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Methodological Proposal for Distance Protection in Transmission Lines for Integration of Non-conventional Renewable Energies

Propuesta metodológica para la protección de distancia en líneas de transmisión ante la integración de energías renovables no convencionales

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Abstract

This paper presents a methodology to set the distance protection (ANSI-21) in power systems that integrate nonconventional renewable energies (NCRE). The modified IEEE 9-bar New England system is used as a case study, with a wind farm comprising 33 2.5 MW wind turbines and control systems validated according to international standards, such as the IEC60909-2016. A fault resistance value calculated using the Warrington method is considered. The proposed settings are simulated using the Digsilent Power Factory® software and a Siemens 7SA522 relay with quadrilateral characteristics. The methodology uses voltage and current data from the instrumentation transformers to calculate the line impedance up to the fault point. The proposed adaptive method demonstrates positive performance under different shortcircuit scenarios, where the fault location, fault resistance, and power fluctuations of generating park are varied. This indicates that the relay effectively operates in the appropriate protection zone.

Keywords: Distance protection, adaptive relay, adaptive quadrilateral characteristic, wind farm, fault resistance, inverter-based sources.

Resumen

Este artículo propone una metodología para ajustar la protección de distancia (ANSI-21) en sistemas de potencia que integran energías renovables no convencionales (ERNC). Se utiliza el sistema New England de 9 barras IEEE modificado como caso de estudio, con un parque eólico compuesto por 33 aerogeneradores de 2.5 MW y sistemas de control validados según estándares internacionales, como el IEC60909-2016. Se considera un valor de resistencia de falla calculado mediante el método de Warrintong. Los ajustes propuestos se simulan utilizando el software Digsilent Power Factory® y un relé Siemens 7SA522 con características cuadrilaterales. La metodología se basa en el uso de datos de voltaje y corriente de los transformadores de instrumentación para calcular la impedancia de la línea hasta el punto de falla. El método adaptativo propuesto demuestra un rendimiento positivo en distintos escenarios de cortocircuito, donde varían el lugar de la falla, la resistencia de la misma y las fluctuaciones de potencia del parque generador. Esto demuestra que el relé actúa en la zona de protección adecuada de manera efectiva.

Palabras clave: Protección de distancia, característica cuadrilateral adaptativa, parque eólico, relé adaptativo, resistencia de falla, fuentes basadas en inversores

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1. Introduction

The integration of nonconventional renewable energies (NCRE) may compromise the reach of the protection zones of distance relays [1], mainly due to the stochastic nature of their resources [2]. Therefore, it is necessary to consider the modification, analysis and redesign of the protections so that they can adapt to the fault current variation produced by renewable energies [3].

The distance relay calculates the apparent impedance to the fault point through measurements of voltage and current, and compares this value with the impedance setting to determine the actuation zone. The difference between the conventional plants and the sources based on inverters lays on the current contribution in a fault scenario. In general, a conventional plant contributes with a current 5 to 6 times the nominal current, in contrast with renewables sources whose fault current is between 1.1 to 2 times the nominal current [3]; therefore, the sequence components are different between these two types of sources. Due to this difference, various authors have proposed possible solutions to avoid the problems of underreach and overreach of the distance protection.

Another point that should be considered when calculating a shortcircuit scenario is the fault resistance, which may cause underreach problems in distance relays. To improve the performance of the protection in this situation, it is proposed the use of new algorithms that incorporate the fault resistance in synchronous generation sources to estimate the line impedance [4]. In addition, the Mho characteristic is used in [5] to set the protection zone and address the problems associated to the relay operation in photovoltaic plants.

On the other hand, a setting methodology using the quadrilateral characteristic is proposed in [6], which results in a change of the relay actuation limit during the variation of the measured impedance, due to the insertion of the fault resistance.

The contributions of this paper include:

- Detailed modeling of the NCRE to verify the fault current contributions seen by the protection relay
- Development of a setting method based on the calculation of shortcircuit phase currents at 80 % and 20 % of the length of the main and adjacent lines. This mathematical expression enables the independent variation of the resistance and reactance in the R-X plane, which addresses the relay underreach problem by considering the fault resistance.
- The performance of the proposed methodology has been verified using data from simulations of different types of faults and variable generation of the wind farm.

The rest of this document is organized as follows. Section 2 presents the basic concepts of distance protection with quadrilateral characteristic for the integration of NCRE, and provides a brief description of the electric scheme to be studied and the effects of the fault resistance in a shortcircuit event. Section 3 details the proposed methodology, and the results that evaluate its performance in different situations are presented in section 3.2. The discussion of the proposed methodology is supported in section 3.3 and, finally, the conclusions of the paper are explained in section 4.

2. Materials and methods

2.1. Electric protections of a power system for the integration of NCRE

The faults in a power system may produce damage to its elements, and thus it is essential to minimize their effect by means of a protection system that makes it more reliable and secure [7]. Since the transmission line is the most vulnerable element of the system, it has a primary protection (distance relay). The operation principles and features of such protection are presented in this section [8].

2.2. Description of the system

The IEEE 9-bus New England system [9] of 230 kV at 60 Hz, shown in Figure 1, is considered as a case study. The system is divided into two sectors: sector 1 is constituted by the gray buses, while sector 2 comprises the black elements.

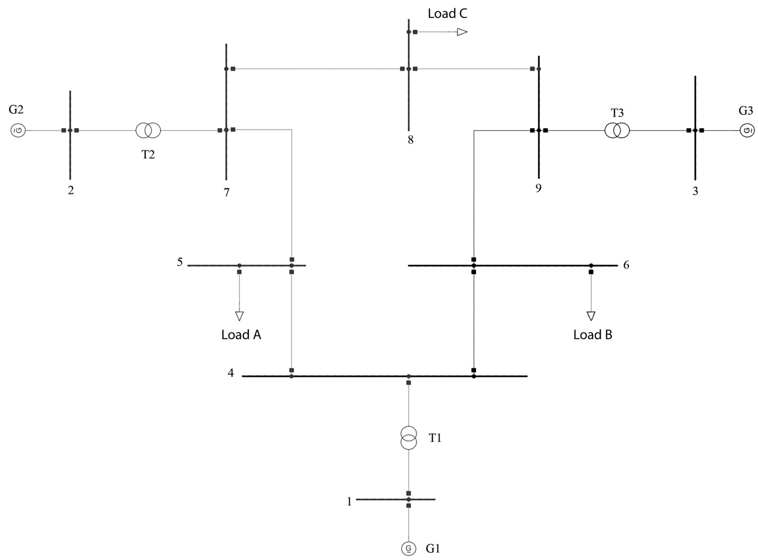


Figure 1. Case study: 9-bus IEEE system [9]

2.3. Equivalent circuit of the modified system

Sector 1 will be replaced by an equivalent circuit calculated using the REI (radial, equivalent and independent) method [10]. This method splits the system in active and passive sectors with the purpose of grouping the passive sectors to a common or equivalent bus, which contains the values of three-phase and single-phase shortcircuit current and power at the common bus, as well as the constant of inertia of the system generators.

The characteristic parameters of the equivalent circuit connected to the system shown in Figure 2, are detailed in Table 1

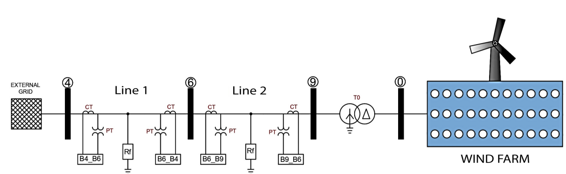


Figure 2. Equivalent circuit of the modified New England 9-bus system [9]

Table 1. Parameters of the equivalent circuit

External Grid	
Type of bus	Oscillation
Operating point	
Voltage magnitude (V_i)	1.025[p.u]
Bus angle (δ_i)	147.783°
RMS data	
Constant of inertia (H_i)	5.892 [s]

To change the structure of the system, it is considered the insertion of a new bus (0) to integrate the wind farm constituted by 11 circuits, each with three 2.5 MW wind generators connected in parallel; this results in a total installed capacity of 82.5 MW for the farm.

The wind generators used belong to the Digsilent Power Factory® library; the wind generator is coupled to the network through a voltage source converter (VSC) with a full-converter technology [11]. The input data of these controllers is detailed in Table 2.

For the subsequent analysis, the length of lines 1 and 2 is 100 km, and their electric parameters are shown in Table 3.

Table 2. Parameters of the full-converter wind generator

Current controller for EMT simulation	
Proportional gain d axis (kd)	5
Integration time constant d axis (Td)	0.01 [s]
Proportional gain q axis (kq)	5
Integration time constant q axis time constant q axis (Tq)	0.01 [s]

Table 3. Electric parameters of the lines

Parameters	Line 1	Line 2
Impedances $[\Omega/km]$		
Positive sequence $r_{1l} + jx_{1l} = r_{2l} + jx_{2l}$	0.2063 + j 0.8993	0.0899 + j 0.4887
Zero sequence $r_{ol} + jx_{0l}$	0.4126 + j 1.7980	0,1799 + j 0.9734
Capacitances $[\mu F/km]$		
Positive sequence $C_{1l} = C_{2l}$	6.7675	2.9869
Zero sequence C_{0l}	3.3838	1.4935

The transformer has a nominal power of 150 MVA, 230/13.8 kV, YnD5 connection, the low voltage side leads the high voltage side by 150° and the shortcircuit reactance is 8.79 %.

2.4. Quadrilateral characteristic of the distance relay

The quadrilateral characteristic is more versatile within the distance protection, since it does not exhibit a reduction in its effective protection zone when there is fault resistance; the relay will operate correctly if the measured impedance is within the quadrilateral [12].

2.4.1. Basic principle

The advantage of this type of relay is that the operation zone only depends on the impedance of the element to be protected, which practically remains constant, i.e., it does not depend on the voltage and current magnitudes [13] The quadrilateral characteristic is one of the most used methods. The horizontal axes of this protection depend only on the reactance "X", while the vertical axes may be modified varying the resistance "R". This is represented in the R-X plane (Figure 3), which results in a larger protection reach when inserting the fault resistance [14].

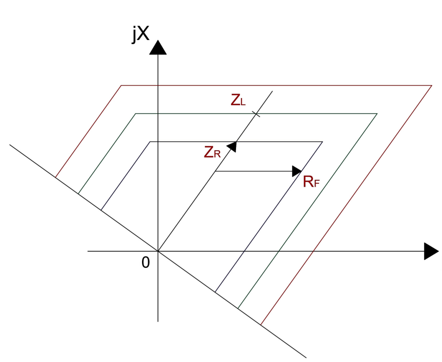


Figure 3. R-X diagram. Quadrilateral characteristic [14]

The quadrilateral characteristic operates if the impedance measured by the relay is within the positive and negative reactance of the right and left sides described in the previous figure.

Where:

- Z_L = Line impedance
- Z_R = Distance reach element
- R_F = Setting of the resistive reach

2.4.2. Relay protection zones

The protection of a transmission line cannot be implemented through a single zone because the instrumentation transformers must be very precise; backup protections are required [1]

The percentage assigned to every zone to be protected is analyzed according to the characteristic of the relay. In the case of the quadrilateral characteristic, the assignments operate as follows:

- Zone 1 is configured to protect between 80 % and 90 % of the line where the fault occurs. The response time of the relay is immediate, $t_1 = 0$ seconds, because the distance protection should be activated before any other protection.
- On the other hand, zone 2 covers the entire line where the fault occurred plus 20 % of the adjacent line. The response time of the relay is $t_2 = 0.4$ seconds.
- Zone 3 has a coordination time interval of $t_3 = 0.8$ seconds, and is able to protect the entire line where the fault occurred plus the entire adjacent line [15].

2.4.3. Effects of the fault resistance

The impedance of a transmission line is uniformly distributed along its length. This characteristic enables the distance relay to distinguish between internal and external faults, which might vary according to the fault resistance. This resistance may arise due to failures in the insulators or by the induction produced by lightning strikes; when this occurs, an electric arc is generated which should be taken into account when setting the relay operation [16].

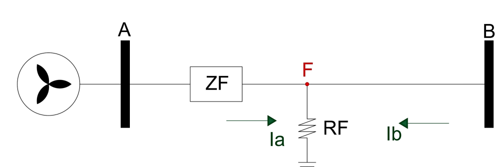


Figure 4. Diagram of a three-phase fault with fault resistance [16]

According to the diagram shown in Figure 4, the impedance seen by the relay considering the insertion of the system fault resistance is given by equation (1)

$$Z_m = \frac{V_F}{I_F} = Z_F + R_F + \left(\frac{I_a}{I_b}\right) \cdot R_F \qquad (1)$$

Where:

- Z_m = Impedance measured at buses A and B
- Z_F = Fault impedance
- R_F = Fault resistance
- I_a = Current measured at bus A
- I_b = Current measured at bus B

It may be seen in Figure 3 that in the quadrilateral characteristic the fault resistance is close to the relay triggering limit, and this causes that the fault is perceived farther than its real location, resulting in a more limited protection reach and wrong response times; for this reason it is necessary to modify the typical setting of the relay and use an adaptive approach [13] [16].

2.4.4. Criteria for setting the distance relay

The relay impedance is estimated using the voltage and current measured by the potential (PT) and current transformers (CT), respectively. Such impedance is expressed as $\Omega_{primary}$. When using the conversion due to the ratio between the PT and the CT, the reading of the equipment is given as $\Omega_{secondary}$. The primary impedance may be converted into secondary impedance using the equation(2) [17].

$$\frac{V_{primary}}{I_{primary}} = Z_{primary} = \frac{V_{secondary \cdot R_{TP}}}{I_{secondary \cdot R_{TC}}} \qquad (2)$$

For the SIEMENS 7SA522 [17] commercial relay, the protection settings are generally the ones indicated in Table 4.

Table 4. Reactances seen by the 7SA522 relay [17]

Reach of $X_{secondary} - Z_1$	$R_{TP}/R_{TC} \cdot 80\% \cdot X_{L1}$
Reach of $X_{secondary} - Z_2$	$R_{TP}/R_{TC} \cdot 120\% \cdot X_{L1}$
Reach of $X_{secondary} - Z_3$	$R_{TP}/R_{TC}\,(X_{L1} + X_{L2})$

The quadrilateral characteristic presents an important feature: the settings of the reactive and resistive reaches are independent. This feature is useful when there is a fault resistance in the system, because this is a parameter that makes difficult the correct measurement of the distance relay [15]. An arc is generated when a fault resistance occurs, and this arc has an electrical resistance that may be calculated using Warrington formula given in equation (3) [18].

$$R_{arc} = \frac{28707(S + 2.046 \cdot v \cdot t)}{I^{1.4}} \qquad (3)$$

Where:

- S = Distance of phase-to-phase insulation [m]
- I = Shortcircuit current [A]
- v = Wind speed [m/s]
- t = Duration time of the shortcircuit [s]

The addition of an arc resistance does not modify the values of line impedance; therefore, the protection continues measuring the direct reactance of the line. However, the resistance seen by the relay does consider this arc resistance [17] as indicated in Table 5.

Table 5. Resistances seen by the 7SA522 relay [17].

Reach of $R_{secondary} - Z_1$	$R_{TC}/R_{TP} \cdot R_{L1} + 0.5 \cdot R_{arc}$
Reach of $R_{secondary} - Z_2$	$R_{TC}/R_{TP} \cdot R_{L1} + 0.5 \cdot R_{arc}$
Reach of $R_{secondary} - Z_3$	$R_{TC}/R_{TP} \cdot R_{L1} + 0.5 \cdot R_{arc}$

3. Results and discussion

3.1. Application to the case study

This section presents a comparison between the protection systems of a synchronous generator and a wind generator with similar operation characteristics. The objective is to validate their correct performance in the stated scenarios.

3.1.1. Shortcircuit calculation

For the analysis the shortcircuit calculation is carried out using the superposition method, which evaluates the fault current at a specific point of the network. Its main objective is to verify if the failure of the protection system is due to a wrong behavior of the relay or to its incorrect settings. To appropriately dimension the protection equipment, it is necessary to know two shortcircuit currents, the maximum one given by a three-phase fault (at the beginning of the line), which determines the triggering limits of the relays, and the minimum one due to a phase-to-neutral fault (at the end of the line), which is used to choose the triggering curve of the relay [19].

3.1.2. Fault current

Due to their topology, the electric systems powered by synchronous generators produce three-phase, two-phase and single-phase faults; this affects the normal flow of current through the transmission lines. On the other hand, due to their structure based on power electronics, the systems with NCRE sources (e.g. wind) do not have ground connections; hence, they do not have zero sequence.

In order to protect the control system of the wind generator, the fault current is in the range between 1.1 to 1.5 times its nominal current; in contrast, the contribution of the synchronous generator is 5 to 6 times its nominal current. This is shown in Table 6, which contains the current resulting from faults at different points of the line, when the system is powered by a synchronous generator and by a wind farm, thus confirming that the *fault current is lower* in a renewable generation system [20]. The R_1 relay is connected to bus 9 that protects line 1, while relay R_2 protects line 2 and is installed at bus 6 of the system.

Table 6. Comparison of the fault currents for a system powered by a synchronous generator and by a wind generator [kA]

Fault location [%]	Synchronous generator		Wind generator	
	Line 1 R_1	Line 2 R_2	Line 1 R_1	Line 2 R_2
0	1.18	0.67	0.23	0.20
10	1.09	0.65	0.23	0.20
20	1.02	0.63	0.22	0.19
30	0.95	0.62	0.22	0.19
40	0.89	0.60	0.21	0.19
50	0.84	0.59	0.21	0.19
60	0.80	0.58	0.21	0.19
70	0.75	0.56	0.20	0.18
80	0.71	0.55	0.20	0.18
90	0.68	0.55	0.20	0.18
100	0.65	0.55	0.19	0.18

3.1.3. Fault impedances

The basic principle of the distance protection is to measure the apparent impedance from the voltage to current ratio *(V/I)*. According to this ratio, in the occurrence of a fault, if the fault current increases the voltage drop will decrease to compensate this effect. Therefore, the impedance is slightly affected by the shortcircuit level, the type of fault or the source powering the system, thus demonstrating that the impedance will exhibit significant changes if the fault has a fault resistance [21]. Based on the above, Table 7 and Table 8 show that the impedance for a three-phase or a two-phase fault in a transmission line powered by a wind or synchronous generator is the same, as long as the fault resistance is zero.

Table 7. Three-phase fault impedance

Fault location [%]	Impedances [Ω]			
	Synchronous generator		Wind generator	
	Line 1 R_1	Line 2 R_2	Line 1 R_1	Line 2 R_2
0	0	0	0	0
10	9,229	4,950	9,229	4,950
20	18,476	9,901	18,476	9,901
30	27,756	14,857	27,756	14,857
40	37,087	19,820	37,087	19,820
50	46,487	24,791	46,487	24,791
60	55,973	29,773	55,973	29,773
70	65,564	34,768	65,564	34,768
80	75,278	39,779	75,278	39,779
90	85,137	44,806	85,137	44,806
100	95,159	49,854	95,159	49,854

Table 8. Two-phase fault impedance

Fault location [%]	Impedances [Ω]			
	Synchronous generator		Wind generator	
	Line 1 R_1	Line 2 R_2	Line 1 R_1	Line 2 R_2
0	0	0	0	0
10	9,229	4,950	9,229	4,950
20	18,476	9,901	18,476	9,901
30	27,756	14,857	27,756	14,857
40	37,087	19,820	37,087	19,820
50	46,487	24,791	46,487	24,791
60	55,973	29,773	55,973	29,773
70	65,564	34,768	65,564	34,768
80	75,278	39,779	75,278	39,779
90	85,137	44,806	85,137	44,806
100	95,159	49,854	95,159	49,854

3.1.4. Fluctuation of the generation

A wind farm consists of various units connected in parallel. It is possible that during the day not all units are in operation due to maintenance or to variability in climatic conditions, which results in a variation of the output power, i.e., the line will transport a varying power. These changes may produce a wrong behavior of the distance relay in case of a fault [22]. Figure 5 shows the active power generated by the wind farm along the day; two moments should be highlighted: at 16:00 the wind farm achieves its maximum daily generation of 47.91 MW and at 7:00 the generation achieves its minimum of 9.53 MW.

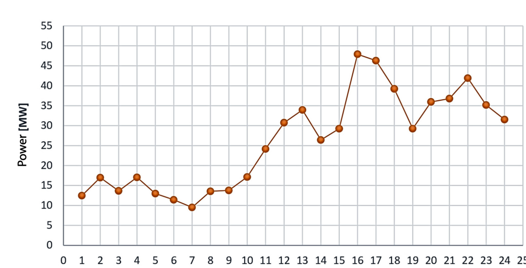


Figure 5. Generation of the wind farm per hour

When calculating the shortcircuit in the line for varying fault locations and for wind farm generation, the fault impedances are evaluated for the power installed (82.50 MW), the maximum power during operation (47.91 MW) and the minimum power during operation (9.53 MW). Once again, it is evident that the impedance seen by the relay is the same in the three operation scenarios with zero fault resistance. (see table 9)

Table 9. Fault impedance evaluated for a fluctuating generation of the wind farm with *Rf=0*

	Maximum operating power		**Minimum operating power**		**Nominal power**	
Fault location [%]	Line 1 R_1	Line 2 R_2	Line 1 R_1	Line 2 R_2	Line 1 R_1	Line 2 R_2
0	0	0	0	0	0	0
10	9,229	4,950	9,229	4,950	9,229	4,950
20	18,476	9,901	18,476	9,901	18,476	9,901
30	27,756	14,857	27,756	14,857	27,756	14,857
40	37,087	19,820	37,087	19,820	37,087	19,820
50	46,487	24,791	46,487	24,791	46,487	24,791
60	55,973	29,773	55,973	29,773	55,973	29,773
70	65,564	34,768	65,564	34,768	65,564	34,768
80	75,278	39,779	75,278	39,779	75,278	39,779
90	85,137	44,806	85,137	44,806	85,137	44,806
100	95,159	49,854	95,159	49,854	95,159	49,854

3.1.5. Method for adaptive setting

Section 2 explained the influence of the fault resistance on the shortcircuit calculation in a transmission line: an underreach of the protection might produce wrong triggers of the relay. For this reason, the typical setting should be modified to an adaptive setting.

The quadrilateral adaptive setting method enables the individual variation of resistance and reactance in the R-X plane, resulting in extended production zones. This provides the system with more flexibility and precision que inserting the fault resistance.

The characteristic of the quadrilateral adaptive relay modified for zone 1 may be represented as: equation (4).

$$Z_{set}^{adap} = Z_{set} = 0.8Z_l = \frac{V_{cc\_80\%Z_m}}{I_{cc\_80\%Z_m}} \tag{4}$$

Where Z_{set} is the conventional impedance setting of the relay, which represents a shortcircuit occurring at 80 % of line 1, located at buses 9-6 (Figure 2). Regarding protection zones 2 and 3, it should be analyzed the adjacent line located at buses 6-4.

When a fault occurs and the fault resistance is zero, the impedance $Z_m = xZ_{L_1}$, where x represents the percentage corresponding to the fault location. However, a fault resistance different than zero results in a change in ΔZ, which produces an error in the measured impedance Z_m and in the fault impedance xZ_{L_1}.

In order to avoid wrong measurements by the relay, Figure 6 represents the increase in the measured impedance Z_m in the R-X plane; the new impedance is determined as Z_{set}^{adap}. This is the new setting of the protection when a fault occurs.

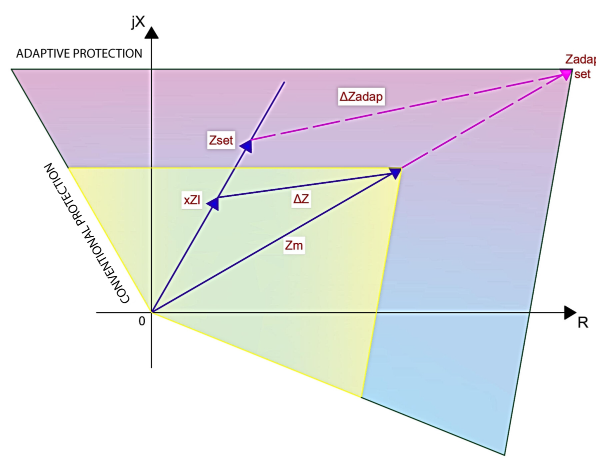


Figure 6. Basic principle of the adaptive quadrilateral characteristic for an internal fault

In order to implement the adaptive method in zone 2, the shortcircuit is calculated at 20 % of the adjacent line (L_2) and for zone 3 a shortcircuit at 100 % of L_2. The adaptive setting of the relay is the following:

Zone 2: equación (5).

$$Z_{2set}^{adap} = \frac{V_{CC\_20\%L_2}}{I_{CC\_20\%L_2}} \tag{5}$$

Zone 3: equación (6).

$$Z_{3set}^{adap} = \frac{V_{CC\_100\%L_2}}{I_{CC\_100\%L_2}} \tag{6}$$

Where:

- Z_{adap} = Adaptive impedance
- $V_{cc-80\%}$ = Shortcircuit voltage at 80 % of L_1
- $I_{cc-80\%}$ = Shortcircuit current at 80 % of L_1
- $V_{cc-20\%}$ = Shortcircuit voltage at 20 % of L_2
- $I_{cc-20\%}$ = Shortcircuit current at 20 % of L_1
- $V_{cc-100\%}$ = Shortcircuit voltage al 100 % of L_2
- $I_{cc-100\%}$ = Shortcircuit current al 100 % of L_1

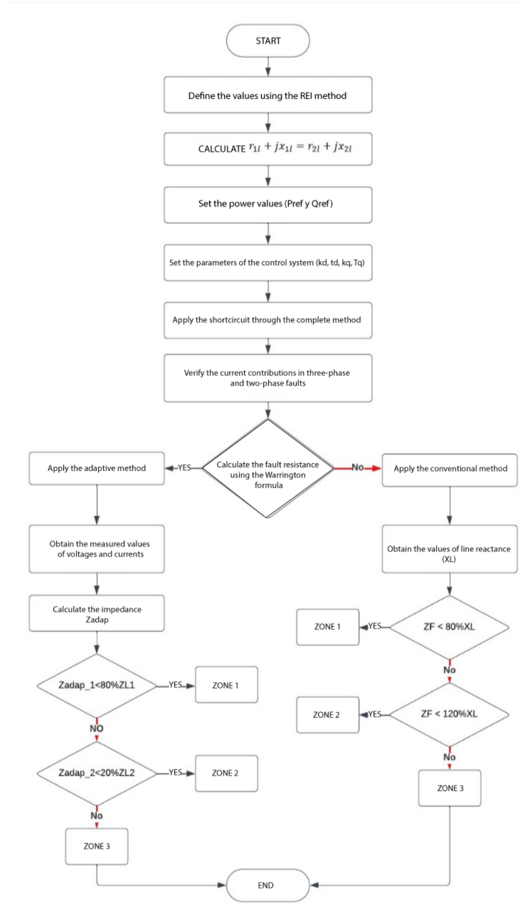


Figure 7. Flow diagram of the proposed adaptive quadrilateral setting

3.1.6. Flow diagram

Figure 7 shows the flow diagram of the proposed method. For the application of this method, an equivalent model should be determined for the base system using the REI method. Then, the positive, negative and zero sequence parameters of the transmission lines are established, and subsequently the power values before the fault are entered; when connecting the wind farm, the parameters of the controller should be considered. Finally, a three-phase shortcircuit is calculated with fault resistances 0 and 25 Ω. When the fault resistance is 0, the conventional method explained in section 2 is employed. On the other hand, when a fault resistance different than zero is obtained by means of Warrington formula, it is necessary to apply the methodology proposed in this paper, where the voltage and current values measured by the transformers are used to calculate the adaptive impedance, considering the values previously established.

3.2. Results

For the subsequent analysis, the relay connected at buses 9-6 is denoted as R_1, while the protection device connected at buses 6-4 is denoted as R_2, as shown in Figure 2. Their performance has been evaluated for different fault situations, with two types of sources, the incorporation of the fault resistance and the variation in the power generated by the wind farm.

3.2.1. Fault resistance

With the purpose of verifying the optimal performance of the protection system, shortcircuit tests were conducted in lines L_1 y L_2 when connected to a synchronous generator and with fault resistances 0 and 25 Ω. It is seen in Table 10 that the conventional setting of the relay with Rf=0 Ω does not exhibit errors in the response time. On the other hand, for Rf=25 Ω the R_1 relay shows a wrong operation at 80 and 90 % of the line length. (Table 10)

Table 10. Operation of the Siemens 7SA522 relay in conventional systems with fault resistance

Fault location %	$R_f = 0$		$R_f = 25$	
	Line 1 R_1	Line 2 R_2	Line 1 R_1	Line 2 R_2
0	Zone 1	Zone 1	Zone 1	Zone 1
10	Zone 1	Zone 1	Zone 1	Zone 1
20	Zone 1	Zone 1	Zone 1	Zone 1
30	Zone 1	Zone 1	Zone 1	Zone 1
40	Zone 1	Zone 1	Zone 1	Zone 1
50	Zone 1	Zone 1	Zone 1	Zone 1
60	Zone 1	Zone 1	Zone 1	Zone 1
70	Zone 1	Zone 1	Zone 1	Zone 1
80	Zone 2	Zone 1	**Not ok**	Zone 1
90	Zone 2	Zone 2	**Not ok**	Zone 2
100	Zone 2	Zone 2	Zone 2	Zone 2

3.2.2. Fluctuating power from the wind farm generation

It is demonstrated in section 3 that when shortcircuit events are calculated in transmission lines powered by a wind farm with variable generation power and $R_F = 0$, the impedance seen by the protection remains fixed as the power varies.

In the following, the results obtained when calculating shortcircuit events for $R_F = 25\ \Omega$ with lines L_1 and L_2 affected by a fault are presented. The settings of relays R_1 y R_2 in the three generation scenarios have operation errors, with the line L_2 being more affected, as shown in Table 11.

Table 11. Operation of the distance protection for a fluctuating power generated by the wind farm, with Rf= 25Ω

	Maximum operating power		**Minimum operating power**		**Nominal power**	
Fault location [%]	Line 1 R_1	Line 2 R_2	Line 1 R_1	Line 2 R_2	Line 1 R_1	Line 2 R_2
0	Zone 1	**Not ok**	Zone 1	**Not ok**	Zone 1	**Not ok**
10	Zone 1	**Not ok**	Zone 1	**Not ok**	Zone 1	**Not ok**
20	Zone 1	**Not ok**	Zone 1	**Not ok**	Zone 1	**Not ok**
30	Zone 1	**Not ok**	Zone 1	**Not ok**	Zone 1	**Not ok**
40	Zone 1	**Not ok**	Zone 1	**Not ok**	Zone 1	**Not ok**
50	Zone 1	**Not ok**	Zone 1	**Not ok**	Zone 1	**Not ok**
60	Zone 1	**Not ok**	Zone 1	**Not ok**	Zone 1	**Not ok**
70	Zone 1	**Not ok**	**Not ok**	**Not ok**	Zona 1	**Not ok**
80	Zone 1	**Not ok**	Zone 1	**Not ok**	Zone 1	**Not ok**
90	**Not ok**	**Not ok**	Zone 2	**Not ok**	Zone 2	**Not ok**
100	**Not ok**	**Not ok**	Zone 2	**Not ok**	Zone 2	**Not ok**

Figure 8 presents the distance-time diagram of the distance protection. For the R_1 relay, zone 1 covers 80 % of the line length, zone 2 136 % and zone 3 covers the main and the adjacent lines. Considering what has been discussed in previous sections, there is an error in the reach of zone 2, since it normally covers only 120 % of the line length. The R_2 relay also exhibits problems, since zone 2 only reaches 112 % of the protection, which is wrong as well.

It should be remembered that the response times of the distance protection were detailed in section 3 (relay protection zones). Based on this criterion, it has been determined that the conventional setting operates in wrong times for different locations of the faults in the lines; these values are highlighted in Table 12.

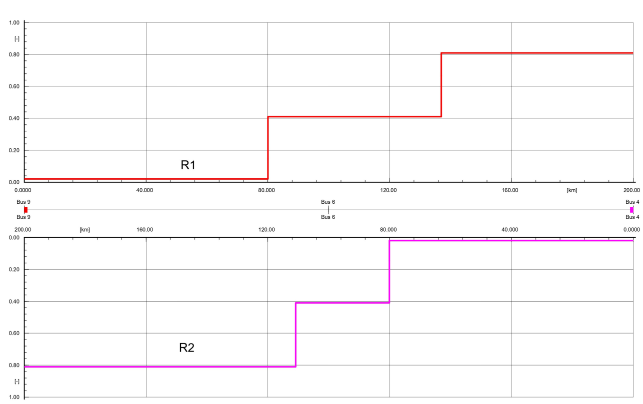
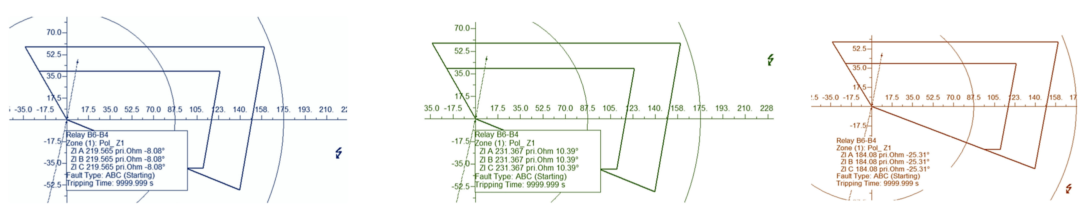


Figure 8. Projection of the protection zones for relays R_1 and R_2

Table 12. Response times of the relay with conventional setting

	Maximum operating power		**Minimum operating power**		**Nominal power**	
Fault location [%]	Line 1 R_1[s]	Line 2 R_2[s]	Line 1 R_1[s]	Line 2 R_2[s]	Line 1 R_1[s]	Line 2 R_2[s]
0	0.02	**9999.99**	0.02	**9999.99**	0.02	**9999.99**
10	0.02	**9999.99**	0.02	**9999.99**	0.02	**9999.99**
20	0.02	**9999.99**	0.02	**9999.99**	0.02	**9999.99**
30	0.02	**9999.99**	0.02	**9999.99**	0.02	**9999.99**
40	0.02	**9999.99**	0.02	**9999.99**	0.02	**9999.99**
50	0.02	**9999.99**	0.02	**9999.99**	0.02	**9999.99**
60	0.02	**9999.99**	0.02	**9999.99**	0.02	**9999.99**
70	0.02	**9999.99**	**0.41**	**9999.99**	0.02	**9999.99**
80	**9999.99**	**9999.99**	0.41	**9999.99**	0.41	**9999.99**
90	**9999.99**	**9999.99**	**9999.99**	**9999.99**	**0.02**	**9999.99**
100	**9999.99**	**9999.99**	**9999.99**	**9999.99**	**9999.99**	**9999.99**

Figure 9 presents the R-X plane of relay (R_2) that protects L_2, after a shortcircuit with R_F=25 Ω. It is observed that the fault impedance is not identified by the distance protection in any of the three scenarios evaluated.



(a) (b) (c)

Figure 9. Shortcircuit in L_2 a) Maximum operating power; b) Minimum operating power and c) Nominal power

3.2.3. Method for adaptive quadrilateral setting

The problems exhibited by a distance protection for a shortcircuit that incorporates a fault resistance were described earlier. The methodology proposed in this paper, the method for quadrilateral adaptive setting, is applied to overcome these errors. Table 13 shows the results of this application.

Table 13. Application of the method for quadrilateral adaptive setting

	Maximum operating power		**Minimum operating power**		**Nominal power**	
Fault location [%]	Line 1 R_1[s]	Line 2 R_2[s]	Line 1 R_1[s]	Line 2 R_2[s]	Line 1 R_1[s]	Line 2 R_2[s]
0	Zone 1	Zone 1	Zone 1	Zone 1	Zone 1	Zone 1
10	Zone 1	Zone 1	Zone 1	Zone 1	Zone 1	Zone 1
20	Zone 1	Zone 1	Zone 1	Zone 1	Zone 1	Zone 1
30	Zone 1	Zone 1	Zone 1	Zone 1	Zone 1	Zone 1
40	Zone 1	Zone 1	Zone 1	Zone 1	Zone 1	Zone 1
50	Zone 1	Zone 1	Zone 1	Zone 1	Zone 1	Zone 1
60	Zone 1	Zone 1	Zone 1	Zone 1	Zone 1	Zone 1
70	Zone 1	Zone 1	Zone 1	Zone 1	Zone 1	Zone 1
80	Zone 1	Zone 1	Zone 1	Zone 1	Zone 1	Zone 1
90	Zone 2	Zone 2	Zone 2	Zone 2	Zone 2	Zone 2
100	Zone 2	Zone 2	Zone 2	Zone 2	Zone 2	Zone 2

Table 13 shows the effective performance of the proposed methodology for faults in lines connected to a wind farm.

The protection zones of the proposed methodology $Z^{adap}_{*set}(* = 1, 2, 3)$ have been calculated with the impedance measured by each relay after a shortcircuit and considering the fault resistance, with the objective that the protection reach of R_1 and R_2 is correct.

Figure 10 shows the settings for relays R_1 and R_2. The protection reach is obtained through equations (4), (5) and (6), where the maximum operation limit of the relay will be given by the impedance measured by the equipment after the fault. This is the difference between the conventional method and the new methodology, namely, the setting of the protection zones does not take into account the own reactance of the line, but it now uses values of the impedance seen by the relay after the fault; this causes that the protections zones are extended to correct the improper operation of the relay

From an analysis of Table 12 it is identified that the relay R_1 that protects line L_1 operates incorrectly starting from 70 % of the line length, while relay R_2 does not fulfill the task of protecting line L_2 when the system considers a fault resistance. For this reason, it is essential to apply the proposed methodology. As shown in Figure 11, for a fault at 0 % of line L_2 with a) maximum operating power, b) minimum operating power and c) nominal power, the protection operates in zone 1 at a response time of 0.02 s, in contrast with the conventional setting where the fault impedance was out of the zone.

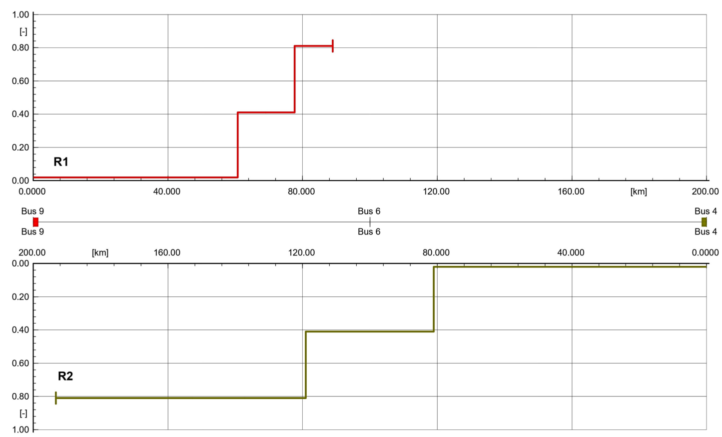


Figure 10. Coordination of the protection zones of the proposed system for maximum power

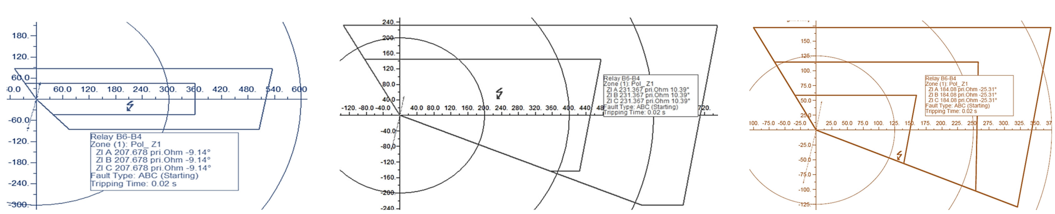


Figure 11. Shortcircuit in L_2, applying the method for adaptive quadrilateral setting with a) maximum operating power, b) minimum operating power and c) nominal power

The results of Table 14 show the performance of the proposed method for adaptive quadrilateral setting. In this case, the relays of both lines L_1 and L_2 correctly identify the faults with their precise location, and correct the wrong response times of the conventional relay.

Table 14. Response times for the adaptive setting for shortcircuits with minimum current

	Maximum operating power		**Minimum operating power**		**Nominal power**	
Fault location [%]	Line 1 [s]	Line 2 [s]	Line 1 [s]	Line 2 [s]	Line 1 [s]	Line 2 [s]
0	0.02	0.02	0.02	0.02	0.02	0.02
10	0.02	0.02	0.02	0.02	0.02	0.02
20	0.02	0.02	0.02	**0.02**	0.02	0.02
30	0.02	0.02	0.02	**0.02**	0.02	0.02
40	0.02	**0.02**	0.02	**0.02**	0.02	0.02
50	0.02	**0.02**	0.02	**0.02**	0.02	0.02
60	0.02	**0.02**	0.02	**0.02**	0.02	**0.02**
70	0.02	**0.02**	**0.02**	**0.02**	0.02	**0.02**
80	0.02	0.41	**0.41**	**0.41**	0.41	0.41
90	**0.41**	0.41	**0.41**	**0.41**	**0.41**	0.41
100	**0.41**	0.41	**0.41**	**0.41**	**0.41**	0.41

3.3. Discussion

When nonconventional renewable energies are integrated in the power system, the performance of the distance protection changes when there is a nonzero fault resistance. Due to this, it is possible to have a wrong operation of the relay, thus deteriorating the reliability of the power system. To address this issue, this paper proposes a protection of quadrilateral characteristic with adaptive setting. The results of simulations performed on the case study show that for internal faults, the aforementioned method corrects the response times of the relay. With respect to the traditional setting method, the proposed methodology exhibits advantages such as:

1. The consequences of the insertion of a fault resistance are considered and completely eliminated because the protection zone tends to be larger than usual.

2. The analysis of the behavior of faults in this paper is unique for a wind farm, and thus the proposed protection structure and methodology are applicable for the insertion of NCRE (wind farm).

3. The different protection zones of the proposed scheme are modified so that they get adapted to the variation of the additional impedance. This additional impedance (Z_{set}) is due to the fault resistance, and causes a variation in the fault current.

4. The proposed scheme is designed for a unique network code, where it was considered a fault resistance of 25 Ω calculated by means of Warrington formula.

5. Compared to the adaptive setting based on the Mho characteristic, the quadrilateral adaptive setting has more advantages because, depending on the location of the fault, the zone can be expanded only in the R axis, in the X axis or in both; in other words, it has a greater resistive reach because they do not depend on each other. This results in a higher reliability and security for the power system, even though this requires equipment with better technology and higher cost.

6. The methodology applied does not estimate the automatic detection of external faults of systems; for this purpose, the internal characteristics of the relay should be modified through its exclusive programming.

4. Conclusions

This work implements an adaptive setting for the IEEE 9-bus New England system, modified with the insertion of a wind farm constituted by 33 2.5 MW wind generators. The operation zones of the adaptive quadrilateral characteristic are set according to the fault that has occurred, to avoid errors in the operation of the SIEMENS 7SA522 relay. The following can be concluded in this work:

The distance relay with conventional quadrilateral setting operates incorrectly when there is a three-phase shortcircuit that considers the fault resistance. On the other hand, the adaptive quadrilateral setting correctly identifies the fault impedances shifted in the X axis due to the increase of the fault resistance.

The proposed adaptive method exhibits a favorable response for different shortcircuit scenarios, with variations in the fault point, fault resistance and oscillation in the power generated by the wind farm, thus demonstrating that the relay operates in the correct protection zone.

The proposed method uses voltage and current data from the instrumentation transformers, and calculates the line impedance up to the fault point. The relay operates according to its protection setting. Specifically, if the fault is located at 80 % of the line length, zone 1 operates in t=0 seconds. On the other hand, if the fault occurs at 20 % of the length of the line adjacent to the relay, zone 2 operates in t=0.4 seconds. Finally, if the shortcircuit event occurs at 100 % of the line adjacent to the relay, zone 3 operates in t=0.8 seconds.

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