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The effect of soil temperature on the ampacity values of Underground cables in jalingo, north-east nigeria

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ABSTRACT

Cables are like bridges that connects the machine that generate electricity and the appliances that uses it. Electrical cable can be a single conductor (solid or stranded) insulated through its full length; or several conductors spread together with each given its insulation under one outer protective covering. Electricity flowing in a conductor generates heat. A resistance to heat flow between the cable and the ambient environment causes the cable's temperature to rise. This work examined the effect of soil temperature on the current rating of a Cross Link Polyethylene Low Voltage Cable laid in three power substations in Jalingo, Taraba State. The findings revealed a mean soil temperature and ampacity value of 95.25 ºC and 245.12 A for coarse soil, 95.06 ºC and 318.90 A for clay soil and 94.8 ºC and 318.70 A for loamy soils. Comparison of the ampacity values of the different soils with the standard value of 320 A, the current rating of the cable is reduced by 74.88 A, 1.1 A and 1.3 A respectively for coarse, clay and loamy soils. Results also indicated that the current rating of the cables laid on loamy soil is 1.3 times greater than that on coarse soil at their respective temperatures. The study suggested that clay and loamy soil are suitable materials for local backfilling, while coarse soil is not.

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1. INTRODUCTION

Cables form the necessary connection between the machine that generate electricity and the appliances that uses it. Electrical cable can be a single conductor (solid or stranded) insulated through its full length; or several conductors spread together with each given its insulation under one outer protective covering [1]. The size and types of cable manufactured depends on the maximum amount of current the conductor can continuously carry without causing over-heat. Cables used in electrical circuit have three (3) main parts; the conductor which allow free passage of electrical current; the insulation part (that served as a core protector and separator) and mechanical protection that protect the cable from harsh environmental conditions. When electrical energy is passed through a wire or cable, heat is dissipated. Excessive heat can damage the wire or cable insulation.

Electricity flowing in a conductor generates heat. A resistance to heat flow between the cable and the ambient environment causes the cable's temperature to rise. Moderate temperatures are within the range for which the cable was designed, but temperature above the design temperature shortens cable life [2]. Power cables are used frequently in transmission and distribution of power networks. Most often, overhead lines are used for transmission of power, because the cost of building and servicing are minimal. However, the use of underground lines are safer, more reliable, and does not require much maintenance they are not exposed to road accident and the natural harsh weather [3]. In terms of accessibility, the overhead option gives allowance to easily locate and repair faults. The underground lines are favoured when it is necessary to run power lines above infrastructures like buildings, rail ways, highways etc. [3].

The maximum operating temperature of a cable is a function of the damage that the insulation can suffer because of high operating temperature [4]. The insulation withstands different temperatures as function of the duration of the current circulating in the conductor [3]. Aside the heat dissipated by the wire conductor, the temperature of the operating environment will also have effect on the ampacity of the conductor. According to Cyril and Difference [4], temperature varies with depth. The temperature of the soil increases as we go down the earth. The thermal resistivity of the soil surrounding the cable is the main factor determine the rate at which heat can be conducted away from the cable, hence the ultimate amount of current a cable carry. The variation of soil weather condition with its thermal conductivity is shown in Table 1.

2. RESEARCH METHOD

Explaining research chronological, including research design, research procedure (in the form of algorithms, Pseudocode or other), how to test and data acquisition [1-3]. The description of the course of research should be supported references, so the explanation can be accepted scientifically [2, 4].

Tables and Figures are presented center, as shown in Table 1 and Figure 1, and cited in the manuscript before appeared.

Table 1: Variation of soil weather condition with thermal conductivity

Weather condition	**Soil condition**	**Thermal conductivity (WK-1m-1)**
Continuous moist	Very moist	1.40
Regular rain	Moist	1.00
Sparse rain	Dry	0.50
Little rain or drought	Very dry	0.30

Source: Murat and Ozcan [5]

Usually, concrete in the form of a concrete duct bank are used to surround pipes (conduits) laid underground. The basic aim is for the concrete to offer protection to electrical conduits and the cables enclosed from being destroyed during construction work or excavation on the soil or by traffic [6]. Since electrical conduits are to a large extent stable thermally compared to most soils, the concrete also helps to correct suspected negative effect of any thermal instability in the soil in a given location. Less movement of water is anticipated to pass through a hydrated concrete unlike in soils. Also, the advantage of the duck bank is to provide a larger area where the surrounding moisture goes back to the drying interface, thereby increasing the thermal stability of an underground cable system.

Ampacity is a term given to the current-carrying conductor of a cable. Ampacity in an underground cable system is determined by the capacity of the insulation to extract heat from the cable and dissipate it in the surrounding soil and atmosphere. The maximum operating temperature of a cable is a function of the damage that the insulation can suffer as a consequence of high operating temperatures. The insulation withstands different temperatures as function of the duration of current circulating in the conductors. There are three standardize ampicity rating: steady state, transient (or emergency) and short-circuit [3]. According to Pilgrim et al. [7], ampacity is the maximum current a power line can carry and still maintain it electrical desired properties. It is sometimes refers to as a cables current carrying capacity. The ampacity of power cable is determined by the maximum operating temperature within which the insulation can maintain its best performance. For example, the cable construct with cross-link polyethylene (XLPE) dielectric are typically restricted to a maximum temperature of 90ºC [7]. The major factor affecting ampacity of conductor are ambient temperature, bonding arrangement, duct size, soil resistivity and size of backfill. All these factors have their own effect on underground power cable ampacity [3]. As a result of corrosion, thermal conductivity of soil, temperature variation, bounding arrangement, duct size and backfill, not all ampacity that is passed through underground cable is delivered. Part of the current is lost as a result of these factors. As a result, there is need to examine the ampacity of underground conductor by measuring the output characteristics and comparing with the theoretical values to ascertain the amount that is lost due to varying soil thermal conductivity and temperature.

2. Classification of Cables and Methods of Laying Underground Cables.

Cables for underground transmission can be classified based on manufacturer's specification. This could be based on the type of conducting/insulating material used, or the voltage. However, classification based on the voltage rating is usually preferred. Reddy [8], classified cables into five groups, as follows: Low-Tension (L.T) cables ~1000 V; High-Tension (H.T) cables ~11000 V; Super-Tension (S.T) cables from 22 kV to 33 kV; Extra High Tension (E.H.T) cables from 33 kV to 66 kV and Extra Super Voltage cables beyond 132 kV.

There are two major methods of laying underground cable namely:

(i) Direct-Buried Raceway: In this method, a trench of specified depth is dug, before a bed of fine sand used to prevent moisture from reaching the cables is then laid over it. The power lines are then run directly over this bed of sand. Of the two methods, the direct-buried raceway requires less capital for initial construction, and has superior heat dissipation characteristics; however, maintenance and modification of the lines prove to be very costly as they require excavation. Also, with this method, the process of fault localization (locating faults) becomes challenging.

(ii) Duct-Bank Raceway: This second method involves the use of a casing, rather than the lines being in direct contact with the earth. Here, a trench is excavated and filled with concrete enclosing spaced conduits (PVC, metal fiber etc.) that contain the power cables. The concrete helps protect the conduit/cables from any moisture in the soil, which in turn, prolongs the life of the materials. The conduits however, apart from helping properly space and separate the cables, also facilitate the cable-pulling process, as well as allow modification and easier fault localization than its direct-buried counterparts.

1.2 Factors Affecting Power Distribution

Recent research has shown that there are several different factors to be considered in the design and installation of underground cables. An understanding of soil physics has become critical in the design and installation of underground power transmission and distribution systems. Thermal conductivity of the surrounding material needs to allow for thermal dissipation from the cables. Restricted thermal dissipation can lead to high temperatures at the cable jacket, which will result in an increased risk of thermal breakdown of the underground cables and can reduce their lifespan considerably [5]. Decreased soil water content leads to decreased thermal conductivity. Hence during droughts thermal conductivity is decreased in the soil surrounding the cables. Therefore, it is important that the surrounding soil has sufficient water- holding properties so that the soil water content will not harmfully affect the cable. Knowledge of the various physical factors which affect underground cables is vital in order to increase their efficiency and minimize failure risk in future underground cables. Furthermore, various factors need to be considered when selecting the location of an underground power cable system. Various properties of the area the cables extend through, such as the soil type, vegetation cover, elevation, and distance to water table, must be evaluated. It is reasonable to assume that higher and more stable moisture content in the surrounding soil would be beneficial.

1.3 Power Losses in Underground Cables

There are several types of power cables manufactured and labeled according to voltage, conductor type, dielectric materials used and number of cores. Conductor (usually copper), insulator, shield, and protective layers are the major elements in power cables. When current passes through a conducting material, Ohmic losses may occur [9-13]. Depending on applied voltage, dielectric losses may also occur in a section of cable when insulating materials are exposed to an electric field. Hysteresis and eddy currents losses may also develop on cables if the protective layers are composed of magnetic materials [14-17]. Main source of warming on the power cable is the electrical power loss (I2R) generated by flowing current (I) through its conductor having resistance (R). The electrical power (loss) during time (t) spends electrical energy (I^2Rt), and this electric energy loss turns into heat energy [9-14]. This heat spreads to the environment from the cable conductor. In this case, differential heat transfer equation is given [9].

$$\nabla.(k\nabla\theta) + w = \rho c\frac{\partial\theta}{\partial t} \tag{1}$$

Where; θ = temperature (K) of the independent variable, k = thermal conductivity of the environment surrounding heat source (W/Km), ρ = density of the medium as a substance (kg/m3), c = thermal capacity of the medium that transmits heat (J/kgK), W = volumetric heat source intensity (W/m3). Since there is a close relation between heat energy and electrical energy (power loss), heat source intensity (W) due to electrical current can be expressed similar to electrical power given as

$$\rho = J.Edxdydz \tag{2}$$

Where J is current density, E is electric field intensity; the volume of material in the unit is $dxdydz$. Since J = σE and $E = \frac{1}{\sigma}$, the cable's Ohmic losses can be written as;

$$\rho = \frac{1}{\sigma}J^2\, dxdydz \tag{3}$$

Or

$$\sigma = \frac{1}{\rho_{0(\ 1+\propto(\theta-\theta_0)}} \tag{4}$$

Where σ is electrical conductivity of the cable conductor and it is temperature dependent. It relates electrical conductivity and heat temperature. ρ_0 is the specific resistivity at reference temperature θ_0 (Ω·m); α is temperature coefficient of specific resistivity.

Electric power loss experienced by the power cables are influenced by the current density and conductivity of the conducting materials [18 - 20]. The temperature of the power cables are increased by Ohmic losses on each conductor [21 - 24. The increase in temperature decreases the electrical conductivity of the cable conductor, giving rise to increasing Ohmic losses which causes more heat on the conductor [2, 21, 25, 26].

1.4 Heat Flow in Underground Cable Installations

In an underground cable system, the main heat transfer mechanism is by conduction. With the exception of air inside the conduits in ducts banks or buried ducts installation, all the heat is transfer by conduction. Since the longitudinal dimension of a cable is always much larger than the depth of the installation, the problem becomes a two-dimensional heat conduction problem. In Cartesian coordinates one must solve the diffusion equation given by George [10].

$$\mathrm{E} = \frac{\partial}{\partial x}\left[\frac{1}{\rho}\frac{\partial t(x,y,t)}{\partial x}\right] + \frac{\partial}{\partial y}\left[\frac{1}{\rho}\frac{\partial t(x,y,t)}{\partial y}\right] + W = c\frac{\partial t(x,y,t)}{\partial t} \tag{5}$$

Where; ρ is the density of the material, c is the volumetric thermal capacity of the material, w is the rate of energy (heat) generated

Equation (5) cannot be solved in closed form for the complicated geometry of an underground cable arrangement. Furthermore, in view of the complications of the ampacity problem, engineers found practical solutions by combining analytical solutions to simplified geometries with heuristic result in particular the use of thermal-electrical analogies with empirical work has been very popular with cable engineers. To that effect, the paper published by Neher and McGrath [1, 15, 21] is remarkable. They summarized the knowledge on the ampacity calculation field to that date, and today, Neher-McGrath is still being used and it is the best for the Institute of Electrical and Electronics Engineering (IEEE) and the Electrical Insulation Conference (IEC) [12] standards.

2. MATERIALS AND METHOD

The ampacity of Low voltage underground cables [Cross Link Polyethylene (XLPE)] of size 300 AGW buried in soils in three different power transmission substations in Jalingo was determined. The choice of the substations was based on the type of soil used for the local backfilling. This was to ascertain the most suitable soil for backfilling. In this regard substations with NTA power substations with cables laid on coarse soil, Lassandi power substation with clay used for backfilling and Road Block power substation where cables are laid on loamy soil were selected for the study. XLPE low voltage cable in the three different power substations were buried at a specific depth of 0.5 m.

The ampacity of the XLPE cable was computed using the ampacity equation given by Gerald [13, 16, 20].

$$I = \sqrt{\frac{T_C - T_A}{R_{DC} \times R_{AC}}} \tag{6}$$

where I is the ampacity or current carrying capacity of the cable, RDC is the DC resistance of the underground cables. The values of RDC used are provided in the cable catalogs or black books and the RAC is the AC resistance which is calculated using the equation:

$$R_{AC} = R_{DC}\left[1 + \alpha\left(T_C - T_A\right)\right] \tag{7}$$

Where α is the temperature coefficient of resistance of conductor, TC is the maximum operating temperature of the cable and is equal to 90oC [6] and TA, the ambient temperature of the environment where the cable is buried. The ambient temperature of the soil was measured directly by placing the soil thermometer on the environment where the cable were laid or buried. The temperature of the cables lying directly on the soils was measured and recorded with the cable exposed to variable load conditions. At some reference temperature TA, equation (7) becomes

$$R_{AC} = R_{TA}\left[1 + \alpha\left(T_C - T_A\right)\right] \tag{8}$$

Where RTA is the resistance at temperature TA

The substations include; Lassandi substation, NTA substation and Road-Block substation. The environment temperature TA, where the cable is laid was measured and then, the temperature of the loaded cable determined.

3. RESULTS AND DISCUSSION

The results obtained from the three different power substations in Jalingo are presented Tables 2-4. The ambient temperatures TA were measured to be 42.50 oC, 28.5 oC and 30.03 oC for coarse, clay and loamy soil respectively.

Table 2: The variation of soil temperature (Coarse soil) with ampacity at NTA power substation

S/N	TC (0C)	Ampacity (A)
1	100.02	205.10
2	98.04	208.00
3	98.90	209.00
4	97.22	212.03
5	97.50	213.50
6	96.10	214.30
7	95.00	220.00
8	94.00	230.00
9	93.05	300.10
10	92.10	308.20
11	91.00	309.20
12	90.00	312.00
Mean	95.25	245.12

Table 2 presents the variation of coarse soil temperature with current carrying capacity of the low voltage cable. The coarse soil, which is a mixture of sand and gravels do not retain much water as a result affect the flow of current buried in its environment. When the mean value of the temperature at this soil condition is 95.25oC, the average current rating of the cable is 245. 12 A, this is about74.88 A less than the value of

320 A prescribed by cable manufacturers. Therefore, coarse soil is not a suitable material for backfilling. The ampacity is observed to decrease with increasing temperature.

Table 3 shows the results of the effect of clay soil's temperature on the ampacity of the cable laid on it. The mean value of TC is 95.06 oC while the mean current rating is 318.90 A. This gives a 1.1 A difference between the value obtained and that of recommended by cable manufacturers (320 A). This little variation between theoretical and practical values of the cable rating can be attributed to the moisture retaining ability of clay soil and its ability to conduct heat away from the cable. These properties make clay soil suitable for local backfilling.

Table 3: The variation of soil temperature (Clay) with current carrying capacity of the cable at Lassandi power substation

S/N	TC (0C)	Ampacity (A)
1	98.20	310.00
2	98.60	312.00
3	97.20	312.50
4	96.30	313.20
5	96.12	314.00
6	95.00	315.00
7	94.00	320.00
8	93.20	325.01
9	92.00	330.05
10	90.00	336.04
Mean	95.06	318.90

Table 4: Variation of soil Temperature (loamy) with current caring capacity of the cable at Road-Block substation

S/N	TC (OC)	Ampacity (A)
1	99.06	309.02
2	98.40	311.02
3	97.03	313.00
4	96.30	314.00
5	95.00	315.05
6	94.50	322.05
7	92.00	325.00
8	91.20	327.00
9	90.00	332.00
Mean	94.83	318.70

The ampacity of the cables laid in loamy soil tend to increase with decreasing temperature. The mean values of the soil temperature and cables ampacity are respectively 94.83 oC and 318.70 A (Table 4). This is 1.3 times less than the recommended current rating of the cable (320 A). Therefore, loamy soil may also be considered as a good material for local backfilling. It is also observed that at the maximum operating temperature of 90 oC proposed by the cable manufacturer, the current rating is 332 A. When compared with coarse soil at 90 oC, the ampacity is increased by 20 A and decreased by 4 A when compared with clay soil.

In Fig. 1, the ampacity values for the different soil types were compared using a whisker's box plot. It is observed that coarse soil ampacity is highly variable while clay and loamy soils displayed comparable values with median values of 314.5 and 315.1 respectively.

In Fig. 2, it is observed that when the temperature of the buried cable increases above 100oC as a result of increased in loads added to the cable, the maximum current of the cable drop drastically to about 205A. This is far less than the current rating of the cable as indicated by the cable's manufacturer. In these situations, the cable requires reduction in load to give the best performance or a backfill of higher concentration of moisture should be employed so that the moisture content in the soil will cool or conduct the heat away from the surrounding of the cable.

As observed in Fig. 1, the variation of ampacity with temperature for clay and loamy soils have similar trend (Fig 2). Due to high moisture content and thermal conductivity of clay soil, heat energy is always conducted away from the cable, thereby making the temperature of the cable to decrease and hence increasing the current rating of the cable buried in it. This type of soil is suitable for laying underground cables because it retains more moisture that will cool the cable temperature when subjected to high loads condition. Loamy soils also retain moisture content as a result it can be used as a local backfill. This shows that loamy soil can also be good local backfilling material.

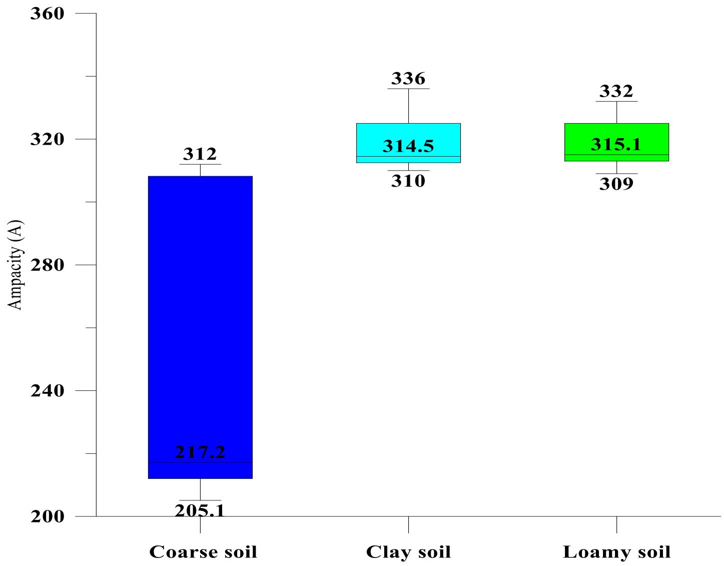

Fig. 1: Whisker's box plot comparing the ampacity values of the different soil types

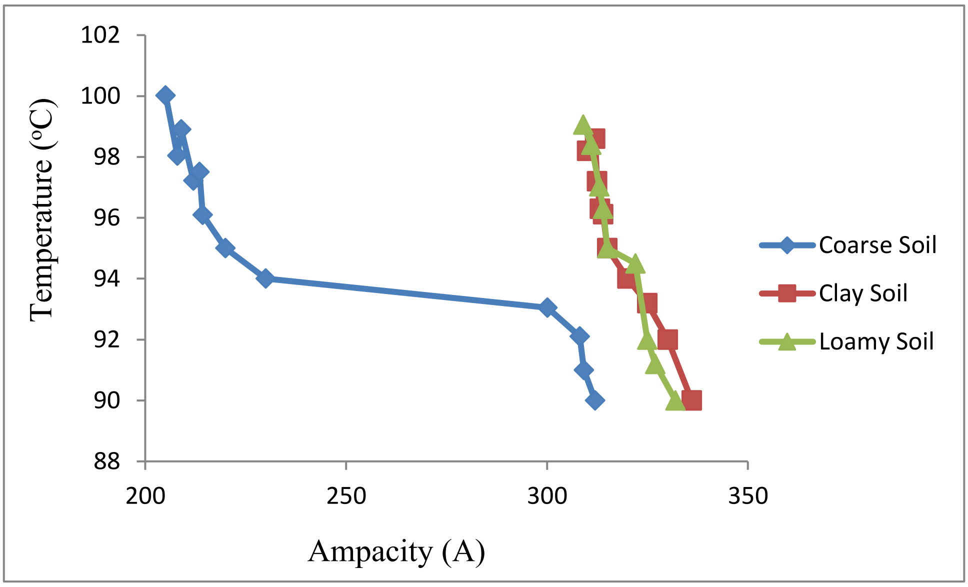

Fig 2: Variation of temperature with Ampacity for coarse, clay and loamy soils

Table 1 gives the general effect of soil thermal conductivity based on weather condition obtained by Murat and Ozcan [16]. In a situation where a cable is buried in the soil with higher moisture content above the normal, the heat generated by the cable can be disperse easily and the temperature of the cable drops as the cable carries more current. The current carrying capacity of cable may drop in areas where rainfall is sparse, leading to high temperature and dry conditions. The table revealed that thermal conductivity and resistivity depends on the weather condition of the region where the cables are installed. At areas where there is continuous rainfall, soil moisture increases, as a result thermal resistivity decreases. Hence, thermal conductivity of different soil materials is higher at continuous rainfall.

The most probable challenge facing underground cables buried directly on the surface of the soil is the inability of the soil to conduct heat generated by the cable away from it. Soil that retains moisture has high thermal conductivity. When different types of soil are used as backfills it affects the current rating of the cable and its life span. Here, three soils are examined to ascertain their suitability for local backfilling of underground cable network. The study revealed that clay and loamy soils are good materials for local back filling while coarse soil is not a suitable material for backfilling.

Table 5 shows the effect of separation between three cables lying side-by-side in a trench. TC decreases as the distance between the cables is increased. Also, the ampacity increases with increasing distance between the cables. Here we consider case where the ambient temperature for each soil sample is neglected and the cables are buried at the same depth. When the separation between the cables is 0.0 mm, the temperature of the cable increased to 100.01 oC, which exceeds the maximum permissible temperature of 90 oC given by Murat and Ozcan [16]. This situation required reduction in load or the size of the middle cable should be higher than that of the other two cables in the trench. When the separation between the two cables is gradually increased, the temperature of the middle cable decreases producing a better current rating of the cable. The Table 5 shows gradual increase of ampacity due to decrease in separation between three cables laid in the same trench. As the separation increases to 36 mm, the temperature of the current dropped to 90oC and a steady current 625.21A starts flowing across the cables. Hence, laying electrical cables under the ground at defined distance increases the current rating of the cable as specified by cable manufacturer.

Table 5: The effect of cable distance on temperature distribution and ampacity

S/N	**Distance between the cables (mm)**	**Cable temperature (0C)**	**Ampacity (A)**
1	0.00	100.01	590.84
2	5.00	98.00	601.02
3	10.00	95.06	603.15
4	15.00	94.50	610.00
5	20.00	92.38	612.16
6	25.00	91.06	614.02
7	30.00	90.45	623.00
8	35.00	90.70	622.01
9	36.00	90.00	625.21

4. CONCLUSIONS

Power transmission by overhead lines had suffered many setbacks over the past years, ranging from accidents, power losses and electrocution. To overcome these challenges, the underground option seems promising. The major problem associated with this method of power transmission is the inability of cables to emit heat generated as result of variable loads from household appliances. For optimum performance of the cable, the environment where the cable is laid should be surrounded by backfill with high thermal conductivity to conduct the thermal energy generated by the cable away to prevent overheating that reduces it life span. Clay soil has proven to be a good material for this purpose. In addition, when laying more than two cables in a trench, the separation

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