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# Comparison the Performances of Three Earthing Systems for Micro-Grid Protection during the Grid Connected Mode

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## ABSTRACT

*This paper presents, tests and compares three earthing systems (TT, TN and IT) for Micro-Grid (MG) protection against various fault types during the connected mode. The main contribution of this work is including the models of all the micro sources which interfaced to the MG by power electronic inverters. Inverters in turns are provided with current limiters and this also included in the inverter models to exactly simulate the real situation in the MG during fault times. Results proved that the most suitable earthing system for MG protection during the connecting mode is the TN earthing system. That system leads to a suitable amount of fault current sufficient to activate over current protection relays. With using TN system, Touch voltages at the faulted bus and all other consumer's buses are less than the safety limited value if current limiter is included with the transformer of the main grid which connects MG. For the two others earthing systems (TT and IT), fault current is small and nearly equal to the over load current which make over current protection relay can not differentiate between fault current and overload current. All models of micro sources, earthing systems, inverters, main grid and control schemes are built using Matlab®/Simulink® environment.*

**Keywords**: *Micro Grid Protection, Earthing Systems, Fault Current, Touch Voltage, Micro Sources and Inverters, Grid Connecting Mode*

## 1. Introduction

The earthing of an electricity supply network requires its network plant and customer electrical equipment to be connected to the earth in order to promote safety and reduce the possibilities of damage to equipment. Effective earthing prevents long term over voltages and minimizes risk of electric shock hazards. Earthing also provides a predetermined path for earth leakage currents, which are used to disconnect the faulty plant or circuit by operating the protective devices. A Micro-Grid (MG) is a unique example of a distribution system and needs careful assessment before deciding on its earthing system.

A MG consists of a cluster of micro sources, energy storage systems (e.g. flywheel) and loads, operating as a single controllable system. The voltage level of the MG is 400 Volts or less. The architecture of the MG is formed to be radial with a number of feeders. The MG often provides both electricity and heat to the local area. The MG can be operated in both grid-connected mode and islanded mode as described in details on our previous research [1-10].

The micro sources are usually made of many new technologies, e.g. micro gas turbine, fuel cell, photovoltaic system and several kinds of wind turbines. The energy storage system often is a flywheel system. The micro sources and flywheel are not suitable for supplying energy to the grid directly [11]. They have to be interfaced with the grid through an inverter stage. The use of power electronic interfaces in the MG thus leads to a series of challenges in the design and operation of the MG. One of the major challenges is protection design of the MG to comply with the relevant National Distribution Codes and to maintain the safety and stability of the MG during both grid-connected mode and islanded mode.

However, the inverter based MG can not normally provide the required levels of short circuit current. In extreme cases, the fault current contribution from the micro sources may only be twice load current or less [12,13].

 

Some over current sensing devices will not even respond to this level of over current. In addition, the over/under voltage and frequency protection may fail to detect faults on the MG due to the voltage and frequency control of the MG. That unique nature of the MG requires a fresh look into the design and operation of the protection. This is the task of this manuscript.

This manuscript presents and applies three earthing systems for MG protection during the connecting mode. The two main contributions of this manuscript are: 1) Consider models of all micro sources (and their inverters) installed in the MG and 2) Included current limiter with each inverter inside the MG to simulate exactly the real situation.

Three earthing systems are implemented and tested on the MG. Comparison between the performance of the three systems is highlighted. The most suitable earthing system is deduced from the comparison.

To conduct the proposed study, this manuscript is organized as follow: Section 2 describes the three designed earthing systems. Section 3 presented the fault behavior in each earthing system plus advantages and disadvantages of each system. MG network included all micro sources, inverters and earthing system is presented in section 4. Section 5 gives the results obtained with applying the three earthing systems and the sequence of the events occur with each earthing system. Conclusions are presented in section 6.

## 2. Types of Earthing Systems

A low voltage (LV) distribution system may be identified according to its earthing system. These are defined using the five letters T (direct connection to earth), N (neutral), C (combined), S (separate) and I (isolated from earth). The first letter denotes how the transformer neutral (supply source) is earthed while the second letter denotes how the metalwork of an installation (frame) is earthed. The third and fourth letters indicate the functions of neutral and protective conductors respectively. There are three possible configurations [14]:

1) **TT:** transformer neutral earthed and frame earthed.

2) **TN:** transformer neutral earthed, frame connected to neutral.

3) **IT:** unearthed transformer neutral, earthed frame.

The TN system includes three sub-systems: TN-C, TN-S and TN-C-S, as discussed in the following sub-sections.

### 2.1. TT Earthing System

In this system, the supply source has a direct connection to earth. All exposed conductive parts of an installation also are connected to an earth electrode that is electrically independent of the source earth. The structure of TT system is shown in **Figure 1** [15].

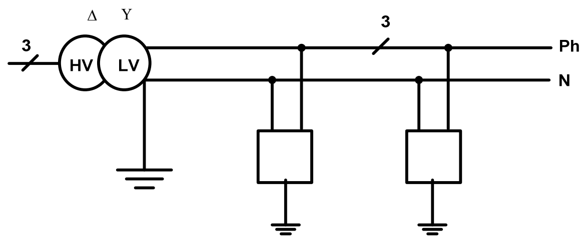


**Figure 1. TT earthing system configuration.**

### 2.2. TN Earthing System

In a TN earthing system, the supply source (transformer neutral) is directly connected to earth and all exposed conductive parts of an installation are connected to the neutral conductor. Safety of personnel is guaranteed, but that of property (fire, damage to electrical equipment) is less so. The three sub-systems in TN earthing system are described below with their key characteristics.

#### 2.2.1. TN-C Earthing System

As shown in **Figure 2(a)**, TN-C system has the following features:

1) Neutral and protective functions are combined in a single conductor throughout the system. (PEN—Protective Earthed Neutral).

2) The supply source is directly connected to earth and all exposed conductive parts of an installation are connected to the PEN conductor.

#### 2.2.2. TN-S Earthing System

TN-S system architecture is shown in **Figure 2(b)** and has the following features:

1) A TN-S system has separate neutral and protective conductors throughout the system.

2) The supply source is directly connected to earth. All exposed conductive parts of an installation are connected to a protective conductor (PE) via the main earthing terminal of the installation.

#### 2.2.3 TN-C-S Earthing System

TN-C-S earthing system configuration is shown in **Figure 2(c)** and has the following features:

1) Neutral and protective functions are combined in a single conductor in a part of the TN-C-S system. The supply is TN-C and the arrangement in the installation is TN-S.

2) Use of a TN-S downstream from a TN-C.

3) All exposed conductive parts of an installation are connected to the PEN conductor via the main earthing terminal and the neutral terminal, these terminals being linked together.

### 2.3. IT Earthing System

In this system, the supply source is either connected to

 

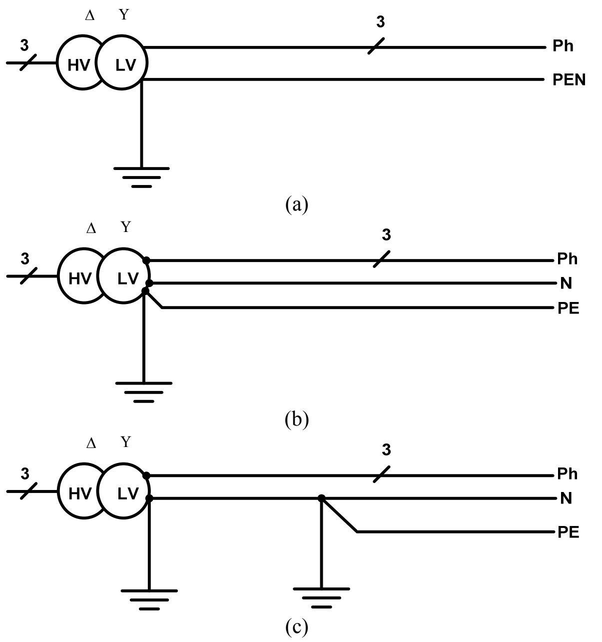


**Figure 2. (a): TN-C earthing system configuration; (b): TN-S earthing system configuration; (c): TN-C-S earthing system.**

earth through deliberately introduced high earthing impedance (Impedance earthed IT system) or is isolated from earth as shown in **Figure 3**. All exposed conductive parts of an installation are connected to an earth electrode.

Every exposed-conductive part shall be earthed to satisfy the following condition for each circuit [16]:

$$R_b * I_d \leq 50V \quad (1)$$

where:

$R_b$: The resistances of the earth electrode for exposed conductive-parts.

$I_d$: Fault current which takes account of leakage currents and the total earthing impedance of the electrical installation.

## 3. Fault Behavior and Characteristics of Different Earthing Systems

An insulation fault in an electrical installation presents hazards to humans and equipments. At the same time it may cause unavailability of electrical power. The fault currents and voltages differ from one earthing system to another as described in the following sub sections.

### 3.1. Fault Behavior in the TN Earthing System

**Figure 4** shows the fault behavior in the TN earthing system and the path of the fault current. When an insulation fault is present, the fault current $I_d$ is only limited by the impedance of the fault loop cables. Short circuit protection devices (circuit breaker or fuses) generally provide protection against insulation faults, with automatic tripping according to a specified maximum breaking time (depending on phase-to-neutral voltage $U_o$). Typical breaking times in the TN earthing system are tabulated in **Table 1** according to IEC 60364 ($U_L$ is the limited safety voltage).

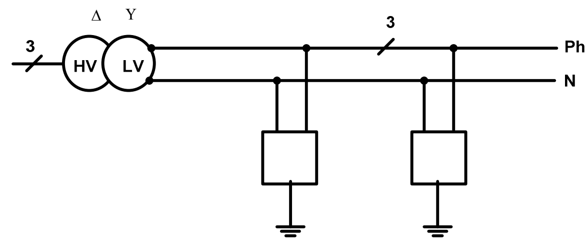


**Figure 3. IT earthing system.**

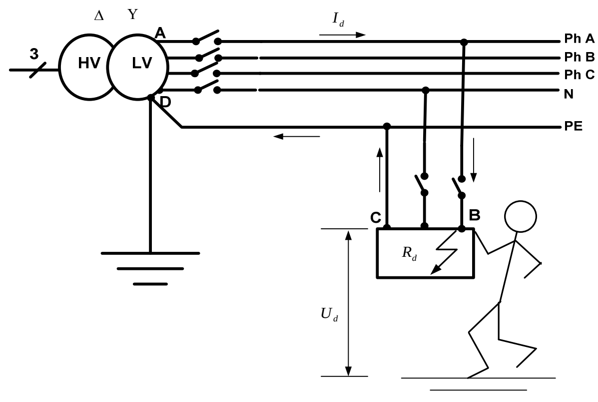


**Figure 4. A fault behavior in the TN-S earthing system.**

#### 3.1.1. Advantages of the TN Earthing System

1) The TN earthing system always provides a return path for faults in the LV grid. The grounding conductors at the transformer and at all customers are interconnected. This ensures a distributed grounding and reduces the risk of a customer not having a safe grounding.

2) Lower earthing resistance of the PEN conductor.

3) TN system has the advantage that in case of an insulation fault, the fault voltages (touch voltages) are generally smaller than in TT earthing systems. This is due to the voltage drop in the phase conductor and the lower impedance of the PEN conductor compared with the consumer earthing in TT systems.

4) No overvoltage stress on equipment insulation.

5) TN-S system has the best Electromagnetic Compatibility (EMC) properties for 50 Hz and high frequency currents, certainly when LV cable with a grounded sheath is applied.

6) TN earthing system could work with simple over current protection.

7) High reliability of disconnection of a fault by over

**Table 1. Braking time in TN system (taken from IEC 60364 tables 41 and 48A).**

| $U_o$ (Volts) Phase/neutral voltage | Braking time (seconds) $U_L$ = 50 Volt | Braking time (seconds) $U_L$ = 25 Volt |
|---|---|---|
| 127 | 0.8 | 0.35 |
| 230 | 0.4 | 0.2 |
| 400 | 0.2 | 0.05 |
| >400 | 0.1 | 0.02 |

current devices (*i.e.* fault current is large enough to activate the over current protection devices).

#### 3.1.2. Disadvantages of the TN Earthing System

1) Faults in the electrical network at a higher voltage level may migrate into the LV grid grounding causing touch voltages at LV customers.

2) A fault in the LV network may cause touch voltages at other LV customers.

3) Potential rise of exposed conductive parts with the neutral conductor in the event of a break of the neutral network conductor as well as for LV network phase to neutral and phase to ground faults and MV to LV faults.

4) The utility is not only responsible for a proper grounding but also for the safety of customers during disturbances in the power grid

5) Protection to be fitted in case of network modification (increase of fault loop impedance).

6) TN-C system is less effective for Electromagnetic Compatibility (EMC) problems.

### 3.2. Fault Behavior in the TT Earthing System

**Figure 5** explain fault occurs in TT earthing system. When an insulation fault occurs, the fault current $I_d$ is mainly limited by the earth resistances ($R_a$ and $R_b$). At least one residual current device (RCD) must be fitted at the supply end of the installation. In order to increase availability of electrical power, use of several RCDs ensures time and current discrimination on tripping [16].

#### 3.2.1. Advantages of the TT Earthing System

1) The most commonly found earthing system.

2) Faults in the LV and MV grid do not migrate to other customers in the LV grid.

3) Good security condition, as the potential rise of the grounded conductive part must be limited at 50 V for a fault inside the installation and at 0V for a fault on the network.

4) Simple earthing of the installation and the easiest to implement.

5) No influence of extending the network.

#### 3.2.2. Disadvantages of the TT Earthing System

1) Each customer needs to install and maintain its own

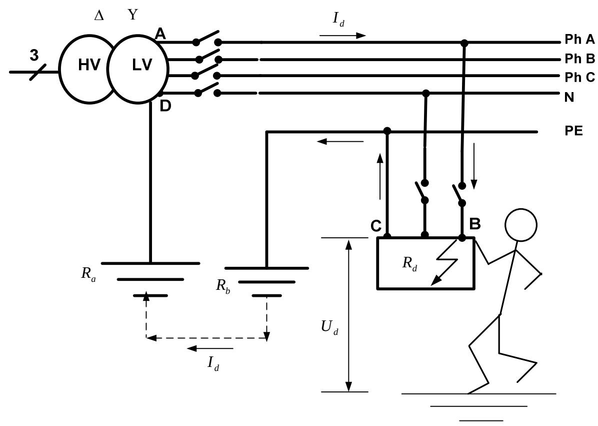


**Figure 5. The fault behavior in the TT earthing system.**

ground electrode. Safety and protection depends on the customer, thus complete reliability is not assured.

2) High over voltages may occur between all live parts and between live parts and PE conductor.

3) Possible overvoltage stress on equipment insulation of the installation.

### 3.3. Fault Behavior in the IT Earthing System

#### 3.3.1. First Fault in the IT earthing system

**Figure 6** shows the occurrence of the first fault in the IT earthing system. The fault voltage is low and not dangerous. Therefore it is not necessary to disconnect an installation in the event of a single fault. However it is essential to know that there is a fault and need to track and eliminate it promptly, before a second fault occurs. To meet this need the fault information is provided by an Insulation Monitoring Device (IMD) monitoring all live conductors, including the neutral [16]. When the neutral is not distributed (three-phase three-wire distribution), the following condition must be satisfied [16]:

$$Z_S \le \frac{0.866U_o}{I_f} \tag{2}$$

where:

$Z_S$ = Earth fault loop impedance comprising the phase conductor and the protective conductor.

$I_f$ = fault current.

$U_o$ = the supply phase to neutral voltage.

When the neutral is distributed (three-phase four-wire distribution and single phase distribution), the following condition must be satisfied [16]:

$$Z_S^1 \le \frac{0.5U_o}{I_f} \tag{6.3}$$

where:

$Z_S^1$ = Earth fault loop impedance comprising the neutral conductor and the protective conductor.

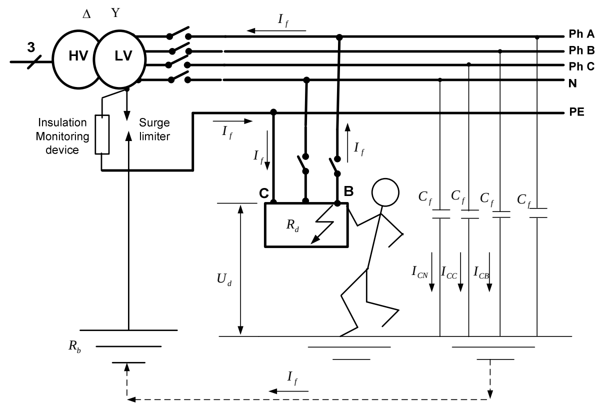


**Figure 6. First insulation fault current in the IT earthing system.**

### 3.3.2. Second fault in the IT earthing system

**Figure 7** shows the occurrence of the second fault in the IT earthing system. Maximum disconnection times for the IT earthing system are given in **Table 2** (as in IEC 60364 tables 41B and 48A) [16].

The IT earthing system used when safety of persons and property, and continuity of service are essentials.

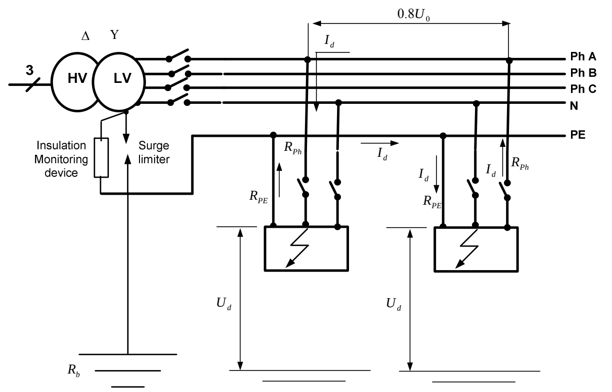


**Figure 7. Second insulation fault current in IT system (distributed neutral).**

**Table 2. Maximum disconnection time in the IT earthing system (second fault).**

| $U_o/U$ (Volt) | $U_L$ = 50 volt Braking time (sec.) | | $U_L$ = 25 volt Braking time (sec.) | |
|---|---|---|---|---|
| | Neutral not distributed | Neutral distributed | Neutral not distributed | Neutral distributed |
| 127/220 | 0.8 | 5 | 0.4 | 1.0 |
| 230/400 | 0.4 | 0.8 | 0.2 | 0.5 |
| 400/690 | 0.2 | 0.4 | 0.06 | 0.2 |
| 580/1000 | 0.1 | 0.2 | 0.02 | 0.08 |

$U_o$ phase to neutral voltage, $U$ phase to phase voltage.

## 4. Architecture of the Studied Micro Grid

**Figure 8** shows a single line diagram of the studied MG. The studied MG is connected to the main grid through three phase 400 kVA, 20/0.4 kV Δ/Y transformer. MG consists of 7 buses. Flywheel (storage device) with rating 30 kW/0.5 kWh is connected at bus 1. Wind generation system (10 kW) is connected to bus 2. Two photovoltaic panels with rating 10 kW and 3 kW are connected to buses 4 and 5 respectively. Single shaft micro turbine (SSMT) with rating 25 kW is connected to bus 6. Bus 7 is provided with solid oxide fuel cell (SOFC) with rating 20 kW. All MG's components (micro sources, inverters with different control schemes, loads, etc.) are modeled in details in our previous research [1-10].

The developed model is general and can be used to investigate the behavior of the MG under all fault types. The fault presented in this study is single phase to ground fault, which is the most common fault in the consumer premises. In the simulation model, micro sources are taken into account. It is assumed that all power electronic inverters which used to interface micro sources are provided by current limiters to limit the fault current to about 150% of the full load current of the inverter. This current limited is included in each inverter circuit to protect inverter semiconductor switches from damages and represent the real situation accurately. **In Figure 8**, the studied MG is illustrated. Line parameters are tabulated in **Table 3** [17-21].

Complete Matlab®/Simulink® model which built for testing the three earthing systems is shown at the end of this paper (**Figure 17**).

## 5. Performance of the Three Earthing Systems in MG Protection during the Connecting Mode

During this case, MG operates in the connecting mode. Main grid represents the slack (reference) bus for the MG. The studied disturbance is a short circuit (single phase to ground fault) occurs at the consumer feeds at bus # 2. Fault current, touch voltages at all consumers, voltage of healthy phases and voltage of the main transformer neutral point are shown in the following figures (**Figures 9**-**16**) when the three earthing systems (TN-S, TT and IT) are employed in the MG.

From the results shown in the previous figures, the following points can be concluded:

1) **Figure 9** shows the fault current in the grid-connected mode. With using TN-S earthing system, the fault current is very high (nearly 1900A maximum value). This is because the main grid participates with the most part of the fault current. In our case, there is no current limiter is used with the main grid. In real situations, a current limiter usually inserted in series with the main

 

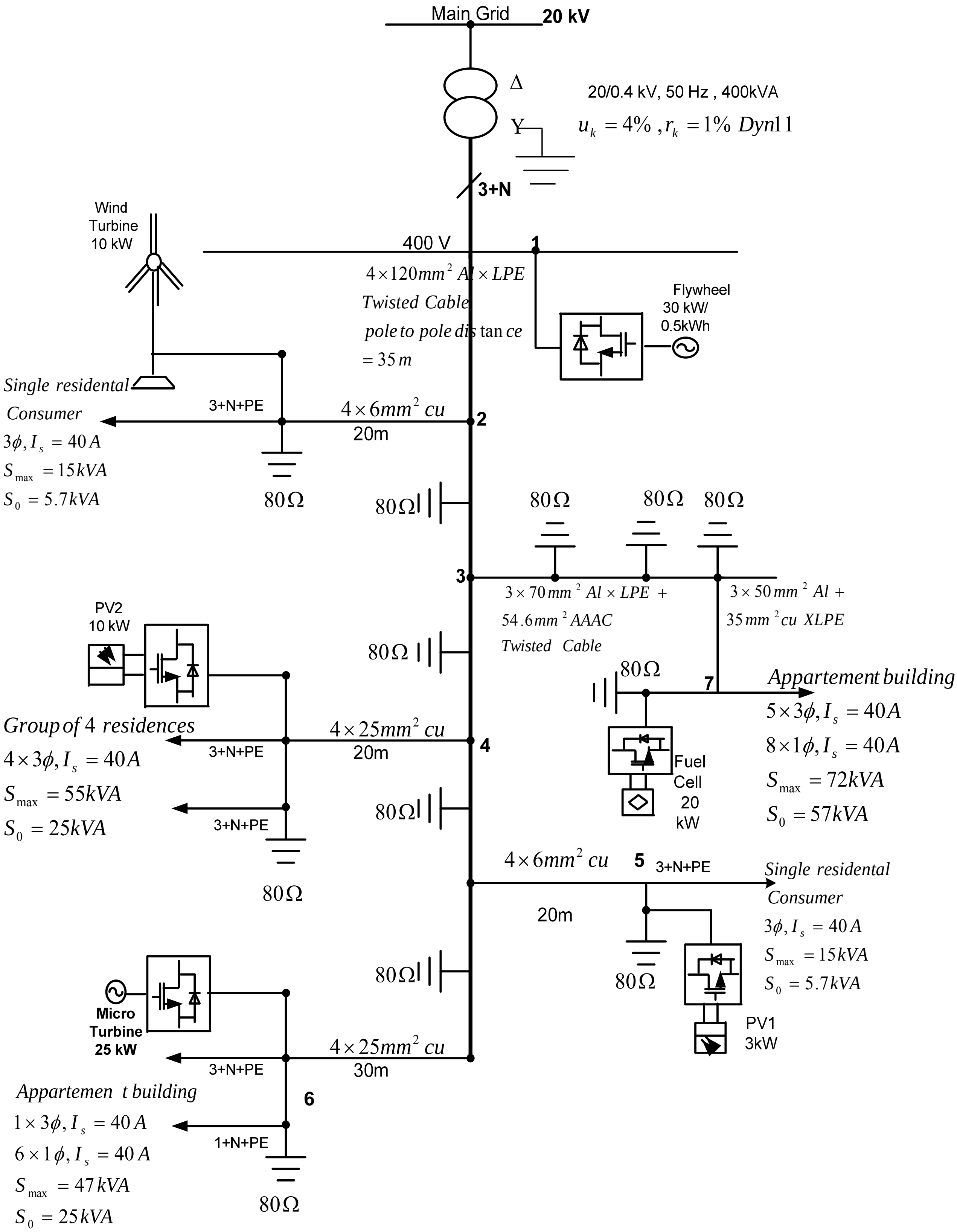


**Figure 8. Single line diagram of the studied MG.**

**Table 3. MG line parameters.**

| Line Type | R (Ω/km) | X (Ω/km) | $R_n$ (Ω/km) |
|---|---|---|---|
| Overhead-Twisted cable 4 × 120 mm$^2$ Al | 0.284 | 0.083 | 0.284 |
| Overhead-Twisted cable 3 × 70 mm$^2$ Al + 54.6 mm$^2$AAAC | 0.497 | 0.100 | 0.63 |
| Overhead-Conductor 4 × 50 mm$^2$ Al | 0.397 | 0.279 | |
| Overhead-Conductor 4 × 35 mm$^2$ Al | 0.574 | 0.294 | |
| Overhead-Conductor 4 × 16 mm$^2$ Al | 1.218 | 0.318 | |
| Underground –XLPE cable 3 × 150 mm$^2$ Al + 50 mm$^2$Cu | 0.264 | 0.071 | 0.387 |
| Connection – Cable 4 × 6 mm$^2$ Cu | 3.41 | 0.094 | |
| Connection – Cable 4 × 16 mm$^2$ Cu | 1.38 | 0.085 | |
| Connection – Cable 4 × 25 mm$^2$ Cu | 0.87 | 0.083 | |
| Connection – Cable 3 × 50 mm$^2$ + 35mm$^2$ Cu | 0.462 | 0.077 | 0.526 |
| Connection – Cable 3 × 95 mm$^2$ +35 mm$^2$ Cu | 0.41 | 0.071 | 0.524 |

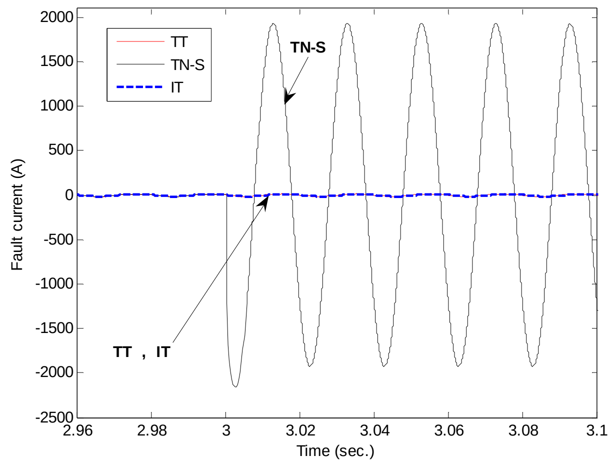


**Figure 9. Fault current with the three earthing systems in the grid connecting mode.**

grid during fault period to limit the fault current to a certain level which can be easily cleared with a small rating overcurrent protection devices. On the other hand, with TT and IT earthing systems, fault current is little increase than the steady state value.

2) **Figure 10** shows the touch voltage at fault location. With using TN-S earthing system, the value of touch voltage is small compared with the two other earthing systems, however it is larger than the safety limited value ($U_L$ = 50 Volt). This is due to the high value of the fault current. In real situation, this touch voltage (with TN-S earthing system) is less than the value shown in **Figure 10** because reducing fault current by inserting current limiter in series with the main grid. On the other hand,

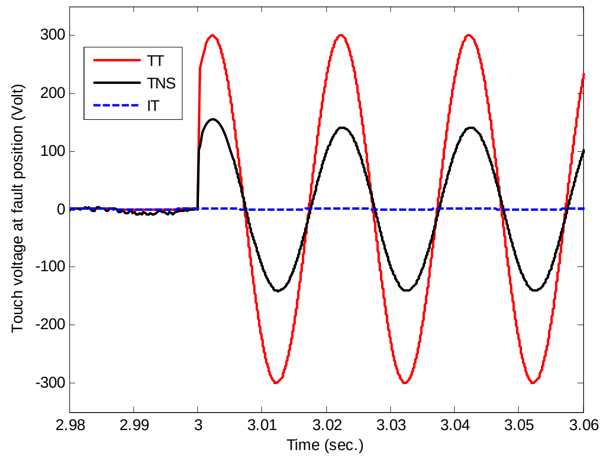


**Figure 10. Touch voltage at consumer of bus # 2 (faulted bus).**

with using TT earthing system, touch voltage at fault location is very high. To reduce that value with TT earthing system, consumers must be use low value resistance earthing electrode. For IT earthing system, touch voltage at fault position is zero. At all MG remaining buses, touch voltage with TN-S earthing system is less than the safety limited value as shown in **Figure 11** to **Figure 14**. Touch voltages at all MG buses except the faulted bus when using TT and IT earthing systems is nearly equal to zero.

3) **Figure 15** shows the voltages of the healthy phases (unfaulted phases) at fault location. As shown, the most dangerous system is the IT system which the healthy phases to neutral voltage jump to value equal to phase to phase voltage (*i.e.* multiplied by $\sqrt{3}$ ) and consequences fault clearing should be cleared fast to protect equipments connected with the two healthy phases at all MG buses. With TT and TN-S earthing systems, the voltages of the healthy phases has little drop.

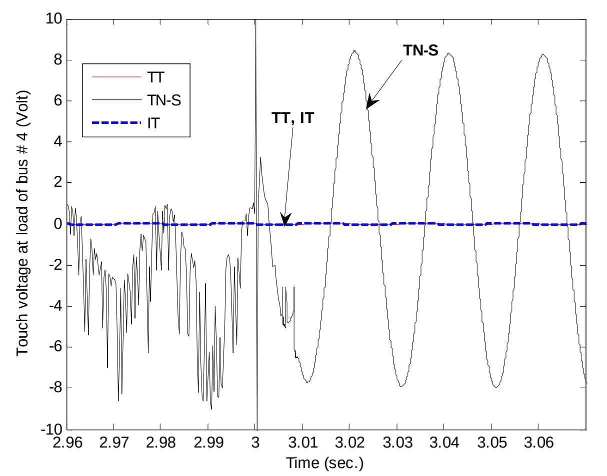


**Figure 11. Touch voltage at consumer of bus # 4.**

 

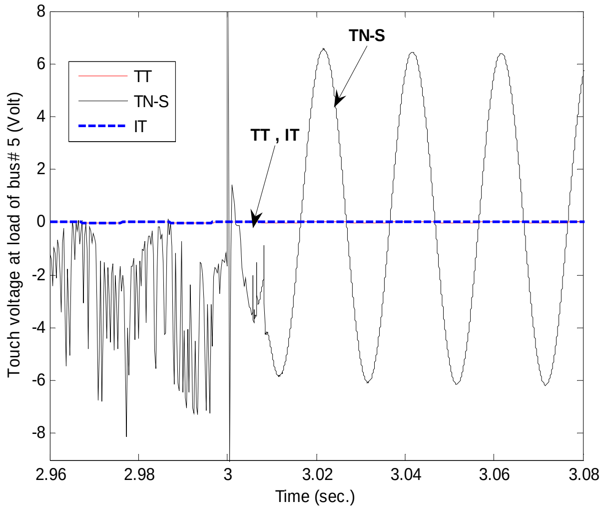


**Figure 12. Touch voltage at consumer of bus # 5.**

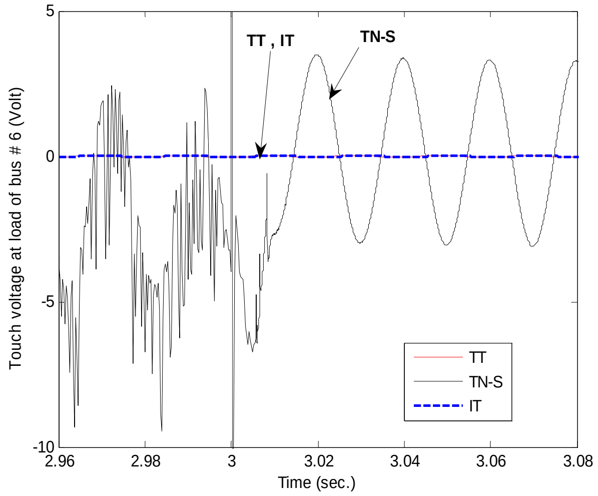


**Figure 13. Touch voltage at consumer of bus # 6.**

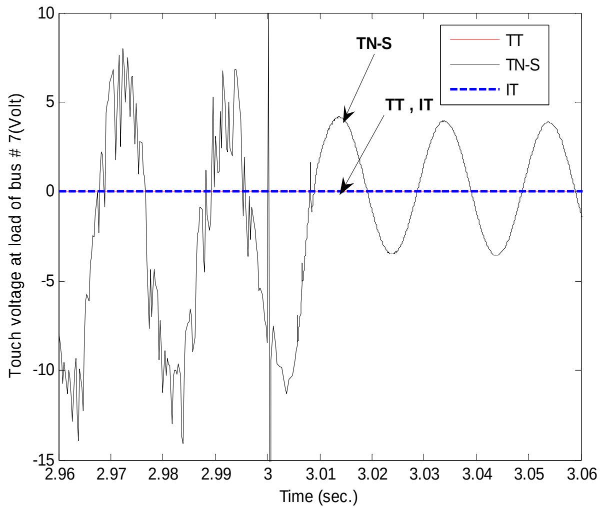


**Figure 14. Touch voltage at consumer of bus # 7.**

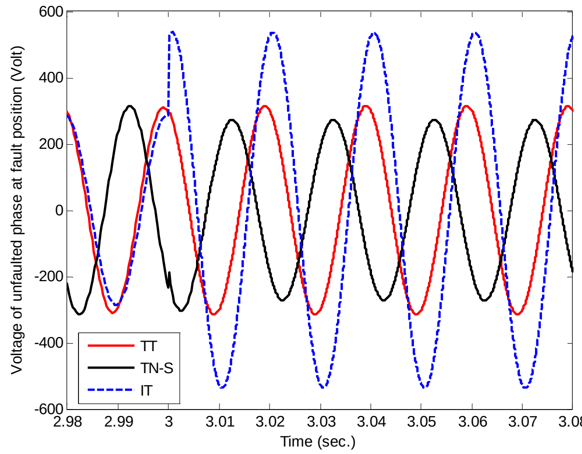


**Figure 15. Voltage of healthy phases (at bus # 2).**

4) **Figure 16** shows the voltage of the neutral point of the main grid. As shown, when using IT earthing system, this value jumps to the value of the phase voltage (ideally equal to zero) and causes jumping of all healthy phases voltages to the line value at all MG buses. With the two other earthing systems (TN-S and TT), the neutral point voltage has a small value due to unbalanced loads in the MG.

5) In conclusions, TN-S system is the most suitable earthing system for MG protection during grid connected mode, however, current limiter should be used in series with the main grid to limit fault current, reduce touch voltage at faulted bus and reduce the rating of the over-current protection devices used to clear faults in the MG during the grid connected mode.

## 6. Conclusions

In this paper, three earthing systems are applied to protect the MG against different faults during the grid connecting mode. It is observed from the results that the

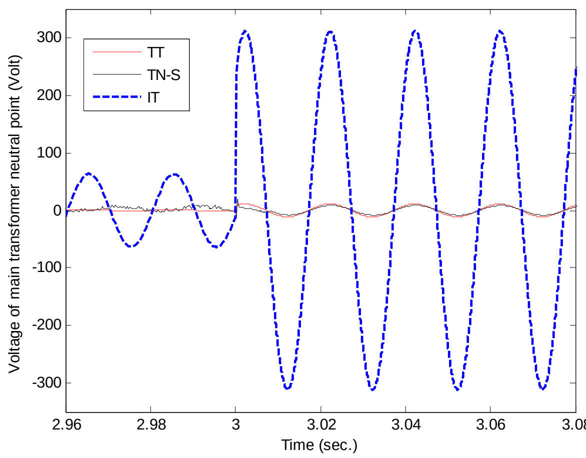


**Figure 16. Main transformer neutral point's voltage.**

 

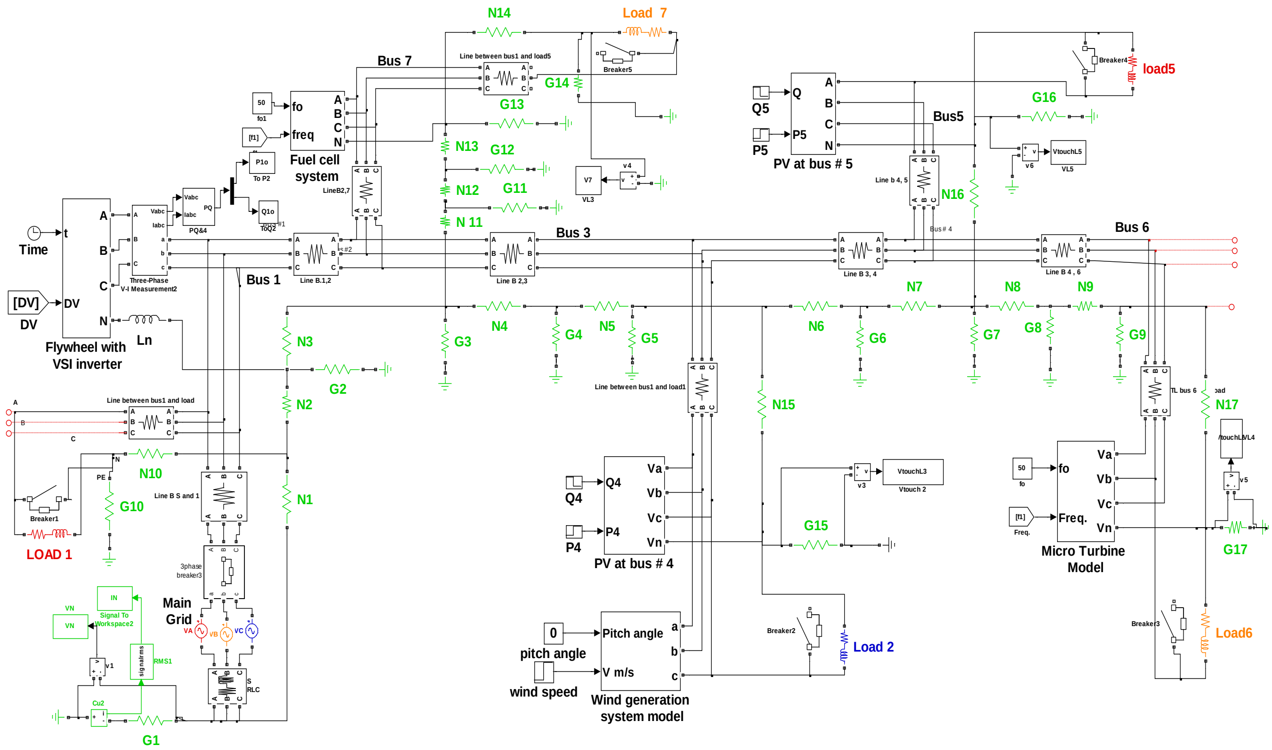


**Figure 17. Matlab© /Simulink© Developed model for MG with the erathing system.**

most suitable system is the TN earthing system. This is because fault current with TN earthing system is sufficient enough to activate the protection relay. On the other hand, for the other two earthing systems (TT and IT), protection relay can not differentiate between the fault current and overload current. Also, touch voltages at the faulted bus is smaller than the touch voltage with using TT earthing system. While, with TT earthing system, touch voltage at the faulted bus is very high and higher than the safety limit value. To overcome this problem, all consumers should be use low resistance earthing electrodes to reduce touch voltage than the safety limit value. With using IT earthing system, voltages of the healthy phases will nearly doubled (220 V became 380 V) and causes voltage stress for all equipments which are fed from the healthy phases. In grid connected mode, current limiter should be used to reduce fault current which is participated by main grid and consequently reduce the touch voltage at the faulted bus.

In conclusions, the TN earthing system is the most superior system for MG protection from the point of view of fault current and touch voltages. From this paper's results, TN earthing system is the most recommended system for MG protection during the grid connecting mode. In addition, main grid current limiter should be employed to reduce touch voltage at all MG's consumers.

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