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Distance Protection Analysis Applied for Distribution System with Distributed Generation

***Abstract**. In power systems, the over-current protection scheme and, optionally with directional function, and distance function are the main protection used, principally, where the power flow is on both sides as in distribution system with distributed generation (DG), for example. However, with the increasing of DG penetration in the distribution system, these protections can not be secure and impacts in the coordination of the protection are caused due to the power flow is on both sides. Therefore, new types of protection as distance protection are candidates to solve the coordination problem in the distribution system with DG. In this paper, is proposed an application of the distance protection in the distribution system with DG, and several cases of faults and the impacts on the distance protection are evaluated in presence of DG. In the simulation and analysis of faults were varied the fault inception angle, fault type, fault resistance, and fault location. The correct and bad trips are analyzed to evaluate the distance relay performance. The distance relay used in the distribution system with DG had good performance in all simulation cases. Besides, the better performance of the distance protection proveswhich may be used in distribution systems with DG.*

Streszczenie.** W systemach energetycznych zabezpieczenie przed przeciążeniem prądowym (opcjonalnie wraz z funkcją kierunku i odległości) jest główną metoda zabezpieczenia, szczególnie gdy moc może być przekazywana w dwóch kierunkach. W artykule zaproponowano nowy typ zabezpieczenia uwzględniający funkcje odległości. Uwzględniono też możliwość wykrywania błędów i możliwość określania ich położenia. **Analiza zabezpieczeń uwzględniających funkcje odległości w rozproszonych systemach wytwarzania energii.

Keywords: Distributed Generation, Distance Protection, Distribution System, Protection Scheme, Faults.
Słowa kluczowe: rozproszone systemy energetyczne, zabezpieczenia, wykrywanie błędów

Introduction

Traditionally, the distribution systems are designed to bring the electricity from substations to loads, in a one direc- tion power flow. For this reason, the protection system was designed with the assumption that the distribution system is single source and radial [1]. Fuses and instantaneous over- current relays are used for radial systems with one direction flow [2]. These devices are coordinated in a way that ensures correct identification and isolation of the faulted section. [3].

With the increase of the electricity consumption, more power plants and transmission lines are needed. However, the restriction to construct new power plants and transmission lines is high, since these projects have high costs and they have the society opposition. These issues aremitigated with the usage of distributed generation (DG). The DG, which are small generating units installed next to the centers of consumption, has gained strength due to the deregulation ofthe energy market, distribution system operation benefits, and due to environmental issues [4–6]. New technologies applied to DG increase the diversity of energy sources, reducing de- pendence on fossil fuels [7].

With the penetration of DG in the distribution system, a new paradigm of protection arises, specially in protection coordination [8–11] due to the power flow being on both sides, turning the distribution system in a meshed power system. The protection used in meshed power systems (transmission lines) is usually the distance and differential protection [12]. Distance protection is the main protection in transmission lines due to several factors such as easy coordination, directionality, and only depends on line impedance [13]. This type of protection is present in several manufacturers relays used in the protection of transmission lines [14–16] and it is a consolidated technology [17].

Despite distance protection being a mature technology used in transmission line protection, several new applications are proposed in literature, such as usage in HVDC lines [18, 19], protection of lines with the presence of flexible AC transmission system (FACTS) with controllers [20], protection of UHV lines [21], protection of high voltage lines in the presence of wind power generator [22].

Regarding distance protection applications in distributed system with DG, in [23], distance protection is applied in an 11 kV power system with minor adaptions, where distance protection proves to be faster and less sensitive to source impedance than the traditional protection, even in the presence of DG. In [24], the distance protection is applied in a distributed system with DG, where distance protection does not have any major problems in the presence of DG. In addition, the advantages of distance protection over the already implanted schemes are shown. The aforementioned papers prove distance protection can be used in distribution systems with DG. However, more studies are needed, because the transient regime of the faults is not taken into account, neither the relay trip speed. These issues affect the distance protection performanceand they can prevent their usage.

In this paper, is proposed an analysis and application of the distance protection in a 33 kV distribution system with DG of 30 MVA, where several fault simulations are simulated varying the fault resistance, inception angle, and location. Moreover, since the power system is modeled using an EMTP like program (Simulink), the system dynamic operation, and the effects of the transient regime in the power system are taken into account.

The results show that the distance protection is suitable for distribution systems with DG, and the DG does not influence the performance of the distance relay. The distance relay performance was the same in both cases (with and without DG) proving that distance protection only depends on the line impedance.

Phasor Estimation

Phasor estimation algorithms need to filter all the harmonics, and the DC exponential decay component. They cannot be affected by off-nominal frequencies, and they need a unity gain for the 60 Hz frequency [25].

The requirements for filtering harmonics and unity gain for the 60 Hz frequency are easily achieved by based discrete Fourier algorithms. However, the discrete Fourier algorithm does not filter the DC exponential decay component and it does not overcome the off-nominal frequencies problem, resulting in additional mathematical manipulations of Fourier algorithm.

An example of mathematical manipulations of Fourier algorithm is the modified cosine filter [26]. This algorithm is simple and it is not affected by the DC exponential decay. However, a fixed frequency is assumed.
This problem can be overcome with additional algo- rithms that estimate frequency.

The modified cosine filter estimates the phasor, as follows:

$$Y_{cp} = \frac{2}{N}\sum_{n=1}^{N} y_n \cos(pn\theta), \tag{1}$$

$$Y_{sp} = \frac{Y_{cp-1} - Y_{cp}\cos\theta}{\sin\theta}, \tag{2}$$

where Y_{cp} and Y_{sp} are the Fourier series coefficients, N is the samples per cycle, $\theta = 2\pi/N$, y_n is the sampled signal.

Distance Protection

Distance protection is suitable for distributed sys- tems with DG because it only depends on the measured impedance between the relay and the protection zone. The general torque equation for distance protection is given by [27]:

$$\begin{aligned} S_{op} &= k_1 I_R \angle\phi + k_2 V_R \angle 0, \\ S_{pol} &= k_3 I_R \angle\phi + k_4 V_R \angle 0, \end{aligned} \tag{3}$$

where I_R and V_R are, respectively, the currents and voltages measured by the relay.

The relay will operate when $\Re(S_{op}S^*_{pol}) > 0$, where S_{op} is the operation torque and S_{pol} is the polarization torque. All the distance characteristics can be designed through the change of the $k_1,\ldots, k_4$ variables, as summarized in Table 1.

Table 1. k values for each distance characteristic.

Characteristic	k_1	k_2	k_3	k_4
Mho	Z_{L1}	-1	0	1
Reactance	Z_{L1}	-1	Z_{L1}	0
Directional	Z_D	0	0	1
Phase selector	1	0	0	1
Right blinder	Z_{BR}	-1	Z_{BR}	0
Left blinder	Z_{BL}	-1	Z_{BL}	0

The polarization voltage affects the mho dynamic behavior which depends on the system steady-state, and source-impedance ratio [28]. The mho can be self, cross, positive sequence polarized, and many more types of polarization in order to operate properly. For three-phase faults or faults nearly the relay, the polarization voltage can be zero. For these situations, memory voltage is needed.

An example of memory polarization is the IIR filter proposed by [29]. For example, the polarization voltage of the relay A phase-ground unit is given by:

$$Va1mem = \frac{1}{16}V_{a1}(0) - \frac{15}{16}Va1mem(\frac{N}{2}), \tag{4}$$

where V_{a1} is the positive symmetrical voltage and V_{a1mem} is the memory positive symmetrical voltage.

Similarly to the mho relay, the directional relay uses different polarization to operate. For example, the relay can use the zero and negative current as polarization. The choice of polarization influence in the general performance of the relay. For ground-phase units, the relay can use the zero and negative current as polarization, whereas the directional relay phase units only use the negative current.

Electric Network Modeling

The main characteristics of modeling the electrical system (Fig. 1)and the synchronous machine and control (Fig.2) used as a source of DG are presented in this section. The modeling and implementation of network components were simulated in the Smulink SimPowerSystem Matlab program [30].

The test power system used presented in Fig. 1 [31] is a 132 kV transmission line Thevenin equivalent connected to a transformer 132/33 kV in delta/wye-ground. The 33 kV distribution system is composed by 5 equivalent RL branches, Table 2. This distribution system is connected to a synchronous generator of 30 MVA, DG, by a transformer 33/6.9 kV in delta/wye-ground.

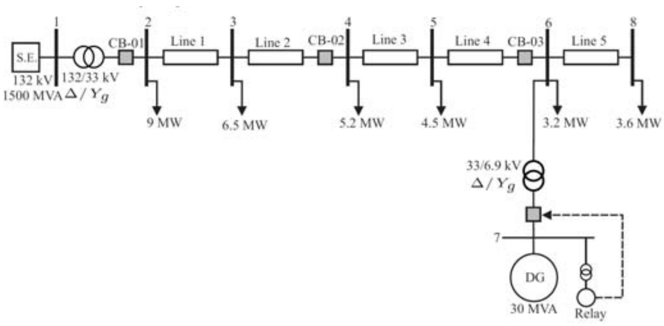


Fig. 1. Electric power system applied.

Table 2. Line data, values in (Ω).

	Line 1	Line 2	Line 3	Line 4	Line 5
R	0.5624	0.4999	0.3124	0.2499	0.1875
X	2.5318	2.2505	1.4066	1.1252	0.8439

The load model dependent of the voltage used in the system [32,33] are represented by:

$$P = P_0(\frac{V}{V_0})^{n_p}, \tag{5}$$

$$Q = Q_0(\frac{V}{V_0})^{n_q}, \tag{6}$$

where P is the active power consumed by the load, P_0 is the load active nominal power, Q is the reactive power consumed by the load, Q_0 is the load reactive nominal power, V is the load nodal voltage, V_0 is the load nominal voltage, n_p is an exponent that indicating the behavior of the load active power in relation to the nodal voltage variation, n_q is an exponent that indicating the behavior of the load reactive power in relation to the nodal voltage variation. These values are presented in Table 3.

Table 3. Definition of electrical load types.

Load type	n_p	n_q
Constant power	0	0
Constant current	1	1
Constant impedance	2	2

The synchronous generator excitation system connected in the distribution networks is usually made to control the ter- minal voltage. For synchronous generators connected to the distribution networks, generally, there are two forms of control that may be employed: constant voltage or reactive constant power [34]. A general scheme for the synchronous gener- ator excitation system is depicted in Fig. 2, which consists in circuits of measuring and signals processing, a regulator system and an exciter system, where Efd is the voltage of exciter field.

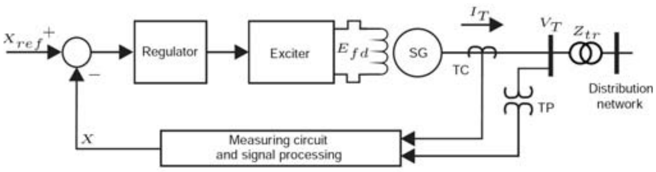


Fig. 2. Control and exciter of synchronous generator scheme.

The model used for the synchronous generator excita- tion system is the IEEE type 1, was based on the model ex- istent in the SimPowerSystem library [30].

Performance Assessment of the Distance Protection in Distribution System with DG

The power system diagrams with and without DG are depicted, respectively, in Fig. 3, and 4. In order to apply faults along the protected line, the line 1 is split in three RL branches, allowing faults with in 33% of the line length . Sev- eral faults in different locations of the power system, varying the ground resistance (R_g), phase resistance (R_{ab}, R_{bc}, and R_{ac}), and fault inception angle were simulated according to Table 4.

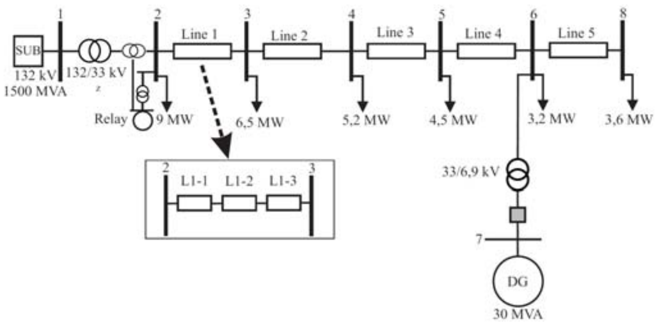


Fig. 3. Power system with DG.

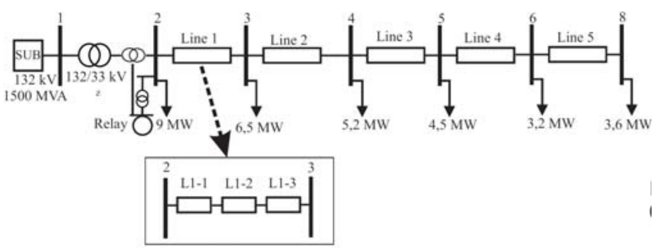


Fig. 4. Power system without DG.

Table 4. Simulated Faults.

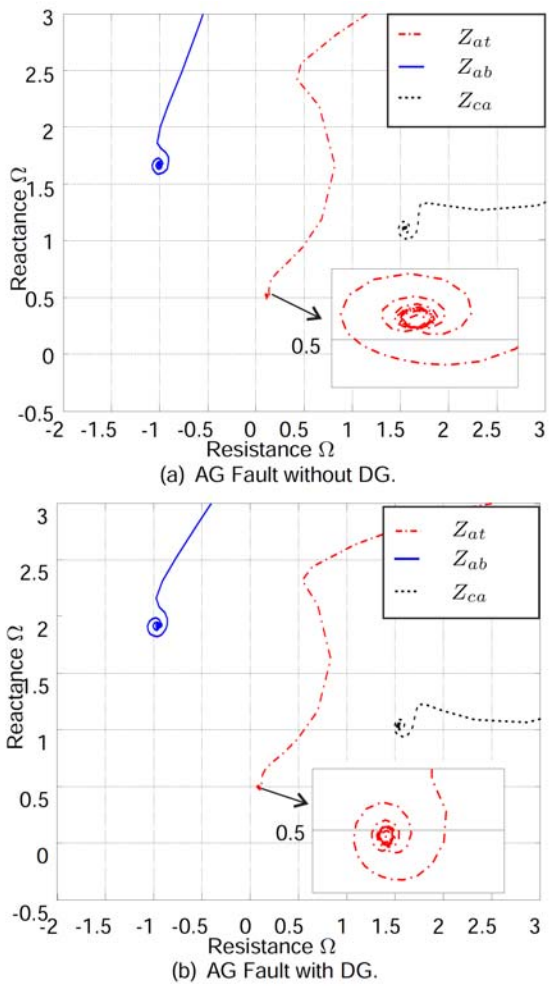
Fault type	AG, AB, ABG, and ABC
Fault inception angle (degrees)	0, 45, 90
$R_g, R_{ab}, R_{bc}, R_{ac}$ (Ω)	0.0001, 0.001, 0.01, 0.1

The fault simulations were simulated in various locations namely, in each bus of the system, and between each RL branch of the Line 1. The relay protection zone is defined to be between bus 2 and bus 3. In the protection zone, a total of 64 faults were simulated with and without DG according to Table 4. In outside of protection zone, a total of 48 faults were simulated without DG and a total of 64 faults were simulated with DG according to Table 4.

Fault Analysis

Several faults applied in the power system are analyzed according to the tripping time, and relay efficiency, comparing the results with and without DG in the system. Also, the dis- tance protection capabilities of coordination are discussed.

The Fig. 5(a) and 5(b) depict an AG fault with and without DG simulated between L_{1-1} and L_{1-2} branch's with a 0.0001 Ω impedance inside the protection zone. When the DG is presented, the trajectory impedance converges to a lower impedance value. This behavior can lead to a misoperation of distance protection, since the estimated impedance is near the operation distance characteristic.



(a) AG Fault without DG.

(b) AG Fault with DG.

Fig. 5. Fault simulated between L_{1-1} and L_{1-2} branch's with a 0.0001 Ω impedance inside the protection zone without DG.

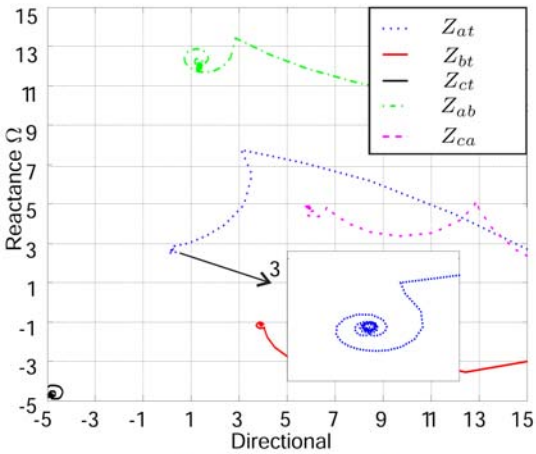
Fig. 6(a) and 6(b) depict an AG fault with and without DG simulated in bus 4 with a 0.0001 Ω impedance located outside the protection zone. When the DG is presented, the trajectory impedance is influenced.

In Table 5, the mho and quadrilateral distance protection trips performed outside protection zone of the power system without DG are summarized. Only for ABC faults the distance protection relay has maloperations. These maloperations oc- curred in the equivalent power system bus 1.

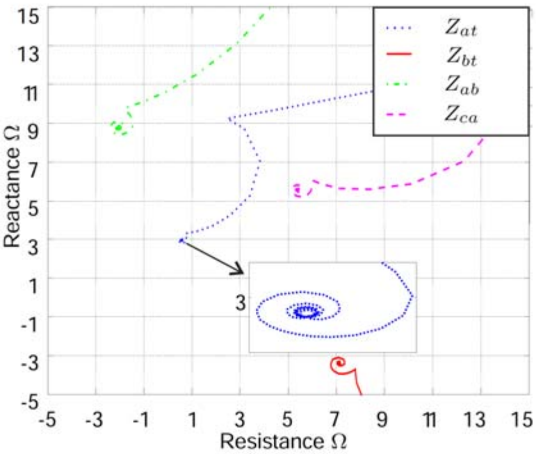
Table 5. Mho and quadrilateral results outside protection zone without DG.

Fault Type	MHO	QUAD	Trip performance	
			MHO (%)	QUAD (%)
AG	0	0	100.00%	100.00%
AB	0	0	100.00%	100.00%
ABG	0	0	100.00%	100.00%
ABC	16	16	66.67%	66.67%

Total Faults: 48



(a) AG Fault without DG - Quadrilateral.



(b) AG Fault without DG - Mho.

Fig. 6. AG fault without DG simulated in bus 4 with a 0.0001 Ω impedance located outside the protection zone.

Table 6. Mho and Quadrilateral results outside protection zone with DG.

Fault Type	MHO	QUAD	Trip performance	
			MHO (%)	QUAD (%)
AG	0	0	100.00%	100.00%
AB	0	0	100.00%	100.00%
ABG	0	0	100.00%	100.00%
ABC	16	16	75.00%	75.00%

Total Faults: 48

In Table 6, the mho and quadrilateral distance protection trips performed outside protection zone of the power system with DG are summarized. Only for ABC faults, the distance protection relay has maloperations. These maloperations oc- curred in the equivalent power system bus 1. However, com- paring the Tables 5 and 6, the distance protection achieves the same results.

In Table 7, the mho and quadrilateral distance protec- tion trips performed in the protection zone of the power sys- tem without DG are summarized. For AG faults, the mho and quadrilateral distance relay have tripped for all simulated situ- ations. However, for the other fault types the mho and quadri- lateral distance relays do not trip for the branch 2-4, but this is not a major problem because it is assured the coordination.

Table 7. Mho and quadrilateral results in protection zone without DG. Total Faults: 64

Fault Type	MHO	QUAD	Trip performance		MHO		QUAD	
			MHO (%)	QUAD (%)	Time Mean (ms)		Time Mean (ms)	
AG	64	64	100.00	100.00	26.00	3.96	25.34	3.59
AB	48	48	75.00	75.00	17.40	11.20	17.47	11.25
ABG	48	48	75.00	75.00	19.50	11.87	19.57	11.85
ABC	48	48	75.00	75.00	20.40	12.36	21.43	12.80

In Table 8, the mho and quadrilateral distance protection trips performed in the protection zone of the power system with DG are summarized. For AG faults, the mho and quadri- lateral distance relay have tripped for all simulated situations. However, for the other fault types the mho and quadrilateral distance relay do not trip for the branch 2-4. Comparing the results between Tables 7 and 8, the mho and quadrilateral distance relay are not affected by the DG. In addition, the trip times are different with and without DG. In the presence of DG, the trip time is faster due to the measured impedance in the distribution system is lower. In conclusion, distance relays are good candidates to protect systems with DG penetration.

Table 8. Mho and quadrilateral results in protection zone with DG. Total Faults: 64

Fault Type	MHO	QUAD	Trip performance		MHO		QUAD	
			MHO (%)	QUAD (%)	Time Mean (ms)		Time Mean (ms)	
AG	64	64	100.00	100.00	25.87	3.66	25.15	3.39
AB	48	48	75.00	75.00	20.03	12.13	19.76	11.98
ABG	48	48	75.00	75.00	20.03	12.13	19.76	11.98
ABC	48	48	75.00	75.00	20.73	12.52	21.47	12.85

Conclusion

In this paper, distance protection applied in a distributed system with and without DG was presented. The distance mho and quadrilateral characteristics were used. The mho relay is composed with reactance and directional character- istics, and fault type supervision. Also, the quadrilateral re- lay is composed with two lateral blinders, reactance and di- rectional characteristics, and fault type supervision. Several faults were simulated in the power systems varying the fault inception angle, location, fault type and fault resistance.

The distance protection presented good results and ac- tuates properly for almost all the simulated faults. The dis- tance protection performance was almost identical in the power system with and without DG in the simulated faults, demonstrating that can be a suitable solution to replace the overcurrent relays in distributed systems. However, the DG inclusion in the power system provoked, in faults situation, an impedance trajectory closest to the relay trip zone. In conclu- sion, the usage of distance protection can be a solution to solve the problems introduced by distributed generation.

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