DE1_Appendix VII

MICROGRIDS

Large Scale Integration of Micro-Generation
To Low Voltage Grids

WORK PACKAGE E

Report for Task TE2

FAULT CURRENT DISTRIBUTION IN A MICROGRID

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Nilanga Jayawarna
Nick Jenkins

UMIST

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1.0 Introduction

A MicroGrid must achieve the same level of safety as any other conventional distribution system. Therefore the grounding of the distributed energy sources, and the transformer connecting the MicroGrid to the utility network, requires to be carefully analyzed and appropriate rules need to be developed. An extensive literature review had been carried out [1-3]. According to this analysis, the most suitable earthing systems for a MicroGrid are identified as follows in the order of their suitability [3].

1. TN-C-S
2. TT
3. IT

The performance of each of these earthing system in a MicroGrid needs to be further investigated via simulation. The IT system was eliminated as a probable candidate for the MicroGrid earthing as it is so rarely used in practice. Therefore further investigation was carried out only on TN-C-S and TT systems.

A substation grounding system is designed as a path to carry electric currents into the earth under normal and fault conditions and to ensure the safety of a person in the vicinity of the substation. The safety of the design is determined by limiting the step and touch voltages to safe levels for personnel within the substation area. The step and touch voltages are directly proportional to the magnitude of the fault current component discharged directly into the soil by the grounding network. It is therefore important to determine the fault current distribution in the system.

The fault current distribution is dependent on the neutral earthing method of the system (TT or TN). A portion of the fault current would return to its source via the neutral wire in a four-wire system. The current discharged into the substation grounding system is smaller than the maximum available fault current in such a system. Therefore it is required to study how the fault current is distributed between the neutral and the earth in order to calculate the step and touch potentials in and around the substation.

2.0 Methodology

A MicroGrid in its simplest form was considered for this study. The main distribution network was assumed to have a short circuit level of 100MVA and a X/R ratio of 5. The MicroGrid consists of a flywheel (200kW), a single micro source (a micro gas turbine, 3ph, 30 kW) and a single load. The MicroGrid is connected to the main distribution network through a transformer (20/0.4 kV, 400kVA).

There are three general faults that could occur in a MicroGrid network.

1. A fault on the main distribution network (F1)
2. A fault on the MicroGrid network (F2)
3. A fault at a load (F3)

A MicroGrid with the above-mentioned faults is shown in Figure 1.

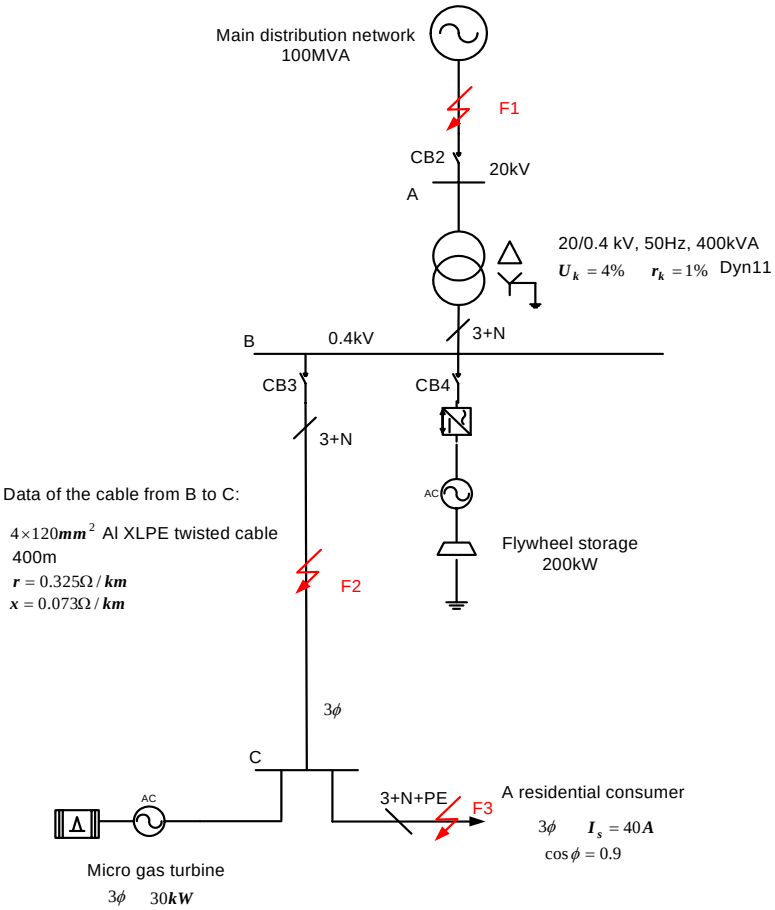


Figure 1: A simple MicroGrid model with typical fault locations

The aim of this study is to evaluate the performance of different earthing systems in this MicroGrid. TN-C-S and TT are the two earthing system proposed for the MicroGrid [3].

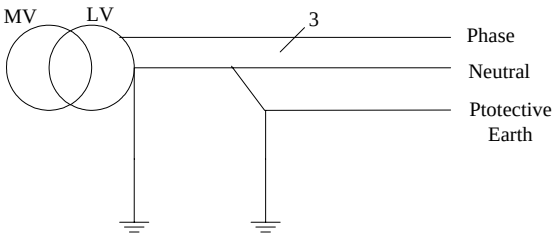


Figure 2: TN-C-S system

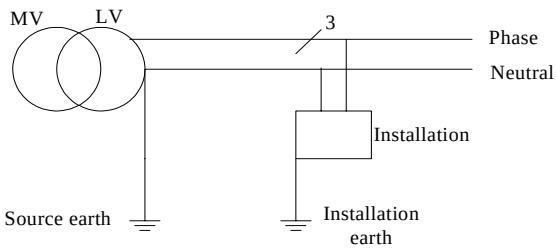


Figure 3: TT system

Figure 2 shows a TN-C-S system. In this earthing system, the transformer neutral is earthed and the supply feeder consists of a TN-C system, where the neutral conductor and the earth conductor are combined. The earthing arrangement in the installations (consumers) is TN-S, with separate neutral and earth conductors.

A TT system is illustrated in Figure 3. In a TT system, the transformer neutral and the consumer installation have independent earth electrodes.

Two scenarios (Case 1 and Case 2) of the MicroGrid were investigated. In Case 1, the MicroGrid is connected to the main network. In Case 2, the MicroGrid operates in islanded mode. Three different faults (F1, F2 and F3) were applied to the MicroGrid. A single-phase-to-ground fault was assumed for the study, as this is the most common type of fault likely to occur.

The specialist grounding software, CDEGS, was used for the computer modelling. One of its subsystems, SPLITS, was used as the simulation tool in this particular study to determine the fault current distribution [4, 5].

ICCS/ NTUA has carried out a similar study investigating the fault current distribution in a MicroGrid [6]. EMTP had been used as the simulation tool in their analysis and a simple network was used initially to verify the simulation results against the theoretical calculations. This system is described in detail in Section 4.

A simple network identical to the above-mentioned NTUA network was used as a preliminary study in order to verify the accuracy of the simulation results obtained using CDEGS. Furthermore, the results obtained with the two different simulation tools, EMTP and CDEGS, could be compared with each other.

3.0 Fault current calculation

When a single-phase-to-earth fault occurs, the fault currents can be calculated using symmetrical components theory. The equivalent circuit for a single-phase-to-earth fault is derived as follows. Figure 4 shows a fault circuit with a single-phase-to-earth fault on its phase C.

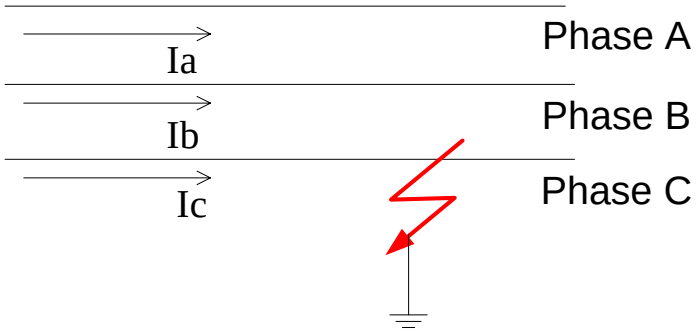


Figure 4: The fault circuit (phase C-to-earth fault)

If assumed that the faults are through zero impedance, the equations defining this fault circuit are

$$I_a = 0$$
$$I_b = 0$$
$$V_c = 0$$

The above set of equations can be converted in to sequence quantities as follows [7, 8].

$$\bar{I}_1 = \bar{I}_2 = \bar{I}_0 = \frac{1}{3} * I_c \qquad \text{Equation (1)}$$

$$\bar{V} - \bar{I}_1 * \bar{Z}_1 = \bar{I}_2 * \bar{Z}_2 + \bar{I}_0 * \bar{Z}_0 \qquad \text{Equation (2)}$$

According to Equation (1) and Equation (2), the equivalent circuit for a single-phase-to-earth fault is obtained by connecting the positive, negative and zero sequence networks in series. This equivalent circuit is shown in Figure 5.

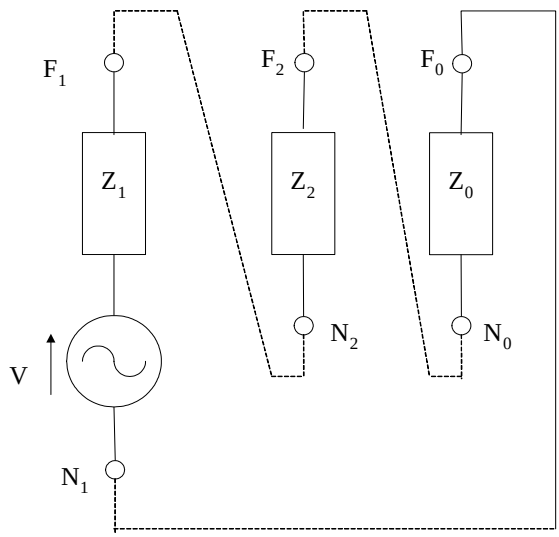


Figure 5: The equivalent sequence circuit for a single-phase-to-earth fault

From Figure 5, $\bar{I}_1 = \bar{I}_2 = \bar{I}_0 = \dfrac{V}{Z_1 + Z_2 + Z_0}$ Equation (3)

From Equation (1) and Equation (3), The fault current magnitude

$$I_{fault} = \frac{3 * V}{Z_1 + Z_2 + Z_0}$$ Equation (4)

Where

V = Phase to earth voltage

Z_1 = Positive sequence impedance

Z_2 = Negative sequence impedance

Z_0 = Zero sequence impedance

It can be assumed that $Z_1 = Z_2$ for a passive network Equation (5)

According to "Protective Relays Application Guide" [5], the zero sequence impedance

$$Z_0 = 3 * Z_N + Z_1$$ Equation (6)

Where Z_N = the impedance of the earth return path

3.1 Fault current calculation for a TN-C-S system

The fault current distribution for a TN-C-S system is shown in Figure 6. A major portion of the fault current returns to the source through the neutral conductor ($I_{Neutral}$). Only a small fraction of the fault current would be conducted in to the ground (I_{earth}). Thus the main earth return path for a TN system is the neutral conductor.

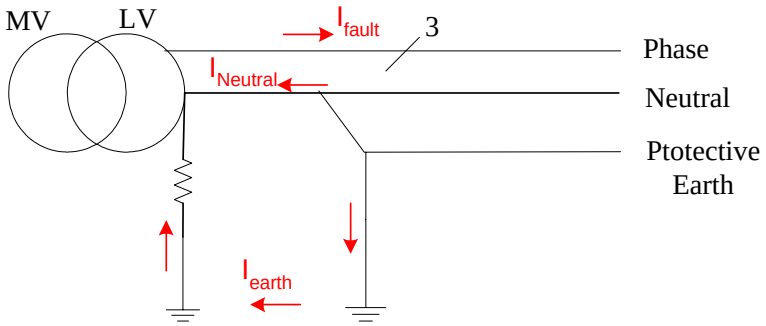


Figure 6: Fault current distribution for a TN-C-S system

Therefore the zero sequence impedance for a TN-C-S system is,

$$Z_{0_TN} = 3 * Z_{Neutral} + Z_1 \qquad \text{Equation (7)}$$

From Equation (4), the fault current magnitude for a single-phase-to-earth fault

$$I_{fault-TN} = \frac{3 * V}{Z_1 + Z_2 + Z_0}$$

From Equations (5) and (7), the fault current magnitude for a single-phase-to-earth fault on a TN-C-S system

$$I_{fault-TN} = \frac{V}{Z_{Neutral} + Z_1} \qquad \text{Equation (8)}$$

3.2 Fault current calculation for a TT system

Figure 7 shows the fault current distribution for a TT system. The fault current returns to the source through the earth.

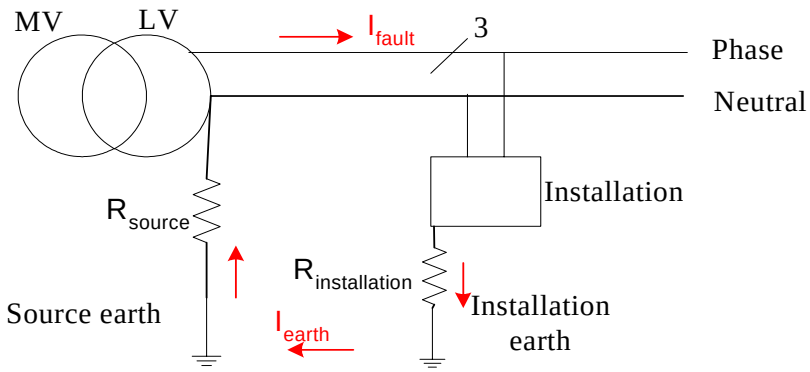


Figure 7: Fault current distribution for a TT system

The impedance of the earth return path for the above TT system is given by

$$Z_{N_TT} = R_{source} + R_{Installation}$$

Therefore the zero sequence impedance for a TT system is,

$$Z_{0_TT} = 3 * \left(R_{source} + R_{Installation}\right) + Z_1 \qquad \text{Equation (9)}$$

From Equations (1), (2) and (6), the fault current magnitude for a single-phase-to-earth fault on a TT system

$$I_{fault-TT} = \frac{V}{R_{source} + R_{Installation} + Z_1} \qquad \text{Equation (10)}$$

4.0 Preliminary study using CDEGS

The simple system initially used by NTUA is the same MicroGrid network as that shown in Figure 1. However there are no micro-sources attached to the MicroGrid in this preliminary case [6]. The transformer secondary represents the main distribution network side. A fault occurs on the MicroGrid network at a short distance away from the 0.4 kV bus bar. The only fault current source would be the supply transformer.

This simple network was implemented in CDEGS to examine the fault currents in a TN-C-S system (Figure 8) and a TT system (Figure 9). The simulation results were compared with the results gained by NTUA using EMTP. The same study was carried out in EMTDC for further verification. An identical network was used in each simulation platform. The fault currents have been derived by theoretical calculations as well.

4.1 TN-C-S system

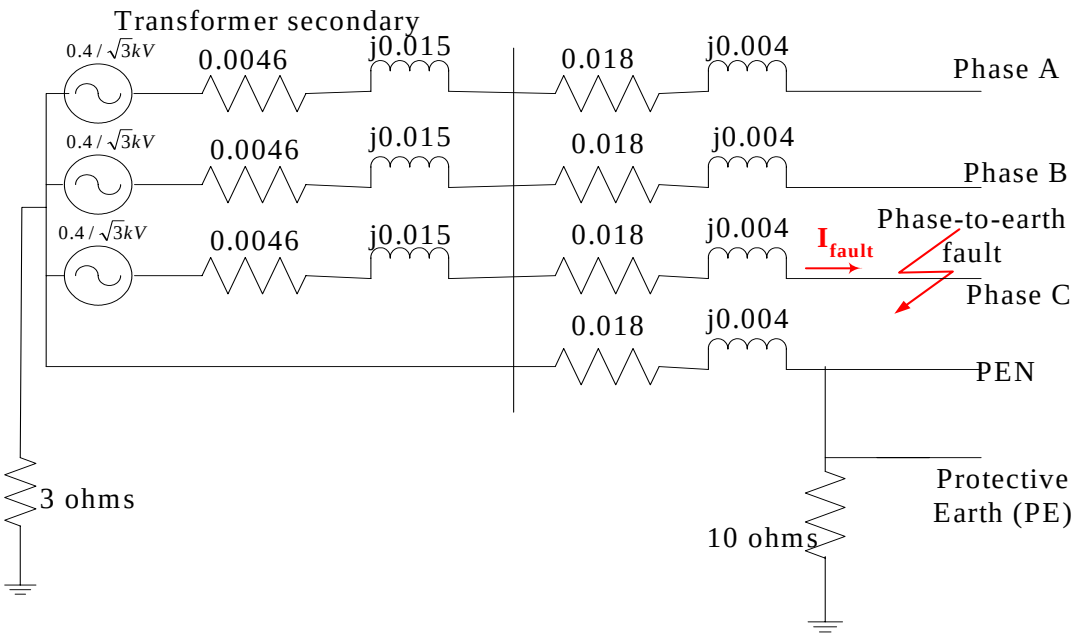


Figure 8: The simple TN-C-S network used in the NTUA study

The simple TN-C-S system used by NTUA is shown in Figure 8. This system was modelled in SPLITS to determine its fault currents magnitudes [7]. A single phase-to-earth fault occurs on the MicroGrid feeder (phase C). It is assumed that the only fault current source in the system is the supply transformer.

4.1.1 Simulation results

Figure 9 shows the total fault current magnitude, which is approximately equal to 4950A. The total earth current magnitude is shown in Figure 10 and this is around 7A. This shows that almost the total fault current returns back through the neutral conductor with only a small amount being discharged in to the ground. The simulation data and the CDEGS report for this fault is given in Annexure A1.

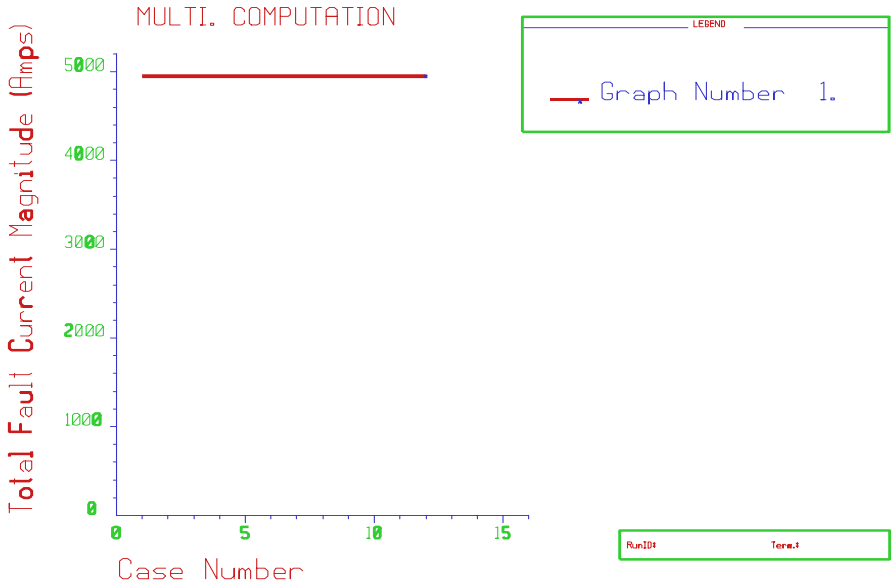


Figure 9: Total fault current for the simple TN network

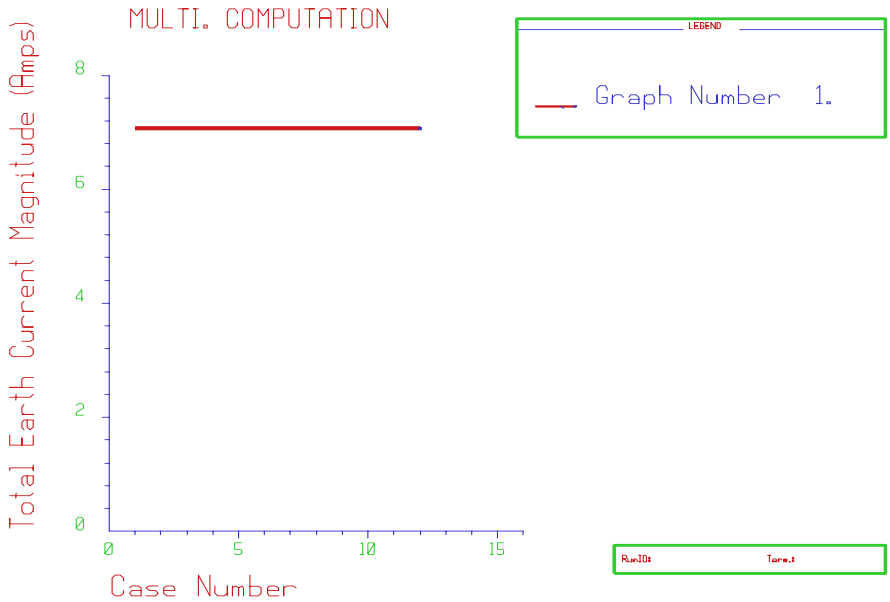


Figure 10: Total earth current for the simple TN network

4.1.2 Manual calculation

According to Equation (8), $$I_{fault-TN} = \frac{V}{Z_{Neutral} + Z_1}$$

The system parameters, $Z_1 = 0.0226 + j\,0.019$

$Z_{Neutral} = 0.018 + j\,0.004$

$$I_{fault-TN} = \frac{230\angle 0}{(0.018 + j0.004) + (0.0226 + j0.019)}$$

The rms value of the fault current,

$$I_{fault-TN} = 4929\ \angle -29.53\ \text{A} \qquad \text{Equation (11)}$$

4.2 TT system

The simple TT system used by NTUA is shown in Figure 11.

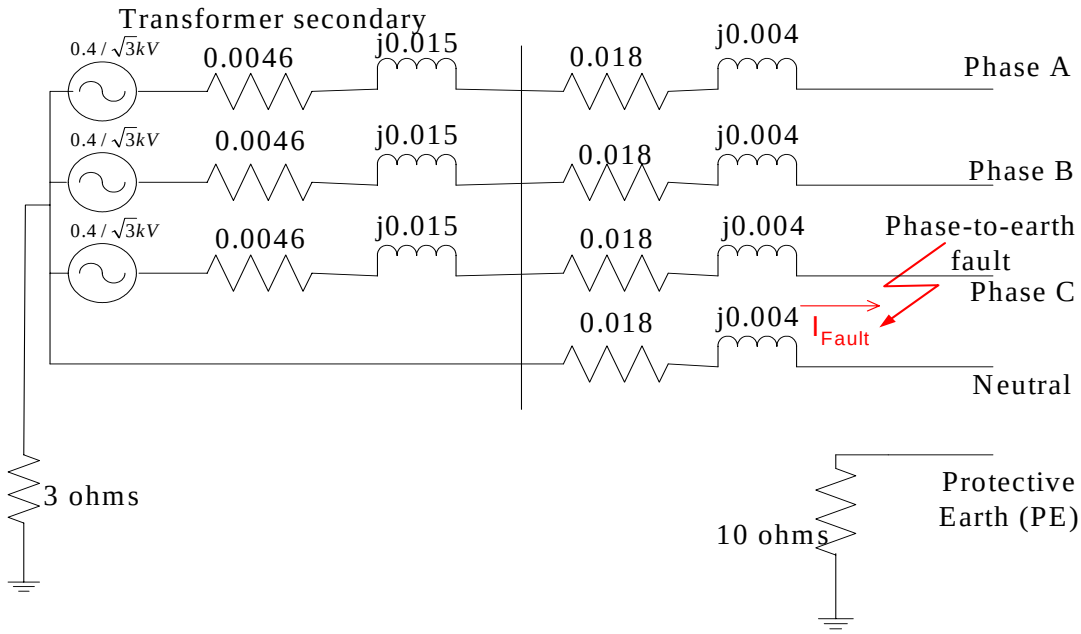


Figure 11: The simple TT network used in the NTUA study

The TT system of the simple network is shown in Figure 4. A single phase-to-earth fault on the MicroGrid feeder (phase C) is simulated with the use of SPLITS. The only fault current source in the system is the supply transformer and the fault current magnitude of the system is presented in the next section.

4.2.1 Simulation results

Figure 12 shows the total fault current magnitude, which is approximately equal to 17.7A. The total earth current magnitude is shown in Figure 13 and this is also around 17.7A. Therefore it is quite clear that almost the total fault current is discharged in to the ground in this TT system. The simulation data and the CDEGS report for this fault is given in Annexure A2.

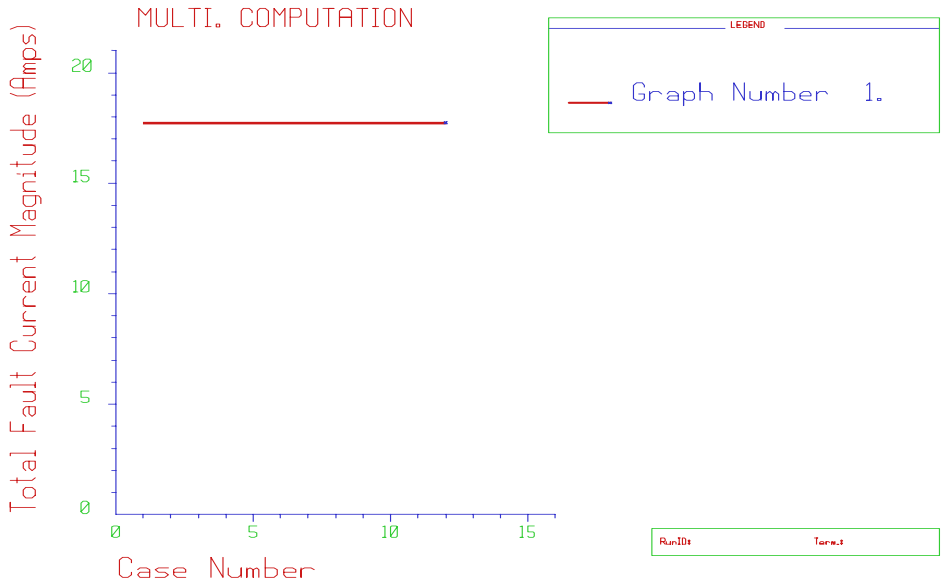


Figure 12: Total fault current for the simple TT network

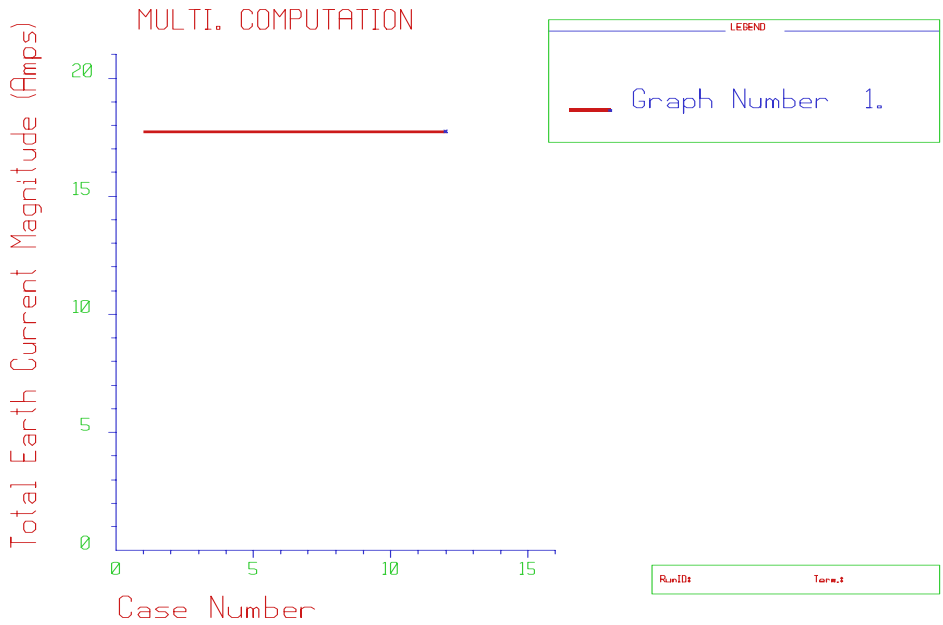


Figure 13: Total earth current for the simple TT network

4.2.2 Manual calculation

From Equation (10), $$I_{fault-TT} = \frac{V}{R_{source} + R_{Installation} + Z_1}$$

The system parameters,

Z_1 = 0.0226 + j 0.019

R_{source} = 3

$R_{installation}$ = 10

The rms value of the fault current,

$$I_{fault-TT} = 17.66 \angle -0.08 \text{ A} \qquad \text{Equation (12)}$$

4.3 Comparison of results

These two systems have also been modelled in PSCAD/ EMTDC to calculate the fault currents. Please find the EMTDC models presented in Annexure B.

Table 1 displays the simulation results derived from the three simulation tools (CDEGS, EMTP and EMTDC) and also the theoretically calculated values using sequence networks theory. The EMTP values are taken from the NTUA report [4].

	TN-C-S system	TT system
CDEGS	4952	17.74
EMTP	4950	17.68
EMTDC	4950	17.68
Manually calculated value	4929	17.66

Table 1: Comparison of results for the simple system

5.0 Grid connected operation

The fault current distribution for the three faults F1, F2 and F3 was investigated when the MicroGrid is interconnected to the main distribution network. A single phase to earth fault was considered in each instance.

5.1 A fault on the main distribution network – F1

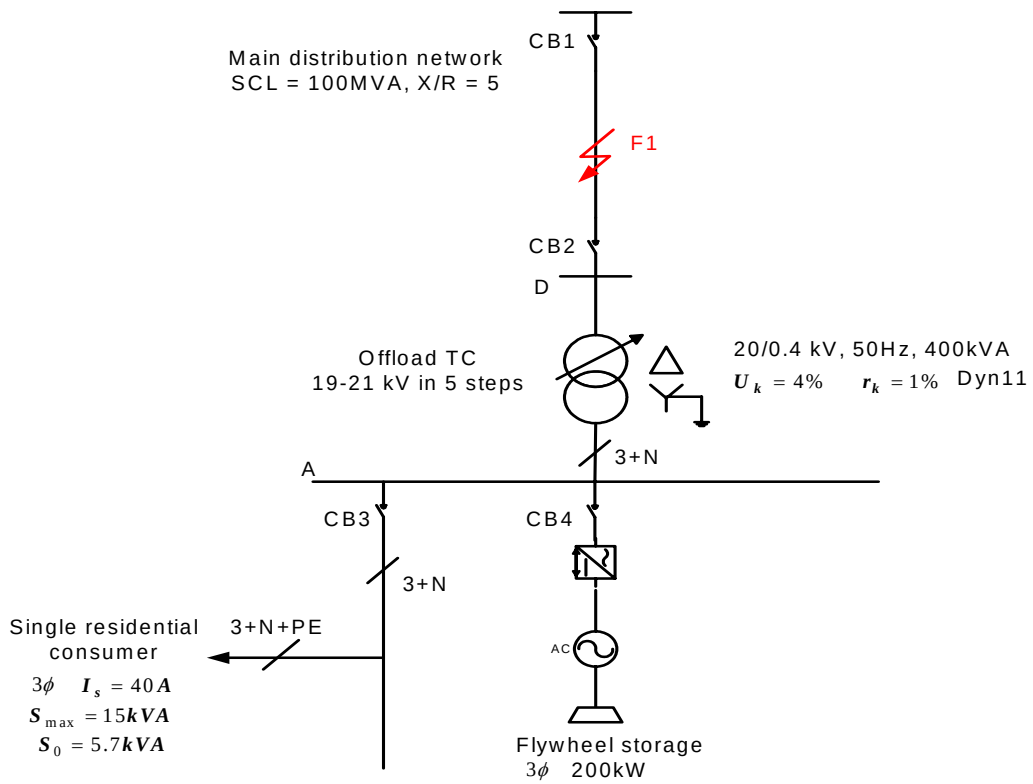


Figure 14: A fault on the main distribution network (F1)

The above network with the fault F1 was simplified as follows. The main distribution network was represented by a voltage source behind a reactance and the primary side of the connection transformer represented the MicroGrid side.

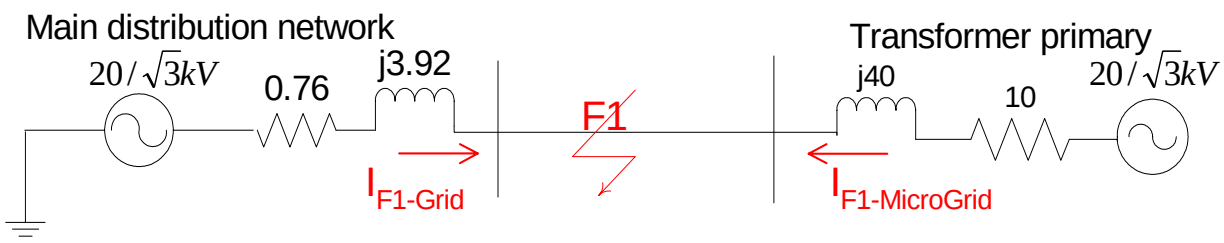


Figure 15: The simplified network for a fault on the main distribution network (F1)

Both the main distribution network and the MicroGrid network feed in to the fault. The fault current from the main grid is denoted by $I_{F1-Grid}$, and the fault current contributed by the MicroGrid is $I_{F1-MicroGrid}$.

5.1.1 Simulation results

The fault current magnitudes were determined by simulating a phase-to-earth fault on the phase C using SPLITS. The simulation data and the CDEGS report for the fault F1 is given in Annexure C1 of this report. The total fault current is shown in Figure 16 and is equal to 3073 A.

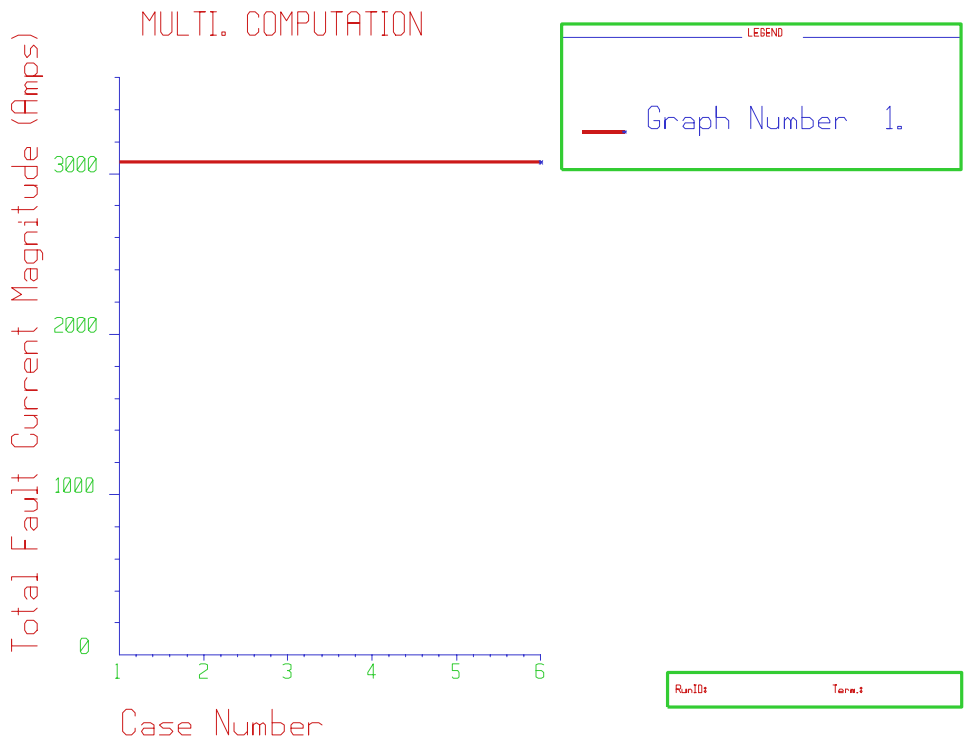


Figure16: Total Fault current for a fault on the main grid (F1)

The fault current from the main distribution network, $I_{F1-Grid}$ is shown in Figure 17 and the fault current from the MicroGrid, $I_{F1-MicroGrid}$ is shown in Figure 18.

The fault current from the main grid, $I_{F1-Grid}$ is approximately equal to 2890 A, while the fault current contribution from the MicroGrid, $I_{F1-MicroGrid}$ is around 180 A.

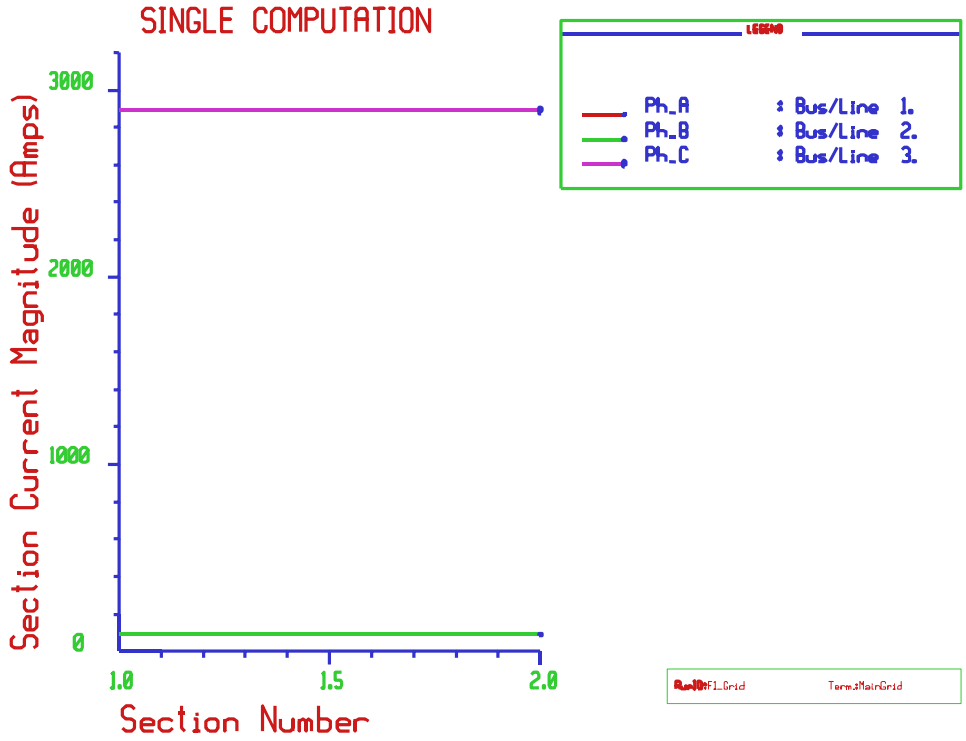


Figure 17: Fault current contribution from the main grid for F1

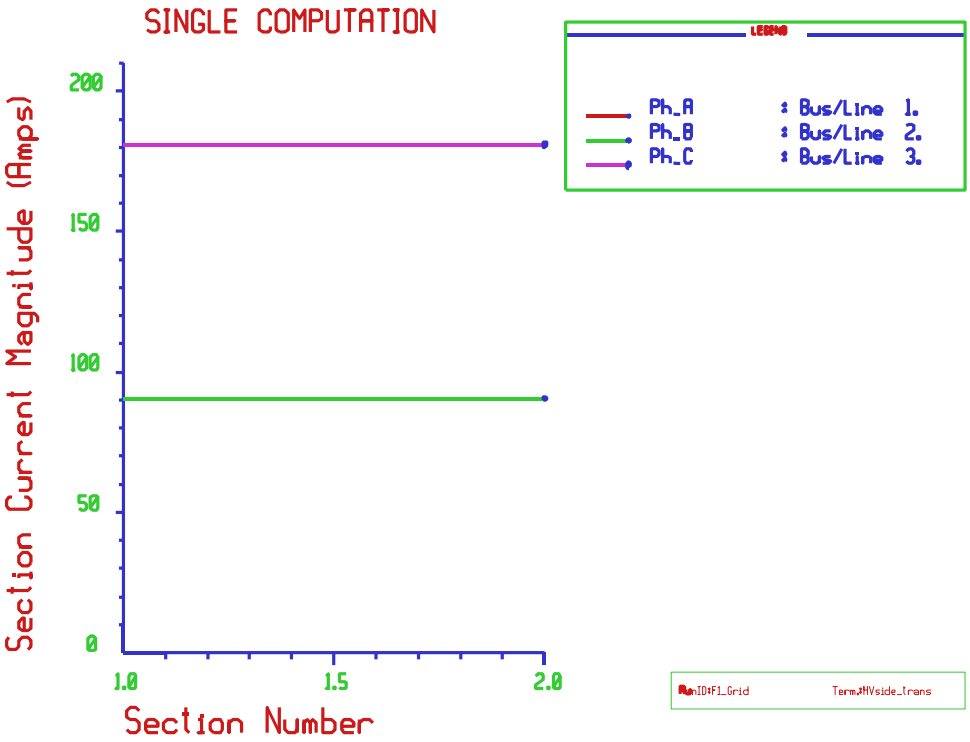
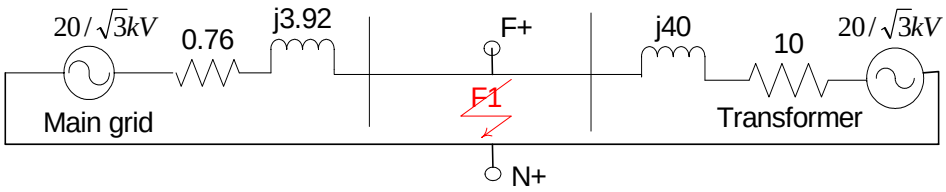


Figure 18: Fault current contribution from the MicroGrid for F1

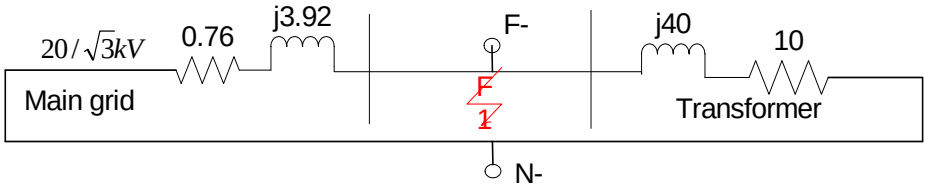
5.1.2 Manual calculation

Fault calculation presented in section 2 is based on the assumption of a single fault current source. However there are two fault current sources for F1, F2 and F3. Therefore the theoretical value for each type of fault is calculated separately with the aid of sequence circuits.

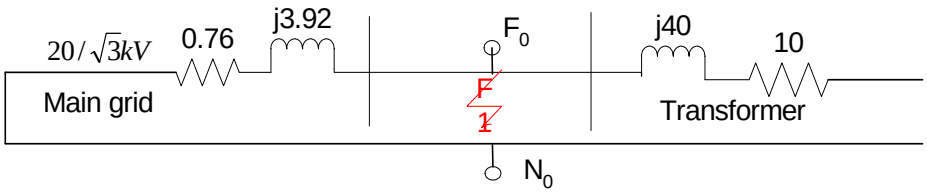
The positive sequence network for F1



The negative sequence network for F1



The zero sequence network for F1



The positive and negative sequence impedances,

$Z_1 = Z_2$ = (0.76+j 3.92) parallel to (10+ j 40)

= 3.64 $\angle 78.8$

Assuming that the 20kV neutral is solidly earthed

$$Z_0 = 3*0 + (0.76 + j3.92)$$

From Equation (4) $$I_{fault} = \frac{3*V}{Z_1 + Z_2 + Z_0}$$

The rms value of the fault current,

$$I_{F1} = 3073\angle -79A \qquad \text{Equation (13)}$$

5.2 A fault on the MicroGrid network – F2

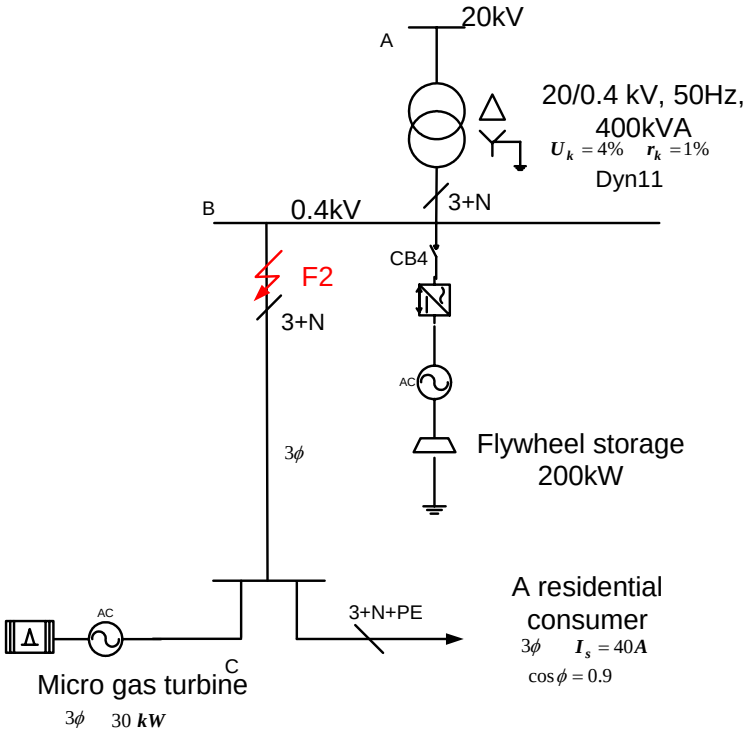


Figure19: A fault on the MicroGrid network for grid-connected operation – F2

A MicroGrid network with a fault F2 on its network feeder is shown in Figure 19. It was assumed that the flywheel converter does not provide any fault current contribution in gird-connected operation. Therefore the only fault current sources for this scenario are the main distribution network and the micro gas turbine connected to the MicroGrid. Hence a simplified model was obtained as follows. The transformer secondary represented the main grid side and the MicroGrid network consisted of a 400m long feeder and the micro-source at the end of the feeder. The micro-source neutral was unearthed according to the proposed guidelines for earthing in a MicroGrid [3]. The fault F2 was assumed to be at the beginning of the feeder. This simplified network is presented in Figure 20. Please note that all the impedances have been calculated at the voltage 0.4 kV.

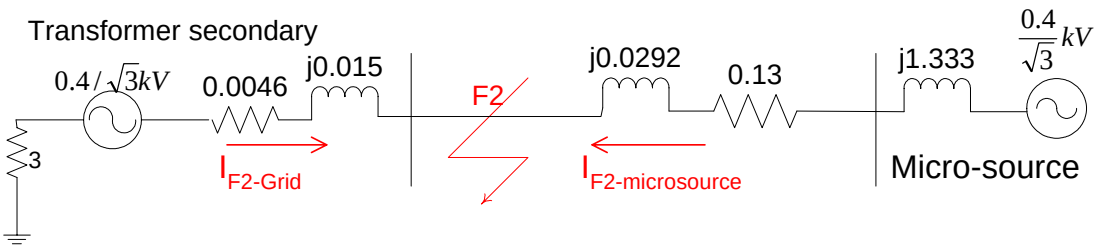


Figure 20: The simplified network for a fault on the MicroGrid network – F2

5.2.1 Simulation results

The fault current magnitudes are determined by simulating a phase-to-earth fault on the phase C using SPLITS. The fault current contribution from the main grid is $I_{F2-Grid}$ and the fault current contribution from the micro-source is $I_{F2-MicroSource}$.

The fault current distribution of a network is mainly determined by its Low Voltage neutral earthing system. Therefore a fault on a MicroGrid network (F2) with a TN-C-S system was simulated first to find out the fault current magnitudes. Then the same fault was modelled in a MicroGrid with a TT system.

5.2.1.1 TN-C-S system

The simulation data and the CDEGS report for the fault F2 in a TN-C-S system in grid-connected operation is given in Annexure C2 of this report. The total fault current is shown in Figure 21 and is equal to 14, 828A at 0.4 kV voltage.

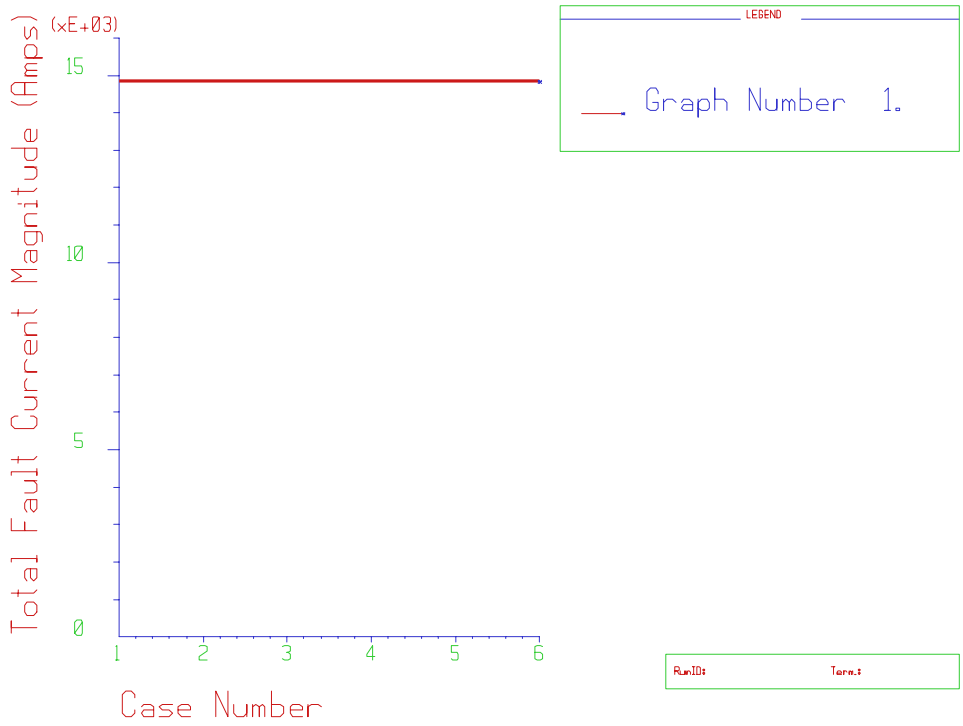


Figure 21: Total fault current for a fault on the MicroGrid network, TN system (F2)

The fault currents $I_{F2-Grid-TN}$ and $I_{F2-MicroSource-TN}$ for a fault F2 on a MicroGrid with a TN-C-S earthing system are shown in Figure 22 and Figure 23 respectively. $I_{F2-Grid-TN}$ is approximately equal to 14, 800A while $I_{F2-MicroSource-TN}$ is just above 110A.

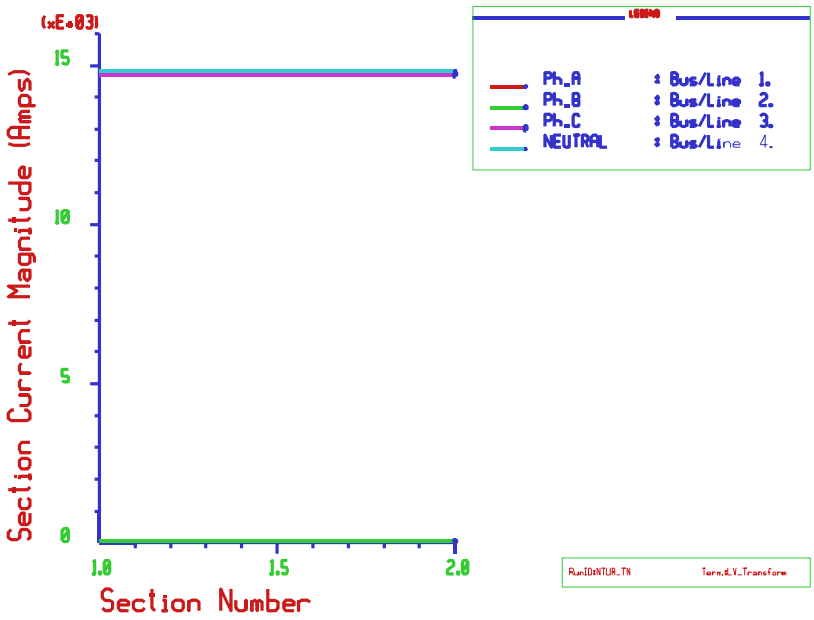


Figure 22: Fault current contribution from the main grid for F2, TN system

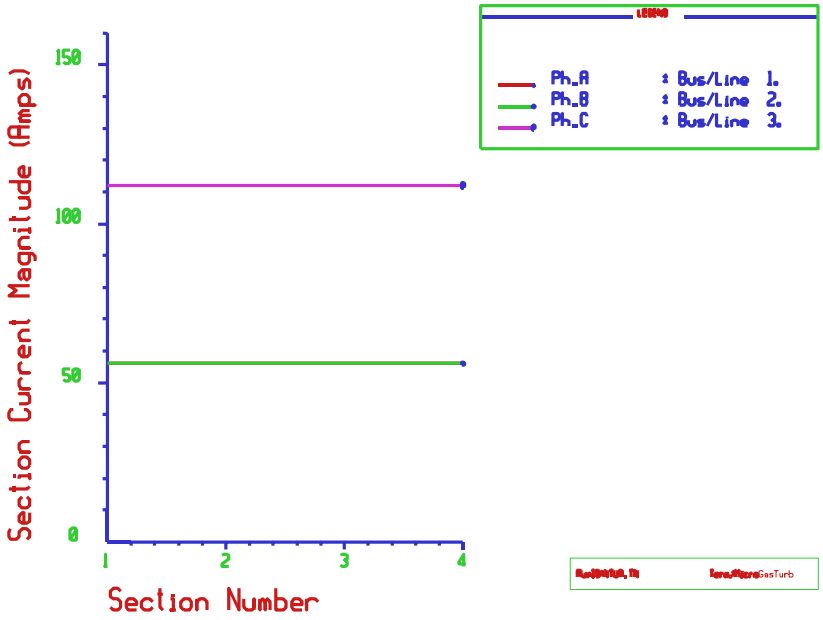


Figure 23: Fault current contribution from the micro-source for F2, TN system

5.2.1.2 TT system

The simulation data and the CDEGS report for the fault F2 in a TT system in grid connected operation is given in Annexure C3 of this report. The total fault current is approximately 18A and is shown in Figure24.

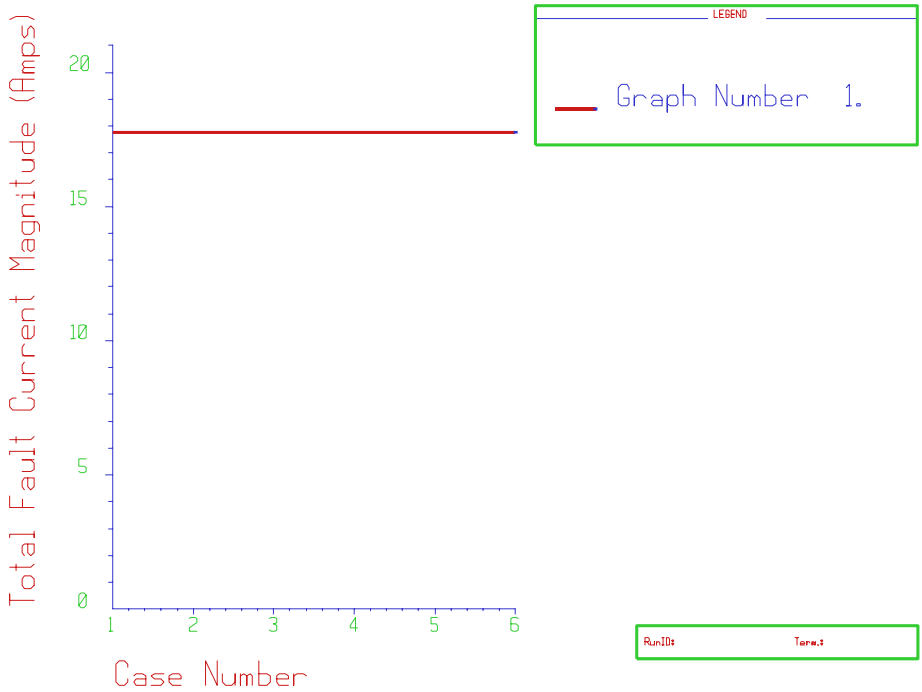


Figure 24: Total fault current for a fault on the MicroGrid network, TT system (F2)

The fault currents $I_{F2-Grid-TT}$ and $I_{F2-MicroSource-TT}$ for a fault F2 on a MicroGrid with a TT earthing system are shown in Figure 25 and Figure 26 respectively. $I_{F2-Grid-TT}$ is approximately equal to 18 A while $I_{F2-MicroSource-TT}$ is almost 0A.

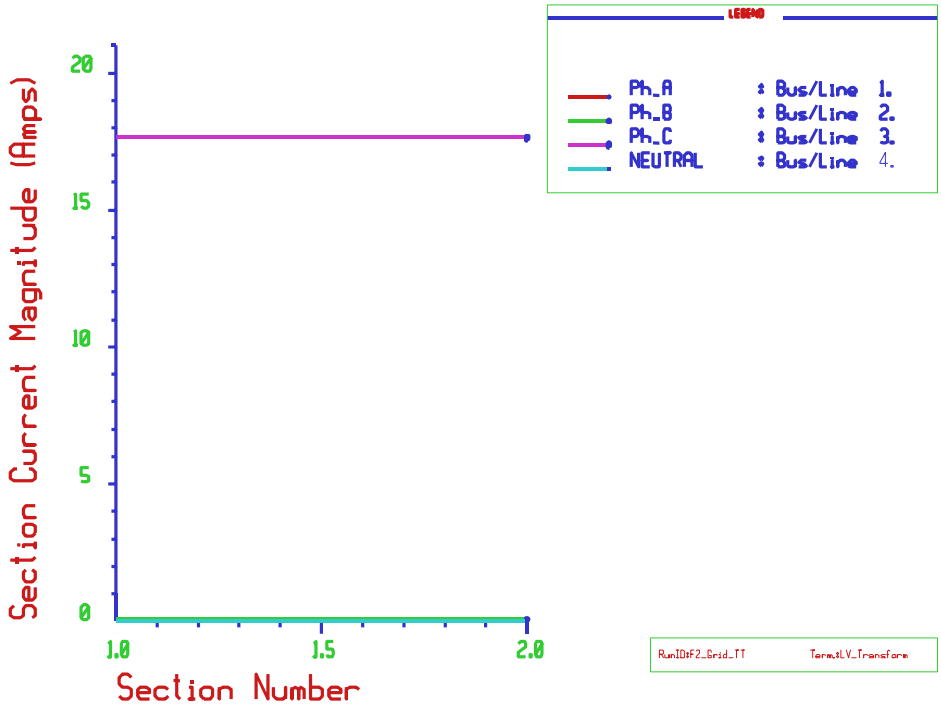


Figure 25: Fault current contribution from the main grid for F2, TT system

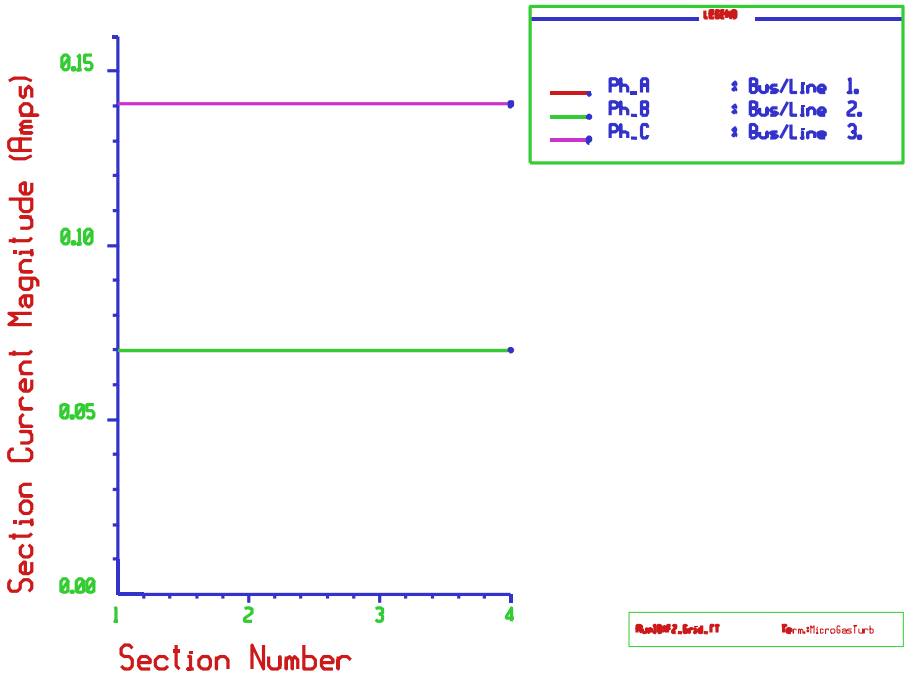


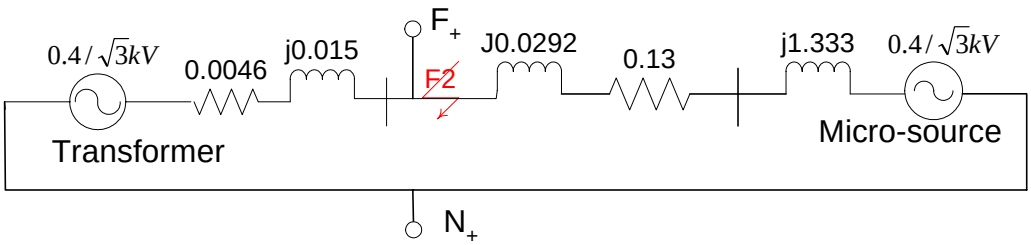
Figure 26: Fault current contribution from the micro-source for F2, TT system

5.2.2 Manual calculation

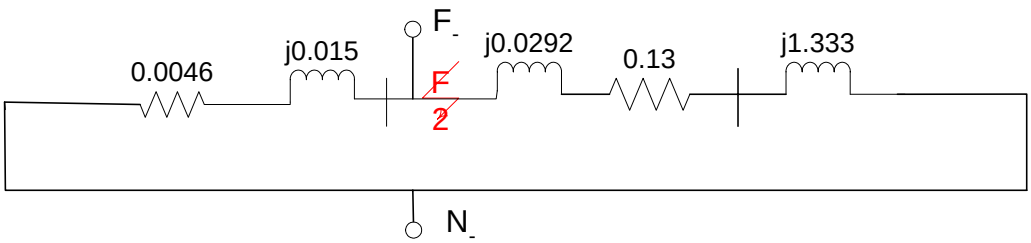
The fault currents for the fault F2 are calculated with the use of sequence networks.

5.2.2.1 TN-C-S system

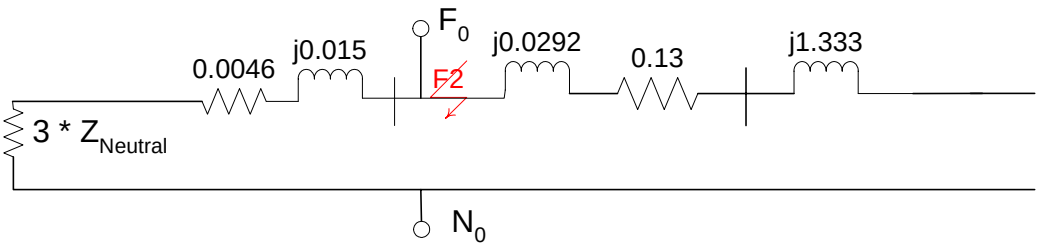
The positive sequence network for F2, TN network at 0.4 kV



The negative sequence network for F2, TN network at 0.4 kV



The zero sequence network for F2, TN network at 0.4 kV



The positive and negative sequence impedances,

$$Z_1 = Z_2 = (0.0046 + j\,0.015) \text{ parallel to } (0.13 + j\,0.0292 + j\,1.333)$$

$$= 0.0155 \angle 73.08$$

Since F2 is at the beginning of the feeder, $Z_{Neutral} = 0$

$$Z_0 = 3 * 0 + (0.0046 + j0.015)$$

From Equation (4) $$I_{fault} = \frac{3 * V}{Z_1 + Z_2 + Z_0}$$

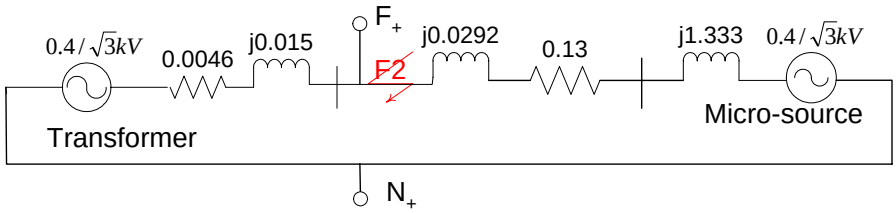
The rms value of the fault current,

$$I_{F2-TN} = 14{,}778 \angle -73.0 A \qquad \text{Equation (14)}$$

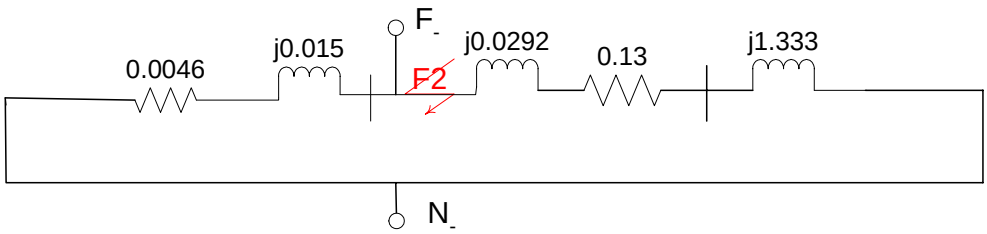
5.2.2.2 TT system

The positive sequence network and the negative sequence network for a TT system are identical to the ones for the TN system. However the zero sequence network parameters change according to the TT earthing method.

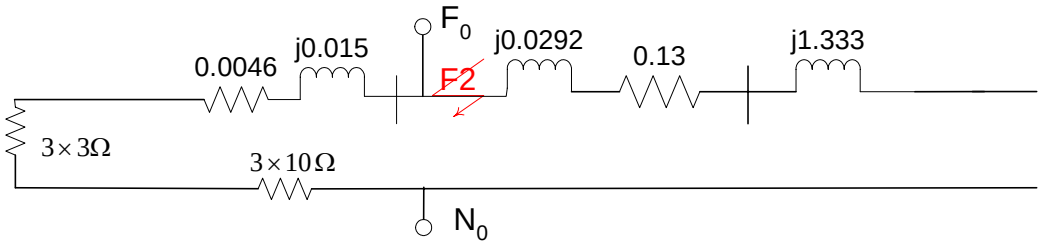
The positive sequence network for F2, TT network at 0.4 kV



The negative sequence network for F2, TT network at 0.4 kV



The zero sequence network for F2, TT network at 0.4 kV



The positive and negative sequence impedances,

$$Z_1 = Z_2 = (0.0046 + j\,0.015) \text{ parallel to } (0.13 + j\,0.0292 + j\,1.333)$$

$$= 0.0155 \angle 73.08$$

Consumer installation earth resistance is taken as 10 ohms. Then the zero sequence impedance, $Z_0 = 3*(10+3)+(0.0046+j0.015)$

From Equation (4) $$I_{fault} = \frac{3*V}{Z_1 + Z_2 + Z_0}$$

The rms value of the fault current,

$$I_{F2-TT} = 18\angle 0A \qquad \text{Equation (15)}$$

5.3 A fault at a load – F3

The fault F3 occurs at a load in the MicroGrid. It is assumed that this load is located at the end of the MicroGrid feeder as shown in Figure 27.

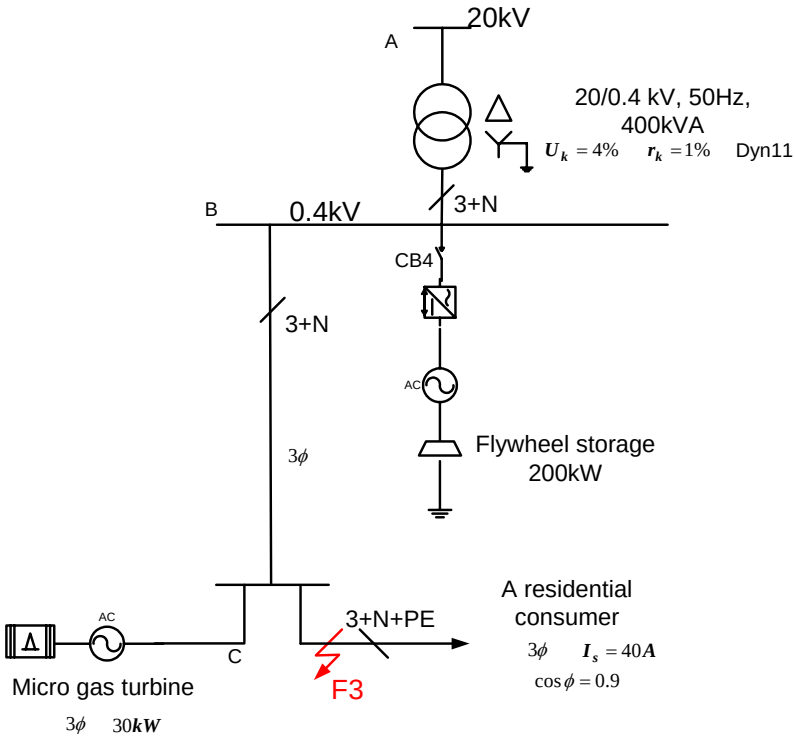


Figure 27: A fault at a load in the MicroGrid for grid-connected operation – F3

The fault current sources for this scenario are the main distribution network and the micro gas turbine because it is assumed that the flywheel is not providing any fault currents. Therefore a simplified model was obtained with the transformer secondary representing the main grid side and the MicroGrid network consisting of a 400m long feeder with a micro-source at the end of it. This simplified network is given in Figure 28. The fault current contribution from the main grid is $I_{F3-Grid}$ and the fault current contribution from the MicroGrid is $I_{F3-MicroSource}$. All the impedances are specified at 0.4 kV voltage.

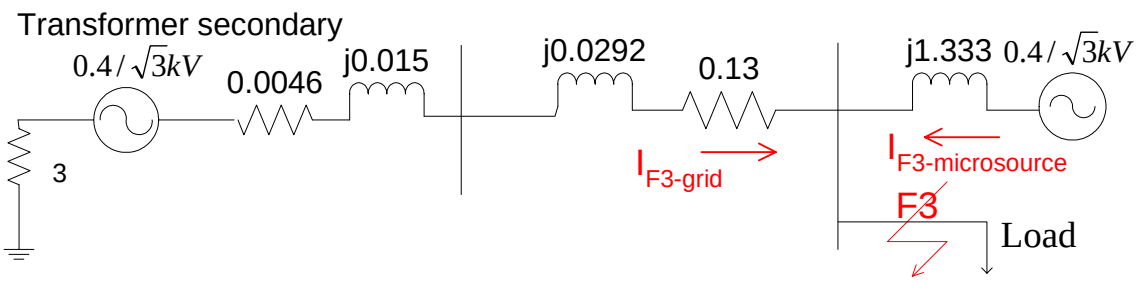


Figure 28: The simplified network for a fault at a load in the MicroGrid – F3

5.3.1 Simulation results

The fault current magnitudes are determined by simulating a phase-to-earth fault on the phase C using SPLITS. The fault F3 was simulated on a MicroGrid network with a TN-C-S system and thereafter on a MicroGrid with a TT system to determine the fault current distribution.

5.3.1.1 TN-C-S system

The simulation data and the CDEGS report for the fault F3 in a TN-C-S system in grid-connected operation is given in Annexure C4 of this report. The total fault current is shown in Figure 29, which is equal to 858A at 0.4kV.

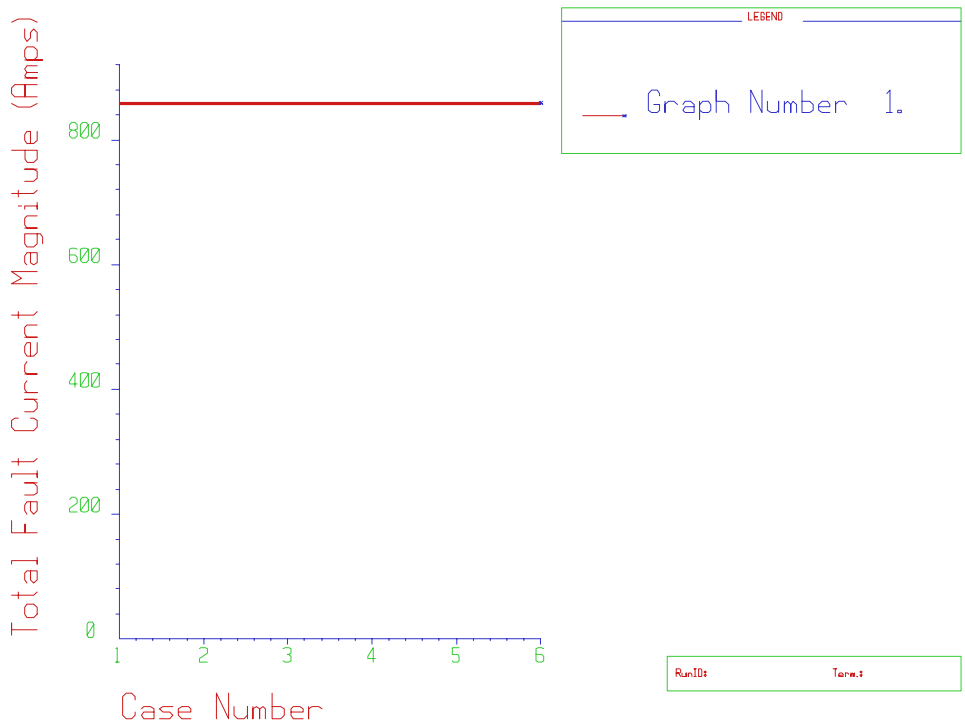


Figure 29: Total fault current for a fault at a load (F3), TN system

The fault currents $I_{F3-Grid-TN}$ and $I_{F3-MicroSource-TN}$ for a fault F3 on a MicroGrid with a TN-C-S earthing system are shown in Figure 30 and Figure 31 respectively. $I_{F3-Grid-TN}$ is approximately equal to 840 A while $I_{F3-MicroSource-TN}$ is just below 60 A.

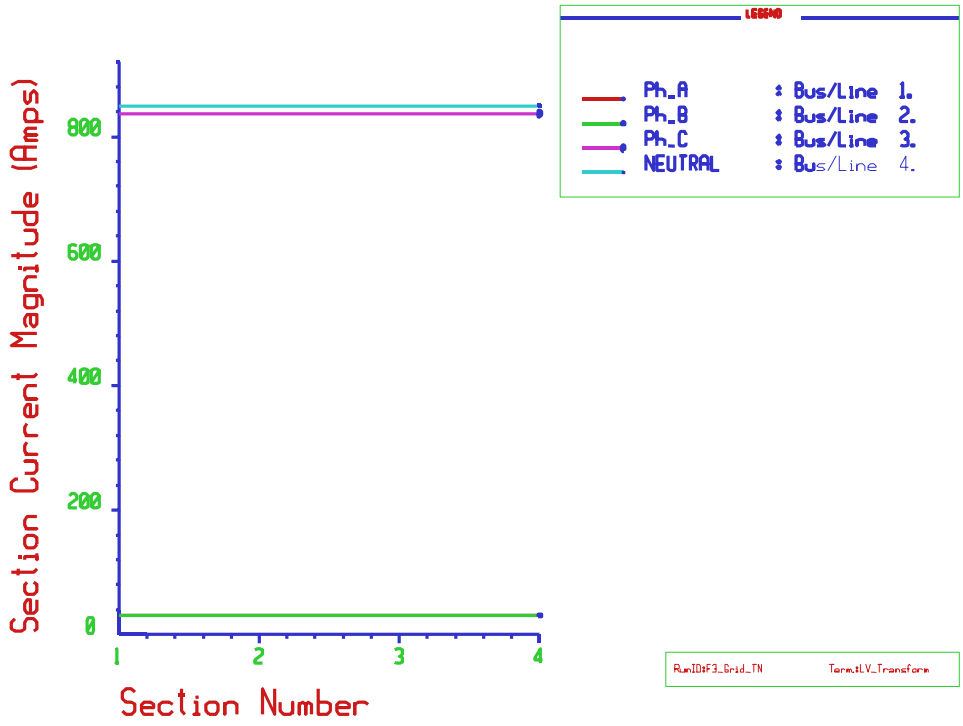


Figure 30: Fault current contribution from the main grid side for F3, TN system

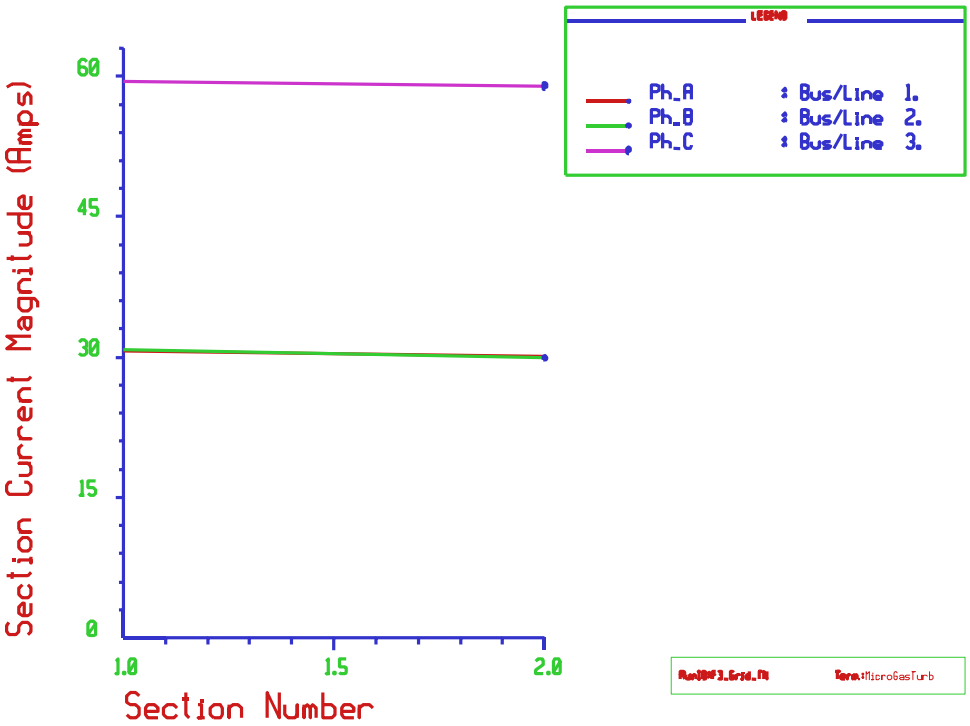


Figure 31: Fault current contribution from the micro-source for F3, TN system

5.3.1.2 TT System

The simulation data and the CDEGS report for the fault F3 in a TT system in grid-connected operation is given in Annexure C5. The total fault current is shown in Figure 32 and is around 18A.

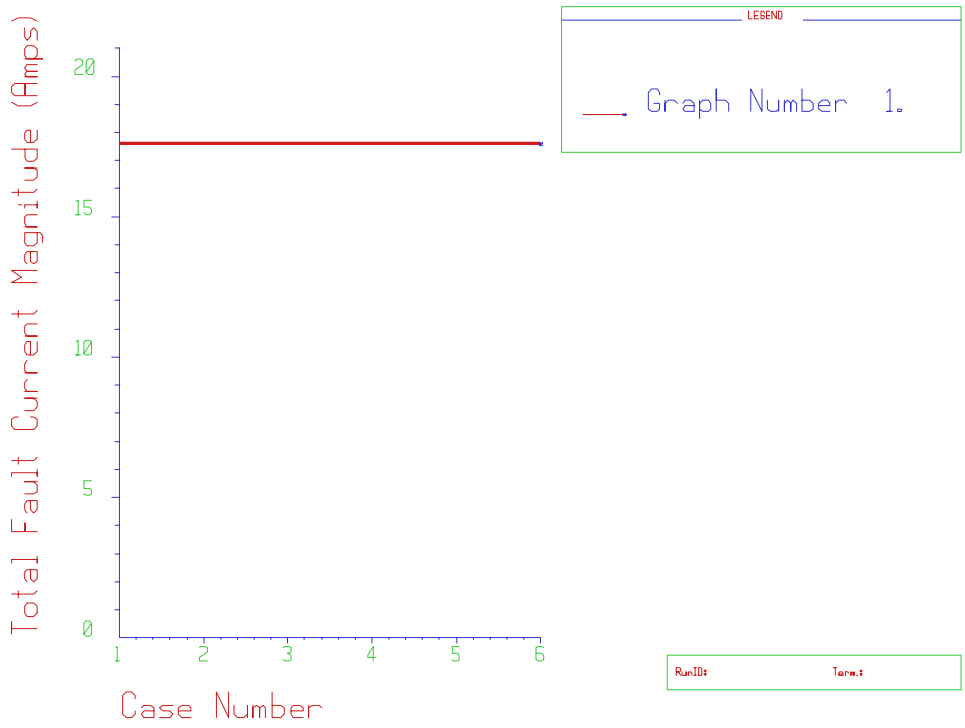


Figure 32: Total fault current for a fault at a load (F3), TTsystem

The fault currents $I_{F3-Grid-TT}$ and $I_{F3-MicroSource-TT}$ for a fault F3 on a MicroGrid with a TT earthing system are shown in Figure 33 and Figure 34 respectively. $I_{F3-Grid-TT}$ is approximately 17A while $I_{F3-MicroSource-TT}$ is around 1.2 A.

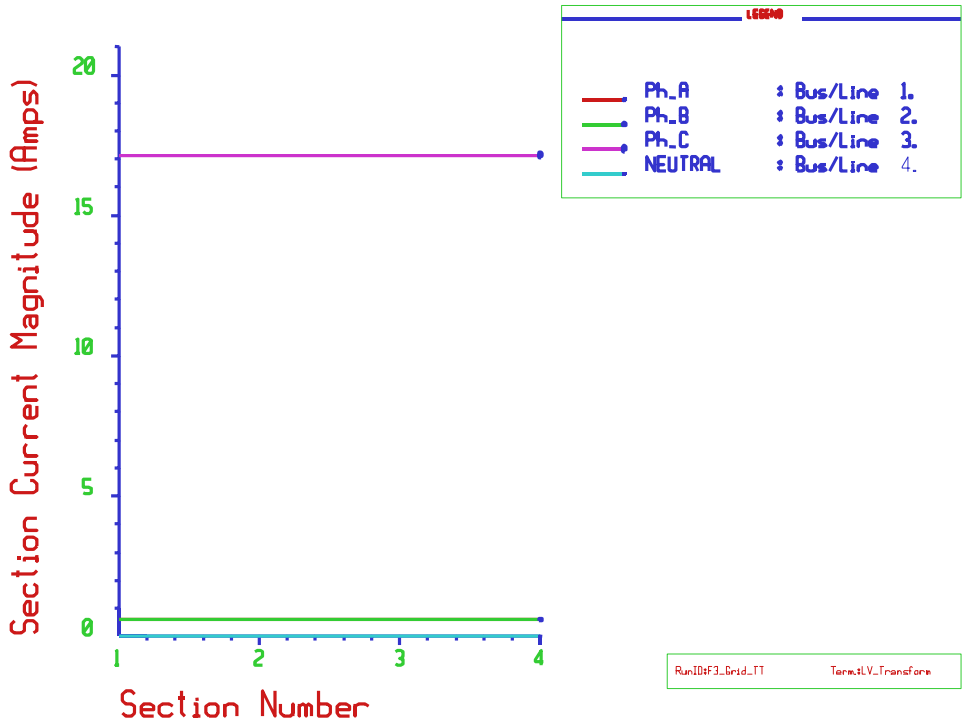


Figure 33: Fault current contribution from the main grid side for F3, TT system

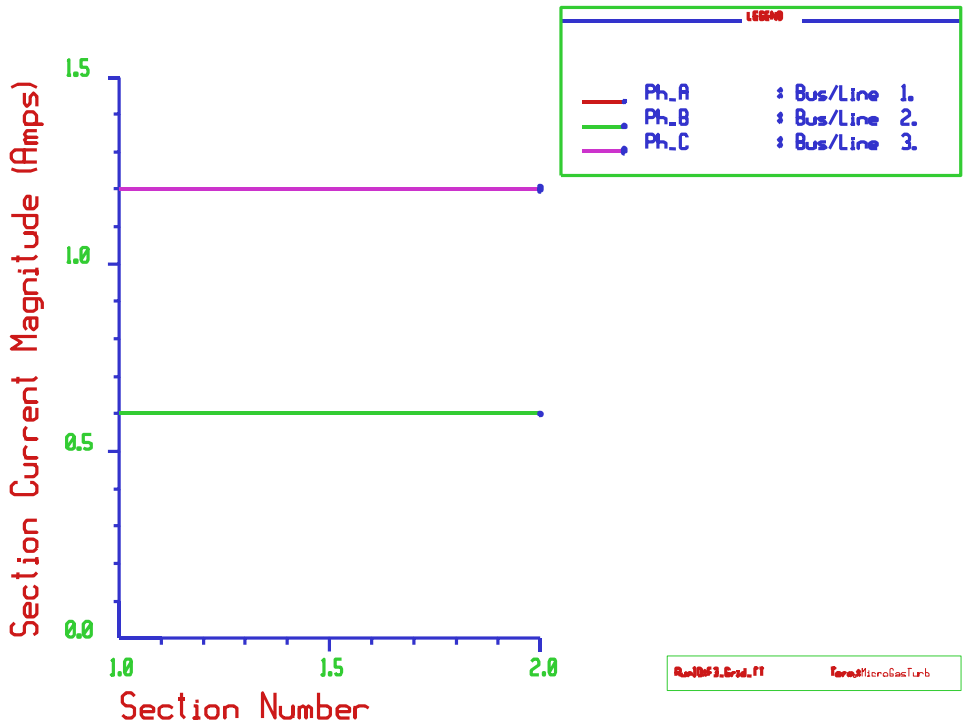


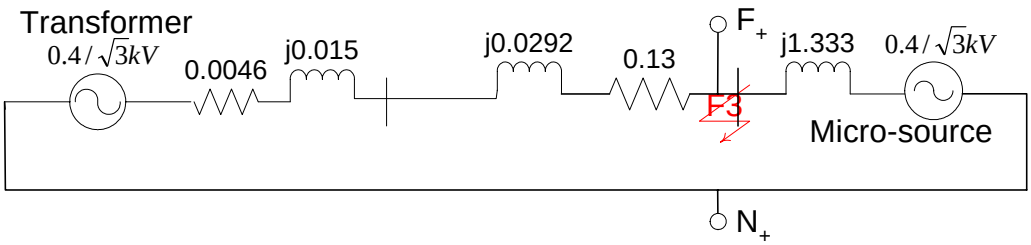
Figure 34: Fault current contribution from the micro-source for F3, TT system

5.3.2 Manual calculation

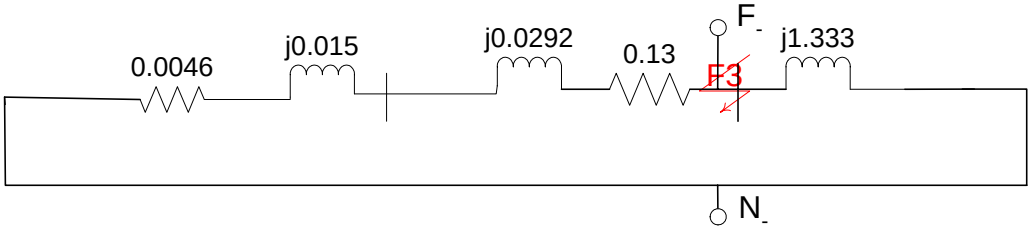
The fault currents for the fault F3 are calculated with the use of sequence networks.

5.3.2.1 TN-C-S system

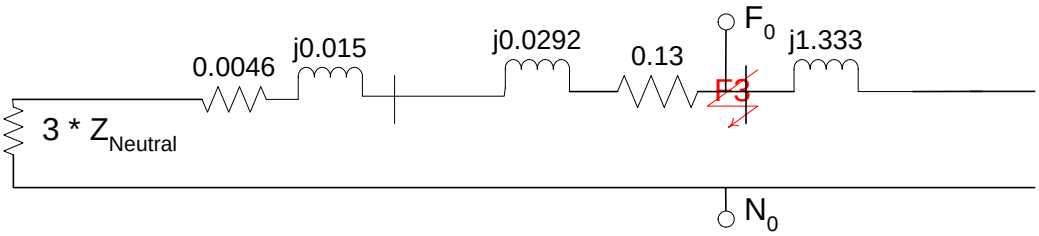
The positive sequence network for F3, TN network at 0.4 kV



The negative sequence network for F3, TN network at 0.4 kV



The zero sequence network for F3, TN network at 0.4 kV



The positive and negative sequence impedances,

$$Z_1 = Z_2 = (0.1346 + j\,0.0442) \text{ parallel to } (j\,1.333)$$

$$= 0.1319 \angle 27.8$$

Since F2 is at the end of the feeder, $Z_{Neutral} = (0.13 + j0.0292)$

$$Z_0 = 3 * (0.13 + j0.0292) + (0.1346 + j0.0442)$$

From Equation (4) $$I_{fault} = \frac{3 * V}{Z_1 + Z_2 + Z_0}$$

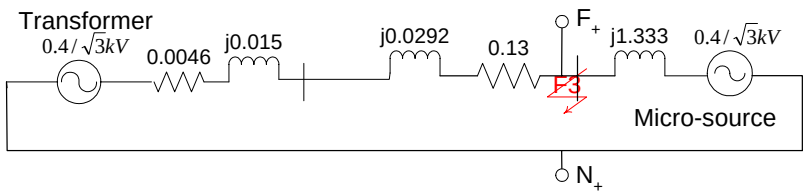
The rms value of the fault current,

$$I_{F3-TN} = 863.8 \angle -18.6 A \qquad \text{Equation (16)}$$

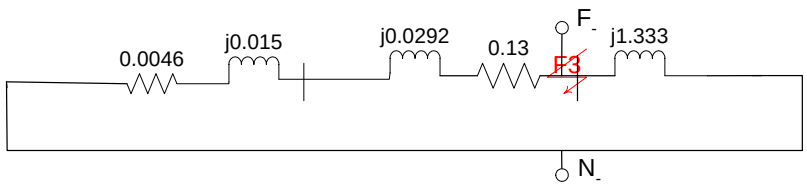
5.3.2.2 TT system

The positive sequence network and the negative sequence network remain the same as for those in the TN system. However the zero sequence network parameters change according to the TT earthing method.

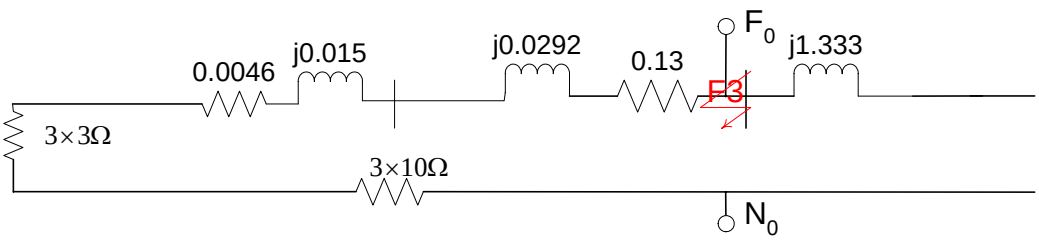
The positive sequence network for F3, TT network at 0.4 kV



The negative sequence network for F3, TT network at 0.4 kV



The zero sequence network for F3, TT network at 0.4 kV



The positive and negative sequence impedances,

$Z_1 = Z_2$ = (0.1346+ j 0.0442) parallel to (j 1.333)

= 0.1319 ∠27.8

Consumer installation earth resistance is = 10 ohms. Then the zero sequence impedance, $Z_0 = 3*(10+3)+(0.1346+j0.0442)$

From Equation (4) $$I_{fault} = \frac{3*V}{Z_1+Z_2+Z_0}$$

The rms value of the fault current,

$$I_{F3-TT} = 17.53\angle -0.2A \qquad \text{Equation (17)}$$

6.0 Islanded operation

According to the proposed control schemes for a MicroGrid, if a fault occurs on the main distribution network, the MicroGrid will continue to operate in an island by opening the circuit breaker upstream of the main distribution transformer [3, 9]. Therefore the MicroGrid would not lose the source earth at the distribution transformer in islanded operation.

The flywheel is considered as the main fault current source in the event of a fault in an islanded MicroGrid. The flywheel provides either 3 per unit or 5 per unit of its rated current under fault conditions.

6.1 A fault on the MicroGrid network – F2

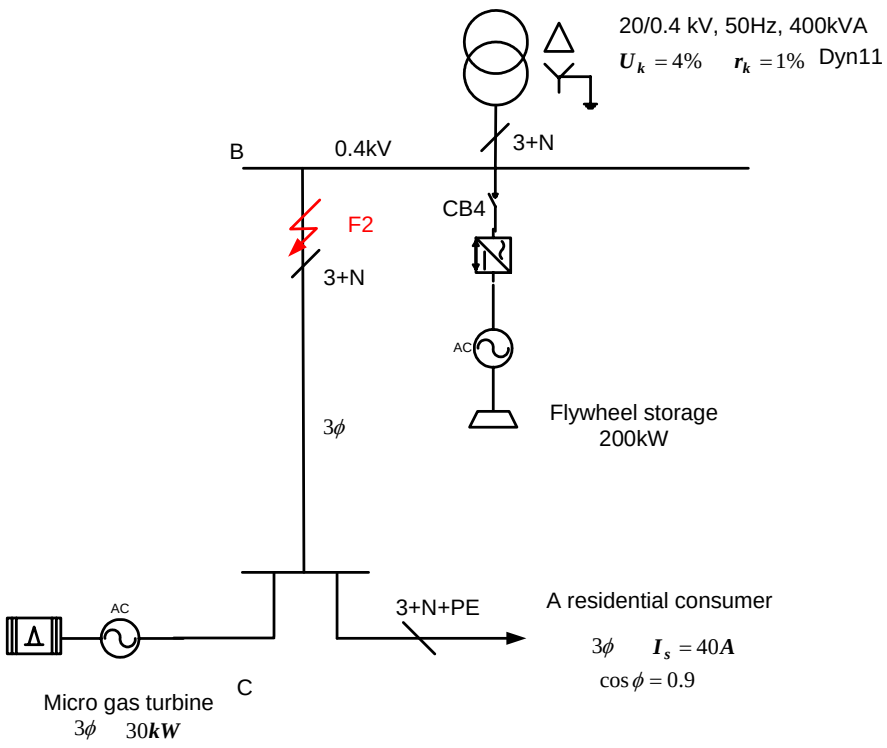


Figure 35: A fault on the MicroGrid network for islanded operation – F2

The flywheel is connected to the 0.4kV bus bar and CB4 is kept closed during islanded operation. The flywheel acts as the main source of fault current and the transformer earth impedance, 3 ohms, is retained in the system. The fault current sources for this scenario are the flywheel and the micro gas turbine. Therefore a

simplified model was obtained as shown in Figure 36. The flywheel parameters are given for the case where it provides 3 p.u. fault current and it was assumed that the flywheel operates with unity power factor. All impedances are specified at 0.4kV voltage.

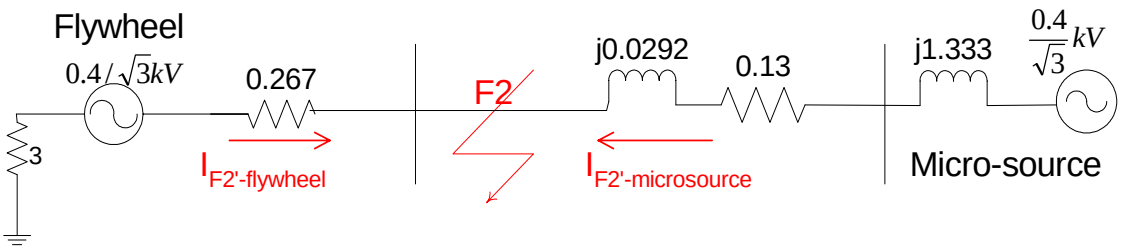


Figure 36: The islanded network for a fault on the MicroGrid network – F2

The MicroGrid network consists of a 400m long feeder and the micro-source at the end of the feeder. The micro-source neutral is unearthed according to the proposed guidelines for earthing in a MicroGrid [3]. The fault F2 is assumed to be at the beginning of the feeder.

6.1.1 Simulation results

The above network was modelled in SPLITS with TN and TT as the earthing system. The fault current magnitudes are determined by simulating a phase-to-earth fault on the phase C. The flywheel is assumed to provide 3 p.u. fault current. The fault current contribution from the flywheel is denoted by $I_{F2'-flywheel}$ and the fault current contribution from the Micro-source is $I_{F2'-MicroSource}$.

6.1.1.1 TN-C-S system

The simulation data and the CDEGS report for the fault F2 in a TN-C-S system in islanded operation is given in Annexure C6 of this report. The total fault current is 889.5A and is shown in Figure37.

The fault currents $I_{F2'-flywheel-TN}$ and $I_{F2'-MicroSource-TN}$ for a fault F2 on an islanded MicroGrid with a TN-C-S earthing system are shown in Figure 38 and Figure 39 respectively. The fault current from the flywheel, $I_{F2'-MicroSource-TN}$ is approximately 860A and the fault current from the micro gas turbine, $I_{F2'-MicroSource-TN}$, is about 112A.

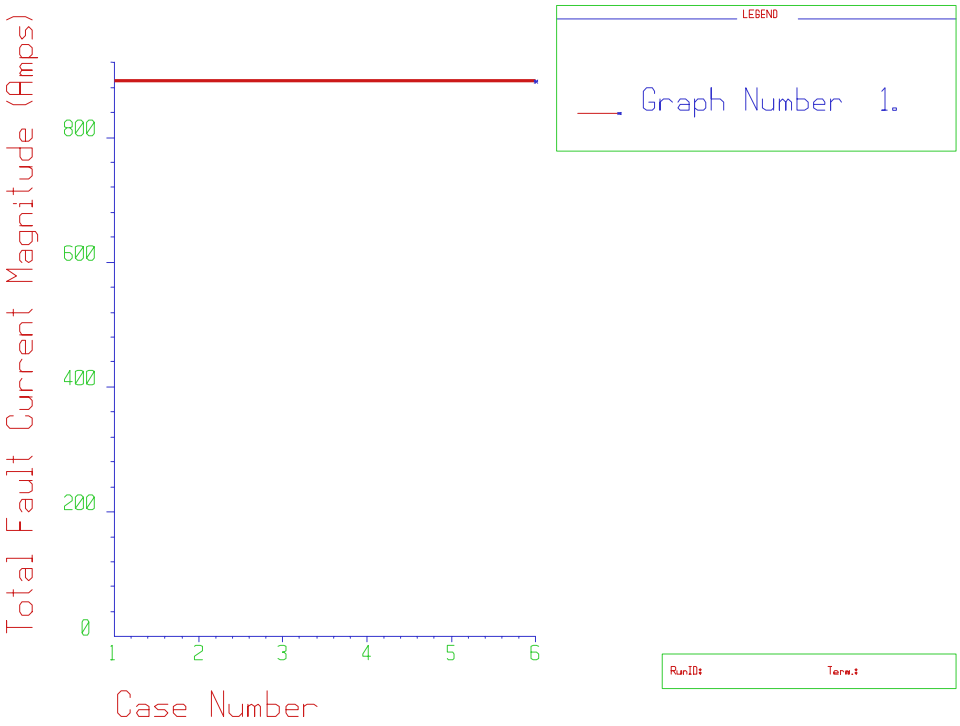


Figure 37: Total fault current for fault F2 in islanded operation, TN network

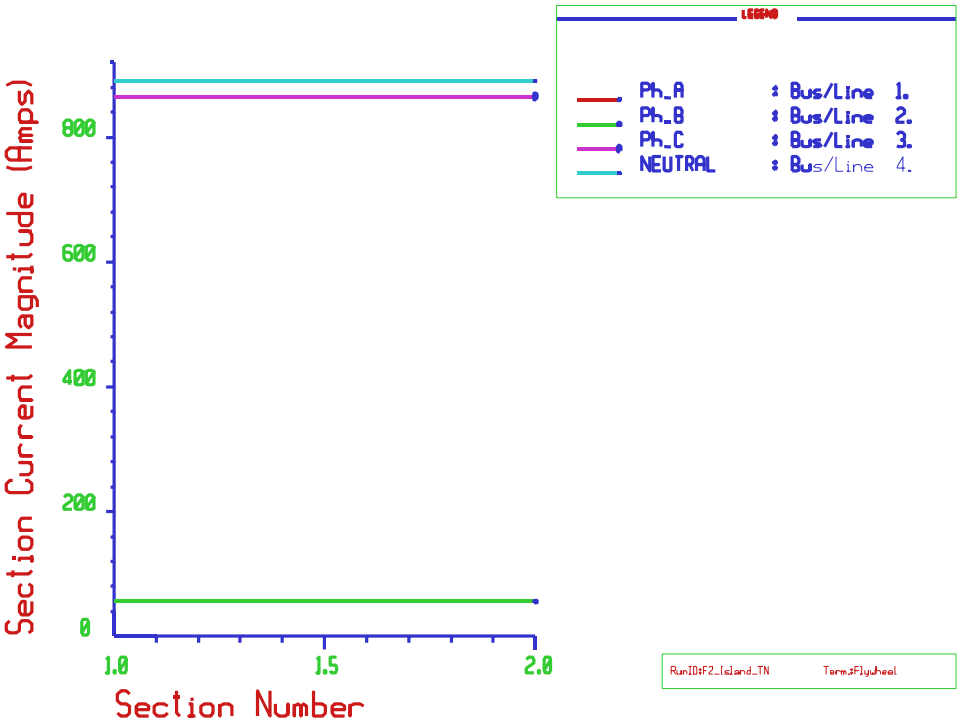


Figure 38: Fault current contribution from the flywheel for F2, islanded, TN

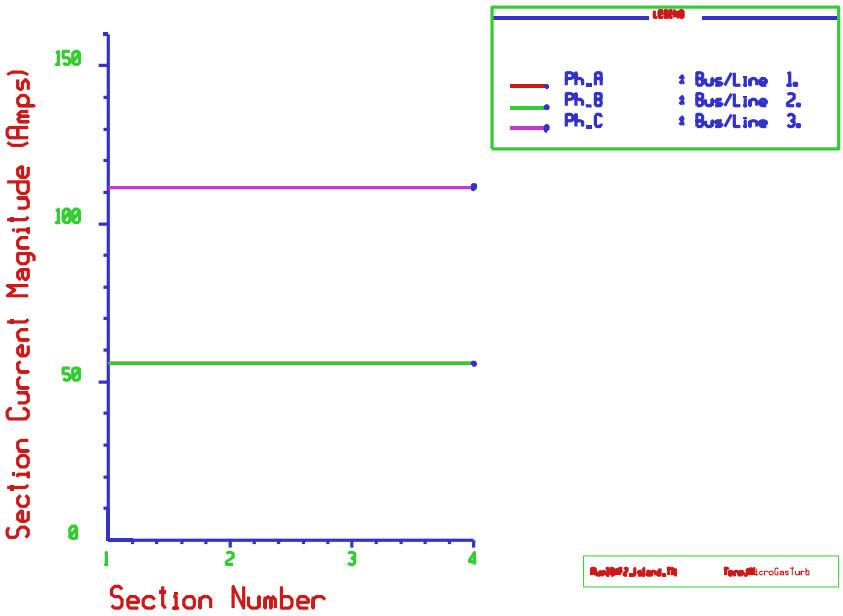


Figure 39: Fault current contribution from the micro-source for F2, islanded, TN

6.1.1.2 TT system

The simulation data and the CDEGS report the fault F2 in a TT system in islanded operation is given in Annexure C7 of this report. The total fault current is around 17A and is shown in Figure 40.

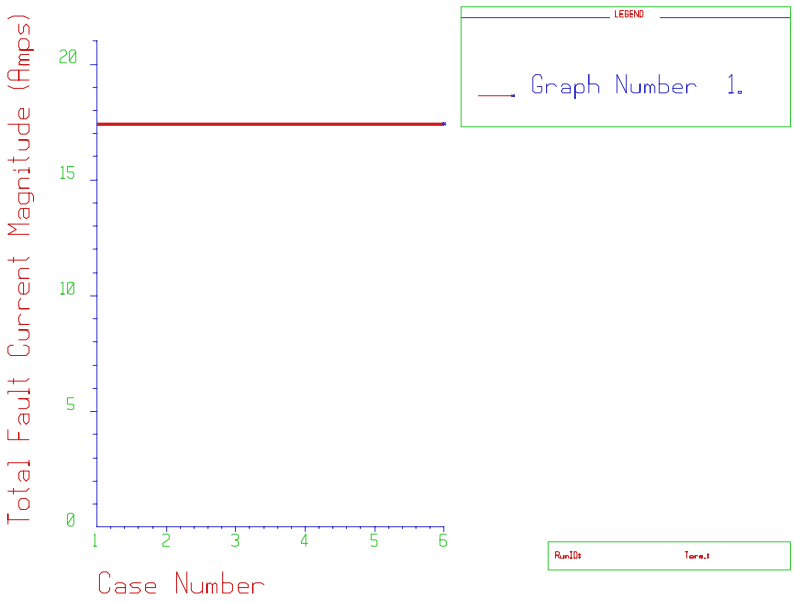


Figure 40: Total fault current for fault F2 in islanded operation, TT network

Figure 41 and Figure 42 show the fault currents provided by the flywheel and the micro-source for a fault F3 on an islanded MicroGrid with a TT earthing system. The fault current from the flywheel is approximately 17A and the fault current contribution from the micro gas turbine is around 2A.

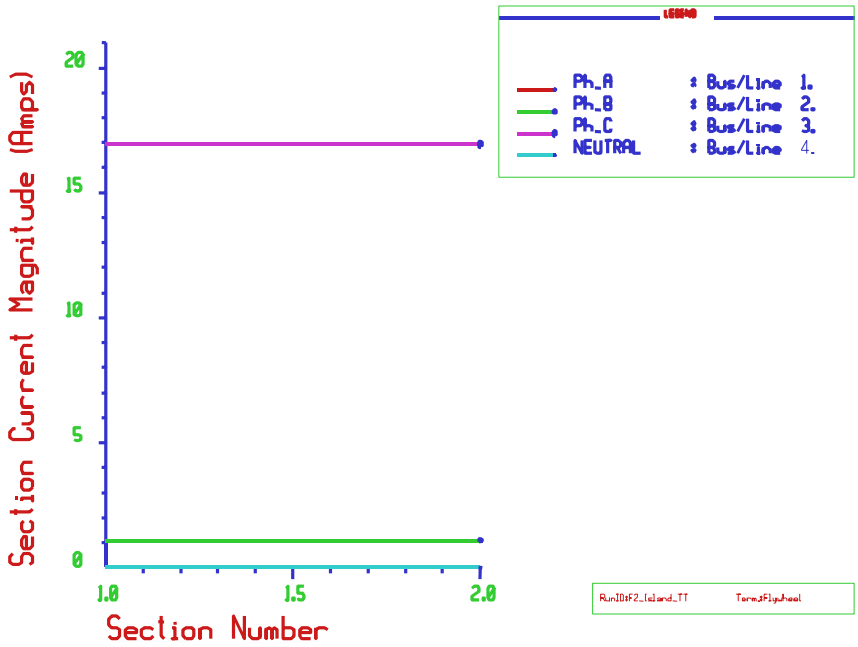


Figure 41: Fault current contribution from the flywheel for F2, islanded, TT

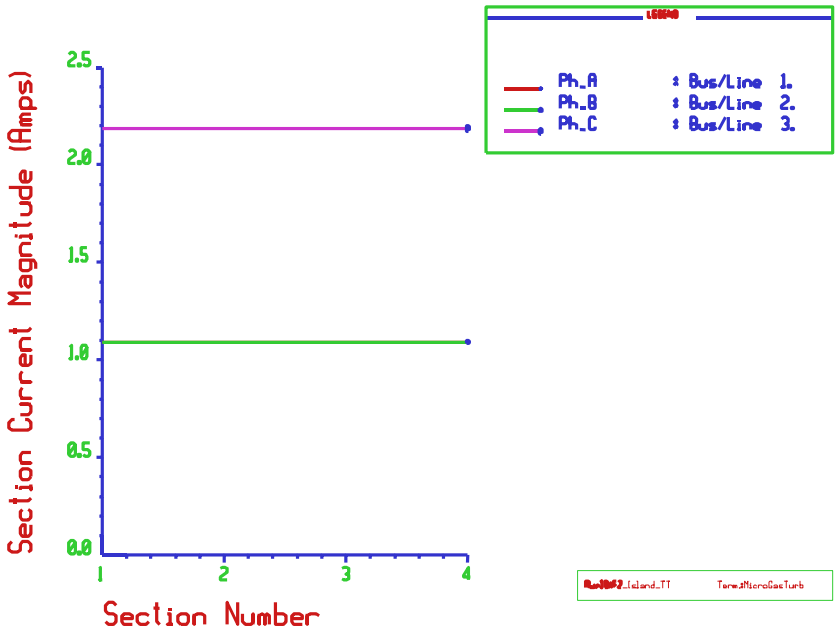


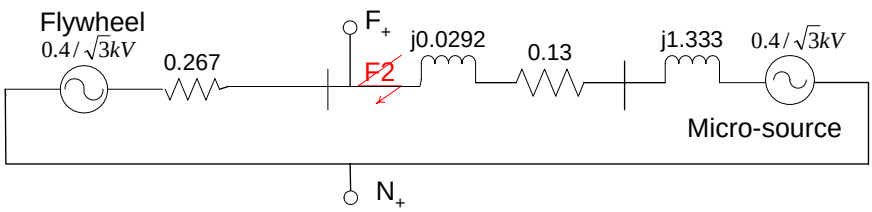
Figure 42: Fault current contribution from the micro-source for F2, islanded, TT

6.1.2 Manual calculations

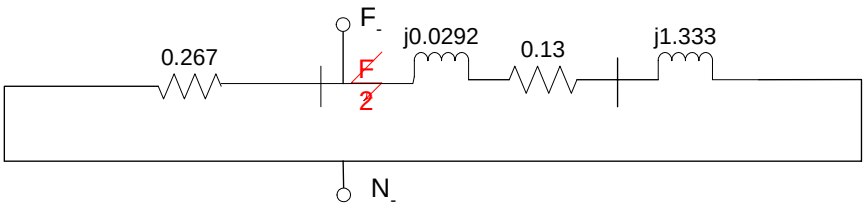
The fault currents for the fault F2 in islanded operation are calculated in this section. The same approach taken for grid-connected operation is carried out with the use of sequence networks.

6.1.2.1 TN-C-S system

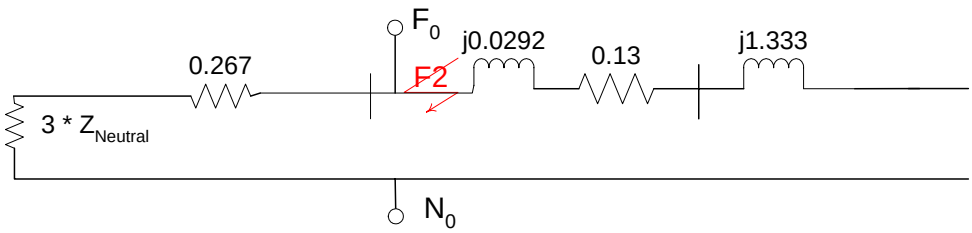
The positive sequence network for F2, islanded, TN at 0.4 kV



The negative sequence network for F2, islanded, TN at 0.4 kV



The zero sequence network for F2, islanded, TN at 0.4 kV



The positive and negative sequence impedances,

$$Z_1 = Z_2 = (0.267) \text{ parallel to } (0.13 + j\,1.3622)$$

$$= 0.257 \angle 10.8$$

Since F2 is at the beginning of the feeder, $Z_{Neutral} = 0$

$$Z_0 = 3 * 0 + (0.267)$$

From Equation (4) $$I_{fault} = \frac{3 * V}{Z_1 + Z_2 + Z_0}$$

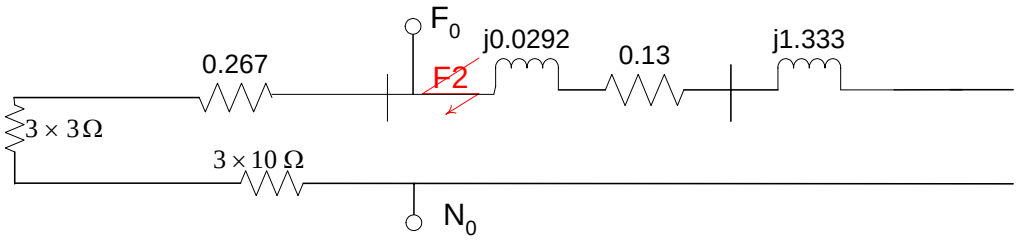
The rms value of the fault current,

$$I_{F2'-TN} = 886.9 \angle -7.0 A \qquad \text{Equation (18)}$$

6.2.2.2 TT system

The positive sequence network and the negative sequence network remain the same as for that in the TN system. However the zero sequence network parameters change according to the TT earthing method.

The zero sequence network for F2, islanded, TT at 0.4 kV



The positive and negative sequence impedances,

$$Z_1 = Z_2 = (0.267) \text{ parallel to } (0.13 + j\,1.3622)$$

$$= 0.257 \angle 10.8$$

Consumer installation earth resistance is taken as 10 ohms. Then the zero sequence impedance,

$$Z_0 = 3*(10+3)+(0.267)$$

$$Z_0 = 39.267$$

From Equation (4) $$I_{fault} = \frac{3*V}{Z_1 + Z_2 + Z_0}$$

The rms value of the fault current,

$$I_{F2'-TT} = 17.35\angle 0A \qquad \text{Equation (19)}$$

6.2 A fault at a load – F3

The fault F3 occurs at a load located at the end of the MicroGrid feeder. The fault currents are fed in to the fault by the flywheel and the micro gas turbine.

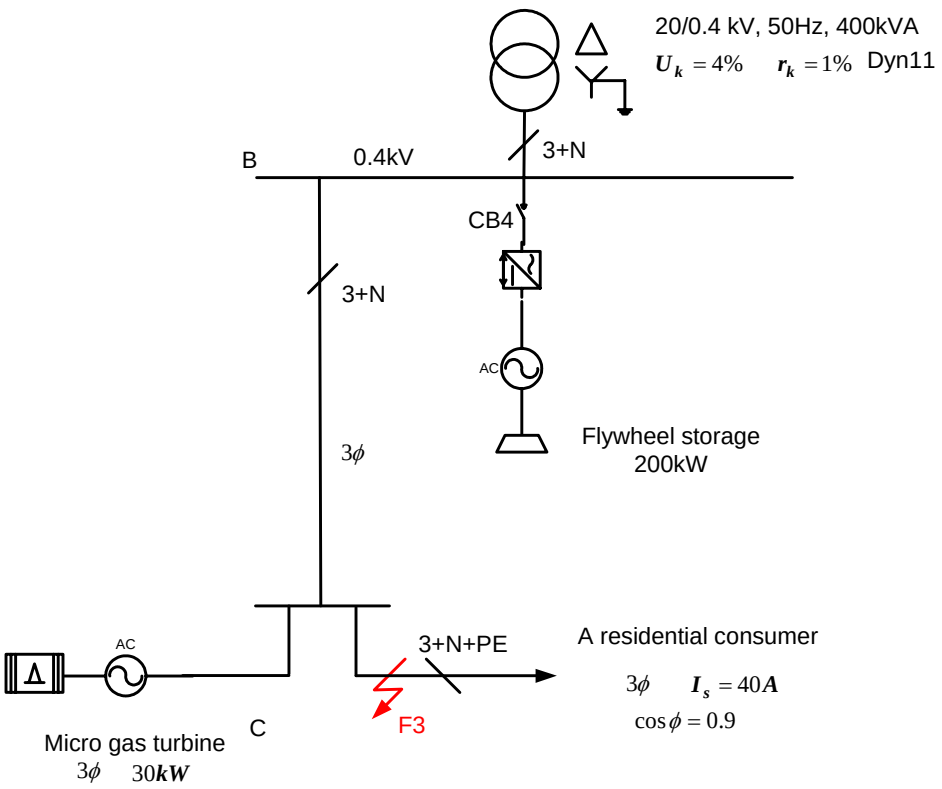


Figure 43: A fault at a load in the MicroGrid for islanded operation – F3

A simplified network of the above MicroGrid is shown in Figure 44 where it is assumed that the flywheel provides 3 pu of its rated current for a fault at unity power factor.

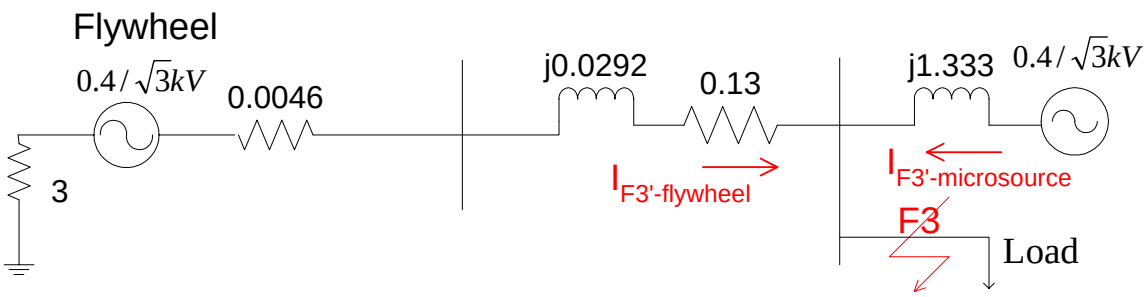


Figure 44: Simple network for fault at a load in an islanded MicroGrid

6.2.1 Simulation results

The fault current magnitudes are determined for a single-phase-to-earth fault on the phase C of the above system. The flywheel is assumed to provide 3 pu fault current. Two cases of the system are simulated, one with TN-C-S earthing and the other with TT earthing. The fault current contribution from the flywheel is denoted by $I_{F3'-flywheel}$ and the fault current contribution from the micro-source is $I_{F3'-MicroSource}$.

6.2.1.1 TN-C-S system

The simulation data and the CDEGS report for the fault F3 in a TN-C-S system in islanded operation is given in Annexure C8 of this report. The total fault current is about 453A and is illustrated in Figure 45.

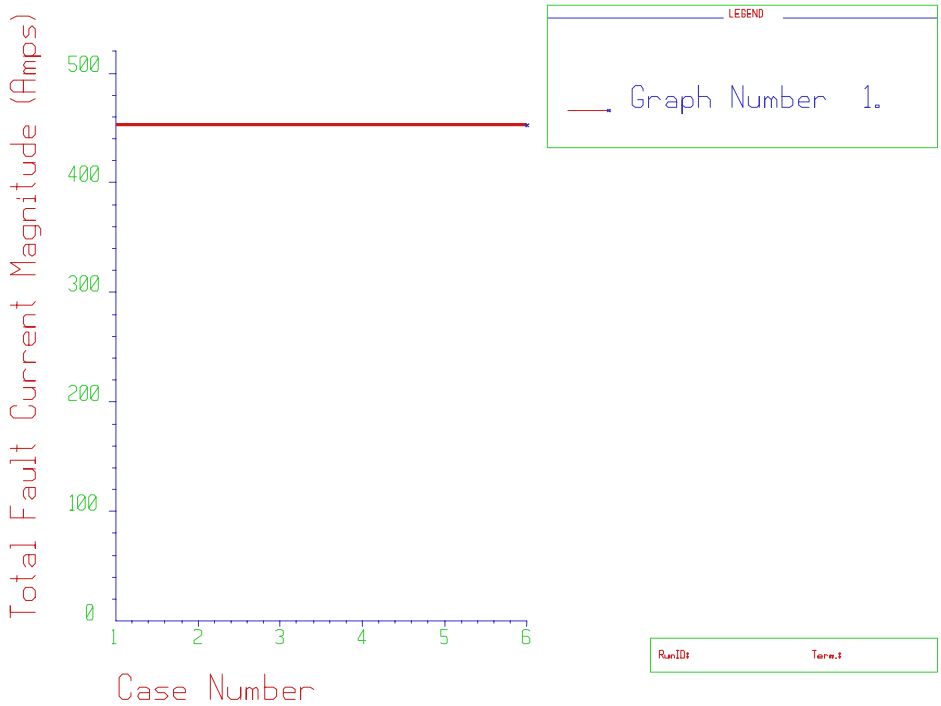


Figure 45: Total fault current for a fault at a load in an islanded MicroGrid, TN

The fault current from the flywheel $I_{F3'-flywheel-TN}$ is shown in Figure 46 and is approximately equal to 430A. The fault current from the micro gas turbine, $I_{F3'-MicroSource-TN}$ is around 85A as shown in Figure 47.

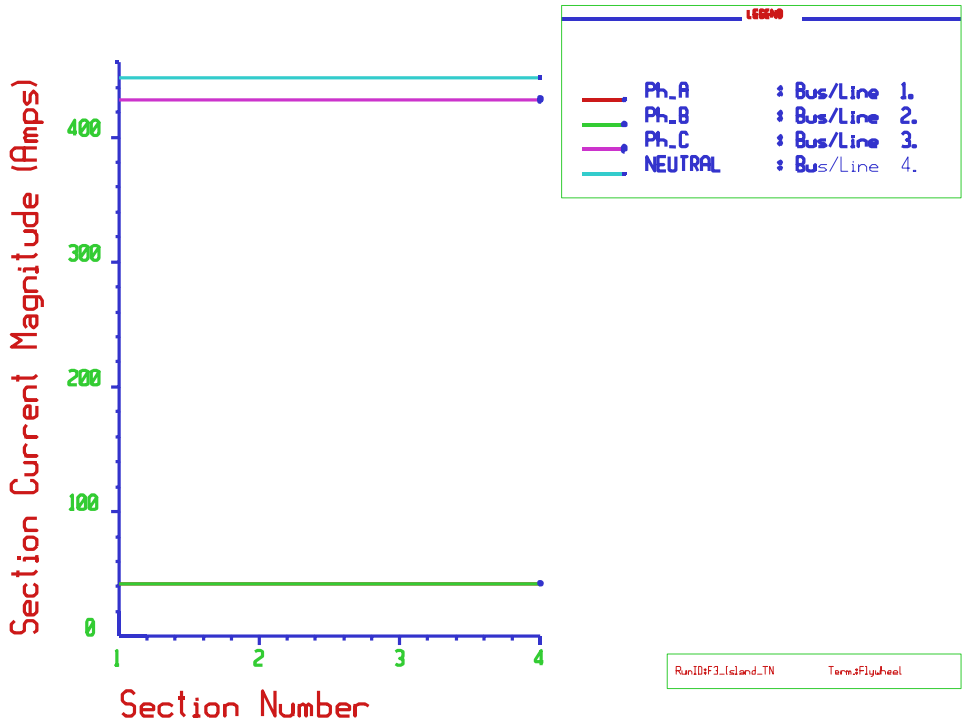


Figure 46: Fault current contribution from the main grid side for F3, islanded, TT

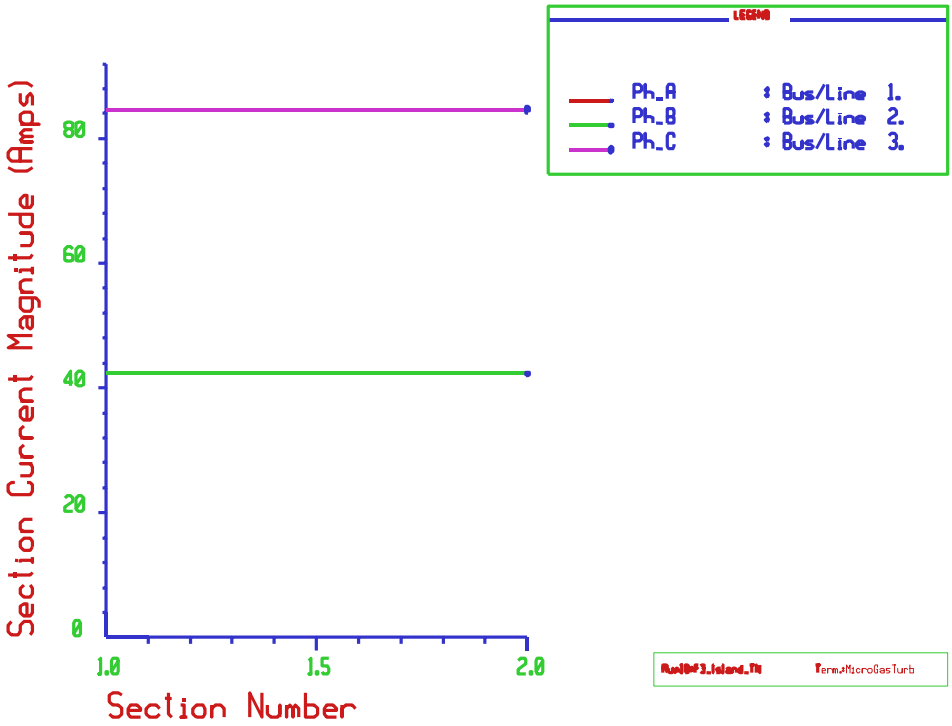


Figure 47: Fault current contribution from the micro-source for F3, islanded, TN

6.2.1.2 TT system

The simulation data and the CDEGS report for the fault F3 in a TT system in islanded operation is given in Annexure C9. The total fault current is approximately 17A, as shown in Figure 48.

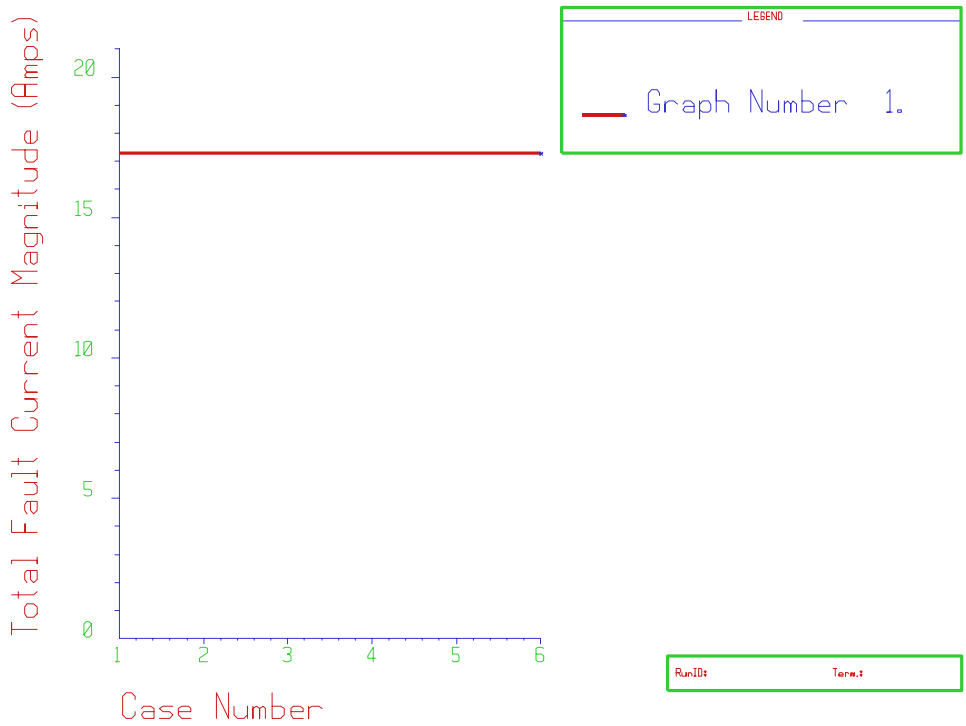


Figure 48: Total fault current for a fault at a load in an islanded MicroGrid, TT

The fault currents $I_{F3'-flywheel-TT}$ and $I_{F3'-MicroSource-TT}$ for a fault F3 on an islanded MicroGrid with a TT neutral earthing system are shown in Figure 49 and Figure 50 respectively. The fault current from the flywheel is approximately 16A and the micro gas turbine provides about 3A of fault current.

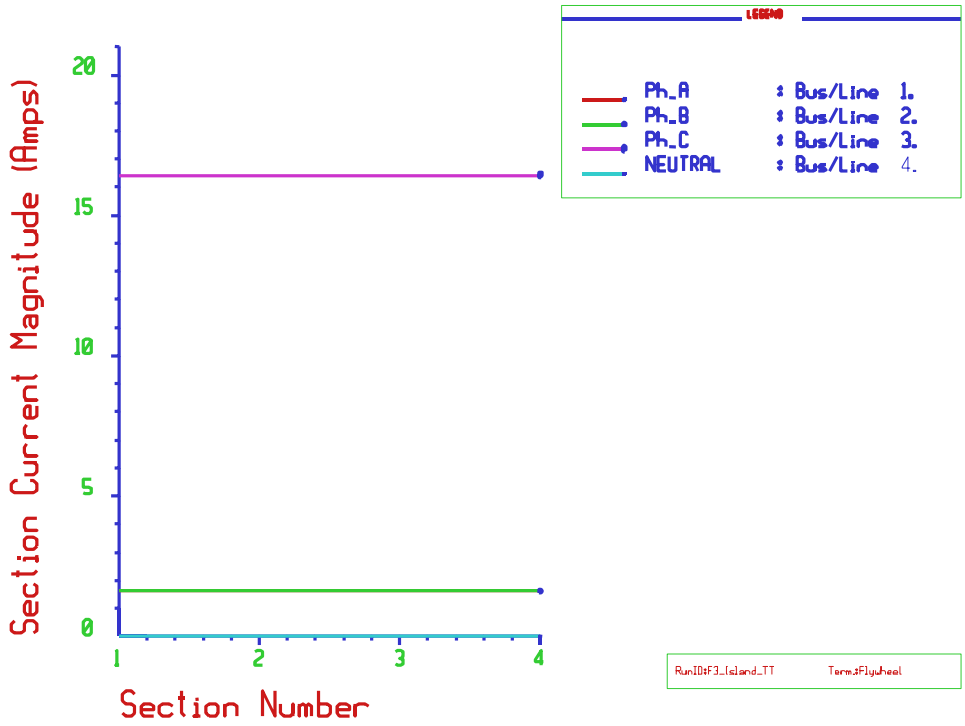


Figure 49: Fault current contribution from the main grid side for F3, islanded, TT

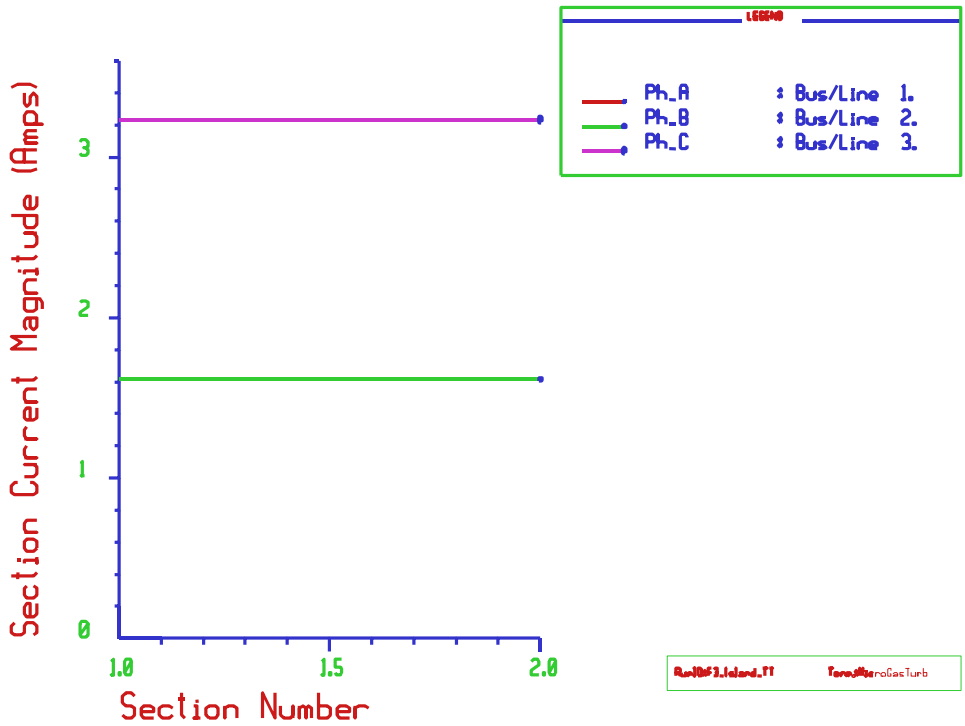


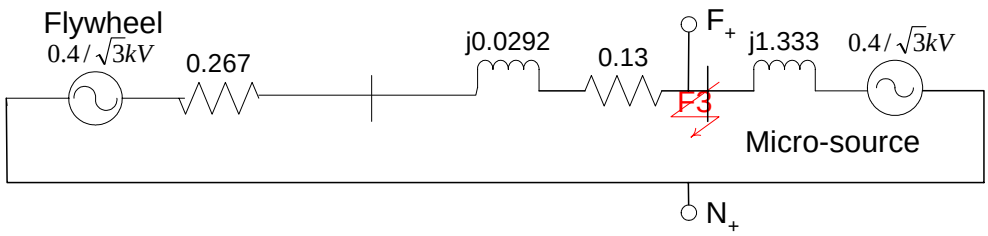
Figure 50: Fault current contribution from the micro-source for F3, islanded, TT

6.2.2 Manual calculation

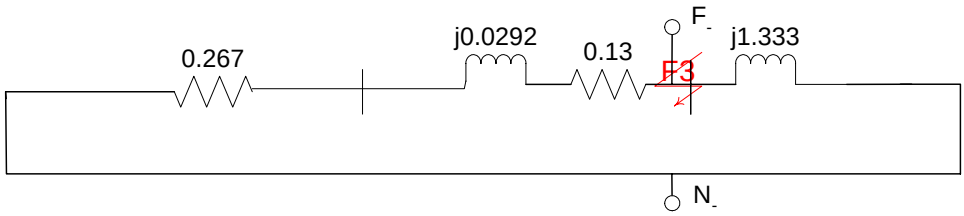
The fault currents for the fault F3 in islanded operation are calculated with the use of sequence networks.

6.2.2.1 TN-C-S system

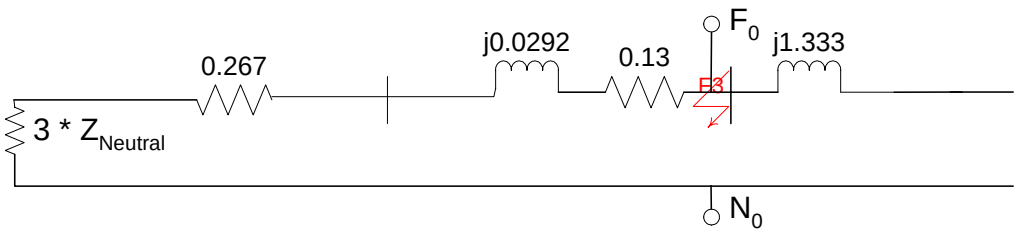
The positive sequence network for F3, islanded, TN at 0.4 kV



The negative sequence network for F3, islanded, TN at 0.4 kV



The zero sequence network for F3, islanded, TN at 0.4 kV



The positive and negative sequence impedances,

$$Z_1 = Z_2 = (0.397 + j\,0.0292) \text{ parallel to } (j\,1.333)$$

$$= 0.376 \angle 27.8$$

Since F3 is at the end of the feeder, $Z_{Neutral} = (0.13 + j0.0292)$

$$Z_0 = 3 * (0.13 + j0.0292) + (0.397 + j0.0292)$$

From Equation (4) $$I_{fault} = \frac{3 * V}{Z_1 + Z_2 + Z_0}$$

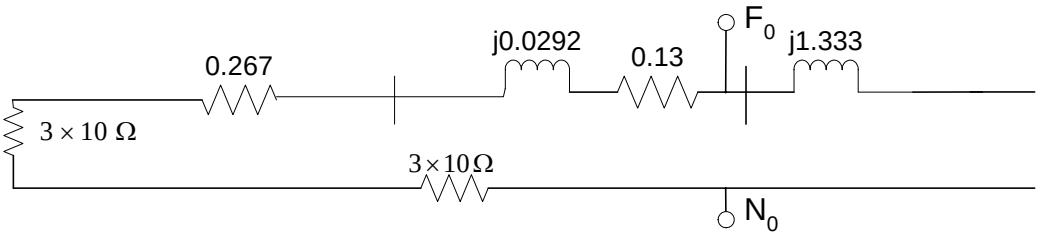
The rms value of the fault current,

$$I_{F3-TN} = 452.3 \angle -17.8 A \qquad \text{Equation (20)}$$

6.2.2.2 TT system

The positive sequence network and the negative sequence network remain the same as for that in the TN system. The parameters for the zero sequence network are changed according to the TT earthing method.

The zero sequence network for F3, islanded, TT at 0.4 kV



The positive and negative sequence impedances,

$Z_1 = Z_2$ = (0.397+ j 0.0292) parallel to (j 1.333)

= 0.376 ∠27.8

Consumer installation earth resistance is taken as 10 ohms. Then the zero sequence impedance,

$$Z_0 = 3*(10+3) + (0.397 + j0.0292)$$

$$Z_0 = (39.397 + j0.0292)$$

From Equation (4) $$I_{fault} = \frac{3*V}{Z_1 + Z_2 + Z_0}$$

The rms value of the fault current,

$$I_{F3-TT} = 17.22\angle -0.5A \qquad \text{Equation (21)}$$

7.0 Conclusions

The fault current distribution in a MicroGrid for different faults in grid-connected operation and islanded operation had been studied. A single-phase-to-earth fault had been simulated using SPLITS sub module of CDEGS software. The fault currents have been derived through simulations and hand calculations. The fault current contributions from each source for different faults have been presented.

Summary of the results are presented in Table 2. The simulation results and the calculated values for the case where the flywheel provides 5 p.u. of its rated current also have been included. Please note that the fault currents for the fault F1 are specified at 20 kV line voltage while all other currents are based on 0.4 kV line voltage.

Operating mode	Earthing system	Fault type	Total Fault current (A)		CDEGS results	
			CDEGS simulation result	Manually calculated value	Total earth current	Neutral current
Grid connected	TN	F1	3,073	3,073	-	-
	TN-C-S	F2	14,828	14,778	0	14,828
		F3	858	864	8.7	850
	TT	F2	17.8	17.7	17.8	0
		F3	17.6	17.5	17.6	0
Islanded (3 pu flywheel current)	TN-C-S	F2	889	887	0	889
		F3	452	452	4.6	452
	TT	F2	17.4	17.6	17.4	0
		F3	17.3	17.2	17.3	0
Islanded (5 pu flywheel current)	TN-C-S	F2	1462	1458	0	1462
		F3	558	557	5.7	552.8
	TT	F2	17.5	17.5	17.5	0
		F3	17.4	17.3	17.4	0

Table 2: Fault currents in a MicroGrid

This study has re-confirmed the following facts regarding the performance of each earthing system.

1. The return path for the fault current in a TN-C-S system is the neutral conductor and only a small current is directed in to the earth.
2. The return path for the fault current in a TT system is the earth and the total fault current flows in to the earth.
3. The fault currents in a TN system are high due to the low impedance of the fault loop impedance (the fault return path being the neutral)
4. The fault current values in a TT system are very low compared to TN systems, due to the high earthing impedance in the fault loop.

It is also interesting to note the following observations about the fault current distribution in a MicroGrid.

- In grid-connected operation, the major fault current contributor is the main distribution network with the micro-source providing only a small fraction of the fault current.
- The flywheel plays a very important role in islanded operation as the main source of fault currents. It is apparent that the micro-source cannot provide enough fault currents in the event of a fault to operate conventional overcurrent protection devices.

Since the fault currents in a MicroGrid have been calculated, the step and touch voltages can be evaluated now to assess the safety of the MicroGrid grounding system.

8.0 References

1. Lorentzou, M., Papathanassiou, S., Hatziargyriou, N., "Review of Earthing Practices in LV networks and installations", Internal report for MicroGrids project, January 2004

2. Jayawarna, N., Jenkins, N., "Low Voltage Earthing in the UK", Draft 2, Internal report for MicroGrids project, May 2004

3. Jayawarna, N., Lorentzou, M., Papathanassiou, S., "Review of Earthing in a MicroGrid", Internal report for MicroGrids project, April 2004.

4. "Large Suburban Substation Grounding System Analysis: Measurements and Computer Modelling", Version 8, January 2000, Safe Engineering Services & technologies Ltd., Montreal, Canada

5. "Urban Area Substation Analysis", Version 8, January 2000, Safe Engineering Services & technologies Ltd., Montreal, Canada

6. Lorentzou, M., "Application of EMTP for investigating the performance of LV earthing systems", Draft, Internal report for MicroGrids project, June 2004

7. G E C ALSTHOM T&D, "Protective Relays Application Guide", 3rd Edition, 1987.

8. Weedy, B.M., Cory, B.J., "Electric Power Systems", John Wiley & Sons, 4th Edition, 1998.

9. Xueguang, W., Jayawarna, N., Jenkins, N., "Electrical Protection Schemes for the MicroGrid", MicroGrids project internal report, July 2004

Annexure A: SPLITS simulation reports for simple NTUA system

Annexure A1: SPLITS report for TN-C-S system

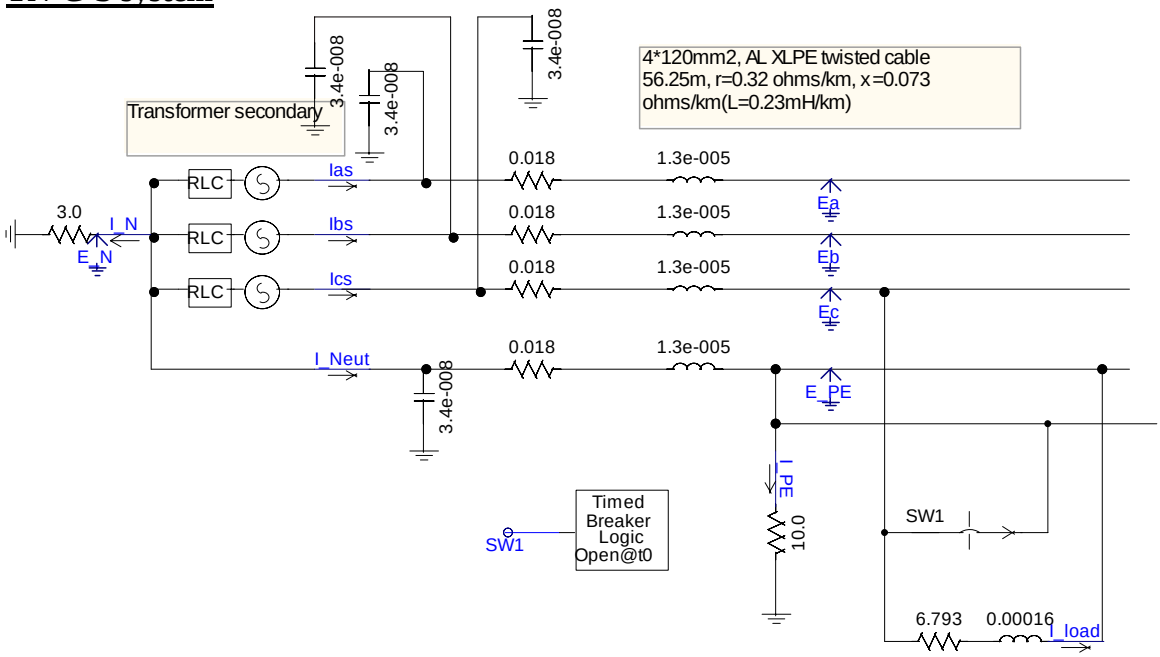
```
Run ID.....................................: NTUA_TN
 Central Station Name.......................: Load
 Total Number of Terminals..................:   1
 Total Number of Busses.....................:   4
 Total Number of Different Resistivity Values.:   6
 Selection of SAFETY Calculations...........: YES
 Printout Option............................: Detailed
 Base Resistivity Value.....................:   100.00     ohm-meters
 Base Fault Current Value...................:   10000.     amperes
1

 Central Station: Load

 Constant Resistance.......................:   10.000     ohms
 Variable Resistance......................:   0.0000     ohms/base
RESISTIVITY
 Reactance................................:   0.0000     ohms


 CENTRAL STATION BUS DATA
 ========================
 ------BUS------- Bus To Substation Neutral Impedance
 NO.     TYPE     RESISTANCE (ohms) REACTANCE (ohms)
 <-> <----------> <---------------> <--------------->
   1 Ph_A             0.10000E+12      0.10000E+13
   2 Ph_B             0.10000E+09      0.10000E+10
   3 Ph_C              0.0000           0.0000
   4 NEUTRAL           0.0000           0.0000
1
 Terminal No.    1 : LV_Transform

 Number of Sections..............:     1
 Constant Ground Impedance.......:   3.0000     +j   0.0000     ohms
 Variable Resistance.............:   0.0000     ohms/base RESISTIVITY

 Bus  Source Voltage (Kvolts)   Source Impedance (ohms)
 No.     REAL      IMAGINARY    RESISTANCE   REACTANCE    STATUS
 <-> <----------> <----------> <----------> <----------> <----->
   1  0.40000       0.0000      0.46000E-02  0.15000E-01   OK
   2 -0.20000      0.34641      0.46000E-02  0.15000E-01   OK
   3 -0.20000     -0.34641      0.46000E-02  0.15000E-01   OK
   4   0.0000       0.0000       0.0000       0.0000       OK
1
 Run Number.................................:     1
 TERMINAL GROUND SYSTEM (Magn./Angle)
 Term:   1 Total Earth Current...:   7.1859     Amps  /  -139.58     deg.
           Earth Potential Rise..:   21.558     Volts /  -139.58     deg.
 Body Current (Safe)...........:  0.16405     Amperes
 Body Current (Actual).........:  0.12665E-01 Amperes
 Stress Voltage (Safe).........:   902.27     Volts
 Stress Voltage (Actual).......:   69.658     Volts
 Top-Layer Resistivity.........:  0.10000E-03 Ohm-meters
 Grid Impedance................:   10.000     +j   0.0000     Ohms
                               < Magnitude / Angle >
 Total Fault Current...........:   4952.1     Amps  /  -149.53     degrees
 Total Neutral Current.........:   4945.3     Amps  /  -149.55     degrees
 Total Earth Current...........:   6.9658     Amps  /  -136.23     degrees
 Ground Potential Rise (GPR)...:   69.658     Volts /  -136.23     degrees
```

Annexure A2: SPLITS report for TT system

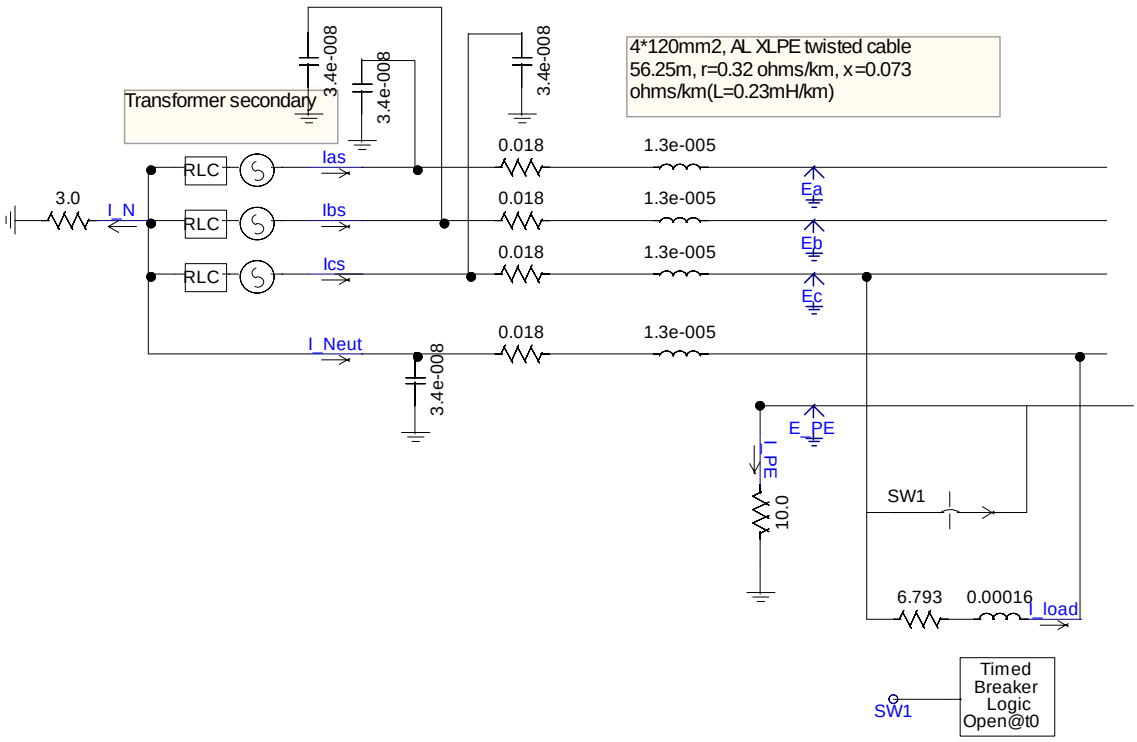
```
Run ID.....................................: NTUA_TT
 Central Station Name.......................: Load
 Total Number of Terminals..................:   1
 Total Number of Busses.....................:   4
 Total Number of Different Resistivity Values.:   6
 Selection of SAFETY Calculations...........: YES
 Printout Option............................: Detailed
 Base Resistivity Value.....................:   100.00     ohm-meters
 Base Fault Current Value...................:   10000.     amperes
1

 Central Station: Load

 Constant Resistance......................:   10.000     ohms
 Variable Resistance......................:   0.0000     ohms/base
RESISTIVITY
 Reactance................................:   0.0000     ohms


 CENTRAL STATION BUS DATA
 ========================
 ------BUS------- Bus To Substation Neutral Impedance
 NO.     TYPE     RESISTANCE (ohms) REACTANCE (ohms)
 <-> <----------> <---------------> <--------------->
   1 Ph_A             0.10000E+11      0.10000E+11
   2 Ph_B             0.10000E+11      0.10000E+11
   3 Ph_C              0.0000           0.0000
   4 NEUTRAL          0.10000E+08      0.10000E+10
1
 Terminal No.    1 : LV_Transform

 Number of Sections..............:     1
 Constant Ground Impedance.......:   3.0000     +j   0.0000     ohms
 Variable Resistance.............:   0.0000     ohms/base RESISTIVITY

 Bus  Source Voltage (Kvolts)   Source Impedance (ohms)
 No.     REAL      IMAGINARY    RESISTANCE   REACTANCE    STATUS
 <-> <----------> <----------> <----------> <----------> <----->
   1  0.40000       0.0000      0.46000E-02  0.15000E-01   OK
   2 -0.20000      0.34641      0.46000E-02  0.15000E-01   OK
   3 -0.20000     -0.34641      0.46000E-02  0.15000E-01   OK
   4   0.0000       0.0000       0.0000       0.0000       OK
1
 Run Number.....................................:     1
 TERMINAL GROUND SYSTEM (Magn./Angle)
 Term:   1 Total Earth Current...:   17.728     Amps  /  -120.08     deg.
           Earth Potential Rise..:   53.185     Volts /  -120.08     deg.
 Body Current (Safe)...........:  0.16405     Amperes
 Body Current (Actual).........:  0.70941E-01 Amperes
 Stress Voltage (Safe).........:   410.12     Volts
 Stress Voltage (Actual).......:   177.35     Volts
 Top-Layer Resistivity.........:  0.10000E-03 Ohm-meters
 Grid Impedance................:   10.000     +j   0.0000     Ohms
                                < Magnitude / Angle >
 Total Fault Current...........:   17.735     Amps  /  -120.08     degrees
 Total Neutral Current.........:  0.23053E-06 Amps  /   150.49     degrees
 Total Earth Current...........:   17.735     Amps  /  -120.08     degrees
 Ground Potential Rise (GPR)...:   177.35     Volts /  -120.08     degrees
```

Annexure B: PSCAD/ EMTDC models for simple NTUA system

TN-C-S system



TT system



Annexure C: SPLITS simulation reports for MicroGrid network

Annexure C1: SPLITS report for F1

```
Run ID.....................................: F1_Grid
 Central Station Name.......................: Grid Fault
 Total Number of Terminals..................:   2
 Total Number of Busses.....................:   3
 Total Number of Different Resistivity Values.:   1
 Selection of SAFETY Calculations...........: NO
 Printout Option............................: Detailed
 Base Resistivity Value.....................:   100.00     ohm-meters
 Base Fault Current Value...................:   1000.0     amperes

 Central Station: Grid Fault
 Constant Resistance.......................:   0.0000     ohms
 Variable Resistance.......................:   0.0000     ohms/base
RESISTIVITY
 Reactance.................................:   0.0000     ohms


 CENTRAL STATION BUS DATA
 ========================
 ------BUS------- Bus To Substation Neutral Impedance
 NO.     TYPE     RESISTANCE (ohms) REACTANCE (ohms)
 <-> <----------> <---------------> <--------------->
   1 Ph_A             0.10000E+07      0.10000E+07
   2 Ph_B             0.10000E+07      0.10000E+07
   3 Ph_C              0.0000           0.0000

 Terminal No.    1 : MainGrid
 Number of Sections..............:     2
 Constant Ground Impedance.......:   0.0000     +j   0.0000     ohms
 Variable Resistance.............:   0.0000     ohms/base RESISTIVITY

 Bus  Source Voltage (Kvolts)   Source Impedance (ohms)
 No.     REAL      IMAGINARY    RESISTANCE   REACTANCE    STATUS
 <-> <----------> <----------> <----------> <----------> <----->
   1   20.000       0.0000      0.76000       3.9200       OK
   2  -10.000       17.321      0.76000       3.9200       OK
   3  -10.000      -17.321      0.76000       3.9200       OK

 Terminal No.    2 : HVside_trans
 Number of Sections..............:     2
 Constant Ground Impedance.......:  0.10000E+11 +j   0.0000     ohms
 Variable Resistance.............:   0.0000     ohms/base RESISTIVITY

 Bus  Source Voltage (Kvolts)   Source Impedance (ohms)
 No.     REAL      IMAGINARY    RESISTANCE   REACTANCE    STATUS
 <-> <----------> <----------> <----------> <----------> <----->
   1   20.000       0.0000       10.000       40.000       OK
   2  -10.000       17.321       10.000       40.000       OK
   3  -10.000      -17.321       10.000       40.000       OK

 Run Number.................................:     1
 TERMINAL GROUND SYSTEM (Magn./Angle)
 Term:   1 Total Earth Current...:   3072.5     Amps  /   161.15     deg.
           Earth Potential Rise..:   0.0000     Volts /   0.0000     deg.
 Term:   2 Total Earth Current...:  0.40894E-06 Amps  /  -119.83     deg.
           Earth Potential Rise..:   4089.4     Volts /  -119.83     deg.
 Top-Layer Resistivity.........:   100.00     Ohm-meters
 Grid Impedance................:   0.0000     +j   0.0000     Ohms
 Total Fault Current...........:   3072.5     Amps  /   161.15     degrees
 Total Neutral Current.........:   0.0000     Amps  /   0.0000     degrees
 Total Earth Current...........:   3072.5     Amps  /   161.15     degrees
 Ground Potential Rise (GPR)...:   0.0000     Volts /   0.0000     degrees
```

Annexure C2: SPLITS report for F2, TN-C-S system– Grid-connected operation

```
Run ID.....................................: NTUA_TN
 Central Station Name.......................: Feeder
 Total Number of Terminals..................:   2
 Total Number of Busses.....................:   4
 Total Number of Different Resistivity Values.:   1
 Selection of SAFETY Calculations...........: NO
 Printout Option............................: Detailed
 Base Resistivity Value.....................:   100.00     ohm-meters
 Base Fault Current Value...................:   1000.0     amperes

 Central Station: Feeder
 Constant Resistance.......................:   10.000     ohms
 Variable Resistance......................:   0.0000     ohms/base
RESISTIVITY
 Reactance................................:   0.0000     ohms


 CENTRAL STATION BUS DATA
 ========================
 ------BUS------- Bus To Substation Neutral Impedance
 NO.     TYPE     RESISTANCE (ohms) REACTANCE (ohms)
 <-> <----------> <---------------> <--------------->
   1 Ph_A             0.10000E+12      0.10000E+13
   2 Ph_B             0.10000E+13      0.10000E+13
   3 Ph_C              0.0000           0.0000
   4 NEUTRAL           0.0000           0.0000
1
 Terminal No.    1 : LV_Transform
 Number of Sections...............:     2
 Constant Ground Impedance.......:   3.0000     +j   0.0000     ohms
 Variable Resistance.............:   0.0000     ohms/base RESISTIVITY

 Bus  Source Voltage (Kvolts)   Source Impedance (ohms)
 No.     REAL      IMAGINARY    RESISTANCE   REACTANCE    STATUS
 <-> <----------> <----------> <----------> <----------> <----->
   1  0.40000       0.0000      0.46000E-02  0.15000E-01   OK
   2 -0.20000      0.34641      0.46000E-02  0.15000E-01   OK
   3 -0.20000     -0.34641      0.46000E-02  0.15000E-01   OK
   4   0.0000       0.0000       0.0000       0.0000       OK
1
 Terminal No.    2 : MicroGasTurb
 Number of Sections...............:     4
 Constant Ground Impedance.......:   99999.     +j   0.0000     ohms
 Variable Resistance.............:   0.0000     ohms/base RESISTIVITY

 Bus  Source Voltage (Kvolts)   Source Impedance (ohms)
 No.     REAL      IMAGINARY    RESISTANCE   REACTANCE    STATUS
 <-> <----------> <----------> <----------> <----------> <----->
   1  0.40000       0.0000       0.0000       1.3330       OK
   2 -0.20000      0.34641       0.0000       1.3330       OK
   3 -0.20000     -0.34641       0.0000       1.3330       OK
   4   0.0000       0.0000      0.10000E-03   0.0000      DUMMY
1
 Run Number...................................:     1
 TERMINAL GROUND SYSTEM (Magn./Angle)
 Term:   1 Total Earth Current...:  0.21704E-02 Amps  /   151.46     deg.
           Earth Potential Rise..:  0.65111E-02 Volts /   151.46     deg.
 Term:   2 Total Earth Current...:  0.77552E-03 Amps  /  -120.08     deg.
           Earth Potential Rise..:   77.552     Volts /  -120.08     deg.
 Top-Layer Resistivity.........:   100.00     Ohm-meters
 Grid Impedance................:   10.000     +j   0.0000     Ohms
                               < Magnitude / Angle >
 Total Fault Current...........:   14828.     Amps  /   166.98     degrees
 Total Neutral Current.........:   14828.     Amps  /   166.98     degrees
 Total Earth Current...........:  0.23294E-02 Amps  /   171.26     degrees
 Ground Potential Rise (GPR)...:  0.23294E-01 Volts /   171.26     degrees
```

Annexure C3: SPLITS report for F2, TT system– Grid-connected operation

```
Run ID.....................................: F2_Grid_TT
 Central Station Name.......................: Feeder
 Total Number of Terminals..................:   2
 Total Number of Busses.....................:   4
 Total Number of Different Resistivity Values.:   1
 Selection of SAFETY Calculations...........: NO
 Printout Option............................: Detailed
 Base Resistivity Value.....................:   100.00     ohm-meters
 Base Fault Current Value...................:   1000.0     amperes

 Central Station: Feeder
 Constant Resistance.......................:   10.000     ohms
 Variable Resistance......................:   0.0000     ohms/base
RESISTIVITY
 Reactance................................:   0.0000     ohms


 CENTRAL STATION BUS DATA
 ========================
 ------BUS------- Bus To Substation Neutral Impedance
 NO.     TYPE     RESISTANCE (ohms) REACTANCE (ohms)
 <-> <----------> <---------------> <--------------->
   1 Ph_A             0.10000E+11      0.10000E+11
   2 Ph_B             0.10000E+11      0.10000E+11
   3 Ph_C              0.0000           0.0000
   4 NEUTRAL          0.10000E+11      0.10000E+10
1
 Terminal No.    1 : LV_Transform
 Number of Sections...............:     2
 Constant Ground Impedance.......:   3.0000     +j   0.0000     ohms
 Variable Resistance.............:   0.0000     ohms/base RESISTIVITY

 Bus  Source Voltage (Kvolts)   Source Impedance (ohms)
 No.     REAL      IMAGINARY    RESISTANCE   REACTANCE    STATUS
 <-> <----------> <----------> <----------> <----------> <----->
   1  0.40000       0.0000      0.46000E-02  0.15000E-01   OK
   2 -0.20000      0.34641      0.46000E-02  0.15000E-01   OK
   3 -0.20000     -0.34641      0.46000E-02  0.15000E-01   OK
   4   0.0000       0.0000       0.0000       0.0000       OK
1
 Terminal No.    2 : MicroGasTurb
 Number of Sections...............:     4
 Constant Ground Impedance.......:   99999.     +j   0.0000     ohms
 Variable Resistance.............:   0.0000     ohms/base RESISTIVITY

 Bus  Source Voltage (Kvolts)   Source Impedance (ohms)
 No.     REAL      IMAGINARY    RESISTANCE   REACTANCE    STATUS
 <-> <----------> <----------> <----------> <----------> <----->
   1  0.40000       0.0000       0.0000       1.3330       OK
   2 -0.20000      0.34641       0.0000       1.3330       OK
   3 -0.20000     -0.34641       0.0000       1.3330       OK
   4   0.0000       0.0000      0.10000E-03   0.0000      DUMMY
1
 Run Number...................................:     1
 TERMINAL GROUND SYSTEM (Magn./Angle)
 Term:   1 Total Earth Current...:   17.760     Amps  /  -120.07     deg.
           Earth Potential Rise..:   53.280     Volts /  -120.07     deg.
 Term:   2 Total Earth Current...:  0.53299E-03 Amps  /  -119.97     deg.
           Earth Potential Rise..:   53.299     Volts /  -119.97     deg.
 Top-Layer Resistivity.........:   100.00     Ohm-meters
 Grid Impedance................:   10.000     +j   0.0000     Ohms
                               < Magnitude / Angle >
 Total Fault Current...........:   17.761     Amps  /  -120.07     degrees
 Total Neutral Current.........:  0.22974E-07 Amps  /  -125.78     degrees
 Total Earth Current...........:   17.761     Amps  /  -120.07     degrees
 Ground Potential Rise (GPR)...:   177.61     Volts /  -120.07     degrees
```

Annexure C4: SPLITS report for F3, TN-C-S system– Grid-connected operation

```
Run ID.....................................: F3_Grid_TN
 Central Station Name.......................: Load
 Total Number of Terminals..................:   2
 Total Number of Busses.....................:   4
 Total Number of Different Resistivity Values.:   1
 Selection of SAFETY Calculations...........: NO
 Printout Option............................: Detailed
 Base Resistivity Value.....................:   100.00     ohm-meters
 Base Fault Current Value...................:   1000.0     amperes

 Central Station: Load
 Constant Resistance.......................:   10.000     ohms
 Variable Resistance......................:   0.0000     ohms/base
RESISTIVITY
 Reactance................................:   0.0000     ohms


 CENTRAL STATION BUS DATA
 ========================
 ------BUS------- Bus To Substation Neutral Impedance
 NO.     TYPE     RESISTANCE (ohms) REACTANCE (ohms)
 <-> <----------> <---------------> <--------------->
   1 Ph_A             0.10000E+12      0.10000E+13
   2 Ph_B             0.10000E+13      0.10000E+13
   3 Ph_C              0.0000           0.0000
   4 NEUTRAL           0.0000           0.0000
1
 Terminal No.    1 : LV_Transform
 Number of Sections...............:     4
 Constant Ground Impedance.......:   3.0000     +j   0.0000     ohms
 Variable Resistance.............:   0.0000     ohms/base RESISTIVITY

 Bus  Source Voltage (Kvolts)   Source Impedance (ohms)
 No.     REAL      IMAGINARY    RESISTANCE   REACTANCE    STATUS
 <-> <----------> <----------> <----------> <----------> <----->
   1  0.40000       0.0000      0.46000E-02  0.15000E-01   OK
   2 -0.20000      0.34641      0.46000E-02  0.15000E-01   OK
   3 -0.20000     -0.34641      0.46000E-02  0.15000E-01   OK
   4   0.0000       0.0000       0.0000       0.0000       OK
1
 Terminal No.    2 : MicroGasTurb
 Number of Sections...............:     2
 Constant Ground Impedance.......:   99999.     +j   0.0000     ohms
 Variable Resistance.............:   0.0000     ohms/base RESISTIVITY

 Bus  Source Voltage (Kvolts)   Source Impedance (ohms)
 No.     REAL      IMAGINARY    RESISTANCE   REACTANCE    STATUS
 <-> <----------> <----------> <----------> <----------> <----->
   1  0.40000       0.0000       0.0000       1.3330       OK
   2 -0.20000      0.34641       0.0000       1.3330       OK
   3 -0.20000     -0.34641       0.0000       1.3330       OK
   4   0.0000       0.0000      0.10000E-03   0.0000      DUMMY
1
 Run Number...................................:     1
 TERMINAL GROUND SYSTEM (Magn./Angle)
 Term:   1 Total Earth Current...:   8.8300     Amps  /  -134.85     deg.
           Earth Potential Rise..:   26.490     Volts /  -134.85     deg.
 Term:   2 Total Earth Current...:  0.66455E-03 Amps  /  -125.41     deg.
           Earth Potential Rise..:   66.455     Volts /  -125.41     deg.
 Top-Layer Resistivity.........:   100.00     Ohm-meters
 Grid Impedance................:   10.000     +j   0.0000     Ohms
                               < Magnitude / Angle >
 Total Fault Current...........:   858.41     Amps  /  -137.31     degrees
 Total Neutral Current.........:   850.00     Amps  /  -137.47     degrees
 Total Earth Current...........:   8.7291     Amps  /  -121.78     degrees
 Ground Potential Rise (GPR)...:   87.291     Volts /  -121.78     degrees
```

Annexure C5: SPLITS report for F3, TT system – Grid-connected operation

```
Run ID.....................................: F3_Grid_TT
 Central Station Name.......................: Load
 Total Number of Terminals..................:   2
 Total Number of Busses.....................:   4
 Total Number of Different Resistivity Values.:   1
 Selection of SAFETY Calculations...........: NO
 Printout Option............................: Detailed
 Base Resistivity Value.....................:   100.00     ohm-meters
 Base Fault Current Value...................:   1000.0     amperes

 Central Station: Load
 Constant Resistance......................:   10.000     ohms
 Variable Resistance......................:   0.0000     ohms/base
RESISTIVITY
 Reactance................................:   0.0000     ohms


 CENTRAL STATION BUS DATA
 ========================
 ------BUS------- Bus To Substation Neutral Impedance
 NO.     TYPE     RESISTANCE (ohms) REACTANCE (ohms)
 <-> <----------> <---------------> <--------------->
   1 Ph_A             0.10000E+11      0.10000E+11
   2 Ph_B             0.10000E+11      0.10000E+11
   3 Ph_C              0.0000           0.0000
   4 NEUTRAL          0.10000E+11      0.10000E+10
1
 Terminal No.    1 : LV_Transform
 Number of Sections...............:     4
 Constant Ground Impedance.......:   3.0000     +j   0.0000     ohms
 Variable Resistance.............:   0.0000     ohms/base RESISTIVITY

 Bus  Source Voltage (Kvolts)   Source Impedance (ohms)
 No.     REAL      IMAGINARY    RESISTANCE   REACTANCE    STATUS
 <-> <----------> <----------> <----------> <----------> <----->
   1  0.40000       0.0000      0.46000E-02  0.15000E-01   OK
   2 -0.20000      0.34641      0.46000E-02  0.15000E-01   OK
   3 -0.20000     -0.34641      0.46000E-02  0.15000E-01   OK
   4   0.0000       0.0000       0.0000       0.0000       OK
1
 Terminal No.    2 : MicroGasTurb
 Number of Sections...............:     2
 Constant Ground Impedance.......:   99999.     +j   0.0000     ohms
 Variable Resistance.............:   0.0000     ohms/base RESISTIVITY

 Bus  Source Voltage (Kvolts)   Source Impedance (ohms)
 No.     REAL      IMAGINARY    RESISTANCE   REACTANCE    STATUS
 <-> <----------> <----------> <----------> <----------> <----->
   1  0.40000       0.0000       0.0000       1.3330       OK
   2 -0.20000      0.34641       0.0000       1.3330       OK
   3 -0.20000     -0.34641       0.0000       1.3330       OK
   4   0.0000       0.0000      0.10000E-03   0.0000      DUMMY
1
 Run Number...................................:     1
 TERMINAL GROUND SYSTEM (Magn./Angle)
 Term:   1 Total Earth Current...:   17.591     Amps  /  -120.22     deg.
           Earth Potential Rise..:   52.772     Volts /  -120.22     deg.
 Term:   2 Total Earth Current...:  0.53562E-03 Amps  /  -119.95     deg.
           Earth Potential Rise..:   53.562     Volts /  -119.95     deg.
 Top-Layer Resistivity.........:   100.00     Ohm-meters
 Grid Impedance................:   10.000     +j   0.0000     Ohms
                               < Magnitude / Angle >
 Total Fault Current...........:   17.591     Amps  /  -120.22     degrees
 Total Neutral Current.........:  0.22755E-07 Amps  /  -125.93     degrees
 Total Earth Current...........:   17.591     Amps  /  -120.22     degrees
 Ground Potential Rise (GPR)...:   175.91     Volts /  -120.22     degrees
```

Annexure C6: SPLITS report for F2, TN-C-S system – Islanded operation

```
Run ID.....................................: F2_Island_TN
 Central Station Name.......................: Fault locati
 Total Number of Terminals..................:   2
 Total Number of Busses.....................:   4
 Total Number of Different Resistivity Values.:   1
 Selection of SAFETY Calculations...........: NO
 Printout Option............................: Detailed
 Base Resistivity Value.....................:   100.00     ohm-meters
 Base Fault Current Value...................:   1000.0     amperes

 Central Station: Fault locati
 Constant Resistance.......................:   10.000     ohms
 Variable Resistance......................:   0.0000     ohms/base
RESISTIVITY
 Reactance................................:   0.0000     ohms


 CENTRAL STATION BUS DATA
 ========================
 ------BUS------- Bus To Substation Neutral Impedance
 NO.     TYPE     RESISTANCE (ohms) REACTANCE (ohms)
 <-> <----------> <---------------> <--------------->
   1 Ph_A             0.10000E+12      0.10000E+13
   2 Ph_B             0.10000E+13      0.10000E+13
   3 Ph_C              0.0000           0.0000
   4 NEUTRAL           0.0000           0.0000
1
 Terminal No.    1 : Flywheel
 Number of Sections...............:     2
 Constant Ground Impedance.......:   3.0000     +j   0.0000     ohms
 Variable Resistance.............:   0.0000     ohms/base RESISTIVITY

 Bus  Source Voltage (Kvolts)   Source Impedance (ohms)
 No.     REAL      IMAGINARY    RESISTANCE   REACTANCE    STATUS
 <-> <----------> <----------> <----------> <----------> <----->
   1  0.40000       0.0000      0.26700       0.0000       OK
   2 -0.20000      0.34641      0.26700       0.0000       OK
   3 -0.20000     -0.34641      0.26700       0.0000       OK
   4   0.0000       0.0000       0.0000       0.0000       OK
1
 Terminal No.    2 : MicroGasTurb
 Number of Sections...............:     4
 Constant Ground Impedance.......:   99999.     +j   0.0000     ohms
 Variable Resistance.............:   0.0000     ohms/base RESISTIVITY

 Bus  Source Voltage (Kvolts)   Source Impedance (ohms)
 No.     REAL      IMAGINARY    RESISTANCE   REACTANCE    STATUS
 <-> <----------> <----------> <----------> <----------> <----->
   1  0.40000       0.0000       0.0000       1.3330       OK
   2 -0.20000      0.34641       0.0000       1.3330       OK
   3 -0.20000     -0.34641       0.0000       1.3330       OK
   4   0.0000       0.0000      0.10000E-03   0.0000      DUMMY
1
 Run Number...................................:     1
 TERMINAL GROUND SYSTEM (Magn./Angle)
 Term:   1 Total Earth Current...:  0.45901E-03 Amps  /   52.885     deg.
           Earth Potential Rise..:  0.13770E-02 Volts /   52.885     deg.
 Term:   2 Total Earth Current...:  0.79165E-03 Amps  /  -127.12     deg.
           Earth Potential Rise..:   79.164     Volts /  -127.12     deg.
 Top-Layer Resistivity.........:   100.00     Ohm-meters
 Grid Impedance................:   10.000     +j   0.0000     Ohms
                               < Magnitude / Angle >
 Total Fault Current...........:   889.49     Amps  /  -127.11     degrees
 Total Neutral Current.........:   889.49     Amps  /  -127.11     degrees
 Total Earth Current...........:  0.33407E-03 Amps  /  -127.12     degrees
 Ground Potential Rise (GPR)...:  0.33407E-02 Volts /  -127.12     degrees
```

Annexure C7: SPLITS report for F2, TT system – Islanded operation

```
Run ID.....................................: F2_Island_TT
 Central Station Name.......................: Load
 Total Number of Terminals..................:   2
 Total Number of Busses.....................:   4
 Total Number of Different Resistivity Values.:   1
 Selection of SAFETY Calculations...........: NO
 Printout Option............................: Detailed
 Base Resistivity Value.....................:   100.00     ohm-meters
 Base Fault Current Value...................:   1000.0     amperes

 Central Station: Load
 Constant Resistance.......................:   10.000     ohms
 Variable Resistance.......................:   0.0000     ohms/base
RESISTIVITY
 Reactance.................................:   0.0000     ohms


 CENTRAL STATION BUS DATA
 ========================
 ------BUS------- Bus To Substation Neutral Impedance
 NO.     TYPE     RESISTANCE (ohms) REACTANCE (ohms)
 <-> <----------> <---------------> <--------------->
   1 Ph_A             0.10000E+11      0.10000E+11
   2 Ph_B             0.10000E+11      0.10000E+11
   3 Ph_C              0.0000           0.0000
   4 NEUTRAL          0.10000E+11      0.10000E+10
1
 Terminal No.    1 : Flywheel
 Number of Sections...............:     2
 Constant Ground Impedance.......:   3.0000     +j   0.0000     ohms
 Variable Resistance.............:   0.0000     ohms/base RESISTIVITY

 Bus  Source Voltage (Kvolts)   Source Impedance (ohms)
 No.     REAL      IMAGINARY    RESISTANCE   REACTANCE    STATUS
 <-> <----------> <----------> <----------> <----------> <----->
   1  0.40000       0.0000      0.26700       0.0000       OK
   2 -0.20000      0.34641      0.26700       0.0000       OK
   3 -0.20000     -0.34641      0.26700       0.0000       OK
   4   0.0000       0.0000       0.0000       0.0000       OK
1
 Terminal No.    2 : MicroGasTurb
 Number of Sections...............:     4
 Constant Ground Impedance.......:   99999.     +j   0.0000     ohms
 Variable Resistance.............:   0.0000     ohms/base RESISTIVITY

 Bus  Source Voltage (Kvolts)   Source Impedance (ohms)
 No.     REAL      IMAGINARY    RESISTANCE   REACTANCE    STATUS
 <-> <----------> <----------> <----------> <----------> <----->
   1  0.40000       0.0000       0.0000       1.3330       OK
   2 -0.20000      0.34641       0.0000       1.3330       OK
   3 -0.20000     -0.34641       0.0000       1.3330       OK
   4   0.0000       0.0000      0.10000E-03   0.0000      DUMMY
1
 Run Number...................................:     1
 TERMINAL GROUND SYSTEM (Magn./Angle)
 Term:   1 Total Earth Current...:   17.419     Amps  /  -120.14     deg.
           Earth Potential Rise..:   52.257     Volts /  -120.14     deg.
 Term:   2 Total Earth Current...:  0.53808E-03 Amps  /  -120.14     deg.
           Earth Potential Rise..:   53.807     Volts /  -120.14     deg.
 Top-Layer Resistivity.........:   100.00     Ohm-meters
 Grid Impedance................:   10.000     +j   0.0000     Ohms
                               < Magnitude / Angle >
 Total Fault Current...........:   17.419     Amps  /  -120.14     degrees
 Total Neutral Current.........:  0.22533E-07 Amps  /  -125.85     degrees
 Total Earth Current...........:   17.419     Amps  /  -120.14     degrees
 Ground Potential Rise (GPR)...:   174.19     Volts /  -120.14     degrees
```

Annexure C8: SPLITS report for F3, TN-C-S system – Islanded operation

```
Run ID.....................................: F3_Island_TN
 Central Station Name.......................: Load
 Total Number of Terminals..................:   2
 Total Number of Busses.....................:   4
 Total Number of Different Resistivity Values.:   1
 Selection of SAFETY Calculations...........: NO
 Printout Option............................: Detailed
 Base Resistivity Value.....................:   100.00     ohm-meters
 Base Fault Current Value...................:   1000.0     amperes

 Central Station: Load
 Constant Resistance......................:   10.000     ohms
 Variable Resistance......................:   0.0000     ohms/base
RESISTIVITY
 Reactance................................:   0.0000     ohms


 CENTRAL STATION BUS DATA
 ========================
 ------BUS------- Bus To Substation Neutral Impedance
 NO.     TYPE     RESISTANCE (ohms) REACTANCE (ohms)
 <-> <----------> <---------------> <--------------->
   1 Ph_A             0.10000E+12      0.10000E+13
   2 Ph_B             0.10000E+13      0.10000E+13
   3 Ph_C              0.0000           0.0000
   4 NEUTRAL           0.0000           0.0000
1
 Terminal No.    1 : Flywheel
 Number of Sections..............:     4
 Constant Ground Impedance.......:   3.0000     +j   0.0000     ohms
 Variable Resistance.............:   0.0000     ohms/base RESISTIVITY

 Bus  Source Voltage (Kvolts)   Source Impedance (ohms)
 No.     REAL      IMAGINARY    RESISTANCE   REACTANCE    STATUS
 <-> <----------> <----------> <----------> <----------> <----->
   1  0.40000       0.0000      0.26700       0.0000       OK
   2 -0.20000      0.34641      0.26700       0.0000       OK
   3 -0.20000     -0.34641      0.26700       0.0000       OK
   4   0.0000       0.0000       0.0000       0.0000       OK
1
 Terminal No.    2 : MicroGasTurb
 Number of Sections..............:     2
 Constant Ground Impedance.......:   99999.     +j   0.0000     ohms
 Variable Resistance.............:   0.0000     ohms/base RESISTIVITY

 Bus  Source Voltage (Kvolts)   Source Impedance (ohms)
 No.     REAL      IMAGINARY    RESISTANCE   REACTANCE    STATUS
 <-> <----------> <----------> <----------> <----------> <----->
   1  0.40000       0.0000       0.0000       1.3330       OK
   2 -0.20000      0.34641       0.0000       1.3330       OK
   3 -0.20000     -0.34641       0.0000       1.3330       OK
   4   0.0000       0.0000      0.10000E-03   0.0000      DUMMY
1
 Run Number..................................:     1
 TERMINAL GROUND SYSTEM (Magn./Angle)
 Term:   1 Total Earth Current...:   4.5896     Amps  /  -121.83     deg.
           Earth Potential Rise..:   13.769     Volts /  -121.83     deg.
 Term:   2 Total Earth Current...:  0.73696E-03 Amps  /  -128.50     deg.
           Earth Potential Rise..:   73.696     Volts /  -128.50     deg.
 Top-Layer Resistivity.........:   100.00     Ohm-meters
 Grid Impedance................:   10.000     +j   0.0000     Ohms
                               < Magnitude / Angle >
 Total Fault Current...........:   452.49     Amps  /  -134.23     degrees
 Total Neutral Current.........:   448.01     Amps  /  -134.36     degrees
 Total Earth Current...........:   4.5924     Amps  /  -121.66     degrees
 Ground Potential Rise (GPR)...:   45.924     Volts /  -121.66     degrees
```

Annexure C9: SPLITS report for F3, TT system – Islanded operation

```
Run ID.....................................: F3_Island_TT
 Central Station Name.......................: FaultLocatio
 Total Number of Terminals..................:   2
 Total Number of Busses.....................:   4
 Total Number of Different Resistivity Values.:   1
 Selection of SAFETY Calculations...........: NO
 Printout Option............................: Detailed
 Base Resistivity Value.....................:   100.00     ohm-meters
 Base Fault Current Value...................:   1000.0     amperes

 Central Station: FaultLocatio
 Constant Resistance.......................:   10.000     ohms
 Variable Resistance......................:   0.0000     ohms/base
RESISTIVITY
 Reactance................................:   0.0000     ohms


 CENTRAL STATION BUS DATA
 ========================
 ------BUS------- Bus To Substation Neutral Impedance
 NO.     TYPE     RESISTANCE (ohms) REACTANCE (ohms)
 <-> <----------> <---------------> <--------------->
   1 Ph_A             0.10000E+11      0.10000E+11
   2 Ph_B             0.10000E+11      0.10000E+11
   3 Ph_C              0.0000           0.0000
   4 NEUTRAL          0.10000E+11      0.10000E+10
1
 Terminal No.    1 : Flywheel
 Number of Sections...............:     4
 Constant Ground Impedance.......:   3.0000     +j   0.0000     ohms
 Variable Resistance.............:   0.0000     ohms/base RESISTIVITY

 Bus  Source Voltage (Kvolts)   Source Impedance (ohms)
 No.     REAL      IMAGINARY    RESISTANCE   REACTANCE    STATUS
 <-> <----------> <----------> <----------> <----------> <----->
   1  0.40000       0.0000      0.26700       0.0000       OK
   2 -0.20000      0.34641      0.26700       0.0000       OK
   3 -0.20000     -0.34641      0.26700       0.0000       OK
   4   0.0000       0.0000       0.0000       0.0000       OK
1
 Terminal No.    2 : MicroGasTurb
 Number of Sections...............:     2
 Constant Ground Impedance.......:   99999.     +j   0.0000     ohms
 Variable Resistance.............:   0.0000     ohms/base RESISTIVITY

 Bus  Source Voltage (Kvolts)   Source Impedance (ohms)
 No.     REAL      IMAGINARY    RESISTANCE   REACTANCE    STATUS
 <-> <----------> <----------> <----------> <----------> <----->
   1  0.40000       0.0000       0.0000       1.3330       OK
   2 -0.20000      0.34641       0.0000       1.3330       OK
   3 -0.20000     -0.34641       0.0000       1.3330       OK
   4   0.0000       0.0000      0.10000E-03   0.0000      DUMMY
1
 Run Number...................................:     1
 TERMINAL GROUND SYSTEM (Magn./Angle)
 Term:   1 Total Earth Current...:   17.277     Amps  /  -120.42     deg.
           Earth Potential Rise..:   51.832     Volts /  -120.42     deg.
 Term:   2 Total Earth Current...:  0.54119E-03 Amps  /  -120.24     deg.
           Earth Potential Rise..:   54.118     Volts /  -120.24     deg.
 Top-Layer Resistivity.........:   100.00     Ohm-meters
 Grid Impedance................:   10.000     +j   0.0000     Ohms
                               < Magnitude / Angle >
 Total Fault Current...........:   17.278     Amps  /  -120.42     degrees
 Total Neutral Current.........:  0.22350E-07 Amps  /  -126.13     degrees
 Total Earth Current...........:   17.278     Amps  /  -120.42     degrees
 Ground Potential Rise (GPR)...:   172.78     Volts /  -120.42     degrees
```