I2 for negative sequence polarization, must be within the Forward region determined from Vpol. This is illustrated in Fig. 3 for zero sequence polarization.

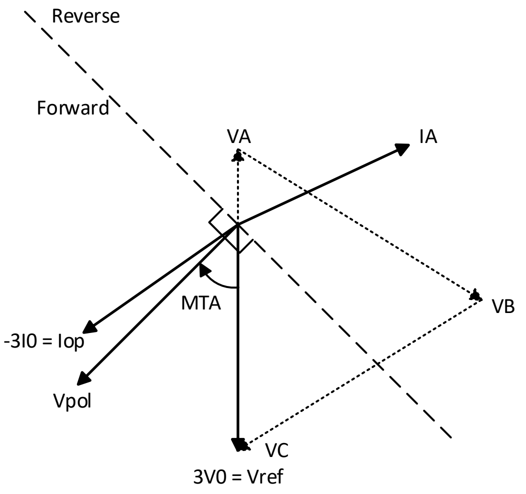


Figure 3. Direction determination characteristic using zero sequence polarization for a single-phase ground fault

For the zero sequence and negative sequence polarization technique, neither the fault resistance nor the stationary transmission angle affects the determination of the RCA setting. The increase in the fault resistance only affects the sensitivity of the polarization and operation quantities. The main factors affecting this method are the system topology and the different equivalent zero-sequence or negative-sequence impedances for forward and reverse faults. In the first group, a major factor affecting the correct direction determination is related to mutually-coupled transmission lines, which depends on the coupled line lengths and the source impedance ratio (SIR), and for which, the exclusive use of negative-sequence polarization is strongly recommended, as described in [3], [6] and [12]. In the second group, different arrangements of power transformers with delta-connected windings, operating scenarios and network contingencies could affect the pre-selected settings, and as a result, there is no general recommended setting for the RCA, although again, some relay manufacturers include typical settings in their reference documents [15], [1].

2.2 Current practices in the determination of directional settings

The previous dissertation showed a widely known set of issues affecting the direction determination algorithms for both phase and ground overcurrent elements applied to transmission networks, already covered by specialized publications; however, a clearly defined methodology for the calculation of directional settings, specially the RCA, has not been defined. On the other hand, the currently used practices, in most utility companies in Latin America continue using default settings for the RCA based on the typical settings outlined in different relay manufacturers technical documents [15], [1] and literature [2]. It is important to clarify that most of these so-called typical settings, are just basic general settings outlined in these documents for describing the polarization algorithms, and they must not be considered as a direct recommendation from the relay manufacturer. Specific studies must be carried out to estimate or verify if a given RCA setting, or a direction determination algorithm, is adequate for a given application or not [3], [1]. Some utility companies stick to the "typical settings", but perform detailed fault studies to verify if these settings are valid for any given application; but in general, as the direction determination problem is sometimes perceived as already solved by the only existence of the polarization algorithms, the way things work is pretty much reactive, only correcting these settings with detailed studies after an incorrect operation occurs.

This paper proposes a new methodology for the optimal determination of the RCA setting defining the directional characteristic of the overcurrent relays in transmission systems. Non-linear programming was used to determine the optimal RCA setting based on the results of a complete fault study, considering different operation scenarios, and variations in network topology.

3 Proposed Methodology

3.1 Short-circuit sensitivity study

Fig. 4 shows the angular variation of different forward faults under different system conditions for a cross-polarization characteristic, where Iop_1 represents the first of a series of different short-circuit simulations, any other than this being represented by Iop_i until the 'n' number of short-circuit simulations is performed. For every simulation, a different Vref is obtained; however, as this phasor is the reference of the directional characteristic, after being skewed by the RCA setting, it is always assumed to be with a phase displacement of 0°, as shown in Fig 4. Then, for every simulated fault, a θ_i angle is computed, which represents the phase displacement between every Iop_i and its corresponding Vref. In order to consider reverse faults in a single comparison analysis, all reverse faults operating currents Iop_i were skewed by 180°, so that both forward and reverse faults can be analyzed using a single reference RCA, for simplification purposes.

All the short-circuit simulations to be carried out must consider different fault locations along the protected transmission line and outside of it, different fault types (single-phase to ground, double-phase to ground and three-phase fault types), variations in fault impedance, operation scenarios and network contingencies. In this way, the short-circuit sensitivity considers both typical and most-severe conditions, for which the directional overcurrent element being analyzed should operate properly.

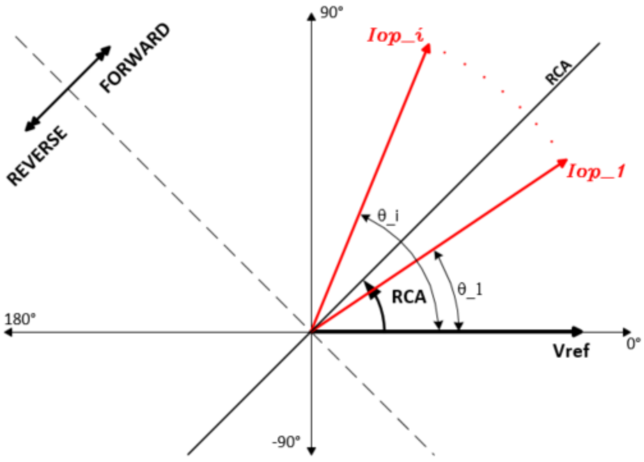


Figure 4. Analysis of directional characteristic in directional overcurrent protection elements

For aiding the execution of the short-circuit sensitivity study, an automation tool is developed to obtain the simulation results of the defined fault cases, thus reducing the time consumed in iterative calculations. All simulations were performed in Power Factory, from the DIgSILENT company, as it allows to develop DPL (DIgSILENT Programming Language) scripts for the automation of the tasks related to simulation and results processing.

3.2 Post-processing of the results from the short-circuit sensitivity analysis

After performing the short-circuit sensitivity analysis, the simulation results are processed to discard those cases where the minimum polarization values were below the given settings. Such cases are stored for all those involving ground faults, so that the polarizing method can be evaluated and changed, if necessary. In this stage, the angle of the operating current phasor is rotated 180° for all cases involving reverse faults, so that the processed results including both forward and reverse faults can take part in the determination of the RCA setting based on the optimization algorithm.

3.3 Optimization problem

Determining the proper RCA setting can be modeled as an optimization problem, in which the only decision variable is the RCA. The objective function consists on minimizing the total sum of the angle displacement between θ_i and RCA, as given by (1).

$$Min\ \sum_{i=1}^{n} k_i|\theta_i - RCA| \tag{1}$$

Where n is related to the total number of short-circuit simulations carried out, θ_i is the angle of every Iop_i phasor, with respect to its corresponding Vref; and k_i is a weighting factor, which depends on the probability of occurrence related to every simulated fault. Note that both θ_i and k_i are parameters to the optimization problem, obtained from every simulation case. Therefore, the only variable in the objective function is the RCA.

As stated in the technical literature [14] and related studies [11], most of the faults (over 80%) in transmission systems are single-phase to ground faults, followed by double-phase to ground faults, with percentage of occurrence is above 12%; and finally, phase-to-phase faults isolated from ground, which represent less than 10% of the faults.

The short-circuit simulations only consider single-phase to ground faults ($k_i = 0.8$), double-phase to ground faults ($k_i = 0.12$), and three-phase faults ($k_i = 0.08$). In this way, the defined weighting factors will penalize those faults with lower probability of occurrence in the objective function, so that they have less incidence in the optimal solution of the RCA setting.

The only constraint related to the optimization problem is given by the setting ranges allowed by a specific numerical protection relay in relation to the RCA setting. Finally, it is important pointing out that all numerical protection relays include minimum pickup values for processing the polarization signals Vref and Iop, and so, for every simulation result to be processed in the optimization model, their corresponding values must be above these limits. This last constraint allows to discard the results in which one of the protected line terminals has a very small contribution to the short-circuit current, even below those obtained during normal operation conditions, as for these values, the overcurrent relay will not detect the fault condition, regardless if the detected direction is forward or reverse. However, such restriction is part of the pre-processing block of the proposed methodology, as it does not fix in the proposed mathematical model.

The only constraint of the optimization problem is given by (2) as follows:

$$-180^\circ \leq RCA \leq 180^\circ \qquad (2)$$

This constraint represents the typical setting range of the RCA found in directional overcurrent elements among different manufacturers.

The absolute value present in the objective function, represents a convex problem with only one optimum solution. So, the generalized reduced gradient (GRG) algorithm was used as solution method for the optimization problem. Due to the simplicity of the objective function, there is no risk for the GRG algorithm to get trapped in a local optimum solution, as there is only one possible for the whole range of values in the objective function.

3.4 Validation of the RCA solution obtained and summary of the methodology

In order to prevent any errors in the model tuning, or the simulation process, from affecting the results of the optimal RCA setting, the obtained solution was evaluated by running again all the simulation cases by using the optimal RCA setting obtained from the optimization problem, and verifying that for all the different simulation cases, the directional characteristic can reliably detect the correct direction of the set of faults included in these cases. If the RCA performance is correct, then the process ends and the RCA setting corresponds to the final solution of the problem. If the performance is incorrect, a detailed revision and analysis should take place in the power system modelling and tuning, as well as in the configuration parameters of the automation tool, before running again the simulation cases and the solution algorithm. This process is repeated until the verified optimal RCA setting is obtained.

Fig. 5 presents a general flow chart of the proposed methodology for the determination of the optimal RCA setting, as described in the above sections.

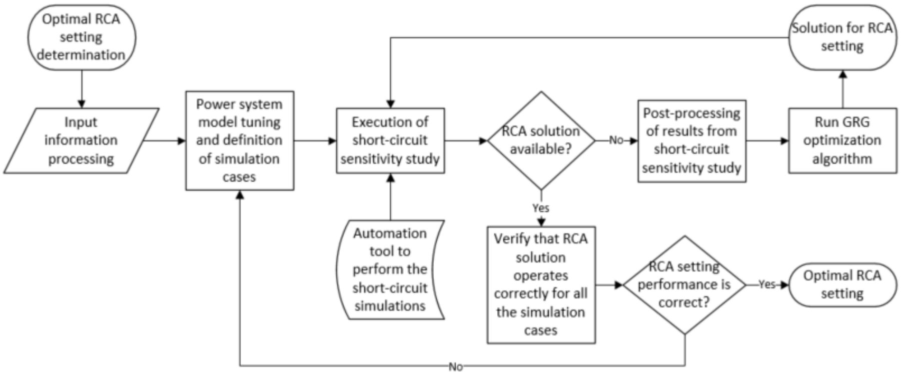


Figure 5. Flow chart for the methodology for determining the optimal RCA setting

4 Tests and Results

4.1 Sample power system

For the reproduction of the proposed methodology, the network presented in Fig. 6 was considered. It includes one equivalent transmission (ST 220 kV) and one regional transmission system (RTS), each with two different operation scenarios with different short-circuit levels. The sample transmission line is a mutually-coupled double-circuit, and there are different sets of two and three-winding power transformers at both sides of the protected lines, so that the zero-sequence voltage polarization can be evaluated under stressing conditions. The data of the sample system is given in the appendix.

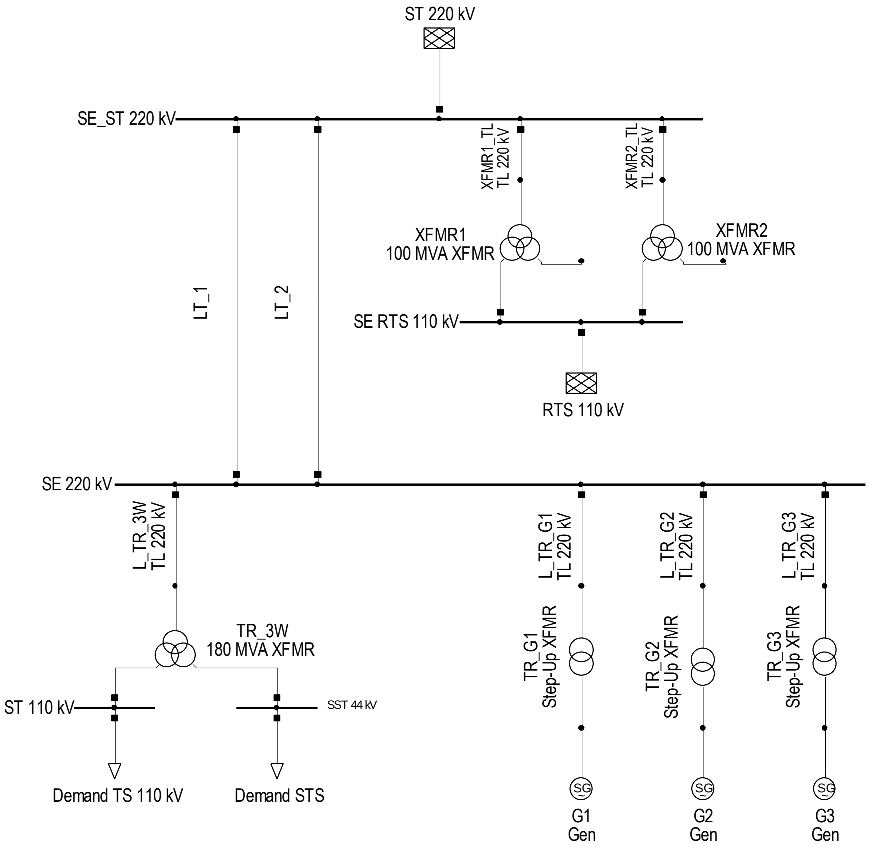


Figure 6. One-line diagram of the sample power system considering for testing the proposed methodology

4.2 Simulation cases

In order to test the proposed methodology, a set of representative simulation cases were considered for estimating the optimal RCA setting for a directional phase overcurrent element (ANSI 67), using cross-polarization algorithm, located at the SE 220 kV substation end of the LT-1 transmission line. Forward faults in different locations of the LT-1 protected line, at 0%, 10%, 20%, …, 100% were considered.

Both forward and reverse faults in the parallel transmission line LT-2 at the same locations used for LT-1 were taken into account. Finally, faults at the 110 kV side of transformers XFMR1 and TR_3W were also considered.

Two different operation scenarios were used, with different short-circuit contributions from the equivalent networks ST 220 kV and RTS 110 kV. For the minimum short-circuit current contribution scenario, an outage of line LT-2 was considered in order to increase the load current through LT-1 to almost its rated current capacity.

Only single-phase to ground and double-phase to ground faults have been considered for the test, as they represent the highest weighting factors in the objective function of the optimization problem previously described. The fault resistance for all the fault locations and fault types, was also varied from 0 Ohms to 50 Ohms, in steps of 10 Ohms, in order to capture the variation of the angular displacement between the operation current and the reference voltage.

4.3 Results

A total of 456 fault cases were simulated according to the previously described considerations; therefore, given the high number of simulation cases, these are not presented, but remain at the disposal, via authors, of those interested in having a closer look to the post-processing block of the proposed methodology. The summary results are presented in Table 1, which shows the maximum displacements for the fault types simulated, discarding all those cases where the starting conditions were not fulfilled. All the angular displacements were considered taking the Vref as reference, and reverse faults were skewed by 180°, as discussed previously.

Table 1. Summary of results obtained from the short-circuit sensitivity study.

Operation Scenario	**Fault Type**	**Maximum positive displacement Theta_i+**		**Maximum negative displacement Theta_i-**	
		Forward Faults	**Reverse Faults**	**Forward Faults**	**Reverse Faults**
Maximum Short-Circuit Contribution and Normal Operation Conditions	Single-phase to ground	82,5378	34,1105	--	-31,4856
	Double-phase to ground	89,1727	58,6049	-17,154	-33,7289
Minimum Short-Circuit Contribution and LT-2 out of service	Single-phase to ground	88,08	38,3596	--	-5,1172
	Double-phase to ground	90,667	48,2276	-21,9971	-32,0093

The results presented in Table 1 demonstrates that all the main factors described in section 2.1 produce angular displacements higher than those justifying the use of

45° as a universal setting for any given system and for any fault condition. These major deviations justify the use of the alternative methodology presented, for finding a proper setting for the RCA, allowing a much better adaptation of the direction determination algorithm to the actual fault conditions to be expected in a given transmission system.

Now, for the solution obtained from the optimization algorithm, the comparative results presented in Table 2, show the effect of considering the weighting factors in the objective function and the solution for RCA. As it can be seen, the RCA solution obtained considering the weighting factors is closer to the single-phase to ground fault angular deviations, presented in Table 1, as a result of the higher fault rate related to this fault type.

Table 2. Effect of the weighting factors in the optimal solution

Weighting factors	**Objective Function at the Optimal RCA [°]**	**Optimal RCA [°]**
According to fault rates	7437,1747	22,2736
Equal to 1 (not considered)	17315,8906	25,4437

The obtained results for the sample transmission system considered for the development of this paper, give a good picture of the risk involved in the application of the so-called "typical settings" in the configuration of phase directional overcurrent elements protecting complex transmission networks, and although the 45° setting for the RCA still works for the wide coverage of forward and reverse regions, the closer the setting is to the actual limit, the higher the risk of obtaining nuisance tripping of such protective elements, especially when they are subjected to current transformer saturation, harmonic content, DC components and other short-circuit related phenomena, affecting the accurate measure of the relevant system variables on which the reliability of the protective functions relies. This is why the proposed settings for all the protective functions must be properly justified and validated for the particularities of every protected system.

5 Conclusions

This paper presented a novel methodology for the optimal determination of the RCA setting in directional overcurrent protection elements. The main contribution of the paper consists on the development of a new alternative to the determination of the RCA setting, critical for the overall security of these protection elements. The use of this alternative would replace the less secure approach of using presumable typical setting values, thus avoiding incorrect operations, which could compromise the overall selectivity of the protection system in a given transmission network.

For the sample power system model used for testing the proposed methodology, it was observed that the consideration of weighting factors has a minor effect on the obtained solution for the optimal RCA setting; however, the obtained solution was more oriented to the reality of the system disturbances, and its application is still recommended, given the variations expected in zero-sequence polarized ground overcurrent elements, as a result of the network topology variations analyzed. The application of the weighting factors can be expanded to the probability of occurrence of a given network contingency, or the permanence of different operation scenarios in the system; however, the effect of considering this expanded application remains subject of further research, as these additional factors are more difficult to obtain from a given power system, than the fault rates according to the fault type.

A future work will cover the application of the presented methodology for more complex power systems, including series compensated transmission lines, and specific cases for the evaluation of the RCA setting in directional ground overcurrent elements. Finally, the same methodology will be oriented to the evaluation of the directional characteristic limits used for distance protection, which presents the same approach in today's practice than that applied for the determination of the RCA setting.

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Appendix: Sample Power System Data

Transformer	**Rated Power [MVA]**	**Nominal Frequency [Hz]**	**Rated Voltage [kV]**		**Vector Group**			**Short-Circuit Voltage [%]**
			HV-Side	**LV-Side**	**HV-Side**	**LV-Side**	**Phase Shift**	
Generation Transformers	220	60	230	16,5	YN	D	1	9,99

Transformer	**Rated Power [MVA]**			**Rated Voltage [kV]**			**Vector Group**	**Short-Circuit Voltage [%]**		
	HV-Side	**MV-Side**	**LV-Side**	**HV-Side**	**MV-Side**	**LV-Side**		**HV-MV**	**MV-LV**	**LV-HV**
XFMR1	100	70	30	220	110	34,5	YN0yn0d1	6,93	6	10,899
XFMR2	100	70	30	220	110	34,5	YN0yn0d1	6,93	6	10,899
TR_3W	180	180	60	220	110	44,6	YN0yn0d1	9,31	9,15	13,06

Line	**Length [km]**	**Rated Current [kA]**	**Positive-Sequence Impedance [Ohms/km]**		**Zero-Sequence Impedance [Ohms/km]**		**Mutual Zero-Sequence Impedance [Ohms/km]**		**Susceptance [uS/km]**	
			R1	**X1**	**R0**	**X0**	**R0M**	**X0M**	**B1**	**B0**
LT_1	84	0,755	0,0488308	0,357862	0,291364	1,00856	0,240715	0,556298	4,65291	2,64295
LT_2	84	0,755	0,0488308	0,357862	0,291364	1,00856	0,240715	0,556298	4,65291	2,64295

Generator	**Rated Power [MVA]**	**Rated Voltage [kV]**	**Rated Power Factor**	**Connection**	**xd'' [p.u.]**	**xd' [p.u.]**	**x0 [p.u.]**	**x2 [p.u.]**	**xd [p.u.]**	**xq [p.u.]**
Generators	224	18	0,85	YN	0,216	0,265	0,111	0,217	1,781	1,74

Network Equivalent	**Angle [°]**	**Voltage Setpoint [p.u.]**	**Maximum Short-Circuit**					**Minimum Short-Circuit**				
			Short-Circuit Current [kA]	**R/X**	**Z2/Z1**	**X0/X1**	**R0/X0**	**Short-Circuit Current [kA]**	**R/X**	**Z2/Z1**	**X0/X1**	**R0/X0**
RTS 110 kV	-5,13	1,03	17,658	0,271	1,015	1,87	0,202	13,572	0,263	1,026	1,96	0,26
ST 220 kV	-3,64	1,07	14,5	0,106	1,021	1,895	0,202	10,68	0,13	1,012	1,94	0,193

Demand Equivalent	**Rated Power [MVA]**	**Power Factor**	**Leading/Lagging**
Demand STS	50	0,9	lagging
Demand TS 110 kV	110	0,92	lagging