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Chapter 10
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Grounding Method for Reliable Operation of Power and Distribution Transformers Substations

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ABSTRACT

Equipment grounding is a necessary and conclusive parts of an installation process in electrical power system networks particularly in power substations. Over years, grounding or earthing of substations has been carried out primarily through preparation of an earth mat which is simply interconnected with several Earth-rods buried around the substation or any other equipment under installation. Apart from the fact that this approach is old, it is in addition required several efforts to have an acceptable and reliable results. Thus, a more sophisticated, reliable and results oriented is required to be in place. This paper presents a modern approach to earthing of transformer substations and other allied equipment. The approach negates the constraints that are obtained in the old approach. A 15MVA, 33/11kV power transformer substation as well as a 500kVA, 11/0.415kV distribution transformer substation's installations were selected as the case study. A flow chart which describe the procedures of carrying out the proposed modern method of earthing is developed and applied to the two case studies. The various earth resistances measured on both cases are presented and discussed. The results from these case study indicates that the earth resistance values obtained from this new approach are reliable and in compliance with IEEE Standards 80,142, 81 and 1100.

Keywords: Earthing; earth – mat; earth resistance; earth – rod; flowchart; power substation; distribution substation.

1. INTRODUCTION

Power System installations and equipment need grounding systems [1-7]. Generally, grounding systems consist of grids integrated with rods at each corner. In modern extra-high-voltage and ultra-high voltage AC substations, grounding has become one of the dominant problems of system design. It is essential to have an accurate design procedure for the grounding system. Grounding provides an increase in the reliability of the electricity supply service as it enhances stability of voltage conditions, preventing excessive voltage peaks during disturbances, and a means of providing a measure of protection against lightning [1-5]. It is required that the voltage rise during a fault be kept to low levels. This dictates that ground resistances in high voltage substations must be very low. The most common method of obtaining low values of ground resistance at high-voltage substations is to use interconnected ground grids.

Over time, corrosive soils with high moisture content, high salt content, and high temperatures can degrade ground rods and their connections. Although the ground system when initially installed, had low earth ground resistance values, the resistance of the grounding system can increase if the ground rods are eaten away [4,5]. Grounding testers are indispensable troubleshooting tools to help one maintain uptime. With frustrating, intermittent electrical problems, the problem could be related to poor grounding or poor power quality. That is why it is highly recommended that all grounds and ground connections are checked at least annually as apart of normal Predictive Maintenance plan. During these periodic checks, if an increase in resistance of more than 20% is measured [1,3], it is required

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to investigate the source of the problem and make the correction to lower the resistance, by replacing or adding ground rods to the ground system [3,4].

Therefore, to bring the incessant Earth failure to the barest minimum, Engineers designed earthing system for both Distribution substation and injection substation. However, there is need to know the regulations and the expected Earth resistance values in different utility companies that requires the supply of electricity. The lower the ground resistance, the safer for people and better protection for the equipment. The IEEE Standard 80 [6] and IEEE Standard 142 [8] state that the earth resistance for large HV substation should be less than 1.0 Ohm especially for Power Transformers of ratings 7.5 MVA, 33/11 KV and above. But for cases of Distribution Transformer either 33/0.415kV or 11/0.415kV having capacity ranging from 100 KVA to 2 MVA [9], it is often difficult to achieve this earth resistance values.

It worth noting that the old conventional ways of doing Power Transformer substation earthing was to dig a large pit and bury all the earth rods and just brought out about two leads which will be extended to all the power transformers and substation equipment.

Factors influencing resistance of grounding (earthing) electrode systems include [9-11]:

1. The resistance of the electrode is a function of the material of the rod and the surface area of the rod. The surface area of the rod is a function of the rod diameter.
2. Difference in ground rod sizes and materials make little appreciable difference in the resistance of the electrode.

The contact resistance between the rod and the surrounding soil also varies depending on the compatibility of the soil. For example, if the rod is driven into well compacted soil, then the resistance between the rod and the surrounding soil is not a significant factor.

3. The resistance of the soil surrounding the electrode.

Thus, in a properly installed grounding electrode system, soil resistance is the key factor that determines what the resistance of a grounding electrode will be and to what depth a rod must be driven to obtain low ground resistance. This imply that the resistivity of soils varies with the depth from the surface and the electrolyte in the soil (the type of concentration of soluble chemical in the soul, the moisture content and soil temperature).

2. IMPORTANCE OF EQUIPMENT GROUNDING IN POWER SYSTEM

Equipment grounding in power system is of some significant importance to the life of Equipment as well as human operating them. Some of them are discussed as follows [12,13,14].

1. Safety of Human life / Building / Equipment

a. Save human life from danger of electrical shock or death by blowing a fuse i.e. to provide an alternative path for the fault current to flow so that it will not endanger the user
b. Protect buildings, machinery and appliances under fault conditions
c. Ensure that all exposed conductive parts do not reach a dangerous potential.
d. Prevent or at least minimize damage to equipment because of heavy fault current (short circuit current) and Lightning and thus improve the reliability of Equipment.
e. Provides stable platform for operation of sensitive electronic equipment i.e. maintaining the voltage at any part of an electrical system at a known value to prevent over current or excessive voltage on the appliance or equipment.

2. Overvoltage Protection

- Lightning, Line surges or Unintentional Contact with higher voltage lines can cause dangerously high voltages to the electrical distribution system. Earthing provide an alternative path around the electrical system to minimize damages in the system.

3. **Voltage Stabilization**

   In power system network, there are various sources of system electricity supply. For example, every Transformer in the system can be considered a separate source. If there were not a common reference point for all these voltage sources, it would be extremely difficult to establish relationships with each other.

4. **Protection of system: The reliability of the power supply is generally improved.**

3. PARALLEL CONNECTION OF EARTH PIT RESISTANCES IN SYSTEM GROUNDING

A Parallel circuit is one with several different paths for the electricity to travel [10,11]. It's like a river that has been divided up into smaller streams, however, all the streams come back to the same point to form the river once again.

Resistors in parallel, on the other hand, result in an equivalent resistance that is always lower than every individual resistor [11,15]. If voltage is applied across a resistor, certain amount of current flows. If another resistor is added in parallel with the first one, one would have essentially opened a new channel through which more current can flow. No matter how large the second resistor is, the total current flowing from the power supply will be at least slightly higher than the current through the single resistor. And if the total current is higher, the overall resistance must be lower.

Consider a 15 MVA 33/11 kV power Injection Substation where the resistance of six number earth pit are R_1, R_2, R_3, R_4, R_5 and R_6 and are connected in parallel. The resultant resistance R_{T1}, is shown in equation (1) [1,4,16];

$$R_{T1} = \frac{R_1R_2R_3R_4R_5R_6}{A+B+C+D+E+F} \quad (1)$$

Where,

$$A = R_2R_3R_4R_5R_6$$
$$B = R_1R_3R_4R_5R_6$$
$$C = R_1R_2R_4R_5R_6$$
$$D = R_1R_2R_3R_5R_6$$
$$E = R_1R_2R_3R_4R_6$$
$$F = R_1R_2R_3R_4R_5$$

In the same way, for a 500 KVA, 33/0.415 KV Distribution Transformer Substation, the equivalent resistance (R_{T2}) of 4 No Earth pit required is also shown in equation (2) [1,4,16];

$$R_{T2} = \frac{R_1R_2R_3R_4}{(A+B+C+D)} \quad (2)$$

Where,

$$A = R_2R_3R_4$$
$$B = R_1R_3R_4$$
$$C = R_1R_2R_4$$
$$D = R_1R_2R_3$$

4. ALGORITHMS FOR WORK SPECIFICATION OF STANDARD GROUNDINGS IN POWER SYSTEM SUBSTATIONS AND DEVELOPMENT OF FLOWCHART

The general algorithm for carrying out Grounding or Earthing in typical Power transformer substations and Distribution transformer substations are as shown below including the flowchart shown in Fig. 1 [1]. This flowchart illustrates the flow process in obtaining a very good grounding result.

4.1 Algorithm for Standard Grounding in Power Transformer Substations

1. Specify 1.5 x 1.5 x 2.0 m earth pit, 150 mm^2 x 1 copper earth conductor, 0.1 x 2.4 m copper earth rod and Earth Grid of l x b x 0.6 m. Where, l and b are respectively length and breadth of the space occupied by the equipment to be protected.
2. Excavate earth grid and the desire number of earth pits. If unable to achieve wet soil after excavation depth of 2 m, increase excavation depth till the desired results is achieved.
3. The Earthing Material (i.e wood coal, Animal dung, water & sand) are poured into the earth pit in layers shown in Fig. 2. Wood coal used as good conductor of electricity while Sand is used to form porosity to cycle water and humidity around the mixture.
4. Put copper earth rod of size 0.1 x 2.4 m in the mid of mixture.
5. Insert/bury 4No. Copper earth rod per pit as shown Fig. 3
6. Lay Copper Conductor round the Earth grid and terminate by soldering or mechanical joining at the two ends.
7. Use copper conductor to bond the two earth rods in each pit and connect the two ends to the grid via soldering.
8. Measure the resistance (R) of each of these pits' conductor to 15 m around the earth pit with another conductor dip on earth at least 0.6 m deep. Each of these resistances should be maintained at a value less than one ohm.
9. Obtain the equivalent resistance (R_{T1}) for R_1, R_2, R_3, R_4, R_5 and R_6. The R_{T1} value should be closer to zero ohm as much as possible for an injection substation and less than 5 Ω for the Distribution transformer substation.
10. Check voltage between earth pit conductor to neutral of mains supply 220 A.C, 50 Hz. The result should be less than 2.0 Volts.

4.2 Algorithm for Standard Grounding in Distribution Transformer Substations

1. Specify 0.1 x 1.8 m Earth rod, 70 mm^2 x 1 copper earth conductor, 1.5 x 1.5 x 2 m Earth pit dimension and Earth Grid of l x b x 0.6 m. Where, l and b are respectively length and breadth of the space occupied by the equipment to be protected.
2. Excavate Earth Grid and the desire number of Earth Pits. If unable to achieve wet soil after excavation depth of 2 m, increase excavation depth till the desired results is achieved.
3. The Earthing Material i.e wood coal, Animal dung, water & sand are poured into the earth pit in layers shown in Fig. 4. Wood coal used as good conductor of electricity while Sand is used to form porosity to cycle water and humidity around the mixture.
4. Put Copper or Galvanize earth rod of size 0.1 x1.8 m in the mid of mixture.
5. Insert/bury 2 No Earth rod per pit (copper or galvanized earth rod type) as shown in Fig. 5.
6. Lay Copper Conductor round the Earth grid and terminate by soldering at the two ends.
7. Use copper conductor to bond the two earth rods in each pit and connect the two ends to the grid via soldering.
8. Measure the resistance (R) of each of these pits' conductor to 15 m around the earth pit with another conductor dip on earth at least 0.6 m deep. Each of these resistances should be maintained at a value less than one Ohm.
9. Obtain the equivalent resistance (R_{T2}) for R_1, R_2, $R_{3\ and}$ R_4. The R_{T2} value should be less than 5 Ω for the Distribution transformer substation.
10. Check voltage between earth pit conductor to neutral of mains supply 220 A.C, 50 Hz. The result should be less than 2.0 Volts.

4.3 Flowchart of the Grounding Method

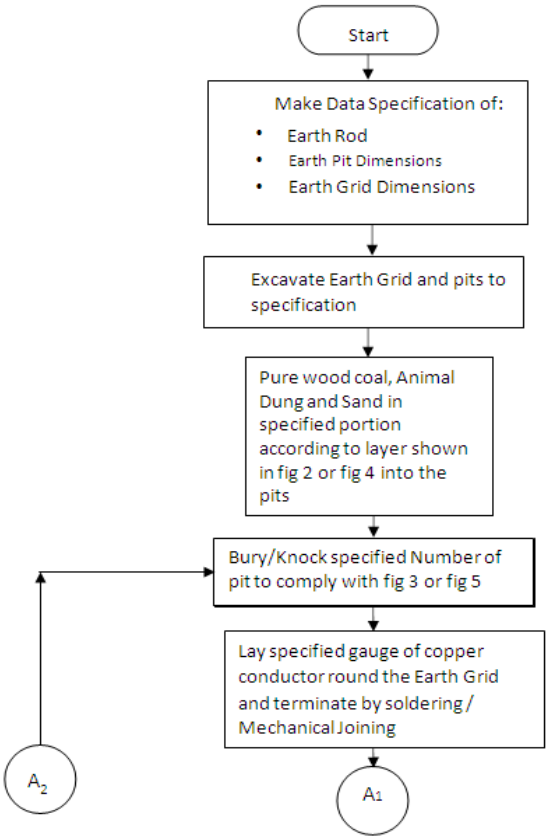
The flowchart in Fig. 1 illustrate pictorially the process involved in the effective grounding of both power and distribution transformer substations. Subsections 4.1 and 4.2 explained why the process of grounding the two transformer substations follow the same pattern.

5. DESCRIPTION OF CASE STUDY

An installation of a 2X15MVA, 33/11kV Injection Station that takes source from a Transmission in one of Nigeria distribution networks in Lagos State is used as a case study. At the completion of the project installation, the result of the conventional formal earthing system of the injection substation was obtained to be 3.5 Ω due to the swampy nature of the land. The procedural steps described in subsection 4.1 and flow process of Fig. 1 were applied to this project installation as shown in Fig. 6.

Fig. 6 illustrates the Line diagram of a 15 MVA, 33/11kV power transformer substation earthing for the case study. Here, the earth wire called grid wire is laid without any connection to it, while the two ends are soldered at the meeting point. Six number earth pit each of dimension 1.5x1.5x2m are being dug with two earth rods buried and well connected. The leads are then brought out by clamp and each earth pit is eventually connected to already laid grid wire in parallel. The resistance of the 6No earth pits R1, R2, R3, R4, R5 and R6 were measured and recorded as shown in Table 2 [1]. Substituting the above resistance values in equation (1), the equivalent resistance is calculated as R_{T1} = 0.47 Ω. Consequently, the newly developed earthing standard has really made it possible to get values of our earthing within the prescribed international value of < 1 Ohm.

Further application of the procedures in subsection 4.2 and the flow process in Fig. 1 to a 500 kVA, 33/0.415 kV distribution transformer substation earthing located in the same environment with power transformer substation analysed above yields a more reliable earthing result. In this case, 4 No Earth Pits instead of 6 No Earth pits used at power Transformer substation were required to be dug. The resistance of the Earth pit R1, R2, R3 and R4 were also measured and recorded as shown in Table 3 [1]. Substituting these resistance values in equation (2), the equivalent resistance (R_{T2}) is obtained to be 0.54Ω. The circuit arrangement of this Grounding of a typical 500 kVA, 33/0.415 kV distribution transformer substation is shown in Fig. 7.



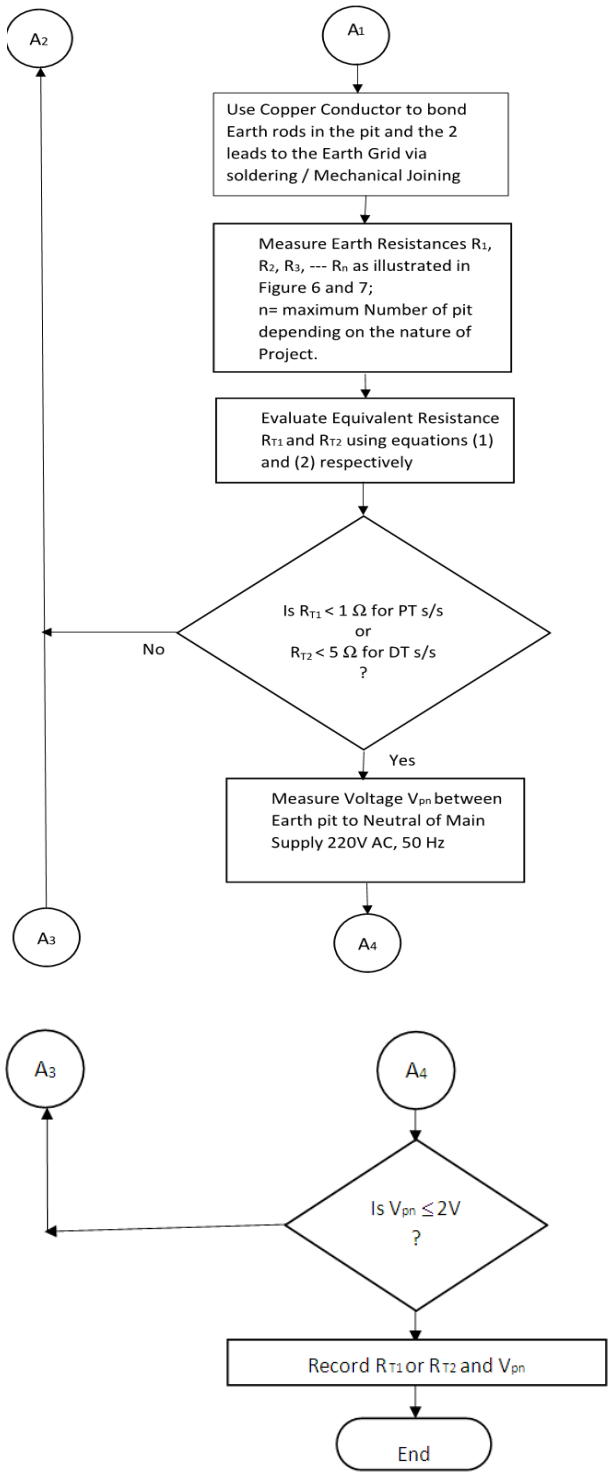


Fig. 1. Flow process of effective grounding in both power transformer and distribution transformer substations

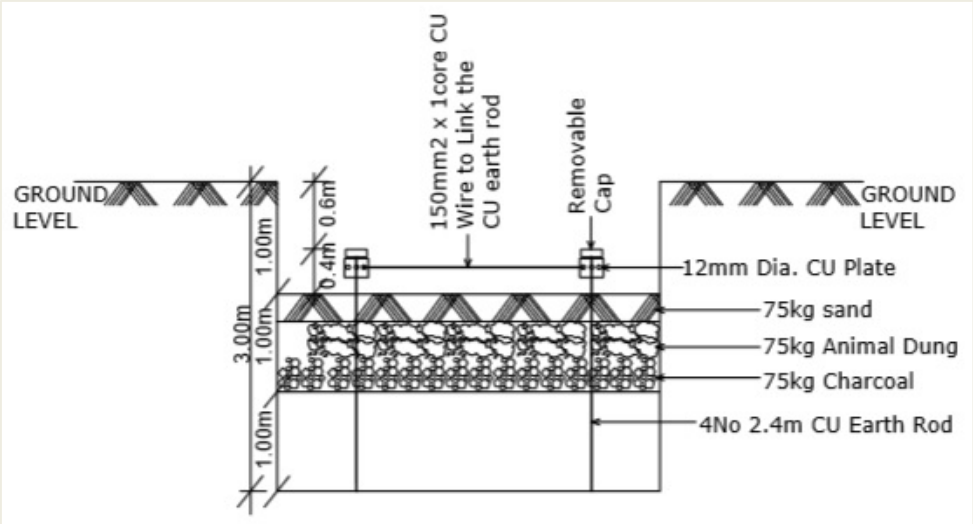


Fig. 2. Cross sectional view of earth pit contents in power transformer substation

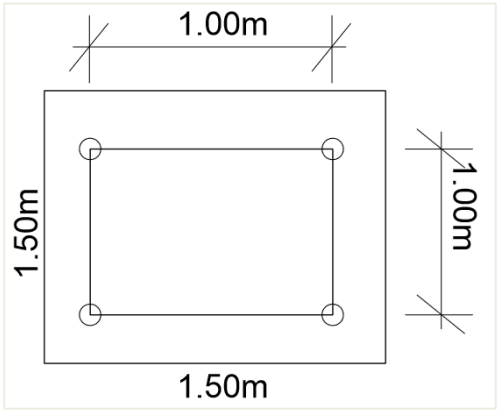


Fig. 3. Plan view of earth rods arrangement in power transformer substation pit

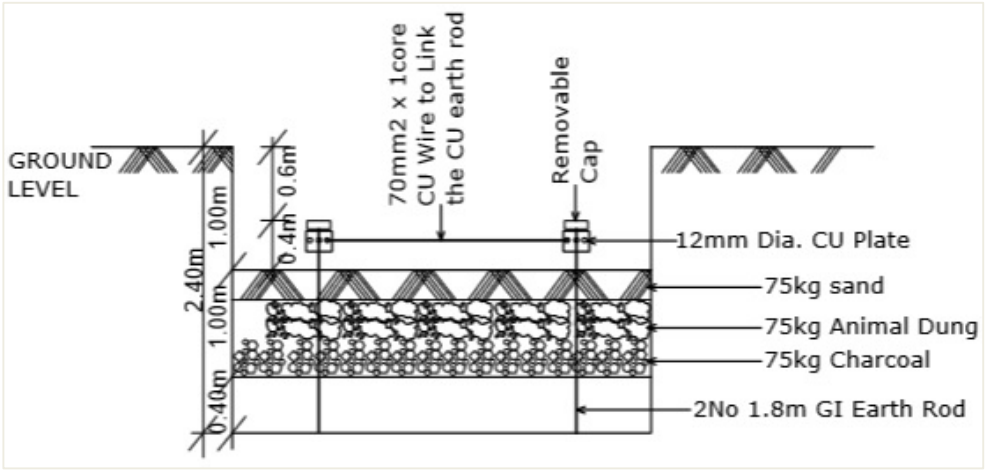


Fig. 4. Cross sectional view of earth pit contents in distribution transformer substation

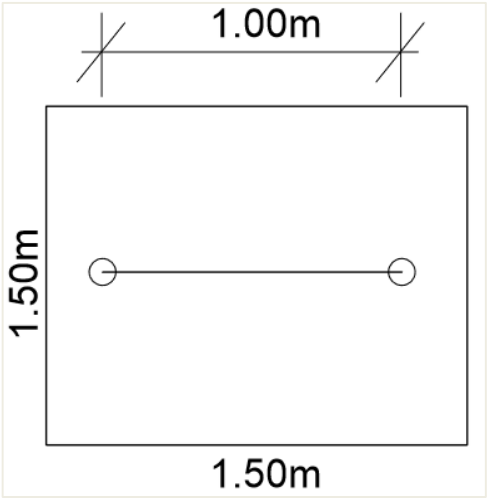


Fig. 5. Plan view of earth rods in DT substation pit

Table 1. List of symbols and their descriptions

Legend	
Symbol	**Description**
	Earth Pit
	150 mm^2 x 1 Cu Bonding Earth Rod and the Earth Grid for PT Station
	70 mm^2 x 1 Cu Bonding Earth Rod and the Earth Grid for DT Station
	Transformer
	Ring Main Unit (RMU)
N	Transformer Neutral Connection with Earth Pit
CT	Current Transformer
VT	Voltage Transformer
LA	Lightning Arrester
	Earth Grid
	Two connections made for each power equipment to the main Grid (Earth Grid).
	Two connections made for each Earth Pit to the Grid.
S/S	Substation
G/ISO	Gang Isolator
CB	Circuit Breaker
Pro	Proposed
PT	Power Transformer
DT	Distribution Transformer
Cu	Copper Conductor

Table 2. Measured earth pit resistance in case study 1

Earth Pit	Measured resistance (Ohms)
1	2.4
2	2.8
3	3.7
4	2.9
5	3.3
6	2.2
Equivalent Resistance, R_{T1} = 0.47 Ω	

Table 3. Measured earth pit resistance in case study 2

Earth Pit	Measured resistance (Ohms)
1	1.5
2	2
3	2.5
4	3.7
Equivalent Resistance, R_{T2} = 0.54Ω	

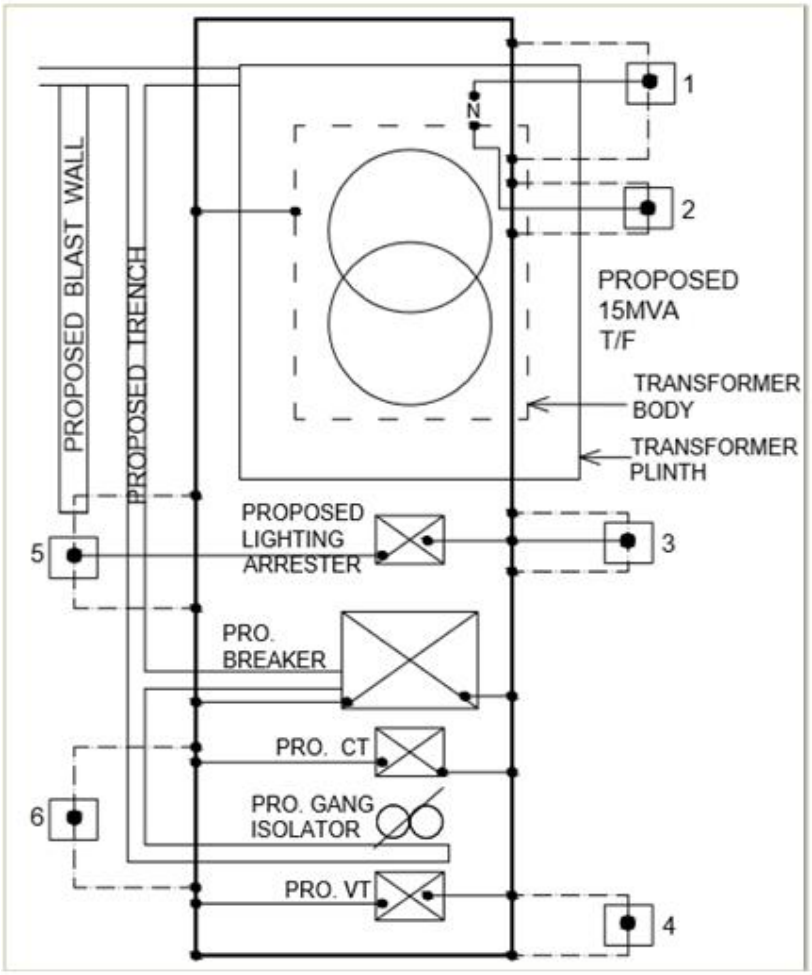


Fig. 6. Line diagram of a 15 MVA, 33/11kV power transformer substation earthing

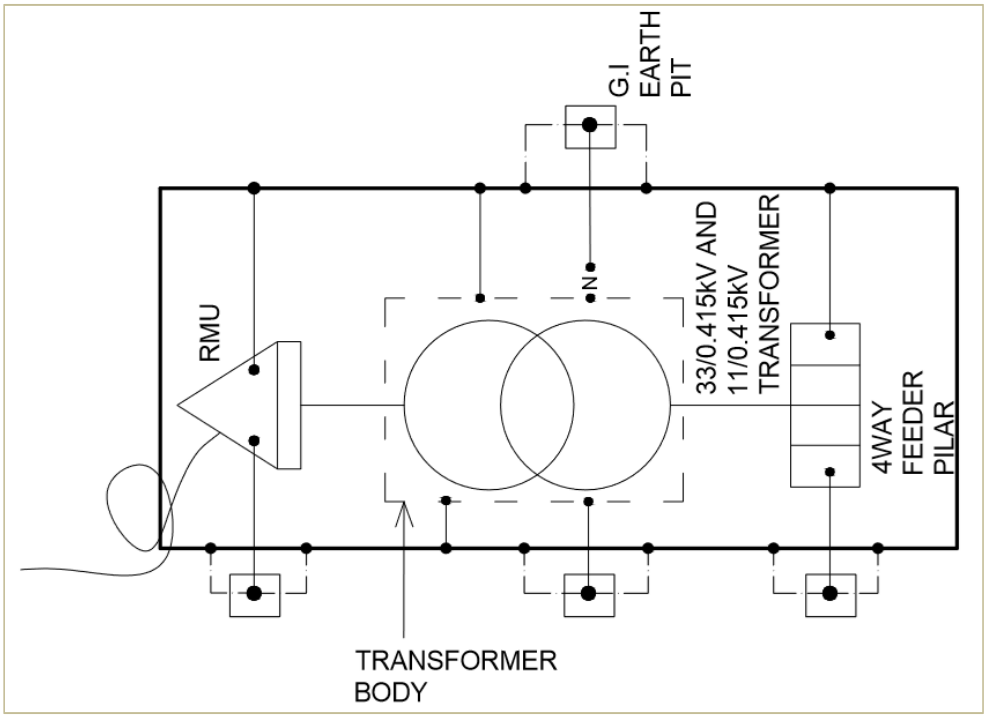


Fig. 7. Line diagram of a 500 kVA, 33/0.415kV distribution transformer substation earthing

6. DISCUSSION OF RESULTS

The pre-commissioning test results of the two case study projects are shown in Tables 2 and 3. These results revealed that the equivalent Earth resistance, R_{T1} of 15 MVA, 33/11 kV Power Transformer substation and R_{T2} of 500 kVA, 33/0.415 kV distribution transformer substation are 0.47 Ω and 0.54 Ω respectively. However, it is required that for a power transformer substation, $R_{T1} < 1\Omega$ while for a distribution transformer substation, $R_{T2} < 5\ \Omega$ are generally the acceptable standards [6,7]. Indeed, the values R_{T1} and R_{T2} follows the two inequality relations described above.

However, it is important to note that the challenges that may be encountered in carrying out the implementation of these substation grounding method has been taken care of. These includes,

1. Ensuring Married Joint are cleverly carried out by Welding via Soldering/Mechanical joining rather than using bidding wire. This prevent easy separation (i.e losing of wires) which often results in high resistance value and thus create error in the overall result.
2. Ensuring that Materials and equipment specifications are strictly complied with.

It is also important to state that the use of Animal dung and wood coal is to fasten the attainment of results and minimizing cost. Otherwise, same results could be achieved by putting up more earth pit that will consume more materials such as Earth rods, Grid Conductor etc. Figs. 6 & 7 shows that each earth pit contents and equipment are connected to the earth grid twice (Parallel connections).

Furthermore, engineers field experience relates that the conventional approach to power system equipment grounding is cumbersome because part of the process are several times repeated before the results are achieved. In the old way of carrying out earthing, a big earth pit is dug, and several earth rods are driven into the earth pit. Then the earth wire is connected across all the earth rods while 1 or 2 earth lead(s) is/are brought out. The earth lead is extended to other apparatus through married joint. In this type of connection, a resistance is developed which opposes the free flow of earth current. This makes the approach and the results obtained unreliable [1]. For illustrative

purpose, let's use the maloperation happening in Nigeria as an example. Some unpatriotic Nigerians often vandalise the copper wire used as connecting leads for earthing of power equipment. This action is often unreported and unknown to power utility company due to poor management style. This vandalism is very common in distribution transformer substations and the affected substations will keep operating unearthly since 1 or 2 leads brought out from the earth pit is Vandalised from the source. The overall consequence includes; possibility of shortening the lives of the equipment, thereby putting the utility customers in darkness and loss of revenue to utility company.

The new approach to equipment grounding has therefore eliminate the problems being faced in convectional approach. The solutions offered includes,

1. The connection of each power equipment in the substation to Earth pit is dual from the earth grid.
2. More than one Earth pits are used in each case study.
3. The problem of repeated process before getting reliable result in the conventional method of earthing is eliminated. This is because the result in this method is obtained at once.
4. Period required for the for the commissioning of the Transformer substation (i.e connection to Grid) is drastically reduced
5. Effects of copper conductor vandalism is minimized.
6. Loss of power utility equipment and revenue would be drastically reduced.

Thus, the reliability of this newly improved power equipment grounding method is high [1] while standardization of other parameters of the transformer add to the high reliability of the substations [2,17,18].

7. CONCLUSION

Engineers show great concern on grounding of power system equipment in substations. This is because, lives of the equipment as well as personnel handling the equipment need to be saved. Thus, this act enhances security of personnel and minimizes installation maintenance cost. However, this paper has presented the importance of Grounding of Power System equipment in substations. A flexible approach to this earthing of transformer substations contrary to the old approach that involves creating earth mat without even achieving results in time is introduced. An algorithm to achieve the set goal was formulated and applied to the two-case study; a 15 MVA, 33/11 kV power transformer substation and a 500 kVA, 33/0.415 kV distribution transformer substation. The results obtained in the two - case studied are presented and discussed. These results are quite satisfactory, reliable and obviously in compliance with IEEE Standards. Thus, the new approach is highly recommended to power utility companies.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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