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Design Of 11/0.415 kV Substation Using Applicable International Codes

Oyeleye, M. O.
Department of Electrical and Electronics Engineering
Federal University of Technology Akure,
Nigeria
mooyeleye@futa.edu.ng

***Abstract*—This research focus on design of 11/0.415 kV distribution substation. The research was carried out to overcome the loss of power supply due to overloading of an existing 11/0.415 kV distribution substation in a community area, Ikorodu, Lagos State, Nigeria. Data were collected from concerned power utility company - peak load current, supply voltage, and frequency. Appropriate existing algorithm, tested and reliable codes on past commissioned of multinational projects were applied to the collected data to achieve the design of this project. Reliable, efficient, safety of the substation, safe operation of end users equipment and properties were put into consideration by carefully design associated protective devices on high tension and low tension sides using suitable and applicable international codes. Grounding of the substation and lightning arrester were properly designed and sized for safety of the personnel, equipment and effective discharge of lightning over voltages to the ground using appropriate codes. Design of 11/0.415 kV substation that meet load demand of 60% loading and 75% of previous loading including 1.25 future expansion factor overloading of the transformer was achieved. Previous loading of 75% which will cater for 2hrs overloading is designed thus long operational life of the transformer. The common tripping of high voltage (HV) fuse when a transformer is overloaded is avoided in HV side. The protection of the transformer and all other elements were highly considered in this work. The life span of the substation transformer increases in this type of design. This research recommends that for high reliability and efficiency of 11/0.415 kV substation, transformer should be loading at 60% loading and 75% previous loading for 2hrs overloading, 1.25 future expansion factor should be considered, transformer should not be design to operate at 100% previous loading and derating factor should be considered in sizing cable when more than one in parallel.**

Keywords*—*substation; code; grounding; overloading; transformer.

1. Introduction

Substations play key role in reliability of any electric power systems. At distribution level, it is use in dividing long power lines into smaller sections. This helps to reduce any interruption to the continuity of supply when a section is not functional or faulty or during maintenance work. Reliability is a major factor that influence power system design, planning and operation, particularly for substation. Substations are used for raising voltage level for transmission and stepping down for power distribution. Substation consists of power transformer, feeder pillars, switching, measurement, and protection and control devices to ensure safe and efficient operation (Johnson, 2015). 11/0.415 kV substations are common sight on streets and perform the function of distributing and coordinating power supply to specific group of consumers in a given neighborhood. 11/0.415kV substation is the final stage of electric power distribution system in Nigeria, as the circuits leaves the substation at 11/0.415 kV to enter consumers' terminals. Much of the outages at distribution level occur at this final stage (Boknam, *et al*., 2007). Therefore, ensuring a very reliable operational substation at this final stage of power distribution is a very important issue. By identifying possible causes of failure and elimination will obviously help to improve reliability (Warwich, 2007). Most power outages are caused by storm and weather-related damage to overhead distribution power lines. Heavy winds and storm can cause trees to touch power lines, contact of two phases and sometimes can cause lines and poles to break and fall. Animal contact (snake, lizard, bird), overloading, vehicular accidents, equipment failure, and human error also contribute to cause of power outages (US Department of Energy, 2012). Aging of equipment and installation; and use of substandard materials are other factor affecting effectiveness of power distribution systems. Reliability is a very broad concept and multiple of definitions abound in many literatures. In Engineering, Reliability is commonly defined as the probability that an item will perform a required function without failure under stated condition for a stated period of time. According to EPRI (2000), the goals of the power distribution system are covering the territory having sufficient capacity for peak demand and being able to operate under adverse conditions thereby providing a stable and quality voltage. However, to achieve these goals there must be a reliable or otherwise well designed substations between the generating stations and load centres. Therefore, this research considered the design of 11/0.415 kV substation to promote the best mode of practicing, sizing of substation elements and code of practice in order to achieve a substation that will meet the need of the end users. This research was motivated due to the existing substation, 500 kVA, 11/0.415kV, 50Hz experiencing frequent tripping and the concerned authority resulted into undesirable load shedding 10years ago. As a result of this, another substation was commissioned about 7years ago. Presently, the area is experiencing same problem of load shedding. The occupants of this substation are high caliber people which include a vice chancellor of a private university in Nigeria, a retired pharmacist of Federal University Teaching Hospital in Nigeria, a Managing Director and medical practitioner in Lagos State, a practicing consulting engineer and lecturer in a Nigeria Federal University, directors in the Lagos States coupled with the high concentration of the people where street lights are highly needed to reduce mischievous characters in the night. Loading of transformer at 60% to cater for future expansion is a necessity. Code recommends 25% future expansion of the load. It therefore means that 25% of the 60% loading yields 75% previous loading. This will allows moderate overloading at 75% previous loading. The design in work is based on this philosophy. This will facilitates long life of the transformers or otherwise the substation. Apart from load shielding that motivated this work which was mentioned earlier, another motivation is inability of the author to design a 33/0.415 kV substation after 2years of obtaining his Master Degree when working with an international consulting firm. This bottleneck should be overcome with our first and second degree holders, thus the high motivation of this research.

1.1 Overview of power system

Power demand is increasing rapidly due to increase in industrial, commercial and agricultural consumers. It is required to have large blocks of power generation in country like Nigeria where transmission and distribution losses are very high (Onohaebi and Kuale, 2007). In order to meet consumer demand, more generating stations (GS) like Thermal, Gas, Hydro and Nuclear are needed which are far away from consumer. To transmit large amount of power up to long distance, extra high voltage lines are necessary for transmission to the load centers for increased reliability of supply, greater system stability and hence cheaper electric energy (Gupta, 2005, Nawaz, 2016). In between power stations and consumers, transformation and switching stations called substations are necessary for the control of electrical power system. This research focus on the design of 11/0.415 kV distribution sub-station (11/0.415 kV) is review in this work.

1.2 Substations

Electric power is produced at the power generating stations which are generally located far away from the load centers. High voltage (HV) transmission lines are used to transmit the electric power from the generating stations to the load centers. Between the power generating station and consumers a number of transformations and switching stations are required. These are generally known as substations. Substations are important part of power system and form a link between generating stations, transmission systems and distribution systems. It is an assembly of electrical components such as bus-bars, switchgear apparatus, power transformers, low voltage panels, protective device and the likes. Their main functions are to receive power transmitted at high voltage from the generating stations and reduce the voltage to a value suitable for distribution. Some substations provide facilities for switching operations of transmission lines, others are converting stations. Substations are provided with safety devices to disconnect equipment or circuit at the time of faults. Substations are the convenient place for installing synchronous condensers for the purpose of improving power factor and provide facilities for making measurements to monitor the operation of the various parts of the power system (Gupta, 2010, Johnson, 2015, Nawaz, 2016)

The substations may be classified according to service requirements and constructional features (Nawaz, 2016). According to service requirements it is classified in to transformer substations, switching substations and converting substations (Nawaz, 2016).

1.2.1 Transformer substations

Majority of the substations in the power system are classified under this type. They are used to transform power from one voltage level to another voltage level. Transformer is the main component in such substations. Transformer substations are further classified into Step-up substations, Primary grid substations, Secondary substations and Distribution substations (Johnson, 2015).

1.2.1.1 Step-up substations: These substations are usually located at the generating stations.

Generating voltage of the order of 11kV needs to be stepped up to a primary transmission voltage level of the order of 330 kV or 400 kV depending on the country.

1.2.1.2 Primary grid substations: These substations are located at the end of primary transmission lines and the primary voltage is stepped down to suitable secondary voltages of the order of 132 kV or 33 kV.

1.2.1.3 Secondary substations: The voltage is further stepped down to 11kV. Large consumers are supplied power at 11 kV (Gupta, 2005, Johnson, 2015).

1.2.1.4 Distribution substations: These substations are located near the consumer localities to supply power at 415V, three phase or 240V, single phase to the consumers.

1.2.2 Switching substations

These substations are meant for switching operations of power lines without transforming the voltage. Different connections are made between the various transmission lines.

1.2.3 Converting substation: Such substations are meant for either converting AC to DC or vice versa. Some are used to change the frequency from higher to lower or vice versa for industry utilizations.

1.2.4 Substation according to constructional features substations

1.2.4.1 Indoor substations: All equipment of the substation is installed within the station buildings.

1.2.4.2 Outdoor substations: All equipment such as transformers, circuit breakers, isolators, etc., is installed outdoors.

1.2.4.3 Underground substations: In thickly populated areas where the space is the major constraint, and cost of land is higher, under such situation the substations are laid underground.

1.2.4.4 Pole mounted substations: This is an outdoor substation with equipment installed overhead on a H pole or 4 pole structure.

1.3 Substation Elements

Substation equipment are required to control and maintain power supply (Johnson, 2015). Substation equipment design is very important from the point of view of reliability of system supply. In this project, main objective is to size 11/0.415 kV substation element which has higher reliability and security from design point of view. The meaning and purpose of substation element are discussed underneath

1.3.1 High Voltage Fuse

The word fuse is a short form of "fusible link" and it is also protection device capable of protecting a circuit from overload currents and short circuit currents. Fuses are rated in terms of many aspects. These include voltage, current and the type of application. A high rupturing capacity (HRC) fuse is a fuse that has a high breaking capacity (higher kA rating. A general approach is that it should operate at 1.25 times the rated current. A typical fuse is made of silver-coated copper strips and granular quartz (Gupta, 2010, Nawaz, 2016).

1.3.2 Lightning Arrester (LA)

The substation elements such as conductors, transformers, etc., are always erected outdoor. Whenever light surges occur a high-voltage pass through these electrical components causing damage to them, either temporary or permanent damage depending on the magnitude of voltage surge (Melodi and Oyeleye, 2017). Therefore, to avoid this difficulty, lightening arresters are placed to pass the entire lightening surges to earth. There are many arresters which are used to ground the switching surges, however metal oxide lighting arresters is used in this research base on superior energy absorption capability, better surge protection, more stable protective characteristics and substantial reduction, overvoltage across equipment as compared to other types of arrester. (Gupta, 2010, Weedy, *et., al* 2012, Nawaz, 2016,) A general approach is that it should operate at 1.1 times the rated voltage (NEC, 2005). The down conductor for discharging current to the ground is sized to 161mm^2 (Oyeleye, 2017).

1.3.3 Transformer

A static electrical machine used for transforming power from one circuit to another through electromagnetic induction circuit without changing frequency is termed as power transformer (Dasgupta, 2007, Gupta, 2010, Nawaz, 2016). The transformers are generally used to step down or step up the voltage levels of a system for transmission and generation purpose. These transformers are classified into different types based on their design, utilization purpose, installation methods, and so on. (Nawaz, 2016). The continuous loading of transformer for high efficiency is 50% (NEMA Standard, 2002, Bureau of energy efficiency, 2005, NAEEEP, 2011, Zenatix, 2015). A variation of 50-60% (Bureau of Energy Efficiency, 2005) and can be considered for a transformer which has not been repaired (Zenatix, 2015). If the transformer is loaded from 60% - 100% the loss varies between 0.4% - 1.9% percent (Schneider, 2015). However the overloading of a transformers depends on the transformer's previous load or the corresponding oil temperature at the beginning of the overloading (Schneider, 2015). The permissible duration and percentage overloading is present in Figure 1 – 3 based on previous loading of 50, 75 and 90 percent respectively (Schneider, 2015).

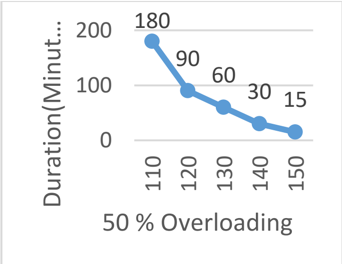

Figure 2: 50% Previous Loading

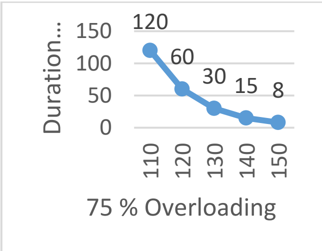

Figure 2: 75% Previous Loading

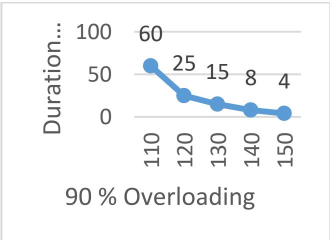

Figure 3: 90% Previous Loading

1.3.4 Conductor and Cable

The material that obeys the electrical property conductance (mostly made of metals such as aluminum and copper) and that allows the flow of electric charge is called conductor. Conductor permits free movement of the flow of electrons through them. These are used for the transmission of electrical energy from one place (generating station) to another place (consumer point) through substations. Conductors are of different types and mostly aluminum conductors are preferred in practical power systems because its cheap and light in weight. Even though electrical conductivity of Aluminum (Al) is lesser than that of copper Cu (60%) for the same resistance for a given length, Al is still frequently prefer to Cu for bare electric conduction over long distance (Lakervi and Holmes, 1989, Gupta, 2005, Nawaz, 2016). Conductors are selected base on rating of loads and ambient conditions (moisture, temperature, exposure to sun and area to be installed). the ampacity of electrical components for the circuits are determined by current ratings and associated voltage drop as contained in Catalogues (ABB, 2005, Kable Metal , 2005, Nigerchin , 2006)**.** Conductor can be for HV or LV distribution. Cable is a conductor covered with insulator (Hilsdorf and Matinez, 2015). Even though electrical conductivity of Al is lesser than Cu (60%) for the same resistance for a given length, Al is still frequently prefer to Cu for bare electric conduction over long distance in power dist**ribution.**

1.3.5 Insulation, Armoured Cable and Underground Cable

The insulation of cable started in late 1880 and the then insulation suffered deterioration of insulation called local electrical discharge. This problem was overcome in 1926 with oil-filled cable designed by Emanuelli. In 1950, increase in copper cost coupled with heavy weight switched attention in cable selection to aluminum for underground installation. Polyvinyl chloride (PVC) came to lime light in 1950 but limited in use by plastic flow at high temperatures and thus creates poisonous acidic gases. This short coming limit its use to low voltage. Underground cables insulating materials and Armoured Cable (AC) or cross linked Cable (XLPE) are used in underground work in order to protect the conductor from mechanical damage. Water and corrosion are also protected in AC and XLPE cables. Polyethylene (PE) is used in medium voltage while XlPE is preferred to PE due to its better heat capability under shortcircuit fault condition and higher temperature for normal operation (Lakervi and Holman, 1989).

1.3.6 Low Tension Panel (LTP)

Feeder pillar is a cabinet for electrical equipment mounted immediately after low voltage side of a transformer in a substation in the street and controlling the electrical supply to a number of in a neighborhood. Feeder pillar can be described as an electrical enclosure used to provide electrical services for low voltage electrical applications. It is designed as a compact and robust for vandalism protection

1.3.7 Current Transformer (CT)

It is used for the measurement of the alternating current by taking samples of the higher currents of the system. These reduced samples are in accurate proportions with the actual high currents of the system. These are used for installation and maintenance of the current relays in substations for protection purpose which are normally has low-current ratings for their operation (Nagrath and Kothari, 2003, Nawaz, 2016). HV CT is used in this work.

1.3. 8 Voltage Transformer (VT)

It is quite similar to the current transformer, but it is used for taking samples of high voltages of a system for providing low-voltage to the relays of protection system and also to the low-rating meter for voltage measurement. From this low-voltage measurement, the actual system's high voltage can be calculated without measuring high voltages directly to avoid the cost of the measurement system (Nagrath and Kothari, 2003, Nawaz, 2016). This is installed in low voltage panel.

1.3.9 Bus-Bar (LTP)

The conductor carrying current and having multiple numbers of incoming and outgoing line connections can be called as bus bar, which is commonly used in the low voltage panel. These are classified into different types like single bus, double bus and ring bus (Siemens, 2006, Nawaz, 2016).

1.3. 10 Line Isolator (HV)

In Power systems an isolator is a switch which is used to completely open a circuit which has been rendered dead by means of opening a circuit breaker for maintenance of equipment. It can be visually seen that an isolator is open and hence service man are assured that it is safe to work on the isolated equipment. The equipment to be worked on is further earthed mostly on either side so that electrical energy that could be in the equipment is completely discharged to earth further enhancing safety of the service man. An isolator is also used for sectionalizing power lines during fault location. Isolators are always opened in no load condition (after opening of circuit breakers) because it lags the mechanism of operating in high voltage (Nawaz, 2016, Gupta, 2005)

1.3.11 Grounding System

Grounding is the connection of part of an electrical circuit, accessible conductive parts of electrical equipment (exposed conductive parts) or conductive parts in the vicinity of an electrical installation (extraneous conductive parts) are connected to earth (Gupta, 2010, Nawaz, 2016)

Earth electrode is a metal conductor, a system of interconnected metal conductors or other metal parts acting in the same manner embedded in the ground and electrically connected to it, or embedded in the concrete which is in contact with the earth over a large area (e.g. foundation of a building). The earthing system in comprises of three main components which are ground conductor, connection between the ground conductor and ground electrode and Ground electrode.

1.4 Design Code

The design code of substation element are summarized in Table 1. The codes have been used on various projects successfully.. These projects include Olokola Liquefied Natural Gas (OKLNG), Ondo State, international petroleum companies and other substation projects.

Table 1: Design Code of Substation Materials (NEC,

2005; British International Standard, 1998, and Oyeleye, 2017)

S/N	SUBSTATION ELEMENT	CODE(MULTIPLYING FACTOR)/ STANDARD
1	Low Voltage fuse(secondary)	1.25
2	High Voltage fuse(primary)	1.25 (3.0, maximum)
3	Isolator	1.25
4	Cable/conductor	1.25 of rated value appropriate derating factor
5	Circuit breaker / Panel/Busbar	1.25
6	Load future expansion	1.25 of the actual load
7	Lighting Arrester	1.1
8	Ground conductor, G_c	$G_c = \frac{1}{2} * Phase\ curret, I_p$
9	Lightning down conductor and rod/mat	161mm^2
10	Grounding resistance	10Ω max (IEC and BS)

2. METHODOLOGY

2.1 Load Data

Existing load was obtained from PHCN record in order to determine and size an appropriate transformer including the substation elements that will cope the new extension of a community area, Lagos State.

2.2 Design Considerations

Design considerations are employed for safety and operation of designed of a substation. The substation design consideration include:

i. availability of an existing high voltage supply (11 kV)
ii. incorporation of future expansion of load (1.25 factor)
iii. reliability of elements used(reliable element from trusted vendor)
iv. effective grounding (code Compliance)
v. ability of protective element to trip when desire (code compliance).
vi. 60% loading of Transformer
vii. 75% previous loading to cater for 2hours overloading.

2.3 Sizing of Substation Elements

Applicable and appropriate codes, guidelines and algorithm were used to size the substation elements, Table 1 in addition to the anticipated load of the substation.

2.3.1 Transformer Sizing

Sizing of transformer is based on Equation 1
Equation (1) is used.

$$P = \sqrt[3]{}I_{pri}V_{pri} \qquad (1)$$

Where I_{pri} is the primary current and V_{pri} is the primary voltage.

2.3.2 High Voltage (HV) Fuse

$$P = \sqrt[3]{}I_{pri}\,V_{pri} \qquad (2)$$

Where P is the three phase power in Volt Ampere (VA).

From equation (2), we obtain equation (3). Equation (3) is used to determine HV fuse.

$$I_{rated} = P/\sqrt[3]{}\,V_{rated}\ A \qquad (3)$$

Where I_{rated} is the primary current that the low voltage circuit will carry without damaging the primary conductor.

2.3.3 0.415 kV Low Voltage Panel (LVP) Sizing

LVP sizing is based on equation (4).

$$LVSP = 1.25 * I_{rated(sec)}\ \text{A} \qquad (4)$$

Where 1.25 is the multiplying factor for panel.

2.3.4 Isolator

According to Table 1, design of HV fuse correspond to isolator sizing since isolator are connected in series with the HV fuse. The same equation (2) is used.

2.3.5 Lightning Arrester (LA) Selection

The determination of LA was done using equation (5)

$$\text{LA size} = 10\% * V_{mpHV} \qquad (5)$$

Where V_{mpHV} is the maximum permissible high voltage.

2.3.6 Low Voltage Circuit Breaker (LVCB)

Required load should be sized to 60% of the transformer in order to cope with the expected load and 75% previous loading of a transformer. 75% loading is essential for 2hours overloading. LVCB is sized using equation (6).

$$I_{\sec F.E} = 1.25 * I_{sec} \qquad (6)$$

Where I_{sec} is the secondary current (load current); $I_{sec\ F.E}$ is the secondary current taking future expansion into consideration; 1.25 it the future expansion multiplier

Where I_{rated} is the current carrying capacity of the secondary side of transformer.

2.3.7 H.V Cable

Equation (7) is used to determine H.V cable size, H.V cable rated.

$$H.V\ cable_{rated} = 1.25 * I_{pri\ rated}\ \text{A} \quad (7)$$

Where 1.25 is the cable multiplying factor and $I_{pri\ rated}$ is the primary rated current.

2.3.8 LV Cable

Low voltage cable (cable $_{sec}$) is sized using equation (8).

$$Cable_{Sec} = 1.25 * I_{sec\ rated}\ \mathrm{A} \qquad (8)$$

Where 1.25 is cable multiplying factor and $I_{sec\ rated}$ is the secondary rated current.

2.3.9 Grounding System

Grounding conductor, G_c, is determined using equation (9).

$$G_c = \frac{1}{2} * I_p \qquad (9)$$

Grounding system resistance value should conform to international standard of BS(1992); and IEC(2006); and Oyeleye & Makanju (2017) of 10Ω maximum.

2.10 Down conductor

Down conductor is sized in accordance to Table 1.

3. RESULTS and DISCUSSIONS

3.1 Results

The results of design of 11/0.415kV using Table 1 and applicable equation 1 to 9 are presented in Table 2.

Table 2: Parameters of 11/0.415 kV Designed Substation

SUBSTATION ELEMENTS	DESIGNED VALUES			RECOMMENDED	1.25 MULTIPLYING FACTOR CONSIDERATON	CABLE SIZING
		60%	25% FE			
Transformer sizing	500 kVA	0.6	0.75			
High Voltage Fuse	26.2A	15.7 A	16A	25A		
Low Voltage panel sizing	696A			800A		
Isolator	26A			200A		
Lightning arrester	12.1 kV					
Low voltage CB	696A	417.4 A	522A	600A		
HV cable	26.2A				33A	22 mm^2 (Al)
LV cable	696A				870A	4nos of 2 x 400mm^2(S-C, Cu)
Earthing conductor	348A			150mm^2		
Down conductor	161mm^2			180mm^2		

From Table 2, Figure 1 is obtained.

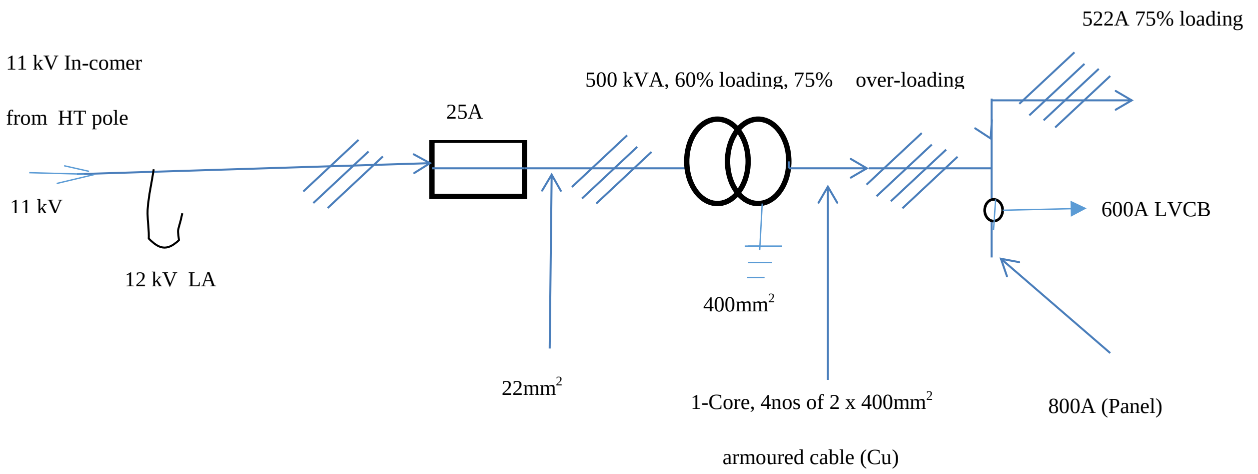

Figure 1: Single Line Diagram of 11/0.415 kV Designed and Recommended Substation Elements

3.2 ANALYSIS

From Table 1, the sizing of the substation elements conform to the designed codes used in this research. The transformer is designed to operate at 60% loading. 25% future expansion was considered. This future expansion consideration, pave way for the transformer to operate at 75% previous loading for 2 hours overloading. The HV fuse is 16A and 25A recommended since 16A designed value is not available. The 25A recommended HV fuse is still lower that the available 26A designed value. This means that the usual frequent blowing of the HV fuse is overcome in this design method thus reduce difficulty in maintenance.

The substation elements are sized based on the renowned international codes, Table 1. This means that the designed substation will be reliable, safe, and efficient and meet the design philosophy. However in sizing the HV and LV cables, single core cable was considered suitable for the load putting derating factor of 0.8 in to consideration since two cables are touching from Nigerchin cable catalogue. The derating factor is necessary to avoid overheating of the cable.

The recommended lightning arrester is adequate to discharge surge current into the ground due to the designed lightning and earthing systems that conform to the existing literatures. This design will allow 11/0.415 kV substation to operate safely, effectively and efficiently thus increase station reliability and efficiency. It is good to know that where the designed element is not readily available, the next available element rating is recommended.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

i. Design of 11/0.415 kV substation at 60% load requirement is achieved.
ii. 75% previous loading of the transformer including future expansion was achieved.
iii. Previous loading of 75% which will cater for 2hrs overloading is achieved thus long operational life of the transformer and cheapness in overall maintenance cost.
iv. The common tripping of HV fuse when a transformer is overloaded is avoided in HV side in this work.
v. The protection of the transformer and all other elements are achieved.
vi. The lightning arresting system is adequate to discharge surge current safely into the ground.

4.2 Recommendations

In order to achieve high operational performance of 11/0.415 kV substation, the followings are recommended:

i. transformer should be design to operate at 60% loading without future expansion consideration,
ii. adequate substation future expansion should be put into consideration,
iii. transforms should not be designed to operate at 100% loading (previous loading), and
iv. derating factor should be considered to avoid cable overheating.
v. this work can be applied to substation design.

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