PERFORMANCE OF DIRECTIONAL RELAYS USING SVM CLASSIFICATION WITH DOUBLE-LINE-TO-GROUND FAULTS

Trung Dung LE
Supelec E3S – France
trungdung.le@supelec.fr

Marc PETIT
Supelec E3S – France
marc.petit@supelec.fr

ABSTRACT

Directional relays may be a good solution for the protection of MV distribution networks with distributed generators (DG) [1]-[3]. In more advanced protection scheme, with some protections distributed along the feeders [4]-[5], the directional algorithms without voltage sensors would be more interesting because of investment cost reduction. These algorithms use only sequence current ratios (i.e. $\Delta I^-/\Delta I^0$ and $\Delta I^-/\Delta I^+$) coupled with a SVM classifier to determine the fault direction [6]-[7]. In this paper, the algorithms will be analysed in the case of double-line-to-ground faults: theoretical base is explained; offline simulations are performed with Simulink/SimPowerSystems. The simulation results are subsequently used for training SVM classifiers.

INTRODUCTION

Massive integration of distributed generators (DGs) into MV distribution networks brings many great challenges to protection engineers: among them there is the sympathetic tripping problem [1]-[3]. One possible solution is to use directional relays to determine the fault direction. In the previous work [6]-[7], algorithms were proposed to estimate fault location (downstream or upstream towards the detector) without using the voltage sensors. The main advantage of these algorithms is that they can be implemented conveniently into protections along MV feeders [4]-[7] where voltage measurements are rarely available.

The proposed directional algorithms are based on ratios of variation of sequence currents during and before fault ($\Delta I^-/\Delta I^0$ ratio for line-to-ground faults and the $\Delta I^-/\Delta I^+$ ratio for line-to-line faults), which will be used as input to SVM (support vector machine) classifiers [8]-[10]. Trained beforehand with offline simulations, these classifiers will classify the input ratio into “upstream” or “downstream” category, which is also the fault direction estimation. Test with simulations shows good performances of the directional algorithms with regards to different network configuration, different DG interface with grid (synchronous machines or power converters) and to uncertainties of grid parameters.

In this paper, the performance test is extended to the case of double-line-to-ground faults. In this case, the interesting point is that both mentioned ratios ($\Delta I^-/\Delta I^0$ and $\Delta I^-/\Delta I^+$) could be taken as input of SVM classifier. Therefore, comparison tests are needed to indicate the best candidate ratio. Impact of neutral grounding in these cases will also be studied.

DIRECTIONAL ALGORITHMS WITHOUT VOLTAGE MEASUREMENT

Theoretical base of directional algorithms

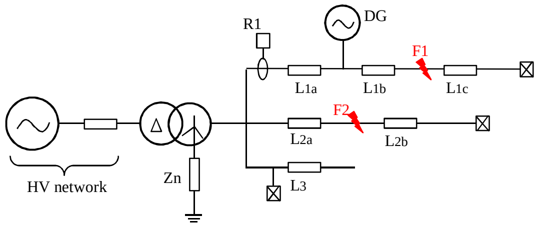


Figure 1. Simplified radial MV distribution network

Based on a simplified radial MV distribution network (Fig.1), I^-/I^0 and I^-/I^+ ratios, seen by relay R1, are deduced for downstream/upstream faults with respect to this relay [7]. The formulas from (1) to (4) resume the results of this analysis:

$$\left(\frac{I_{R1}^-}{I_{R1}^0}\right)_{F1} = \frac{I_{F1}^-}{I_{F1}^0} \cdot \frac{Z_{DG}^-}{Z_{DG}^- + Z_s + Z_{1a}} \cdot \frac{1+3Z_n.j\omega C_0.(L_1+L_2+L_3)}{1+3Z_n.j\omega C_0.(L_2+L_3)} \quad (1)$$

$$\left(\frac{I_{R1}^-}{I_{R1}^0}\right)_{F2} = \frac{I_{F2}^-}{I_{F2}^0} . \frac{Z_s}{Z_s + Z_{DG}^- + Z_{1a}} \cdot \frac{1+3Z_n.j\omega C_0.(L_1+L_2+L_3)}{3Z_n.j\omega C_0.L_1} \quad (2)$$

$$\left(\frac{I_{R1}^-}{I_{R1}^+}\right)_{F1} = \frac{I_{F1}^-}{I_{F1}^+} \cdot \frac{Z_{seqF1}^-}{\left(\frac{E_S}{E_{seqF1}}-1\right)\left(Z_{seqF1}^+ + Z_{seqF1}^- + 2Z_{1b} + R_f\right) + Z_{seqF1}^+} \quad (3)$$

$$\left(\frac{I_{R1}^-}{I_{R1}^+}\right)_{F2} = \frac{I_{F2}^-}{I_{F2}^0} \cdot \frac{Z_{seqF2}^-}{\left(\frac{E_{DG}}{E_{seqF2}}-1\right)\left(Z_{seqF2}^+ + Z_{seqF2}^- + 2Z_{2a} + R_f\right) + Z_{seqF2}^+} \cdot \frac{Z_{DG}^+ + Z_{1a}}{Z_{DG}^- + Z_{1a}} \quad (4)$$

<u>In these formulas</u>:
“Exponent” +, -, 0: positive, negative and zero-sequence
I_{F1}, I_{F2}: fault current at fault point (F1&F2)
I_{R1}: measured current at R1
L_1, L_2, L_3: length of feeder 1, 2, 3 ($L_1 = L_{1a}+L_{1b}+L_{1c}$ and $L_2 = L_{2a}+L_{2b}$)
Z_{1a}, Z_{1b}, Z_{2a}: impedance of line section L_{1a}, L_{1b}, L_{2a}
C_0: line zero-sequence capacity (per km)
Z_n: neutral impedance (*2 types of grounding system: appendix*)
R_f: fault resistance
Z_s: source impedance (HV voltage network+transformer)
Z_{seqF1}, Z_{seqF2}: equivalent impedance of source//DG for F1 and F2 respectively
E_s, E_{DG}: Thevenin voltage of source (HV network) and DG
E_{seqF1}, E_{seqF2}: equivalent Thevenin voltage of source//DG for F1 and F2 respectively

Table 1: Downstream and upstream areas created by sequence current ratios on the complex plane

	I_{R1}^{-}/I_{R1}^{0} ratio for single line-to-ground faults **A&G** **(I_F^-/I_F^0=1 in (1)&(2))**		I_{R1}^{-}/I_{R1}^{+} ratio for line-to-line faults **B&C** **(I_F^-/I_F^+=-1 in (3)&(4))**
	Compensative grounding (Z_n=600//jX_{comp} Ω, k_{comp}=1)	Resistive grounding Z_n=80 Ω	
Downstream fault of R1	Argument: from 15° to 75°	Argument: 0°; Area near to 1+0j	Argument : -180°; Area near to -1+0j
Upstream fault of R1	Argument: -90°; Module : smaller than one of downstream fault	Argument: -75° to -25°	Argument: different from -180° IIDG case: area near to origin

By analysing these formulas with typical parameters of French MV distribution networks, it can be concluded that the ratios will create two distinctive areas on the complex plane for downstream and upstream faults (Table 1). Simulation results confirmed these conclusions [6]-[7].

Delta algorithms and SVM technique

Nevertheless, simulations also indicate that downstream and upstream fault areas can overlap each other due to some additional factors, which are not taken into account in the analytical study (i.e. unbalance, load current, measurement noise...). Hence the "delta algorithms" (i.e. ratio between variations of sequence currents during and before fault inception: $\Delta I^-/\Delta I^0$ and $\Delta I^-/\Delta I^+$, seen by relay) are chosen for directional relays, in order to compensate the impact of those factors.

Moreover, a powerful classification method is also required to separate more efficiently ratios from two areas and consequently reduce the potential errors in the fault direction estimation. With its best capacity of generalization and its robustness, the Support Vector Machine (SVM) technique is chosen for this purpose. Details about this classification technique, which tries to maximize the margin between classes, are shown in [8]-[10]. It should be noted that this "machine learning" technique requires training and test processes that will be done by offline simulations [6]-[7]. These simulations give the "measured ratios" that will be used as input for the processes. The outcome is parameters of a classifier:

- A set of support vectors SV and their class $\{t_i\}$
- Lagrange multipliers $\{\alpha_i\}$
- A coefficient *b*
- Kernel function *K* (with its optimized "hyperparameters")

The classifier will classify a new ratio "*x*" (i.e. it is not used as training input), by performing the following calculation of sign function:

$$class\ of\ x = sgn(\sum_{i\in SV} \alpha_i t_i K(x, x_i) + b) \qquad (5)$$

Proposed implementation in [6]-[7]

Once a fault is detected (via a threshold), the algorithms will at first identify the fault type:

If *two line currents* > *line current threshold* then *L-L faults*
If *residual current* > *residual current threshold* then *L-G faults*

And then, a corresponding ratio '*x*' will be calculated according to the fault type ($x = \Delta I^-/\Delta I^+$ or $x = \Delta I^-/\Delta I^0$). After that, the sign function (5) will be calculated to give the fault direction estimation.

DOUBLE-LINE-TO-GROUND FAULTS

This fault type is identified when both line currents and residual current measured by relays exceed the corresponding thresholds. In fact, both $\Delta I^-/\Delta I^0$ and $\Delta I^-/\Delta I^+$ ratios can be taken as input of SVM classifier. In this section, an analysis will be done to choose better input.

Analytical formulas (B-C-G faults)

For simplicity's sake, the ***analytical calculation*** is performed again with ***I^-/I^0 ratio and I^-/I^+ ratio***. The delta algorithms (to eliminate the load currents) will be used with transient simulations in the next paragraph.

I_{R1}^-/I_{R1}^0 ratio

Formulas of the I_{R1}^-/I_{R1}^0 ratio are given in (1) and (2), with the sequence current ratio at fault location (F1 or F2):

$$\frac{I_F^-}{I_F^0} = \frac{Z_{grid}^0 + 3R_f}{Z_{grid}^-} = \frac{(3Z_n//Z_{ctot}) + 3R_f}{Z_{grid}^-} \qquad (6)$$

with Z_{grid}^0 and Z_{grid}^- : equivalent zero- and negative-sequence impedance of the network (seen from fault location)

and $Z_{ctot} = 1/(j\omega C_0.(L_1 + L_2 + L_3))$

It should be noted that I_F^-/I_F^0=1 in case of line-to-ground faults (A-G). This means that the I_{R1}^-/I_{R1}^0 ratios here (B-C-G faults) and in case of A-G faults are related by the factor depicted in (6), which is a complex number. Hence the upstream and downstream fault areas in case of B-C-G faults can be obtained by "transforming" the corresponding areas in case of A-G faults (Table 1) with this factor (6). It can be seen that the value of Z_n will have a clear impact on this "transformation". Two cases are considered [6]-[7]:

- Resistive grounding: Z_n = 80 Ω
- Compensative grounding: Z_n = 600//jX_{comp} Ω, with $X_{comp} = 1/(3\omega C_0.(L_1 + L_2 + L_3).k_{comp})$

For example, in case of compensative grounding, if k_{comp}=1, ($3Z_n//Z_{ctot}$)=3*600=1800Ω. In this situation, if Z_{grid}^- could be considered as a reactance (line resistance between source and fault is neglected), the argument of I_F^-/I_F^0 will be -90°. The corresponding areas for downstream/upstream faults in Table 1 will be both rotated by -90° here. Furthermore, because they are both multiplied by module of the same complex number (6), the module of upstream fault ratio is kept being smaller than one of downstream ratio (Table 1) and thus these two areas are kept distinctive with this fault type. In case of resistive grounding, the "transformation" of areas will depend on relation between Z_n and Z_{ctot}, which varies with the variation of total length of network cables. If this variation is important, the corresponding areas (for downstream/upstream faults of R1) resulting from the "transformation" will become wider. Therefore, there are more chances that the two areas overlap each other in case of B-C-G faults.

I_{R1}^-/I_{R1}^+ ratio

Formulas of the I_{R1}^-/I_{R1}^+ ratio are given in (3) and (4) with the sequence current ratio at fault location (F1 or F2):

$$\frac{I_F^-}{I_F^+} = -\frac{Z_{grid}^0+3R_f}{Z_{grid}^0+Z_{grid}^-+3R_f} \approx -1 \qquad (7)$$

supposing that $Z_{grid}^0 >> Z_{grid}^-$ (it is the case in French MV distribution network)

In case of line-to-line faults (B-C), I_F^-/I_F^+=-1. Therefore, I_{R1}^-/I_{R1}^+ ratios here (B-C-G faults) and in case of B-C faults can be considered to be equal. The upstream and downstream areas here are the same as the defined ones in Table 1, and they are distinctive.

Simulation & SVM classifiers

The analytical formulas in the previous paragraph indicate that there will be two distinctive areas on the complex plane, which correspond to downstream and upstream faults if the I^-/I^0 ratio is used in case of compensative grounding or the I^-/I^+ ratio is used. In case of resistive grounding, by using of the I^-/I^0 ratio, two areas may be more close to each other or even have overlap if the variation of Z_{ctot} is high.

To confirm these conclusions, transient simulations are performed in this paragraph with Simulink/ SimPowerSystems. As previously mentioned, to deal with uncertainty factors, delta algorithms ($\Delta I^-/\Delta I^0$ and $\Delta I^-/\Delta I^+$ seen by protections) will be used. The training and test of SVM classifiers corresponding to each ratio will help to choose the best algorithm.

Simulation - Investigated network

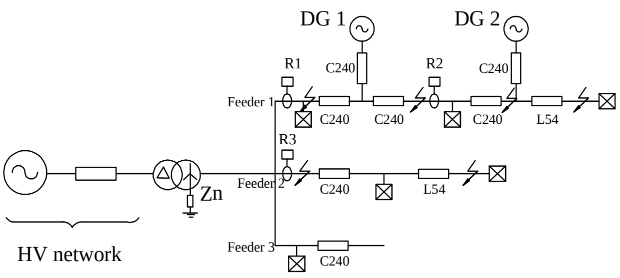


Figure 2. Investigated grid with two DGs connected on a feeder (Simulink/SimPowerSystems model)

The grid topology is shown in Fig.2: a radial network with three feeders with underground cables (C240) and overhead lines (L54). Feeder 1 has two DGs connected in two sections that are protected by relays R1 and R2 respectively. Two types of generator are considered: directly connected synchronous generator (SG) as in case of CHP or small hydro plants, or inverter-interfaced distributed generator (IIDG) as in case of PV plants or windmill with permanent magnet SG. The total rated power of the DGs is less than 9 MVA (in order to avoid overvoltages). Faults only strike feeders 1&2 while feeder 3 is used for aggregating line capacitances of the other feeders. Detailed grid characteristics are given in Appendix. Simulation model of DGs is presented in [6]-[7]. Grid parameters in training and test simulations are shown in Table 2&3&4.

In these simulations, the HV voltage is 63 kV with its normal deviation σ_U=1.25%. Line parameters deviation are considered around values given in Appendix (σ_{line}=5%). To take into account the effects of the network unbalance, a negative-sequence voltage is introduced and superposed on the positive-sequence voltage source in the simulation model via The Three-phase Programmable Voltage Source block of SimPowerSystems Toolbox. The maximal imposed negative-sequence voltage is set to 2% of the positive-sequence one.

Table 2: Grid parameters for training simulations (discrete values)

Parameters	Variations
Length of feeders	Feeder 1: 10-15km Feeder 2: 5-15km Feeder 3: 5-10-20-30-40km
Connection points from substation	DG1: 1-5km DG2: 6-10km
DG powers	S_{DGn} (Table 4)
Total load on Feeder 1	1-2-4MVA
Fault impedance	R_f=0-10-100-200Ω
Tuning factor k_{comp} (compensated grounding)	0.9-0.95-1-1.05-1.1

Table 3: Grid parameters in test simulations (random values with uniform distribution in the intervals)

Parameters	Variation
Length of feeders	Feeder 1: 10→20km Feeder 2: 5→15km
Connection points from substation	DG1: 1→5km DG2: 6→10km
DG powers	$0.5S_{DGn}$→S_{DGn}
Total load on Feeder 1	0.5→5MVA
Fault impedance	R_f=0→200Ω
Tuning factor k_{comp} (compensated grounding)	0.9→1.1

Table 4: Studied cases of DG rated powers

Case	1	2	3	4	5
S_{DG1} (MVA)	6	4	4	2	2
S_{DG2} (MVA)	2	2	4	4	6

Table 5: Misclassification rates τ_{mis} in test cases - 10th period classifier for R1 (t_{decR1}=200ms)

Case	SG case		IIDG case		IIDG&SG case	
	Compensative grounding	Resistive grounding	Compensative grounding	Resistive grounding	Compensative grounding	Resistive grounding
τ_{misR1} with $\Delta I^-/\Delta I^0$	0.21%	0.84%	0%	1.23%	0%	2.06%
τ_{misR1} with $\Delta I^-/\Delta I^+$	0%	0%	0%	0%	0.19%	0.20%

Performance of algorithms

In this study, DFT technique is used for calculating current phasors (I_A, I_B, I_C) and afterward the ratios through a sliding window of 20ms width: a ratio is calculated for each frame of 20ms. The training and test processes will not take into account all frames but one. The choices of this frame are made in consideration of classification performances and time settings of each relay [6]-[7]. Here, in case of relay R1, the 10th frame from fault inception is chosen for training and then the trained SVM classifier is called "10th period classifier". Moreover, it gives also the fault direction estimation at 10th period after fault inception (t_{dec} = 200ms).

The performance of SVM classifiers is then evaluated with ratios from a series of "test simulations" where grid parameters are varied differently with respect to those in "training simulations" (Table 2&3). For one simulation, a ratio can be calculated and then classified. For N_{test} simulations (and thus N_{test} corresponding ratios), if there are $N_{misclassification}$ ratios that are misclassified, then the misclassification rates (τ_{mis}) can be defined as follows:

$$\tau_{mis} = \frac{N_{misclassification}}{N_{test}} \qquad (8)$$

With $N_{misclassification}$: number of misclassified ratios

N_{test}: total number of test ratios

It should be noted that measurement errors [11] is also taken into account by introducing noise in current phasor estimation. The noise is introduced randomly with normal distribution.

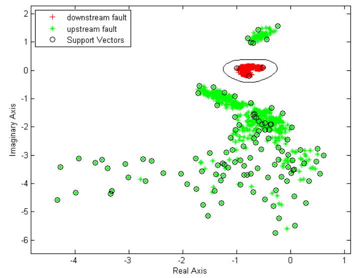
Table 5 shows test results for R1 in three cases:

- SG Case: both DGs (DG1&DG2) are SGs
- IIDG Case: both DGs are IIDGs
- IIDG&SG Case: DG1 is IIDG and DG2 is SG

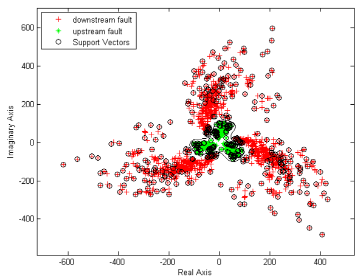
As can be seen in this table, performances with $\Delta I^-/\Delta I^+$ *ratio* for double-line-to-ground faults are good (τ_{misR1}=0%) for SG case and IIDG case. However, for IIDG&SG case, there are a few errors in classification (τ_{misR1}≈0.2%). Neutral grounding does not have influence on results. It should be noted that the same conclusion was given in case of line-to-line faults with $\Delta I^-/\Delta I^+$ ratio [6]-[7] and that was also predicted by analytical formulas in previous paragraphs.

On the other hand, performances with $\Delta I^-/\Delta I^0$ *ratio* depend clearly on neutral grounding. <u>With compensative grounding</u>, as also discussed in the analytical analysis, the downstream/upstream areas for double-line-to-ground faults are rotated by -90° on the complex plane with respect to ones in Table 1 and are kept separated. Test performances confirm this remark as $\boldsymbol{\tau_{misR1}}$ is small (<0.21%) for all three cases. <u>With resistive grounding</u>, as the variation of Z_{ctot} is important (Table 2&3), the variation of argument of $\boldsymbol{\Delta I^-/\Delta I^0}$ ***ratio*** is also important. Consequently, there will be more risks to have overlap between downstream and upstream fault areas. It is confirmed by the test results: $\boldsymbol{\tau_{misR1}}$ can be up to 2.06% (IIDG&SG case) with this neutral grounding.

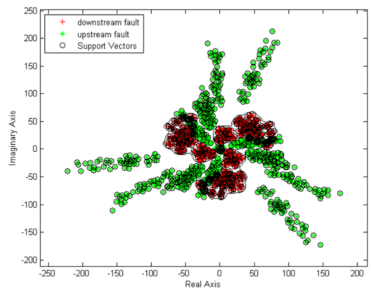
To illustrate the areas on the complex plane, the SG case is chosen as an example (Fig.3): downstream fault area in red colour and upstream area in green colour.



a) $\Delta I^-/\Delta I^+$ ratio



b) $\Delta I^-/\Delta I^0$ ratio - compensative grounding



c) $\Delta I^-/\Delta I^0$ ratio - resistive grounding

Figure 3. Simulation results in case of double-line-to-ground faults with different ratios (SG Case, Relay R1)

CONCLUSION

This paper presents algorithms for directional relays using only current measurement in the case of double-line-to-ground faults. Both $\Delta I'/\Delta I^0$ and $\Delta I'/\Delta I^+$ ratio are analyzed, analytically as well as by transient simulations. The results, in good agreement between different approaches, show that the $\Delta I'/\Delta I^+$ ratio can be efficiently used for this fault type, as training input of SVM classifiers as well as the criterion for fault direction estimation by the classifiers. In fact, this ratio is not influenced by neutral grounding. On the other hand, the use of the $\Delta I'/\Delta I^0$ ratio should be limited only for MV networks with compensative grounding because of higher misclassification rates with resistive grounding. This research can also be extended to the case in which there are two ground-to-line faults (e.g. an B-G fault and an C-G fault) at the same time but at different locations (even in different feeders) of the network. This is a possible situation in reality when the first ground fault in one phase induces a temporary overvoltage on the two other phases and leads to the second ground fault at another point of network [12].

REFERENCES

[1] Kauhaniemi, K., and Kumpulainen, L., 2004, "Impact of distributed generation on the protection of distribution networks", *Proc. Int. Conf. Developments in Power System Protection 8th*, pp. 315–318

[2] Deuse, J., Grenard, S., Bollen, M.H.J., Häger, M., and Sollerkvist, F., 2007, "Effective impact of DER on distribution system protection", *Proc. CIRED, Vienna, Austria*, pp. 1–4

[3] Fraisse, J.-L., and Horson, J.-P., 2010, "Technical considerations of distributed generation interconnection in distribution systems", *Technique de l'ingénieur D4242* (in French)

[4] Ukil, A., and Kamala, A.R., 2013, "Current Only Directional Overcurrent Protection for Distribution Automation Using Neural Network", *Proc. IEEE PES Conf. 10th PowerTech, Grenoble, France*, pp. 1–6

[5] Jecu, C., Raison, B., Caire, R., Chilard, O., Grenard, S., Deschamps, P., and Alibert, P., 2011, "MV distribution protection schemes to reduce customers and DGs interruptions", *Proc. IEEE PowerTech, Trondheim, Norway*, pp. 1–7

[6] Le, T.D., and Petit, M., 2014, "Directional Relays without voltage sensors for distribution networks", *IET Gen., Trans., Distr.*, Vol. 8 (12), pp. 2074-2082

[7] Le, T.D., 2014, "Contribution des moyens de production dispersés aux courants de défaut. Modélisation des moyens de production et algorithmes de détection de défaut", *PhD thesis, SUPELEC*, France

[8] Wu, X., et al., 2008, "Top 10 algorithms in data mining", *Journal Knowledge and Information Systems*, Vol. 14 (1), pp. 1-37

[9] Matlab R2014a Documentation, "Support Vector Machines (SVM) "

http://www.mathworks.fr/fr/help/bioinfo/ug/support-vector-machines-svm.html

[10] Chang, C.-C., and Lin, C.-J., 2011, "LIBSVM: a library for support vector machines", *ACM Transactions on Intelligent Systems and Technology*, Vol. 2 (3), pp. 27:1--27:27.

http://www.csie.ntu.edu.tw/~cjlin/libsvm

[11] ABB, 2009, "Instrument Transformers, Application Guide"

[12] EDF, 1994, "Protection of MV distribution networks –Principles", *Technical guide B.61-21*

Appendix

Grid characteristics

- HV network: 63 kV, P_{cc} = 500 MVA, X/R = 10
- HV/MV Transformer: 63/20 kV, S_{rated}= 20 MVA, U_{cc} =15%
- Neutral impedance:
  Z_n=600//jX_{comp} Ω for compensative grounding with $X_{comp} = 1/(3\omega C_0.L_{cable\_tot}.k_{comp})$; and 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 C240: 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: 1-2-4 MVA, total load of Feeder 2: 2 MVA, total load of Feeder 3: 8 MVA
- Model of SG (per unit): round rotor, R_s=0.005, X_d=X_q=2.5, X_d'=X_q'=0.25, X_d"=X_q"=0.15, X_l=0.067, T_d'= 0.5s, T_q'= 0.1s, T_d"=0.03s, T_q"=0.048s
- Coupling transformer of DG (IIDG and SG) : 400V/20kV, S_{rated}=S_{DGn}, U_{cc} =6%