Designing an Earthing and Bonding System for High Voltage Substation

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Abstract - There are a number of factors that need to be considered when designing high voltage substations. Therefore, designing a high voltage substation is a challenging task. The first step in designing a high voltage substation is to design an earthing and bonding system. An earthing system connection is one to which transformer and generators neutrals or earthing impedances may be connected in order to pass the maximum fault current. In this paper designing an earthing and bonding system for high voltage substation using one and half circuit breaker layout has been briefly explained.

Keywords - Substation, earhing and bonding, step and touch voltages, mesh voltage, transformer and circuit breaker, layout

I. INTRODUCTION

The earthing system should be designed to ensure the lowest possible and most economical resistance to earth mass for the expected fault currents flowing to earth, and to ensure that the potential difference induced by these fault currents into the earth mat, is kept within internationally accepted safety margins. Normally the design engineer had to rely on experience or even worse, guess, in determining the dimensions of, and the total amount of material to be used in the design of an effective earthing system. Because of this, many earthing systems were overdesigned, while some designs might even be a safety hazard under fault conditions.

The worldwide global market requires electrical engineers to have a deep understanding of the bonding and earthing practices adopted in different countries around the world. This knowledge is essential to obtain effective designs and high safety standards and can promote the elimination of technical obstacles that can still create market barriers. Industrial and commercial low-voltage (i.e., not exceeding 1 kV) power systems, persons are exposed to the risk of electric shock. Thus, standard protective measures, properly installed and maintained, must be in place to prevent persons from being in contact with energized parts for a harmful length of time. We define direct contact as contact with parts that are normally live (e.g., a damaged wire) and indirect contact as contact with metal parts that are normally not energized but likely to become live upon faults (e.g., faulty equipment). Protections against direct and indirect contacts are also respectively referred to as basic and fault protections [1].

The bonding of electrical equipment plays a crucial role in maintaining the same potential between conductive parts likely to be energized and conductive parts liable to introduce a “zero” potential into the premises. Voltage rises between such parts are unsafe, as they may induce harmful currents through the human body, the magnitude of which may vary depending on a number of factors. If the conductive part is in good contact with the bonded enclosure, there is no need for a further bonding connection; on the other hand, if the conductive part is not in good contact with the bonded enclosure, its grounding connection is against safety, as it would unnecessarily energize the part under fault conditions [2].

II. EARTHING AND BONDING

The first step in designing a substation is to design an earthing and bonding system. The function of an earthing and bonding system is to provide an earthing system connection to which transformer neutrals or earthing impedances may be connected in order to pass the maximum fault current. The earthing system also ensures that no thermal or mechanical damage occurs on the equipment within the substation, thereby resulting in safety to operation and maintenance personnel. The earthing system also guarantees equipotential bonding such that there are no dangerous potential gradients developed in the substation. In designing the substation, three voltages have to be considered.

1)Touch Voltage:-The potential difference between the ground potential rise (GPR) and the surface potential at the point where a person is standing while at the same time having a hand in contact with a grounded structure [3].

2)Step Voltage:-The difference in surface potential experienced by a person bridging a distance of 1 m with the feet without contacting any grounded object [3].

3) Mesh Voltage:-This is the maximum touch voltage that is developed in the mesh of the earthing grid.

III. SUBSTATION EARTHING CALCULATION METHODOLOGY

Calculations for earth impedances and touch and step potentials are based on site measurements of ground resistivity and system fault levels. A grid layout with particular conductors is then analysed to determine the effective substation earthing resistance, from which the earthing voltage is calculated.

In practice, it is normal to take the highest fault level for substation earth grid calculation purposes. Additionally, it is necessary to ensure a sufficient margin such that expansion of the system is catered for.

To determine the earth resistivity, probe tests are carried out on the site. These tests are best performed in dry weather such that conservative resistivity readings are obtained.

One of the important steps in determining the size and basic layout of a earthing system for an ac substation is the estimation of ground resistance of the earthing grid. The simple formulas proposed by Laurent, Niemann and Sverak are based on the formula for the ground resistance of a circular plate.The shape of the grounding grid depends on the shape of the substation area. It may be square, rectangular, triangular, L-shaped, T-shaped or any other shape. The simple formulas give fairly accurate results for the grids which are nearly square. Schwarz proposed a formula which is also applicable to rectangular grids for a limited value of length to width ratio [4]. Earthing materials used in substation are:-

A. Conductors

Bare copper conductor is usually used for the substation earthing grid. The copper bars themselves usually have a cross-sectional area of 95mm^2 , and they are laid at a shallow depth of 0.25-0.5m, in 3-7m^2. In addition to the buried potential earth grid, a separate above ground earthing ring is usually provided, to which all metallic substation plant is bonded.

B. Connections

Connections to the grid and other earthing joints should not be soldered because the heat generated during fault conditions could cause a soldered joint to fail. Joints are usually bolted, and in this case, the face of the joints should be tinned.

C. Earthing Rods

The earthing grid must be supplemented by earthing rods to assist in the dissipation of earth fault currents and further reduce the overall substation earthing resistance. These rods are usually made of solid copper, or copper clad steel.

D. Switchyard Fence Earthing

The switchyard fence earthing practices are possible and are used by different utilities. These are:
1). Extend the substation earth grid 0.5m-1.5m beyond the fence perimeter. The fence is then bonded to the grid at regular intervals.
2). Place the fence beyond the perimeter of the switchyard earthing grid and bond the fence to its own earthing rod system. This earthing rod system is not coupled to the main substation earthing grid.

E. Earth Mat Design

Earthing system in a sub station comprises of earth mat or grid, earth electrode, earthing conductor and earth connectors [5]. The factors which influence the earth mat design are:

- Magnitude of Fault Current
- Duration of Fault
- Soil Resistivity
- Resistivity of Surface Material
- Shock Duration
- Material of Earth Mat Conductor
- Earthing Mat Geometry

IV. LAYOUT OF SUBSTATION

The layout of the substation is very important since there should be a security of supply. In an ideal substation all circuits and equipment would be duplicated such that following a fault, or during maintenance, a connection remains available. Practically this is not feasible since the cost of implementing such a design is very high. Methods have been adopted to achieve a compromise between complete security of supply and capital investment. There are four categories of substation that give varying securities of supply:

1) Category 1: No outage is necessary within the substation for either maintenance or fault conditions.
2) Category 2: Short outage is necessary to transfer the load to an alternative circuit for maintenance or fault conditions.
3) Category 3: Loss of a circuit or section of the substation due to fault or maintenance.
4) Category 4: Loss of the entire substation due to fault or maintenance.

The different layouts for substations are following:-

A. Single Busbar

The general schematic for such a substation is shown in the Fig.1. With this design, there is an ease of operation of the substation.

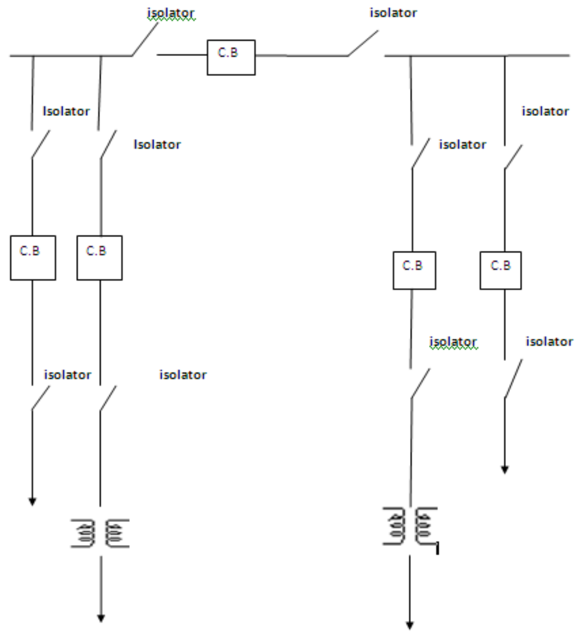

Fig.1. The layout for single bus bar substation

This design also places minimum reliance on signaling for satisfactory operation of protection. Additionally there is the facility to support the economical operation of future feeder bays. Such a substation has the following characteristics.

- Each circuit is protected by its own circuit breaker and hence plant outage does not necessarily result in loss of supply.
- A fault on the feeder or transformer circuit breaker causes loss of the transformer and feeder circuit, one of which may be restored after isolating the faulty circuit breaker.
- A fault on the bus section circuit breaker causes complete shutdown of the substation. All circuits may be restored after isolating the faulty circuit breaker.
- A busbar fault causes loss of one transformer and one feeder. Maintenance of one busbar section or isolator will cause the temporary outage of two circuits.
- Maintenance of a feeder or transformer circuit breaker involves loss of the circuit.
- Introduction of bypass isolators between bus bar and circuit isolator allows circuit breaker maintenance facilities without loss of that circuit.

B. Mesh Substation

The general layout for a full mesh substation is shown in the Fig. 2.

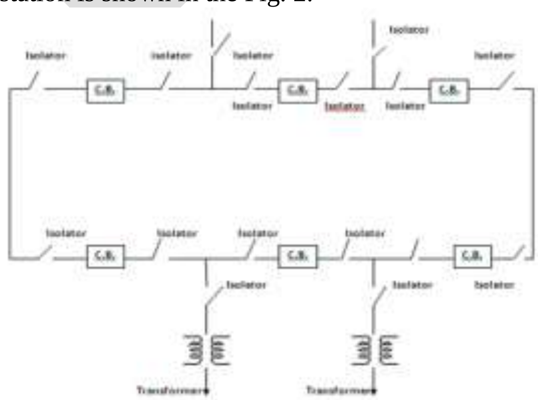

Fig. 2. The layout for mess substation

The characteristics of such a substation are as follows:

- Operation of two circuit breakers is required to connect or disconnect a circuit, and disconnection involves opening of a mesh.
- Circuit breakers may be maintained without loss of supply or protection, and no additional bypass facilities are required.

- Bus bar faults will only cause the loss of one circuit breaker. Breaker faults will involve the loss of a maximum of two circuits.
- Generally, not more than twice as many outgoing circuits as in feeds are used in order to rationalize circuit equipment load capabilities and ratings.

C. One and a Half Circuit Breaker layout

The layout of a 1 1/2 circuit breaker substation is shown in Fig.3.

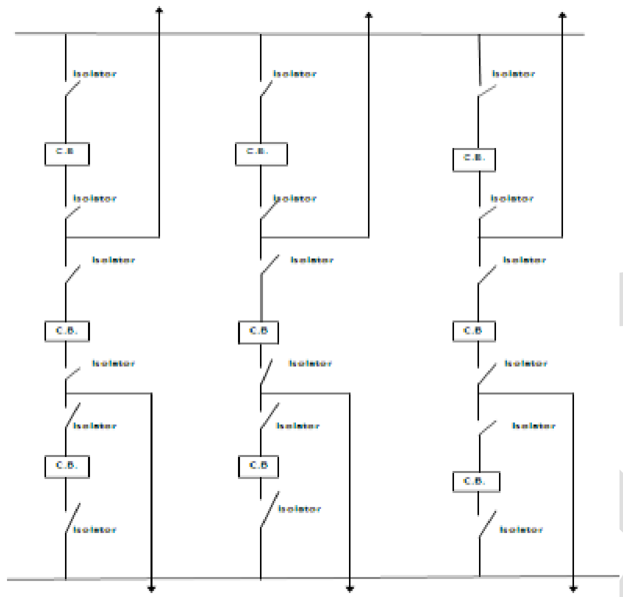

Fig.3. The layout of a one and half circuit breaker substation

The reason that such a layout is known as a 1 1/2 circuit breaker is due to the fact that in the design, there are 9 circuit breakers that are used to protect the 6 feeders. Thus, 1 1/2 circuit breakers protect 1 feeder. Some characteristics of this design are:

- There is the additional cost of the circuit breakers together with the complex arrangement.
- It is possible to operate any one pair of circuits, or groups of pairs of circuits.
- There is a very high security against the loss of supply.

V. PRINCIPLE OF SUBSTATION LAYOUTS

Substation layout consists essentially in arranging a number of switchgear components in an ordered pattern governed by their function and rules of spatial separation.

A. Spatial Separation

- Earth Clearance: - this is the clearance between live parts and earthed structures, walls, screens and ground.
- Phase Clearance: - this is the clearance between live parts of different phases.
- Isolating Distance: - this is the clearance between the terminals of an isolator and the connections thereto.
- Section Clearance: - this is the clearance between live parts and the terminals of a work section. The limits of this work section, or maintenance zone, may be the ground or a platform from which the man works.

B. Separation of Maintenance Zones

Two methods are available for separating equipment in a maintenance zone that has been isolated and made dead.

1).The provision of a section clearance.

2). Use of an intervening earthed barrier

The choice between the two methods depends on the voltage and whether horizontal or vertical clearances are involved.

- A section clearance is composed of the reach of a man, taken as 8 feet, plus an earth clearance.
- For the voltage at which the earth clearance is 8 feet, the space required will be the same whether a section clearance or an earthed barrier is used. Hence,
  Separation by earthed barrier = Earth Clearance + 50mm for barrier + Earth Clearance
  Separation by section clearance = 2.44m + Earth clearance
- For vertical clearances it is necessary to take into account the space occupied by the equipment and the need for an access platform at higher voltages.
- The height of the platform is taken as 1.37m below the highest point of work.

C. Establishing Maintenance Zones

Some maintenance zones are easily defined and the need for them is self evident as is the case of a circuit breaker. There should be a means of isolation on each side of the circuit breaker, and to separate it from adjacent live parts, when isolated, either by section clearances or earth barriers.

D. Electrical Separations

Together with maintenance zoning, the separation, by isolating distance and phase clearances, of the substation components and of the conductors interconnecting them constitute the main basis of substation layouts. There are at least three such electrical separations per phase that are needed in a circuit:

1). Between the terminals of the bus bar isolator and their connections.
2). Between the terminals of the circuit breaker and their connections.
3). Between the terminals of the feeder isolator and their connections.

VI. COMPONENTS OF A SUBSTATION

The substation components will only be considered to the extent where they influence substation layout.

A. Circuit Breakers

There are two forms of open circuit breakers:

1) Dead Tank: - circuit breaker compartment is at earth potential.
2) Live Tank: - circuit breaker compartment is at line potential.

The form of circuit breaker influences the way in which the circuit breaker is accommodated. This may be one of the following ways.

(a) Ground Mounting and Plinth Mounting

The main advantages of this type of mounting are its simplicity, ease of erection, ease of maintenance and elimination of support structures. An added advantage is that in indoor substations, there is the reduction in the height of the building. A disadvantage however is that to prevent danger to personnel, the circuit breaker has to be surrounded by an earthed barrier, which increases the area required.

(b) Retractable Circuit Breakers

These have the advantage of being space saving due to the fact that isolators can be accommodated in the same area of clearance that has to be allowed between the retractable circuit breaker and the live fixed contacts. Another advantage is that there is the ease and safety of maintenance. Additionally such a mounting is economical since at least two insulators per phase are still needed to support the fixed circuit breaker plug contacts.

(c) Suspended Circuit Breakers

At higher voltages tension insulators are cheaper than post or pedestal insulators. With this type of mounting the live tank circuit breaker is suspended by tension insulators from overhead structures, and held in a stable position by similar insulators tensioned to the ground. There is the claimed advantage of reduced costs and simplified foundations, and the structures used to suspend the circuit breakers may be used for other purposes.

B. Current Transformers

CT's may be accommodated in one of six manners:

- Over Circuit Breaker bushings or in pedestals.
- In separate post type housings.
- Over moving bushings of some types of insulators.
- Over power transformers of reactor bushings.
- Over wall or roof bushings.
- Over cables.

In all except the second of the list, the CT's occupy incidental space and do not affect the size of the layout. The CT's become more remote from the circuit breaker in the order listed above. Accommodation of CT's over isolator bushings, or bushings through walls or roofs, is usually confined to indoor substations.

C. Isolators

These are essentially off load devices although they are capable of dealing with small charging currents of busbars and connections. The design of isolators is closely related to the design of substations. Isolator design is considered in the following aspects:

- Space Factor
- Insulation Security
- Standardization
- Ease of Maintenance
- Cost Some types of isolators include:
- Horizontal Isolation types
- Vertical Isolation types
- Moving Bushing types

D. Conductor Systems

An ideal conductor should fulfill the following requirements:

- Should be capable of carrying the specified load currents and short time currents.
- Should be able to withstand forces on it due to its situation. These forces comprise self weight, and weight of other conductors and equipment, short circuit forces and atmospheric forces such as wind and ice loading.
- Should be corona free at rated voltage.
- Should have the minimum number of joints.
- Should need the minimum number of supporting insulators.
- Should be economical.

The most suitable material for the conductor system is copper or aluminium. Steel may be used but has limitations of poor conductivity and high susceptibility to corrosion. In an effort to make the conductor ideal, three different types have been utilized, and these include:

- Flat surfaced Conductors
- Stranded Conductors
- Tubular Conductors

E. Insulation

Insulation security has been rated very highly among the aims of good substation design. Extensive research is done on improving flashover characteristics as well as combating pollution. Increased creepage length, resistance glazing, insulation greasing and line washing have been used with varying degrees of success.

F. Power Transformers

EHV power transformers are usually oil immersed with all three phases in one tank. Auto transformers can offer advantage of smaller physical size and reduced losses. The different classes of power transformers are:

- O.N. : Oil Immersed, Natural Cooling
- O.B. : Oil Immersed, Air Blast Cooling
- O.F.N. : Oil Immersed, Oil Circulation Forced, Natural Cooling
- O.F.B. : Oil Immersed, Oil Circulation Forced, Air Blast Cooling

Power transformers are usually the largest single item in a substation. For economy of service roads, transformers are located on one side of a substation, and the connection to switchgear is by bare conductors. Because of the large quantity of oil, it is essential to take precaution against the spread of fire. Hence, the transformer is usually located around a sump used to collect the excess oil. Transformers that are located and a cell should be enclosed in a blast proof room.

G. Overhead Line Terminations

Two methods are used to terminate overhead lines at a substation.

1) Tensioning conductors to substation structures or buildings
2) Tensioning conductors to ground winches.

The choice is influenced by the height of towers and the proximity to the substation. The following clearances should be observed as shown in Table I.

Table I. GROUND CLEARANCE

Sl. No.	*Voltage Level*	*Minimum Ground Clearance*
1.	less than 66kV	6.1m
2.	66kV - 110kV	6.4m
3.	110kV - 165kV	6.7m
4	Greater than 165kV	7.0m

VII. SIMULATION OF SUBSTATION EARTHING GRIDS WITH UNEQUAL-POTENTIAL

Substation earthing grids are made of interconnected conductor bars, buried under substations. The purpose of the grids is to reduce the earthing resistance of electric installations and smooth the potential gradient on the earth surface to ensure safety to the persons in the substation during short-circuit fault of the power system. The possibility of the hazard can be judged by computing the maximum step and touch voltages. The design of earthing systems must meet the requirement of the safety and the electrical properties. Meanwhile, the reduction of the earthing resistance is able to reduce the rise of the potential around the grid, caused by the fault current emanating to the earth, so that the electromagnetic interference with the communication system nearby can be decreased. In the simulation of earthing grids, most of the methods presented previously were based on equal-potential models, i.e., ignoring the resistance of the conductor and the potential drop caused by the interior resistance of the conductor. The assumption that the earthing grid is of equal-potential arises from that the resistivity or the resistance of the conductors is much smaller than that of the soil. For ordinary earthing grids, the equal-potential grid model is able to meet the requirement of general engineering design, i.e., calculation accuracy of the earthing resistance and the step as well as the touch voltage. However, if the radius of conductors supposing the conductor is in the shape of a cylinder) is very small, their resistance may cause an obvious potential difference on the grid. On the other hand, if the radius of conductors is great enough, further increasing of the radius influences the parameters of the grid very slightly, so that it is not necessary to adopt conductors of a very large radius to construct grids. Otherwise, only material consuming,

but nothing else can be achieved. Therefore, it is of great significance to investigate the proper radius of conductors for grids of certain sizes, buried in the earth of a certain value of conductivity [6-8].
Another use of the unequal-potential model is analyzing the electromagnetic interference between the communication or electronic instruments whose earthing terminals are connected to the earthing grid, but not to the same point. The potential difference of the grid may produce potential difference between the terminals, which will create electromagnetic interference between the instruments. Based on the analysis of the grid with unequal-potential model, the interference can be decreased by connecting the earthing terminals of associated instruments to the points located on or near an equal-potential line [9].

There are number of softwares which are very useful in designing high voltage substations like ESGSD (Economical Substation Grounding System Designer), GGS (Grounding Grid System) module. These softwares can be used in design of grounding system for high voltage substations for different grid shapes in two types of soil models. Software ESGSD is quite satisfactory for design of grounding system design in uniform as well as two layered soils and it also meets IEEE safety criteria [10, 11, 12, 13].

VIII. CONCLUSION

Earthing and bonding is extremely important and required for designing any substation layout. In designing the substation, three voltages (namely step, touch and mesh) have to be considered. The biggest advantage of one and half circuit breaker substation layout is that it is possible to operate any one pair of circuits, or groups of pairs of circuits. The form of circuit breaker influences the way in which the circuit breaker is accommodated. The various components of substation must be as per required standard. It is very important that metal parts required to be bonded for safety reasons are only a subset of the whole set of possible conductive parts present in electrical systems. Their identification is crucial to create an effective protection against indirect contact. The conditions that must be fulfilled to assure protection against indirect contact indeed provide the designer with effective, and safe, criteria to size the electrical installation. The simulation of earthing grids with unequal-potential is of great significance in the design of grids and the analysis of electromagnetic compatibility. The main work of simulating grids with unequal-potential is the same as that with equal-potential, which is the calculation of the resistance coefficients.

ACKNOWLEDGEMENT

The author is grateful to Dr. H.C. Sharma for his guidance and moral support provided during this research effort. The author is also thankful to Dr. Jarnail Singh, Professor & Principal of Laxmi Devi Institute of Engineering & Technology, Alwar, Rajasthan for their motivation.

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