Analysis of a Grid-Based Rural Electrification Scheme for Ekpe-Aggah Community in Rivers State, Nigeria

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Abstract

Electrical energy is the basic necessity for the economic development of a country due to its importance to human life and occupies the top position in the energy hierarchy. It finds innumerable uses in the home, industry, agriculture, and transport. This study is geared towards the analysis of a Grid-Based Rural Electrification Scheme for the Ekpe-Aggah Community in Rivers State, Nigeria. The method used in achieving this, relies on optimization principles based on iteration & analysis. The essential material used in the design of the distribution network is Electrical Transient Analyzer Program (ETAP) technology which was used for the simulation. The results obtained from the analysis showcase a wide-ranging single-line diagram for easy implementation; other results obtained include, short circuit analysis carried out on Bus1, Bus2, Bus3, and Bus4 showing the fault levels of these buses to be 8.767MVA, 3.165MVA, 2.626MVA & 2.331MVA respectively and fault protection coordination was observed that at the occurrence of fault on any of the feeders, the affected feeder is isolated from the rest of the system through the fuse protecting that feeder. Finally, this design is focused on a distribution substation, its classification, type, design diagrams, calculation, rating, and cost estimation among others.

Keywords: *Analysis, ETAP, Grid-Based, Optimization Principle, Rural Electrification*

1. INTRODUCTION

Electrical energy occupies the top position in the energy hierarchy. It finds innumerable uses in the home, industry, agriculture, and transport. Besides its use for domestic, commercial, and industrial purposes, it is required for increasing defense and agricultural production. In agriculture, it is used for pumping water for irrigation, methods of production improvement, and numerous other operations. The greater the per capita energy consumption in a country, the higher the standard of living of its people (Ijeoma & Nwauzi, 2019).

A substation serves as a source of electrical energy supply in an area in which it is located. While some substations serve as switching stations where various transmission lines are connected without transforming the voltage, others are either to convert A.C to D.C or vice-versa or convert frequent from higher to lower or vice-versa. Substations may be owned and operated by an electrical utility or may be owned by a large industrial or commercial customer (Mukund, 2019).

Substations generally have switching, protection & control equipment, and transformers. In an injection substation, circuit breakers are used for power interruption of any short circuits or overload currents that may occur on the network. In a power system, high voltages are required for transmission to minimize the voltage drop and power loss along the line. Transformers are used in stepping up the generation voltage to transmission line voltage (Gupta, 2013).

2. LITERATURE REVIEW

Fundamentally, rural electrification refers to the electricity supply to areas outside of cities. However many researchers have given the model highly different elucidations.

John et al. (2013) examined the impact of the electrification of a small rural community, six years after electrification. Before the electrification of the village a baseline study was undertaken and thus their results are based on a comparative analysis. The area featured government offices, a well-developed commercial sector, some small-scale businesses, and a reasonably dense residential area. Even if all the potential domestic consumers had been connected, their electricity uses would still have been less than 50% of the total.

Oyejide et al. (2014) published a work on Development of a Grid-Based Rural Electrification Design: A Case Study of Ishashi and Ilogbo Communities in Lagos State, South Western Nigeria which is based on a grid-based rural electrification designs developed using Ishashi and Ilogbo which are two rural communities located in Lagos State, South Western Nigeria as case studies.

Munasinghe (2019) found that the tendency to overestimate productivity gains in the industrial and commercial sectors during the economic appraisal of electrification schemes has been systematic. He thinks that rural electrification seems to stimulate agro-industrial and commercial activity, although the direction of causality is not completely clear. He also reports that the electrification of rural areas in developing countries promotes agricultural development best when certain complementary inputs, such as electric pumps and financial services are included.

Uppal & Rao (2013) confirm that substations may be on the surface, in fenced enclosures, underground, or special-purpose buildings. High-rise buildings may have several indoor substations. Indoor substations are usually found in urban areas to reduce the noise from the transformers and protect switch gear from extreme climate or pollution conditions. Where a substation has a metallic fence, it must be properly grounded to protect people from high voltages that may occur during a fault in the network. Earth faults at a substation can cause a ground potential rise. Currents flowing in the Earth's surface during a fault can cause metal objects to have a significantly different voltage than the ground under a person's feet; this touch potential presents an electrocution hazard.

Stockton (2016) said that the design of a distribution substation and transformers plays a central role. It takes place in several stages in sequence, starting at the generating plant where the voltage is increased for transmission purposes and is progressively reduced in the substation for distribution to household or industrial uses.

According to Pooler (2014), a distribution substation uses a circuit breaker or fuse for distribution circuit protection. Substations do not usually have generators, although a power plant may have a substation nearby. Other devices such as capacitors and voltage regulators may also be located at a substation.

Alexandra (2016) argues that in all relevant sectors including electricity supply, "rural" suffers from the same definitional problems. Surveys have revealed that most rural electrification projects in the past referred to communities of between 500 and 2000 people.

Lathrop et al. (2019) state that the definitions of rural electrification vary considerably between countries. In one country 'rural' also includes provincial towns with a population of up to 50,000, and in another, it refers to small farming villages and surrounding areas. One of the consequences of these differences in interpretation is that comparison between rural electrification projects in different countries is extremely difficult, if not impossible.

Shehab (2013) correctly states that uniformity as to the interpretation is not, per se, necessary but that it is important to identify those areas that require special financing and technical and institutional approaches.

3. MATERIALS AND METHOD

3.1 Materials

The theoretical aspect of the grid-based rural electrification was considered, the design criteria and the load list will be defined, and noted that they were necessary to know before the design of the electrical system. To achieve this, manual calculations of the required power should first be performed to assist us in the equipment selection and bus bars.

The material used for the design:

Electrical Transient Analyzer Program Technology (ETAP) 19.0.1C simulation software.

In this design, three number distribution substations of 500KVA, 50HZ, and 11/0.415KV distribution substations were simulated in ETAP 19.0.1C software. In addition, some electrical standards are the design criteria. Some big companies' manual such as ABB Ltd. is used as references.

3.2 Design Equations

In this section of the work, using optimization principles based on iteration and analysis, useful equations crucial to the electrical model development design of the Ekpe-Aggah community are presented. Based on the estimated load demand of each household within the community (Oyejide et al. 2014), the overall energy requirement, Perv in kilowatt (kW) of the community will be calculated using equation (1):

$$P_{erv} = P_h\, n \qquad (1)$$

Where Perv = Overall energy requirement of the community in kilowatt (kW)

Ph = Energy requirement of each household in kilowatt (kW)

n = Number of households (including other energy users) in the community

With 30% of the total estimated energy requirement of the community allowed for future load demand, the overall energy requirement Per in kilowatts (kW) of N number of villages to be served by a given substation will be calculated by equation (2):

$$\text{Per} = 1.3 \sum_i^N \text{Pervi} \quad (2)$$

Since the allowed 30% increase of the total estimated load demand of the community will not be constant for the periods for which load growth is expected, equation (2) is modified into equations (3), (4), and (5) respectively to allow for 15% load increase for the first growth period, 10% load increase for the second growth period and 5% load increase for the third growth period). The equations (3), (4) and (5) are termed load growth equations:

$$\text{Per 1} = 1.15 \sum_i^N \text{Pervi} \quad (3)$$

$$\text{Per 2} = 1.10 \sum_i^N \text{Pervi} \quad (4)$$

$$\text{Per 3} = 1.05 \sum_i^N \text{Pervi} \quad (5)$$

Where Per 1 = Total energy demand for the first growth period in kW

Per 2 = Total energy demand for the second growth period in kW

Per 3 = Total energy demand for the final growth period in kW

For the sizing of the distribution transformer to serve N number of villages in a community, equation (6) will be used:

$$S = \frac{\text{Pergp}}{\text{Cos } \emptyset} \quad (6)$$

Where S = KVA rating equivalent to the energy consumption of N number of villages with

30% allowance connected to a substation to determine the size of the distribution transformer.

Pergp = Total load demand at the end of the assumed growth period with due consideration

of the load factor.

Cos Ø = Power factor (for this work, cos Ø will be taken as 0.8) (7)

Load factor is the ratio of average demand to the maximum demand during a certain period which could be a day, month, or year. It is usually less than unity and has low characteristics for rural communities. It is expressed by equation (8):

$$Load\ Factor = \frac{D_{ave}}{D_{max}} \quad (8)$$

Where Dave = Average demand in kW

Dmax = Maximum demand in kW

The rated current Ii in amperes of each distribution transformer to serve a village within a community will be estimated by the equation (9):

$$I_i = \frac{S}{\sqrt{3} \times V_{L-L}} \quad (9)$$

Where VL-L = Line-to-line voltage (kV) for a three-phase supply system

i = Specific village in a community

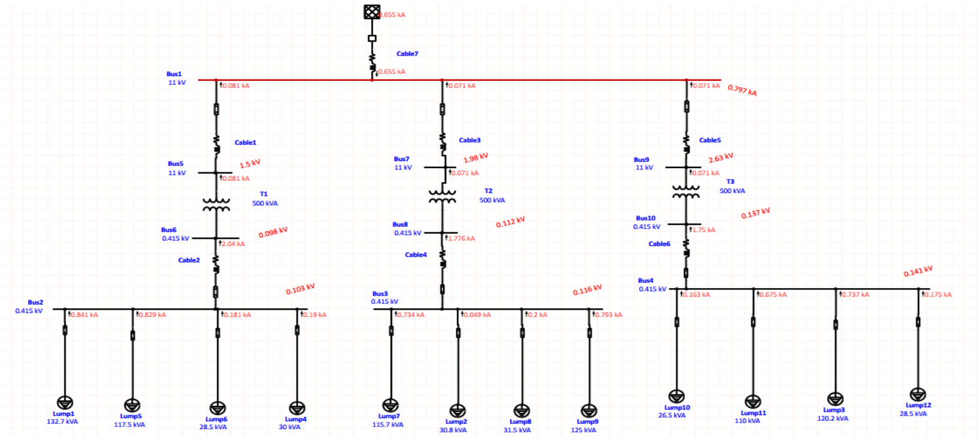

Figure 1: Cable Short Circuit Analysis

The short circuit analysis carried out on Bus1, Bus2, Bus3, and Bus4 show the fault levels of these buses to be 8.767MVA, 3.165MVA, 2.626MVA, and 2.331MVA respectively.

3.2.1 Voltage Drop Limits

Normal operation voltage drop

In this work, cable voltage drops at load shall be limited to the following values according to IEE Regulation.

At the loads terminals: 5%

3.2.2 Short Circuit Current Limits

Power systems with a voltage over 1000V shall be designed somehow so that the root mean square (RMS) value of the a.c components of the short-circuit breaking current of the circuit breakers shall not exceed 25KA as per (IEC 62271-100, 2021). For power systems with a voltage less than 1000 volts, the RMS value of the a.c. component of the short circuit breaking current of the circuit breaker designed shall be as per (IEC 60947-2, 2016) and shall not exceed 50KA.

3.2.3 Power Factor

The overall system power factor and reactive power losses in transformers and other distribution system equipment shall not be less than 0.85 lagging at the rated design throughout the station. The power factor shall be determined at the terminals of the transformer(s).

3.3.4 Transformer

In case of trip on one transformer, another transformer should be able to withstand the entire downstream load. In addition, each transformer should at least have 20% spare in normal operation according to (IPS-E-EL-100, 2021). The short-circuit voltage in percent VK% according to (IEC 60909-0, 2016) for 500 KVA is 5%

3.2.5 Cable Sizing & Equipment Selection Calculation

An electrical power cable sizing & equipment selection calculation is determined as shown below.

Cable Sizing

For the determination of electrical power cables it is necessary to do the following studies:

- Cable Ampacity
- Voltage drop
- Short circuit withstanding current

Since there are different methods for the physical arrangement of cables and the possibility of having different environmental and physical conditions, therefore before cable sizing, it is necessary to accurately consider the physical, and environmental conditions of the cable route.

- **Cable Ampacity**

Load wattage, voltage, power factor, and electrical efficiency, it possible to calculate the current that passes through the cable in the ideal situation. By having ampacity easily cable cross-section can be selected but this cross-section in real situations must be calculated considering physical and environmental conditions. Respectively, cable capacity for passing current depends on the ambient condition and method of laying cable. If the cable is buried underground, passing above ground, or in the water, different de-rating factors should respectively be applied. In this project, all the cables are buried cables and the following de-rating factors such as ambient temperature, soil temperature, soil thermal resistance, type of cable armor, the distance between cable adjacent, burial depth, etc. have been taken into account according to (IEC 60502, 2021). After calculating the ampacity of the cable cross-section, it can be selected but should still be checked against the short circuit withstanding ability and voltage drop.

3.2.6 500KVA, 11/0.415KV Distribution Transformer incoming cable sizing

For the sizing of the primary cable, the 500kva transformer primary current is considered.

The line ampacity is given by:

$$I = \frac{P(KVA)}{\sqrt{3} \times V} \quad (10)$$

Where I = Line current

P = 500 KVA Maximum transformer power

V = 11kv Line-rated voltage

$$\text{Ip} = \frac{500 \times 1000}{\sqrt{3} \times 11000} = 26.3\text{A}$$

Reference to IEE Table 4B1 gives a correction factor of 0.80 for single layer single core on cable buried direct to ground = 0.80 x 26.3A = 21.04A.

From Pirelli general cable manufacturer Table for 19000/11000V Single core XLPE Insulated Cable.

For the sizing of the secondary cable, the 500kva transformer secondary current is considered.

The line ampacity is given by: Using equation (10)

Where I = line current

P = 500 KVA maximum transformer apparent power

V = 0.415 KV line-rated voltage

$$\text{Ip} = \frac{500 \times 1000}{\sqrt{3} \times 415} = 696.43\text{A}$$

Reference to IEE Table 4B1 gives a correction factor of 0.80 for single layer Single core on cable buried direct to ground = 0.80 x 696.43 = 557.14A

From Nigerchin cable manufacturer, Table for 600/1000V Single core PVC/SWA/PVC Insulated Cable, 1Core x 500sq.mm Cable with a current carrying capacity of 655A and volt drop of 0.21mV Laid directly to ground is recommended

- **Cable Voltage Drop is calculated using the formula**

Voltage drop analysis is evaluated against permissible allowable voltage requirements for consumer load, Indicated in the design criteria.

Given the following parameters;

Length of run in meter = 10m,

secondary cable current, I = 696.43A

Volt drop for 500sq.mm Cable, Vd = 0.21mV

Recall the formula for volt drop,

$$V_{drop} = mV \times A \times m \qquad (11)$$

Hence, $V_{drop} = \frac{0.21 \text{ x } 696.43 \text{ x } 10}{1000} = 1.46\text{V}$

Based on the above voltage drop analysis within the permissible limit of 5%, the selected 1-core x 500 sq. mm PVC/SWA/PVC Cable is adequate.

The cables must also be evaluated against short circuit rating current. Cables should withstand the highest symmetrical short circuit current of the network at the point of consideration. Short circuit withstanding time is usually considered 1 second and the conductor's maximum temperature not to exceed 150ºC for PVC sheathed, and 250ºC for XLPE insulated cables.

The general formula for cable short circuit current is:

$$Isc = \frac{K \times A}{\sqrt{t}} \qquad (12)$$

Where t = Short circuit time duration

A = Cable cross-section in mm

I_{SC} = Effective short circuit current level as r.m.s value

K= Depends on the cable conductor and insulation material

- **For Transformer Secondary Cable**

Given the following parameters;

Cable cross-section area = 500sq.mm

Constant K for PVC Cable = 115

Time, t = 3Sec.

Therefore, $Isc = \frac{115 \times 500}{\sqrt{3}}$ = 33,198A = 33.2KA

3.2.7 Feeder Pillar Selection & Sizing

From the above ampacity calculation, it is given that the secondary current for a 500KVA transformer is 696.43amps, hence the recommended feeder pillar size is given as; 800A, 400V, 50KA, and 50Hz Feeder pillar with 3no. x 800Amps, 2nos. x 100Amps and 2nos. x 50 Amps Outgoing HRC Fuses.

4. RESULTS AND DISCUSSION

4.1 Load Flow Studies

Load flow studies are carried out to calculate all bus voltages, branch power factors, currents, and power flows throughout the electrical system. The load flow reports shall show the magnitude of active (real) power and reactive power supplied by the transformer, feeder, and bus bar with the total connected load. Load flow diagrams shall be prepared for both main and essential systems and indicate KW, KVAR figures, bus bar volts, and voltage phase angles.

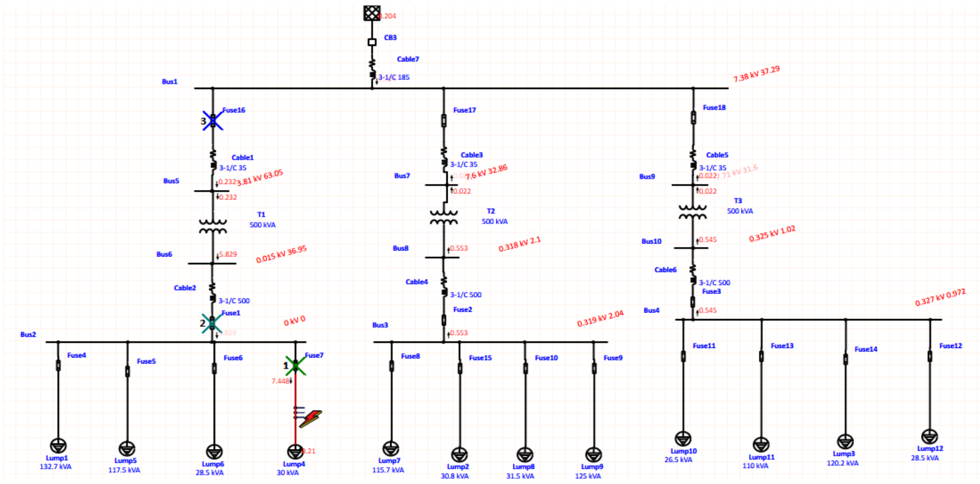

Figure 2: Fault Protection Coordination

It is desired to protect the electric power supply system so that in the event of any abnormality caused by a faulty system, only the faulted section is removed from the system and the healthy is left in service. This further goes on to ensure the continuity and reliability of the utility supply system. This study, ETAP 19.0.1C was used to simulate the protection coordination of the power supply to the communities under study. It was observed that at the occurrence of a fault on any of the feeders, the affected feeder is isolated from the rest of the system through the fuse protecting that feeder. It is only when the fuse protecting the feeder fails to act, that the fuse protecting the bus to which the faulty feeder is connected will act to protect the bus and leave other sections of the supply in healthy operation. Consequently, the sequence of operation of the protective fuses selected at random from the three load buses is as follows:

When lump load-1 was faulted, fuse-4 was the first protective device to act at a fault current of 6.853kA and timeless than 4.0ms. If fuse-4 fails to open, fuse-1 will open at a current of 5.829kA and act between the time 19.6 – 40.9ms. If fuse-1 fails to open, fuse-16 will open at a fault current of 0.232kA at a time of 61.3ms.

When lump load-9 was faulted, fuse-9 was the first protective device to act at a fault current of 5.616kA and time 4.1ms. If fuse-9 fails to open, fuse-2 will open at a current of 4.807kA and act between the time 13.9 – 28.9ms. If fuse-2 fails to open, fuse-17 will open at a fault current of 0.193kA at a time of 159ms.

When lump load-11 was faulted, fuse-13 was the first protective device to act at a fault current of 4.984kA and timeless than 6.4ms. If fuse-13 fails to open, fuse-3 will open at a current of 4.077kA and act between the time 25.3 – 52.8ms. If fuse-3 fails to open, fuse-18 will open at a fault current of 0.166kA at a time of 425ms.

Hence, the distribution network is protected while ensuring continuity of supply to healthy sections when faults occur in any part of the network.

5. CONCLUSION

Rural Electrification is the process of bringing electrical power to rural and remote areas. Rural communities suffered colossal market failures as the national grids fell short of their electricity demand. Electrification typically begins in cities and towns and gradually extends to rural areas; however, this process often runs into obstacles in developing nations. Ekpe-Aggah community has great potential that if this project is implemented will improve their standard of living. The method used in achieving this, relies on optimization principles based on iterative and analysis. The essential material used in the design of the distribution network is Electrical Transient Analyzer Program (ETAP) technology used for the simulation, design approach, location, and relevant data, components needed to design a grid-based rural network are considered & achieved. The results obtained from the analysis showcase a wide-ranging single-line diagram for easy implementation. Another result obtained is fault protection coordination that shows the first fault on fuse number nine & second on fuse number two with magnitudes of 5.615 and 4.809 respectively. Design of rural electrification for Ekpe-Aggah community using a three-number, 3-phase 50HZ 500KVA 11/0.415KV distribution substation taking into consideration, the incoming voltage of 11KV, a 500KVA transformer rating with an output voltage of 0.415KV, 30% future load demand was achieved. Based on the optimization principles of the structure, Net Present Cost (NPC), the installation is viable at N132,321,040.00.

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