PERFORMANCE OF DIRECTIONAL RELAYS WITHOUT VOLTAGE SENSORS: IMPACT OF DISTRIBUTED GENERATION TECHNOLOGIES

Trung Dung LE
E3S SUPELEC Systems Sciences – France
trungdung.le@supelec.fr

Marc PETIT
E3S SUPELEC Systems Sciences – France
marc.petit@supelec.fr

ABSTRACT

Radial distribution networks are mainly protected with overcurrent relays, which are used for both earth and phase fault protection. Nevertheless, higher capacitive current of underground cables can cause false tripping problem for overcurrent relay of a feeder during a line-to-ground fault on the adjacent feeder. The contribution of distributed generation (DG) to the fault current during a line-to-line fault also leads to a similar situation. To solve this problem, a novel algorithm of directional relay has been proposed in a previous work [1]. Based on the symmetrical components method, the algorithm only uses current measurements to determine fault direction and thereby suppresses the cost of voltage sensors.

This paper presents effect of distributed generators on the directional algorithm by comparing the cases of Inverter-interfaced Distributed Generators (IIDGs) in PV systems and of synchronous generators (SGs) in CHP plants. Results show good performances in both cases during earth faults. However, during line-to-line faults, this algorithm gives better results in case of IIDGs.

INTRODUCTION

To improve power quality of medium voltage (MV) distribution networks, the French DSO has adopted [2] a new structure for rural networks: underground cables for mainlines and overhead lines for laterals. As a result, earth fault protection relays, which can now measure a higher capacitive current, may trip the breaker during fault on an adjacent feeder (false tripping). To solve this problem, a directional earth fault relay (67N) can be installed.

Symmetrical components method is widely used for power protection purpose. Based on this well-known method, a novel principle was proposed using only current measurements to detect fault direction (upstream or downstream of detectors) [1]. The $I_2/I_{1(0)}$ ratio was used to classify faults. This protection algorithm is advantageous in term of cost reduction compared to a traditional directional relay which needs both voltage and current sensors to operate. Therefore, the algorithm is particularly suitable for protections that are installed along feeder where voltage measurements are usually unavailable. It can also be considered as a back-up solution for traditional directional relay of feeder protection following voltage measurement failure. However, with the introduction of Distributed Generators (DGs) into MV grids, the contribution of DGs to current fault alters the ratio and consequently the performance of the algorithm. In a previous work [3], the influence of synchronous generators (SGs) was considered. The I_2/I_0 ratio was used to determine the earth fault direction by creating two distinctive areas on the complex plane, for upstream and downstream faults. Recently, Inverter-interfaced Distributed Generators (IIDGs) have been growing not only in number but also in rated power. Although the contribution of this kind of DG to fault current is limited [4], a high power IIDG can still weaken the efficiency of our algorithm.

Besides, line-to-line faults do not occur frequently but still need to be paid attention to: both SGs and IIDGs can cause false tripping for conventional overcurrent protections and phase directional relays may be necessary [3]-[5]. In Ref. [5], the authors have investigated the case of IIDGs for line-to-line faults with the "non-voltage-sensor" algorithm by using the I_2/I_1 and $\Delta I_2/\Delta I_1$ ratios, but case of SGs has not been covered yet. This paper shows the impact of SGs and IIDGs during both earth faults and line-to-line faults. In this study, simulations are done with Simulink/ SimPowerSystems for a radial grid. To estimate the fault direction, the I_2/I_0 ratio is considered for earth faults while the I_2/I_1 ratio is used for line-to-line faults. Based on Support Vector Machine (SVM) technique [6], optimal decision boundary is defined on the complex plane for upstream and downstream fault areas.

INVESTIGATED GRID

The investigated grid topology is shown in Figure 1: a radial network with three feeders, which consists of underground cables (C240) and overhead lines (L54). This network is grounded with the impedance Z_n, whose value depends on neutral grounding method (compensative grounding or resistive grounding). Feeder 1 has two DGs connected in two sections that are protected by relays R1 and R2 respectively. The sum of rated power of the DGs is less than 9 MVA. As mentioned in previous section, two kinds of DGs are taken into account in the study: one is IIDGs and the other is SGs. Simulation model of the former is built as shown in [5]; whereas model of the latter is a built-in model of synchronous machine of Simulink Library. Detailed grid characteristics are given by APPENDIX.

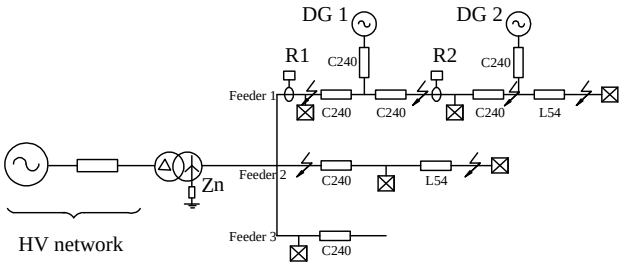


Figure 1. Investigated grid with two DGs connected on a feeder.

To test the algorithm, simulation parameters of DG powers, load consumption, feeders' length, fault resistance and position are varied. The uncertainty is taken into account for substation voltage (σ_U=1.25%) and for line parameters (σ_{line}=5%). Fluctuations in phasor measurements (I_2/I_0 and I_2/I_1) are also introduced with standard deviations in module σ_{mod}=5% and in argument σ_{arg}=2°. Only two first feeders are subject to grid faults while feeder 3 is used to aggregate line capacitances of the other feeders.

LINE-TO-GROUND FAULT

In this section, algorithm performance with IIDGs and SGs during earth faults is shown. The I_2/I_0 ratios are calculated and gathered from simulations. Then they are presented on the complex plane, which create two areas for upstream and downstream faults with respect to the locator (i.e. the protective relay). To better distinguish these areas, a separating hyperplane, i.e. a decision boundary, is defined by using the SVM technique. This technique is well-known as a kernel method for machine learning, which can be used for classification purpose. In this study, the training data for the SVM technique are the ratios between sequence currents (I_2/I_0 ratios in this section). From input space (the complex plane – 2D space), the training data are then transformed to a higher dimensional feature space (F dimensional space) where a linear hyperplane can be defined as follows:

$$w^T \cdot \phi(x) + b = 0 \qquad (1)$$

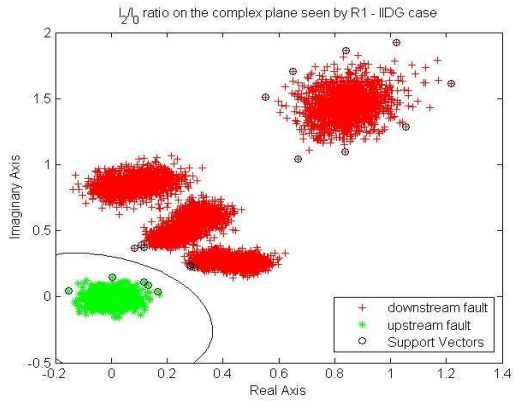
in which: w is a parameter vector (F dimensional space)
b is bias, a real number
ϕ denotes a feature space transformation
x is input vector (2D space)

Details of the SVM technique are explained in [6]. From the decision boundary (1), a new observed point x_k can be classified using the function $\text{sign}(w^T \cdot \phi(x_k)+b)$.

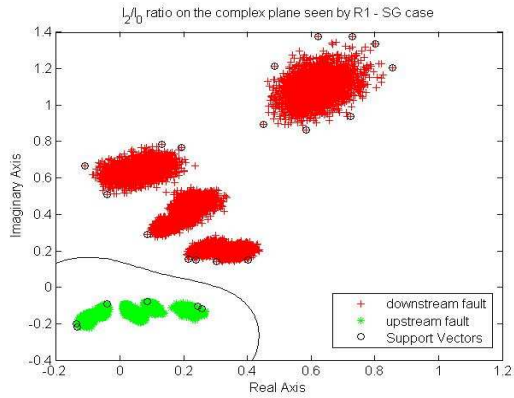
In the following paragraphs, simulation results for relay R1 (Fig. 1) are depicted for different grounding systems as the directional algorithm for this locator is more influenced by DGs.

Compensative grounding

In France, the compensative grounding method has been chosen to gradually replace the resistive grounding method [2] as the former can handle the overvoltage problem and limit more efficiently earth fault currents, especially while developing underground cables in rural networks. In this test case, the neutral impedance consists of a resistance R in parallel with the compensated reactance X_{comp} (Petersen coil). Value of resistance is R=600 Ω so that the active fault current I_{active}> 20 A, which facilitates the fault detection [7]. The compensated tuning factor is varied in simulations k_{comp}=0.8-1.2-1.4.



a) I_2/I_0 ratio seen by R1 – IIDG case



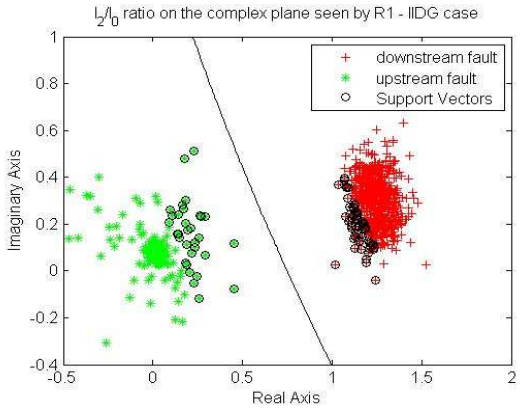
b) I_2/I_0 ratio seen by R1 – SG case

Figure 2. Compensative grounding, line-to-ground fault

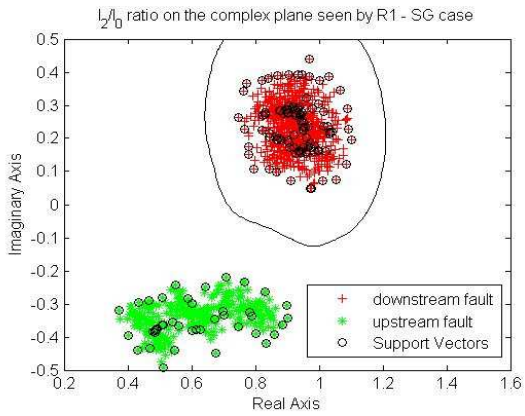
As can be seen Figure 2, the algorithm gives good performances in case of IIDGs as well as of SGs when two distinctive zones are created for upstream faults (green) and downstream faults (red). The separating curve in this figure is the illustration of the decision boundary (1) that is "projected" to the complex plane (2D space). To test this boundary, the I_2/I_0 ratios from simulation results are reused. The phasor uncertainty is also reinitialized to create another set of observed points. The algorithm performance is here evaluated by the error rate τ_{err}, which is the ratio between the number of misclassified points and total number of observed points. This error rate is zero in this test case for both IIDGs and SGs.

Both kinds of DGs do not inject the zero-sequence current to network during fault because of the delta-star connection of coupling transformer. Nevertheless, they can still contribute to the fault negative-sequence current that is measured by the protection. In case of IIDGs, this contribution is also negligible due to control action ($I_{2DG}\approx 0$). As a result, upstream-fault area in this case is centralized toward the origin point of the plane (Fig. 2a) since the current seen by protection is $I_{2up}\approx I_{2DG}\approx 0$. On the other hand, $I_{2DG}\neq 0$ in case of SGs and upstream-fault area here is below the line imag(z)=0 (Fig. 2b). Moreover, the distribution of points in upstream/downstream fault areas in both cases of DGs depends mainly on the tuning factor k_{comp} and the total capacitive current of the network. When these factors are varied, the I_2/I_0 ratio points change considerably their location on the complex plane. The fault resistance does not have a great impact on the distribution of points in case of SGs. However, for IIDGs, a high fault resistance (R_f=1000 Ω) can alter noticeably this distribution.

Resistive grounding



a) I_2/I_0 ratio seen by R1 – IIDG case



b) I_2/I_0 ratio seen by R1 – SG case

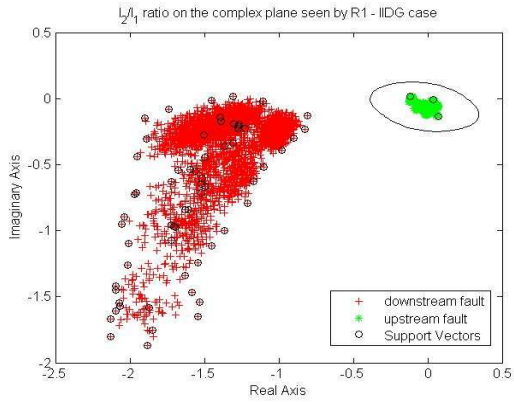
Figure 3. Resistive grounding, line-to-ground fault

Grounding with a low resistance (R_n=40 Ω) is widely used in France for rural networks, which mainly consist of overhead lines. However, with the introduction of underground cables into the networks, the contribution of capacitive current makes the magnitude of fault current higher than expected value. A simple solution to this problem is to use a higher resistance R_n=80 Ω in networks with the total capacitive current less than 100 A [8]. This value of resistance is used in this test case.

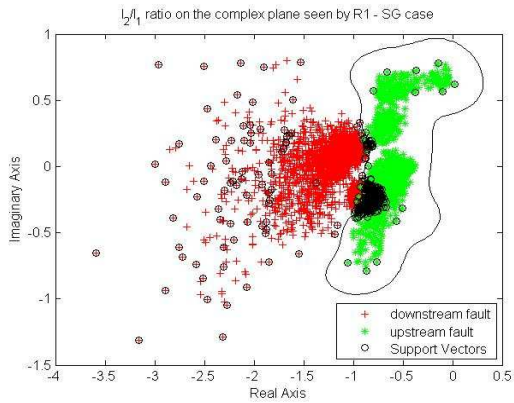
The algorithm performance for both kinds of DGs is good as depicted in Figure 3. The error rate is also zero for both kinds of DGs. The upstream-fault area in case of IIDGs is centralized toward the origin point and this area in case of SGs is below the imaginary axis, which means points in this area have the negative imaginary part. The total capacitances of network have great impact on the distribution of points in each area. Impact of fault resistance in this test case is similar to the test with compensative grounding. In case of SGs, R_f has a small influence but for IIDGs a high value of R_f (1000 Ω) can modify considerably the location of ratio points on the complex plane.

LINE-TO-LINE FAULT

In this section, the same procedure is conducted to compare algorithm performances with IIDGs and SGs but for line-to-line faults. For this kind of fault, the I_2/I_1 ratio is taken into account.



a) I_2/I_1 ratio seen by R1 – IIDG case



b) I_2/I_1 ratio seen by R1 – SG case

Figure 4. Simulation results - I_2/I_1 ratio, line-to-line fault

As can be seen in Figure 4, the different contributions of two kinds of DGs change significantly upstream-fault area. In case of IIDGs, this area is centralized toward the origin point of the plane ($I_{2up}\approx I_{2DG}\approx 0$) and clearly distinctive to the downstream-fault area. In this case the error rate is τ_{err}=0%. On the other hand, in case of SGs, upstream-fault area is very close to downstream-fault one and may have overlap. This overlap causes uncertainty in fault direction estimation. From simulation results, error rate for the case of SGs is τ_{err}=2.7%. Therefore, algorithm performance is better in case of IIDGs than in case of SGs.

During the line-to-line faults, all factors like DG power, load consumption, feeders' length, and fault resistance have certain influence to the distribution of ratio points on the complex plane. DG power factor has more influence in case of SGs than in case of IIDGs whereas fault resistance has the greatest impact to the distribution in both cases.

CONCLUSION

This paper compares the performance of directional algorithm in presence of two kinds of DGs: IIDGs and SGs with cases of earth faults and line-to-line faults. Results show that during earth faults, the algorithm gives good performances for both SGs and IIDGs: the fault direction is estimated without errors in the test cases. On the other hand, during line-to-line faults, algorithm performance with IIDGs is the better one. The error rate in case of IIDGs is also zero. Whereas, in presence of SGs, there is actually overlap between upstream and downstream-fault areas and there are errors in fault direction estimation. However, the optimal decision boundary, which is defined for these areas using the SVM technique, reduce error rate to an acceptable level. Thus it can be said that the algorithm works well in most cases, in spite of influence of DGs. With these promising results, this local algorithm can be taken in consideration for future grid protection.

APPENDIX

Nomenclature

- I_1, I_2: positive- and negative-sequence current during fault. $I_{1(0)}$: positive current before fault.
- ΔI_1, ΔI_2: variations of positive- and negative-sequence current during and before fault, respectively.

Grid characteristics

- HV network: 63 kV, P_{cc} = 500 MVA, X/R = 10
- HV/MV Transformer: 63/20 kV, S_n= 20 MVA, U_{cc} =15%.
- Neutral impedance: Z_n=600+jX_{comp} Ω for compensative grounding; Z_n=80 Ω for resistive grounding.
- Overhead line L54: r_1 = 0.61 Ω/km, x_1 =0.35 Ω/km, r_0 = 0.75 Ω/km, x_0 = 1.6 Ω/km, c_1=12nF/km, c_0=5 nF/km.
- Underground cable C150: r_1 = 0.125 Ω/km, x_1 = 0.11 Ω/km, r_0 = 0.95 Ω/km, x_0 = 1.62 Ω/km, c_1=c_0=250 nF/km.
- Loads: power factor = 0.9. Total load of feeder 1: 2-3-4 MVA, total load of feeder 2: 3 MVA, total load of feeder 3: 8 MVA.
- Model of SG (per unit): salient-pole, R_s=0.0095, X_d=2.11, X_d'=0.17, X_d"=0.13, X_q=1.56, X_q"=0.23, X_i=0.05, T_d'= 0.33 s, T_d"=T_q"=0.03 s.
- Fault resistance R_f = 0-10-100-1000 Ω for earth faults and R_f = 0-4-8 Ω for phase faults.

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