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Analysis of Electrical Substation Installation In a Flood Prone Environment

J. C. Onuegbu[1*], A. E. Anazia[1] and V. N. Agu[1]

[1]*Department of Electrical Engineering, Namdi Azikiwe University, Awka, Nigeria.*

Authors' contributions

This work was carried out in collaboration between all authors. Author JCO designed the study, performed the statistical analysis, wrote the protocol and the first draft of the manuscript and managed literature searches. Authors AEA and VNA managed the analyses of the study and literature search and also ensured quality assurance of the article. All authors read and approved the final manuscript.

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ABSTRACT

A generalized analysis of electrical installations in a flood prone city was carried out. Much attention was paid to both security of the equipment and the safety of the personnel. The range of voltage envisaged here was 33/11KV for a non-specific city. The objective was thinned down to a substation located in a city suddenly exposed to flooding due to urbanization and bad environmental sanitation. The study provided a guide on the management of substation in a flood risk zone considering the financial constraint of relocation. A few managerial measures necessary for the sustenance of such installation were discussed. The result of the study will facilitate availability of power during flooding caused by rain or tidal waves.

Keywords: Flood; equipment; protection; resistivity; grounding.

1. INTRODUCTION

Flooding means to cover a place with water and in this context, the water can be derived from rainfall, rivers overflowing their banks from excessive rain or from tidal waves. Rate of flooding depends on the soil texture – that is its porosity. Flooding begins to develop when the

**Corresponding author: E-mail: onuegbujo@yahoo.com;*

soil takes enough water to its saturation at a depth of 10 to 50 mm [1]. Electrical installations cannot thrive economically in a flood prone area. There could not have been an intentional motive to install electrical equipment in a flood prone city, but due to rapid urbanization, bad environmental management, erosion and climate change, the need may arise to protect such electrical equipment from the influence of flooding. The discussion will highlight the causes of urban city flooding, their management and their effect on power equipment, economic and socio-cultural influence on the people inhabiting the area [2]. A city is an urban area densely populated with not less than ten thousand inhabitants with its characteristic beehive of activities. Flooding often is as a result of urbanization which consequences may not have been envisaged during the initial planning and environmental design.

It is a common phenomenon in modern day's cities to observe the combined forces of nature and man that alter the aesthetic beauty of our urban cities. The flooding results from gutter blockade by garbage mostly from artisans and petty traders, unapproved pipe lines across roads, damage to roads and common mistakes in urban city planning that is, if such city plans existed in the first place. The menace of flooding is rampant in cities world-over ranging from disastrous to mild conditions for different cities. It becomes imperative in this era of electric power system restructuring to look into problems caused by flooding of electrical installations so as to guarantee safe operation and safety of personnel. It is the duty of Engineers in that field to initiate proactive measures to ensure that no substation is lost or made temporarily nonoperational as a result of flooding. In the light of this and for the attainment of the Millennium Development Goal (MDGs) through the electricity reform program, countries will adequately continue to address the challenges of climate change. This will include upgrading of the existing structures and their adaptation not only to emergency operation but also to seasonal changes. The result of this study should show that an overhaul in engineering design and standardization of the existing substations and feeder stations is necessary and overdue possibly by independent consultants [3]. The result gotten from such power equipment analysis in flood prone cities are needed periodically to determine the rate of degradation and possible replacement.

1.2 Thunder Strike Estimation

Rainfall of all magnitude is associated with thunder storm. However, the number of strikes varies in different locations. One reliable means to the forecast of the number of strikes of thunder is the number of hours of exposure of a square kilometer to thunder storms.

The Meteorological information of a proposed site is imperative in marking a site for the installation of power stations and substations. Thunder strike causes internal over voltage in power systems necessitating proper grounding of all electrical equipment. With reference to the theme of discussion, certain measures recommended to guarantee safe operation of any substation located in a flood prone city in the world over. They include but not limited to protection against thunder storm, proper grounding and optimization of the base insulation of transformers and over current limiting devices, short circuit coordination and insulation coordination, dehydration of transformer and total overhaul of the entire distribution network.

1.3 Protection against Thunder Strikes

Thunder protection is considered for a 33/11KV supply where overhead earth wire is absent. The protection is done with a single standing thunder protector. Firstly, the over voltage caused by thunder storm is considered. The current generated by thunder storm has the form of a unipotential non-periodic impulse of amplitude $I_{m,\ max}$ and the average impulse steepness of

$$a = I_{m,max}/T_f \quad (1)$$

where T_f is the length of impulse front. The intensiveness of thunder storm is characterized by n_d – number of stormy days/year or n_h - number of stormy hours per year, the coefficient $n_h = 1.5*n_d$. Experimentally, a = (2 to 50) kA/µsecond and $I_{m,max}$ = 150KA. On the average, taking 1 km^2 surface area as reference, there is about 0.1 strike per stormy day. This strike occurs on an isolated thunder receptor of height (h) on a given surface radius of r = (3 to 3.5)*h at a number defined by

$$N = h^2 n_d * 10^{-6} \quad (2)$$

times. On the other hand, the number of strikes on power line of the category

$$33/11KV \text{ is } N = n_h * l * h_{av} * 10^{-4} \quad (3)$$

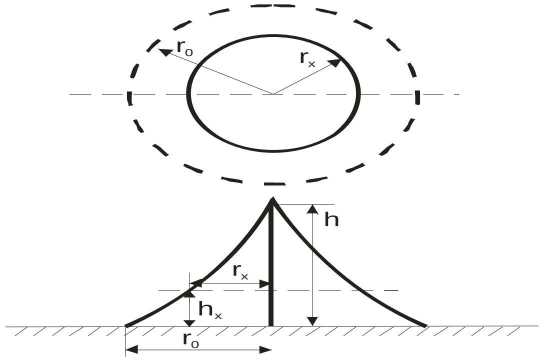


Fig. 1.1. Protection zone for single standing thunder protector

times, where *l* is the total length of the power line [5]. Similarly, for high voltage transmission lines, N can be defined as:

$$N = [5h_{t,av} + (h^2_{l,av}/30) + b_t]*l*n_h*10^{-4} \quad (4)$$

(lines with overhead thunder protector), and

$$N = [5h_{l,av} + (h^2_{l,av}/30) + b_l]*l*n_h*10^{-4} \quad (5)$$

(lines without overhead thunder protector),

where b_t and b_l – distance between the two earth wires and that of the conducting wires by the sides respectively, while $h_{t,av}$ and $h_{l,av}$ – average height of the thunder protector and that of the power line measured from the ground respectively.

Thus: $$h_{l,av} = h_l - (2f_l/3) \quad (6)$$

and, $$h_{t,av} = h_t - (2f_t/3) \quad (7)$$

where f_t and f_l –height of sag of the horizontal thunder protector and power line between two poles respectively. Thunder protector in form of independently standing pole is recommended for installation at 33kV substation. The zone of protection is defined as:

$$\frac{r_x}{h-h_x} = p * \frac{1.6}{1+\frac{h_x}{h}} \quad (8)$$

where p = 1 if h ≤ 30 m and p = 5.5/√h if h>30 m [5], where h_x – height of internal zone of protection, r_x – radius of internal zone of protection. From Fig. 1.1, h_x can be taken as ⅓ of the vertical height of the thunder protector from the ground surface while r_x is the radius of the circle formed by h_x.

From Fig. 1.2, the maximum voltage of a thunder protector after a strike is defined as

$$V_{H,max} \approx I_{m,max}*R_{z,imp} + L(di_m/dt)_{av}, \text{ KV} \quad (9)$$

where $R_{z,imp}$ - resistance of grounding impulse in ohms and L – inductance of thunder protector from the earthing device to the striking point at a height of (H) in meters; $(di_m/dt)_{av}$ = *a*– average steep of the striking current, kA/microsecond. For ease of calculation, $I_{m,max}$ can be assumed to be 150 KA and H is the height of the protected equipment. It is evident that the flashpoint of electric charge in air E_a=500 KV/m showing that the zone of protection of independently standing thunder protector can conveniently cover a distance represented by

$$l_a = 0.3*R_{z,imp} + 0.1*H \quad (10)$$

where

$$R_{z,imp} = \alpha_{imp}* R_z, \quad (11)$$

R_z is the resistance of the grounding wire and α_{imp} – impulse coefficient, $\alpha_{imp} < 1$ if total length of grounding wire is in the range of 200 to 300 meters. For length of grounding wires greater than 300 meters, $\alpha_{imp} > 1$. Similarly, impulse voltage of thunder strike is

$$V_{z,imp} = R_{z,imp} * I_{z,imp}, \quad (12)$$

where $I_{z,imp}$ is obtained from measurement.

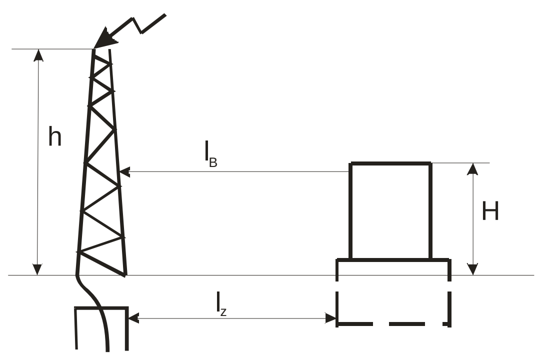


Fig. 1.2. Dimensions of thunder protector and electrical equipment

If there is power line at the height of equipment H, the electric charge in air E_a decreases to 300 KV/m then the maximum potential difference on the grounding device at a thunder strike will be

$$V_{z,max} = I_{m,max}*R_{z,imp}, \quad (13)$$

This gives length of coverage of about $l_z \geq 0.5*R_{z,imp}$, which should not be less than 7 meters.

1.4 Power System Earthing

For a transformer of 6-35KV with isolated or resonance earthed neutral, the resistance of the grounding unit has to be

$$R_z \leq \frac{250}{I_z}, \text{ ohms} \quad [6], \qquad (14)$$

where I_z – value of short circuit current to earth, Amperes. For power systems of 6-35 kV, grounding resistance should not be above 10ohms, and for power systems of up to 1KV, the grounding resistance should be $R_z \leq (125/I_z)$, ohms for systems of isolated neutral. For these low voltage systems, 10 ohms is recommended at an average of 100 kVA and 4o hms for higher power values [7]. The foregoing is the first step in calculating earthing resistance of a unit. The second step is to determine the natural resistance of the grounding metal R_e. As shown in Fig. 1.3(a), the artificial grounding rod resistance will be calculated as in (15).

$$R_{art} = \frac{R_e R_z}{R_e - R_z}, \text{ ohms.} \qquad (15)$$

The artificial grounding metal can be a vertical rod of length *l* = (3 to 5)m and diameter (12 to 20) mm using a horizontal earthing device made of iron plate (40 by 4) mm. Next, the resistance of all the horizontal grounding rods is defined as:

$$r_r = \left(\frac{0.366\rho_c}{l}\right) * \log\left(2 * \frac{l^2}{b} * t\right), ohms \qquad (16)$$

where *l* – length of vertical grounding rod (m), b – width of horizontal grounding plate, t – depth of grounding pit (m) and ρ_c – calculated resistivity of the soil as shown in table 3.

$$\rho_c = k_c * \rho, \qquad (17)$$

defined as $R_r = \frac{r_r}{\eta_r}$, where η_r - coefficient of utilization of the vertical rods grounding rods which, depends on the distance between the vertical rods and their length.

$$\eta_r = \frac{a}{l}, \qquad (18)$$

Equation (18) depends on the moisture content of the soil. To standardize the value, a mixture of salt and charcoal is used to retain the moisture content of the soil.

If $R_r < R_{art}$, then vertical earthing devices are not required but if $R_r > R_{art}$, vertical grounding is a must and it will have the resistance:

$$R_V \leq R_r * \frac{R_{art}}{R_r + R_{art}}, \quad \text{ohm} \qquad (19)$$

Table 1. Thunder storm as a function of number of rainfall hours [4]

Thunder storm hour/year	10 -20	30- 40	40 - 60	60– 80	80 and above
Average strike(s), n	1	3	6	9	12

Table 2. Determination of natural ground metal resistance

S/N	Relationship between R_e and R_z	Recommendation
1.	$R_e = R_z$	No need for R_z
2.	$R_e < R_z$	No need for vertical rods. The series adjoining should not have more than two contact rods
3.	$R_e > R_z$	There is need for artificial grounding rods to reduce R_e

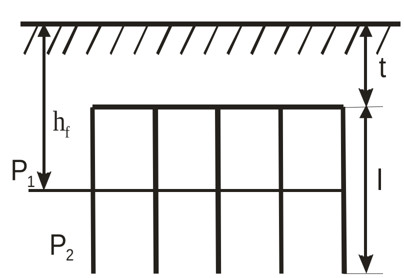
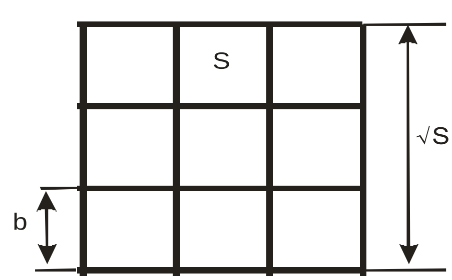


Fig. 1.3 (a) Vertical earthing device



(b) Horizontal earthing device

As a guide in choosing the resistance of each of the horizontal rod, thee following equation can be applied as in (20).

$$r_v = \left(\frac{0.366*\rho_c}{l}\right) * [\log\left(2 * \frac{l}{d}\right) + 0.5 * \log\left(\frac{4*t+l}{4*t-l}\right)] \quad (20)$$

where l – length of the vertical rod, d – diameter of the vertical rod, t – dept of grounding pit, which is equal to half the length of the vertical rods. Lastly, the number of the vertical rods needed is defined as:

$$n_v = \frac{r_v}{R_v * \eta_r} \quad (21)$$

1.5 Short Circuit Co-ordination

Short circuit co-ordination is important because of the expectations of a city with fast growing population, economy and industrialization. The reasons for the short circuit coordination could be such as to enable power system upgrade, and increased interconnectivity. The needs for expansion in labour and equipment, and increased reliability of power supply to match increasing load demand. The boundary parameters of short circuit in systems of 35KV and above are limited by the parameters of switchgears, transformers, power lines, reactors and a few other power system peripherals. The most outstanding methods of limiting short circuit current is sectionalization of buses and distribution conductors, installation of current limiting reactors and the use of distribution transformers 33/11KV with sectionalized secondary windings. Sectionalization of power distribution systems entails paralleling of transformers and the compulsory application of switchgears. With this scheme, during short circuit, only one transformer will be affected and the short circuit current will be reduced by the incoming line resistance. As shown in Fig. 1.4, the multiple transformer winding reduces the resistance by half thereby causing the short circuit power to be virtually halved. If the input voltage is 10KV or less, the sectionalized bus can operate separately, each supplied by a unit transformer. With sectionalized secondary winding of transformer or the incorporation of limiting reactor, short circuit value will be reduced in the distribution systems.

Table 3. Resistivity of soil samples [6,8]

S/N	Type of soil	Resistivity ρ, ohm/m	S/N	Type of soil	Resistivity ρ, ohm/m
1.	Sand	400-1000	5.	Rocky soil	2000-4000
2.	Sandy loam	150-400	6.	Clay soil	8-70
3.	Loamy soil	40-150	7.	Black sand	10-50
4.	Garden soil	40	8.	---	---

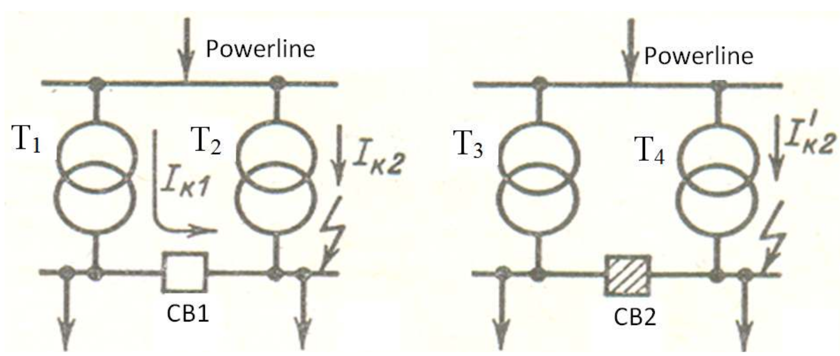


Fig. 1.4. Sectionalized single bus to reduce short circuit a) switchgear on, b) switchgear off

Table 4. Coefficient of utilization of the vertical grounding rods [7,8]

$\eta_r = \frac{a}{l}$	Number of vertical grounding rods						
	4	6	8	10	20	30	50
1	045	0.04	0.36	0.34	0.27	0.24	0.21
2	0.55	0.48	0.43	0.40	0.32	0.30	0.28
3	0.70	0.64	0.60	0.56	0.45	0.41	0.37

1.6 Insulation Co-ordination

It is obvious that a substation in a flood prone city may not comply with the norms of electrical energy distribution due to wetness of the ground, high humidity, increased concentration of gasses and high capacitance. The first step is to measure the base insulation resistance of major system equipment, the wetness and conductivity rate of transformer oil and its flashpoint as well as resistance of all cables leading in and out of such electrical installation [9]. The coefficient of absorption for such a flood zone has to be defined for early detection of weak points along cables, transformers and distribution buses. Insulation conductivity test is done in two time intervals. The standard timing is first for 15 seconds, and then for 60 seconds, to give R15″ and R60″ respectively. The ratio of the two values (15, 60) seconds gives the polarization index of the windings. The polarization index is an indication of the extent of deterioration of the insulation from moisture.

$$K_{ab} = R60''/ R15'' \qquad (22)$$

Equation (22) gives rise to a coefficient known as coefficient of absorption (K_{ab}). Coefficient of absorption for dry insulation can be $K_{ab} > 1$ but for wet insulation, it is about 1. The value of K_{ab} shows the conditions of an insulation as $K_{ab} < 1$, insulation is bad; $K_{ab} = 1$, insulation is on critical condition and $K_{ab} > 1$, the insulation is in good condition. The wet condition in which the unsuspecting electrical equipment is located will lead to dielectric loss resulting in the production of active leakage current (I_a) and capacitive current (I_c) as shown in Fig. 1.5 [10].

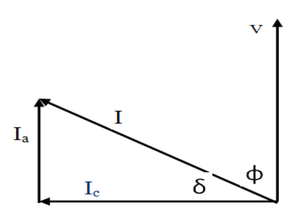


Fig. 1.5 Vector diagram of currents of an insulator

The active leakage current originates from the metallic contacts to the ground while the capacitive current originates from between three phase conductors and between the overhead lines and the ground [11]. From Fig. 1.5, the tangent angle of dielectric loss is defined by the arctangent of the current ratio I_a/I_c, where $\delta = \tan^{-1}(I_a/I_c)$. The active leakage current can be gotten from a similar setup to what is shown in Fig. 1.6.

The capacitive current is a function of the electric discharge (q) on the power line at a frequency of 50Hz to the earth's surface defined as: [11].

$$C = \frac{q}{V_{rated}},\ X_c = (2\pi f C)^{-1}, and\ I_c = \frac{V_{rated}}{X_c} \qquad (23)$$

Besides the calculation method with hindered accessibility, the practical method of capacitance measurement can be applied and there are two ways of doing so, namely:

i) **Capacitor-frequency method**

This is based on the principle of changing the capacitance of machine windings and apparatuses depending on the frequency. Windings with high degree of moisture have a relationship measured at 2Hz and 50Hz respectively. For dry transformers, the relationship is represented as

$$k_c = \frac{C_2}{C_{50}}$$

and could be in the range of unity.

The chat is limited to low and medium range voltage.

The x-axis bears the temperature dependent capacita-nce represented by a function of two capacitance values (K_C) measured at two different temperatures.

where C_2 represents the capacitance at the initial frequency and C_{50} represents capacitance at a frequency of 50Hz. From the graph, it is observed that in all values of the voltage, capacitance increases with rise in temperature and the magnitude is higher as the voltage decreases as can be seen in Fig. 1.7.

ii) **Capacitance temperature method**

This is based on the principle that the capacitance of dry insulation virtually remains unchanged with increase in temperature but the capacitance of wet insulators increases with temperature rise. The rate of wetness of insulation determines the change in capacitance at about 10℃ to 80℃. The capacitance of a transformer can be measured for any choice temperature between each winding and the bank while

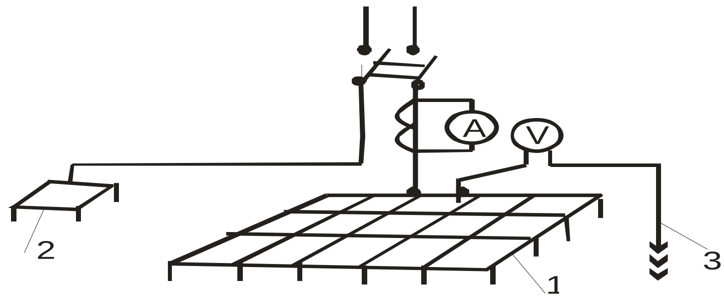


Fig. 1.6 Volt-ammeter method of measuring earthing rod leakage current
1) Horizontal earthing device, 2) Auxiliary earthing device, 3) Probe

grounding every free winding [10]. After experimental analysis, the hot temperature of the capacitance can be obtained as shown in (24).

$$T_2 = \left[\frac{R_2(T_1+235)}{R_1}\right] - 235 \quad (24)$$

where T_1, T_2 – initial and final heating temperature; R_1, R_2 – resistance of transformer winding at lower and upper limit temperatures respectively. Inductive reactance is not included in the above equation because its value is independent of increase in temperature. The windings are not seen to be wet if

$$\frac{C_{hot}(70°\text{C})}{C_{cold}(20°\text{C})} \leq 1.15. \quad (25)$$

Fig. 1.7 is a graph used to determine the capacitance ratio K_c of any wound apparatus at two deferent levels of temperature.

1.7 Transformer Oil Regeneration

Operational transformers located at humid areas are exposed to high risk of their insulation being mixed with condensed vapour from the atmosphere.

This water increases the transformer capacitance invariably reducing the quality of the oil as a characteristic insulator. This insulation breakdown increases the capacitive current and active leakage current from the transformer windings to earth. The diagram in Fig. 1.8 is useful in the ongoing discussion. It shows how to dry the moisturized transformer oil when the silica gel in the conservator can no longer be effective due to high humidity. This is the method of transformer oil regeneration. The setup incorporates a heater, adsorber and filtra-press. It should be noted that if the conservator is filled properly as recommended, water cannot enter the transformer even if it is submerged except by convection. However, the oil of a submerged transformer must be emptied and replaced with fresh one before drying. The process of transformer dehydration should be done at a top oil temperature of 75℃ and should be held thus for about 30 minutes before switching on the load. However, one disadvantage of transformer oil regeneration is that the gas relay has to be deactivated to avoid false alarm and unintentional switch off by the gas relay.

1.8 Dehydration of Transformer

An experimental dehydration of wet transformer of 6 MVA 33KV was carried out using zero sequence current. The heat loss was done at the core and the bank and the heat was generated by the zero sequence current. This was accompanied by hot air blower to hasten the drying process. The magnetization process was actually done using the transformer neutral and the other three phase windings connected in parallel using 415 Volts alternating current while the secondary output winding was left at open circuit [13]. After the test drying, the copper winding- transformer bank resistance increased by about 40% from what it was before the drying and active resistance between phase windings increased by about 5%. This test was performed on 33kV transformer. A similar test conducted on 132kV transformer gave the same result in addition to 8% increase in capacitance and about 25% decrease in loss angle characteristics, tanδ. Other methods of transformer drying exist and can be adopted to achieve similar results as the one explained above but rate of convergence of result can be slower. They include: vacuum pump heating, radiator heating by steam, induction heating using coils wound on the transformer bank, and transformer short circuit method in which 10% of the transformer rated voltage is input on the primary winding and the secondary winding is short circuited and heated to about 95℃ [14].

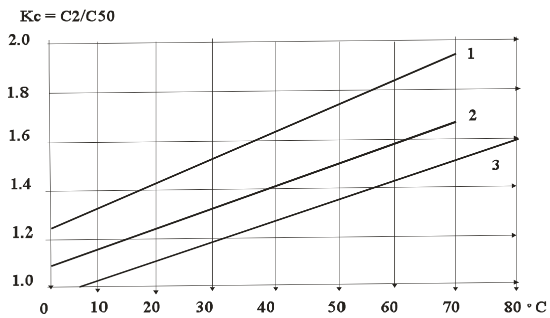


Fig. 1.7. Dependence of capacitance on temperature 1) 6-10 kV, 2) 35 kV, 3) above 35 kV [12]

1.9 Management of Substation

A flood prone area is subject to high humidity, wet ground resulting to increased leakage current and false signalization of protection devices. The floor base of such a substation hosting 33/11 KV should be reconstructed and should be raised to a reasonable height to ward off percolated water. The floor should be cemented and filled with gravel to a thickness of about 30cm. This will facilitate quick drying of the base insulation to reduce high humidity, leakage current, contact voltage and to increase the ground resistance. Provision must be made for water pumping device to evacuate water from the territory of the power installation in the case of flooding to forestall submerging of transformer and distribution equipment. In addition to this, the installation should be fenced properly but not with cement block. The use of cement blocks increases the temperature of transformers and prevents free movement of the air. A study carried out for a block fenced transformer installation showed that the ambient temperature of the transformer taken at a distance of 1.5 meters away from the transformer and at a midpoint of the transformer bank exceeded 10℃. The rated value is 8℃ to 10℃ [12]. This temperature was less when compared with a similar test conducted for a one-transformer substation with non-cement block fencing. Where possible, it is recommended that for single transformer substation, the transformer should be mounted above the ground between two concrete poles [14]. When this is done, cost is minimized and the transformer is in a better cooling condition. This eliminates the risk of possible invasion of the equipment by flood. The observation showed that when the transformer is raised to a height as is being recommended, the ambient temperature is reduced and the atmospheric pressure is also reduced. This in turn reduces the critical electric field intensity which is responsible for the ionization of the air mass around the entire substation as can be seen in (26).

$$E_o = \left(3 * \frac{10^6}{\sqrt{2}}\right) * \delta * m_o, \qquad \frac{V}{m} \tag{26}$$

where

$$\delta = \frac{p}{760} * \left(\frac{273+\theta_o}{273+\theta}\right), \tag{27}$$

p – the prevailing atmospheric pressure, θ_0 = atmospheric ambient temperature and θ – temperature rise, m_o = constant.

The reduction of critical electric field intensity coupled with proper earthing helped most especially in single transformer substation to work in its natural state. Critical electric field intensity is the cause of some of the artificial faults noticed in the power installations due to high level of ionization of the air mass.

2. DISCUSSION

The concept of this paper came for the consumption of people living in river boundaries or places that may be flooded by rivers overflowing their banks or places that may suddenly be exposed to high density of rainfall in a year. It tried to proffer solution in an emergency situation as has been enumerated above. A situation where a substation is submerged was assumed with the accompanying problems and solutions. The sample situation can take place anywhere in the world and the same recovery method should be applied to save the substation. The security of equipment, protection of life and property are paramount in such a life threatening situation. Implementation of the proposals in this paper will help to save the cost of relocation of substations and so save huge economic loss, waste of human and material resources. A situation where meteorological warning cannot help was envisaged. However, measures to avert flooding must be incorporated in the energy policy. The work gave suggestions on how to avoid contact voltage, reduce short circuit, and hinder the formation of active and reactive leakage current. The research work has revealed that high humidity and high temperature are themselves serious faults in the power line circuit and should be watched. Also areas of many thunder strikes per year are likely to be flooded frequently and many times in a year. This should be put into consideration during site selection for the construction of distribution substations.

3. CONCLUSION

A similar 33 KV substation constructed in line with the recommendations here showed significance decrease in number of faults per year. Less personnel attention is needed with lower amortization costs at high efficiency and availability of electricity. Also, the benefit of a sectionalized bus system was highlighted as a tool to fight unpredicted outages in the quest to guarantee uninterruptible power supply to the users. Transformer drying is recommended if a sample of oil taken from the transformer bank showed the presence of water molecule. It has been proven that submerged transformers in a substation can be regenerated and restored to normal operation. From the analysis conducted, it was shown that winding-bank resistance was improved by 40% and the resistance between phase windings was found to have increased by 5% and the overall dielectric loss was reduced by 25% as a result of regeneration considering the initial state before flooding.

COMPETING INTERESTS

We the authors declare that no competing interests exist.

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