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Performance Evaluation of Six-Phase Power Transmission Line With Limited Right-Of-Way

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Abstract

This study eradicates insufficient installed capacity, power interruption, down time, outages, etc, by upgrading existing three-phase lines to six-phase lines while maintaining its right-of-ways. It modeled a six-phase transmission line and compares it with an existing 73Km, 132kV three-phase transmission line (casestudy) in Akwa Ibom State using PSAT and PSCAD power softwares. *Power system analytical tool (PSAT) was utilized in obtaining the transient stability of both lines, whose comparative analysis indicated that 6-phase line has reduced critical clearing time (CCT), higher current and voltage value, more reliable with better power distribution ability. Its load flow performance is better and its power loss is 50% less than that of the three-phase line. It has a reduced magnetic & electric field, resulting to a reduced right-of-way. It is therefore recommended that the case study area be replaced with a 6-phase transmission line for efficient power transmission.*

Keywords: **6-Phase Transmission, Right-of-Way,** ***Multi Phase, Six-phase, simulation*****.**

1. Introduction

1.1 Background of the study

Nigeria has a problem of insufficient installed & transmission capacity of power supply (World Bank Data, 2016). Access to electricity is a major constraints in Nigeria having negative impact on domestic, commercial and industrial activities (Oladeinde Olawoyin, 2020). 47% of Nigerians are not connected to the national grid (World Bank, 2020), with a population of over 190.9 million and generating capacity of 7,500MW (World Bank 2017), its consumption / capita of 155kwh/capita is the lowest globally Christie Etukudor, Ademola Abdulkareem, Olayinka Ayo (2015); indicating insufficiency and poor living standard (USAID, 2017). From its 22 gas-fired and 3 hydro plants, the total installed capacity is 12,522MW, only 7,141MW is available due to operational inefficiencies (IEA, 2021). Its System Average Interruption Duration Index (SAIDI) is less than 60,000minutes as compared with 90 - 180mins acceptable standards and its rate of occurrence is less than 600 interruptions per year as against 1 or 2 acceptable standards (MAN, 2018). Nigerian Bureau of Statistics (2018) shows that, 1 out of every 7 industries collapse due to inadequate power supply. Even the national grid has collapsed twice in May 2021, 29 times in 2018 and 206 times from 2019 to 2020 (Oge Udegbunam, 2021). Successive administrations in Nigeria tried in vain to solve this power problem; Olusegun Obasanjo's in 2006, projected generating capacity to 10,000MW by 2007 and 35,000MW by 2020. Yet no result. Umaru Yar'Adua's in 2009, promised 20,000MW by 2015. Yet no result. In 2013, Goodluck Ebele Jonathan privatized Power Holding Company of Nigeria into 6 generation companies (GenCos), 11 distribution companies (DisCos),while government handles the transmission section. Yet no result. Muhammadu Buhari's in 2015 aimed promised 11,000MW by 2021 and 25,000MW by 2025. Yet no result. Alternative solutions were sort to solve this problem, among such alternatives were; line compaction, high temperature low sag (HTLS) conductors, etc, but high phase order (HPO) was selected as a potential alternative to achieve sufficient installed & increase transmission capacity, while maintaining existing right-of-ways. HPO uses six, nine, twelve, or more phases instead of 3-phase for power transmission. Amongst these, six-phase was taken as a potential alternative to replace the three-phase systems owing to its various advantages such as; increase transmission & power transfer capacity, lower - operational voltage, phase-to-phase voltage, line spacing, smaller right-of-way with smaller and compact structures & towers, reduce overall cost, reduced magnetic fields, environmental impact, radio & audible noise, less power losses, line balancing, compatibility with existing lines, increase power at receiving end, improve power factor, minimal current unbalances, single pole switching, field mitigation, reduced corona etc. More effort is needed to model, analyze and evaluate the performance of this six-phase system in Nigeria. Hence the purpose of this thesis.

1.2 Statement of the Research Problem

- The major problem in Nigeria is insufficiency in electricity supply and inadequate transmission capacity.
- The single grid system & its frequent collapse is another problem.
- Constraint in erecting new transmission lines and increasing transmission voltages to extra-high & ultra-high voltage levels (EHV–132Kv) & (UHV –330Kv).
- The problems concerning power flow and stability of transmission lines is very critical. Hence this study.

1.3 Aim and Objectives of the Study

The aim of this study is to achieve sufficient installed & transmission capacity of electricity in Nigeria using Six-Phase 330Kv transmission line while maintaining its existing right-of-way. The objectives of the study are;

i. To review the existing studies on transient stability of three-phase 132Kv transmission line.
ii. To acquire the line diagram and data of an existing three-phase 132Kv transmission line and model it using power system analytical tool box (PSAT) in MATLAB.
iii. To replace this modeled three-phase 132Kv transmission line with a 132Kv Six-phase transmission line using power system analytical tool (PSAT) in MATLAB.
iv. To simulate the modeled 132Kv Six-phase transmission line in (PSAT) and obtain the power system.
vi. To simulate the modeled 132Kv Six-phase transmission line in (PSCAD) and obtain the right-of-way based on magnetic and electric field effects with respect to lateral distance power system.

1.4 Methodology

The transient stability of a 73Km, 132Kv six-phase transmission line with its right-of-way was modeled and compared with an existing 73Km, 132kV three-phase transmission line (case study) located in Akwa Ibom State. Power System Analytical Toolbox (PSAT) and Power System Computer Aided Design (PSCAD) were used to simulate both lines. PSAT was utilized to simulate the transient stability (current, voltage stability & the load flow analysis) of both 3-phase and 6-phase lines. PSCAD was used to simulate the magnetic & electric field effect of both lines to determine the right-of-way. The comparison of both lines showed a better outcome for the 6-phase line in terms of reduced power loss, improved voltage and current reliability, limited right-of-way, better critical clearing time (CCT), and critical clearing angle (CCA) with better stability.

1.5 Scope of the Study

This study used the 73Km, 132kV 3-phase transmission line (the case study) from Ibom power plant to the Afaha-Ube transmission substation in Akwa Ibom State. Its line diagram was acquires and modeled with a six-phase line of same voltage magnitude and distance using PSCAD and PSAT in MATLAB. PSAT determine the system transient stability using its critical clearing time (CCT), voltage, current and power flow as parameters. While PSCAD was used to get its right-of-way using it's magnetic and electric field densities as parameters. On comparism, 6-phase showed a better outcome with a reduced power loss, improved voltage and current reliability, limited right-of-way, better critical clearing time (CCT) and critical clearing angle (CCA) with better stability. This technique will be extended to the Nigerian 24 Bus 330kV National Grid network to eradicate its frequent collapse.
Limitation of this research is the non-availability of 6-phase line in Nigeria.

1.6 Significance of the Study

On completion of this study, six-phase transmission lines will adopted into the national grid to achieve increase transmission capacity, maximum power transfer, uninterrupted power supply, eradicate frequent line collapse, transmission line losses, insufficient installed capacity, power interruption, and so on. This will boost industrialization, attract foreign investors, and improve the economic status and standard of living.

2. Literature Review

2.1 Related Literature on High Phase Order (HPO) Technology

Research work in this field has been performed by other researchers such as: Zakir Husain, Ravindra Kumar Singh, & Shri Niwas Tiwari (2007), Xianda Deng (2012), Ebha Koley, Anamika Yadav & A. S. Thoke (2014), T. Charan Singh, K. Raghu Ram, B.V. Sanker Ram & P.S. Subramanyam (2014), G. Chandra Sekhar, & I. Satish Kumar (2016) and so on. This literature review examines their works, to spotlight their findings and recommendation.

2.1.1 Multi-phase (6-Phase & 12-Phase) Transmission Lines Performance Characteristics by Zakir Husain, Ravindra Kumar Singh, & Shri Niwas Tiwari (2007)

This comparative analysis of (6-phase & 12-phase) lines with 3-phase line showed that (6-phase & 12-phase) lines has: increase power capacity, reduced power losses, receiving-end power increase, reduced reactive power for maintaining stable load voltage, reduced compensating devices rating, better voltage stability. It can be used by utility providers for planning, development and design of multiphase network.

2.1.2 Exploring Six-Phase Transmission Lines For Increasing Power Transfer With Limited Right-Of-Way by Xianda Deng (2012

This thesis, compared 6-phase with 3-phase double circuit transmission lines using line voltage, current,power, electric & magnetic fields, and right-of-way as criteria for comparism. The result shows that 6-phase line had better ground level magnetic field, higher power transfer capability with better right-of-way. It was concluded that the existing protection technology has adequate capability to protect 6-phase transmission lines.

2.1.3 Investigation On Transient Stability Of Six-Phase Transmission System And Proposal For Integrating With Smart Grid by T. Charan Singh, K. Raghu Ram, B.V. Sanker Ram & P.S. Subramanyam (2014).

This paper shows the smart grid capability of delivering electricity from suppliers to consumers via a two-way digital technology, controlling the consumer's energy consumption by reducing the cost of generation, transmission, efficiency and reliability. The result showed improved efficiency, power transfer capability, transient stability, reliability of power transmission, less power interruptions, less radio interference, and optimal energy consumption.

2.1.4 Calculation Of Electric Fields Underneath Six-Phase Transmission Lines By R. M. Radwn1 & M. M. Samy (2016).

This paper calculated the electric fields underneath 6-phase and double circuit 3-phase transmission lines and concluded that, the electric field produced by the 6-phase system is less than that for 3-phase lines. The dimensions of the tower and the right-of-way of the 6-phase transmission systems is less than the 3-phase system.

2.1.5 Calculation Of Electric Fields Underneath Six-Phase Transmission Lines by Radwin (2016)

The comparative analysis at one meter above the earth level of the electric fields of a 6-phase transmission line and a double circuit three phase line using the charge simulation technique (CST) showed better outcome for 6-phase in terms of magnetic field reduction, increase in voltage and lesser right-of-way.

But on research study in is field has been conducted in Nigeria. This study will investigate the possibility of replacing or upgrading existing 3-phase double circuit transmission lines with 6-phase transmission line to achieve uninterrupted power transfer while maintaining existing right-of-way.

3. Materials and Methods

3.1 Introduction

The idea of high phase order transmission was first introduced as a means of compacting transmission lines, maximizing the power density in a given right-of-way (ROW), and generally employing existing transmission corridors as efficiently as possible. High Phase Order (HPO) Techniques is the use of Multi-phase system i.e. 3, 6, 9, 12 phases and so on for power transmission. Six-phase systems have been chosen to be the most attractive alternative to replace the three-phase systems.

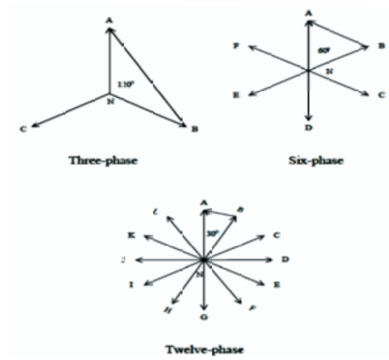
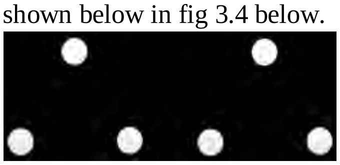


Fig. 3.1 Three-phase, Six-phase and Twelve-phase phasors

The phasors of three-phase and six-phase high phase order systems are shown in Fig. 3.1. Note that the electrical angles between phases decrease as the phase order increases. The electrical angle between the phases in 3-phase is 120^0, that of 6-phase is 60^0, and that of 12-phase is 30^0 and so on. That is as the phase order increases, the electrical angle decreases. Eg, if a two, 3-phase transmission lines (line1 and Line2) are placed side by side, as shown in fig 3.2 below. And Line 2 is rotated 60^0 (electrical degrees) as shown below in fig 3.3. Then Line 2 can be inserted into Line 1 to form a 6-phase transmission line as shown below in fig 3.4 below.



Line 1 Line 2

Fig. 3.2 Two, 3-phase Transmission lines placed side by side

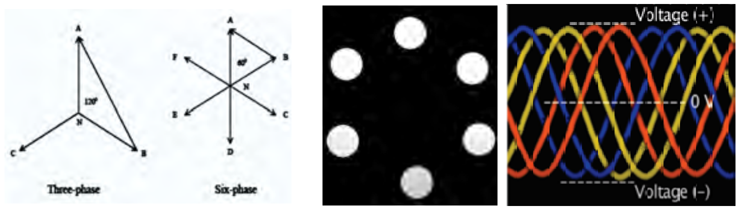
Line 1 Line 2

Fig. 3.3 Line 2 to 60^0 (electrical degrees)

Line 1 Line 2 6-Phase Line

Fig. 3.4 Six-phase Transmission line

Observe that the 3-phase line has changed to a 6-phase line, having twice the line power with increased transmission density because of the increased number of conductors in the transmission corridor, and the voltage per foot between phases is the same because the voltage between phases is reduced by changing the electrical angle. The electrical angles between phases decrease as the phase order increases. The electrical angle between the phases in 3-phase is 120^0, that of 6-phase is 60^0. The phase-phase voltage in the 3-phase system is $\sqrt{3}$ times the phase-ground voltage. In the 6-phase system, the phase-phase voltage reduces to (equaling) the phase-ground voltage, and in a 12-phase system, the phase-phase voltage is reduced to $2.\mathrm{Sin}(15^0)$ times the phase-ground voltage (approximately by a half). It therefore means that, the higher the number of phases, the smaller is the phase-phase voltage (assuming constant phase-ground voltage), and thus, the smaller is the phase-phase spacing.



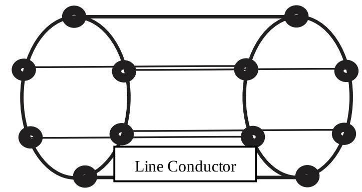


Fig. 3.5(a) Voltage per foot in the Six-phase Transmission line *(b) Six-phase transmission corridor with 6 conductors*

Also, notice that the right-of-way (ROW) or the transmission line corridor has not changed or grown bigger. The transmission line corridor when the line was initially 3-phase remains the same when it is now 6-phase, the only difference is the increase in the number of conductors that has filled up the circumferential line corridor with 6 conductors instead of 3 conductors, as shown above in fig 3.5(b). It is like a conductor tube with the circumferential conductors separated by 60^0 with the air acting as an insulator or die-electric, meaning that it is possible to add more numbers of conductors into the transmission corridor with a resultant dramatic increase in power density. This is precisely what Barnes and Barthold (1972) had in mind when they first suggested the use of HPO technology in line compaction. In addition, by arranging the conductors in a circular array, they achieved the compact HPO configuration that would utilize corridor space optimally.

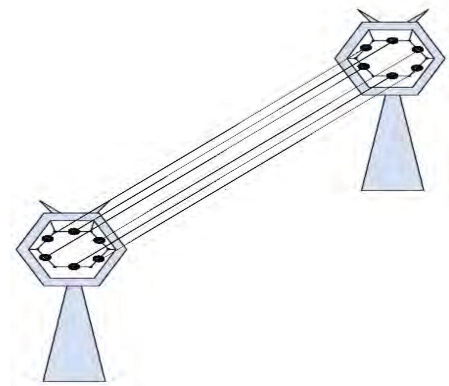


Fig. 3.5(c) 6-phase Transmission Line

Mathematical Expression For 6-phase Line

Phase-to-phase voltage and phase-to-ground voltage of 3, 6 & 12-phase HPO systems can be expressed as follows,

$$V_{1g\,3\varphi} = V_{1g6\varphi} = V_{1g\,12\varphi} \qquad (1)$$
$$V_{ll\,3\varphi} = \sqrt{3}\,V_{ll\,6\varphi} = 3V_{ll\,12\varphi} \qquad (2)$$
$$V_{ll\,6\varphi} = V_{1g6\varphi} \qquad (3)$$
$$\sqrt{3}V_{ll12\varphi} = V_{1g\,12\varphi} \qquad (4)$$

Where:

$V_{1g\ 3\varphi}$, $V_{1g6\varphi}$ *and* $V_{1g\ 12\varphi}$ are the phase-to-ground voltage of three-phase system, six-phase, and twelve-phase order respectively,

$V_{ll\ 3\varphi}$, $\sqrt{3}\ V_{ll\ 6\varphi}$ *and* $3V_{ll\ 12\varphi}$ are the phase-to-phase voltage of three-phase system, six-phase, and twelve-phase order respectively.

The power delivered by a three-phase transmission line and higher phase order transmission lines can be expressed as,

$$P_{3\varphi} = 3V_{1g\,3\varphi}\,I_{phase} \qquad (5)$$
$$P_{6\varphi} = 6V_{1g\,6\varphi}\,I_{phase} \qquad (6)$$
$$P_{12\varphi} = 12V_{1g\,12\varphi}\,I_{phase} \qquad (7)$$

It is assumed that phase-to-phase voltages, total currents in 3-phase and HPO transmission lines are equal.

The power transfer capability of 3, 6 & 12-phase HPO transmission lines can be expressed as,

$$P_{12\varphi} = \sqrt{3}\,P_{6\varphi} = 3\,P_{3\varphi} \qquad (8)$$

The equations above also indicate that if the same amount of power is to be delivered by HPO transmission lines, phase-to-phase voltages will be lower, compared to the 3-phase transmission line. It suggests less separation space between phases and smaller right-of-way are required in HPO transmission lines T. F. Dorazio (1990). The higher the number of phases, the smaller is the phase-phase voltage (assuming constant phase-ground voltage), and thus, the smaller is the phase-phase spacing. With the huge time lags involved in installation of new transmission lines, the ever growing demand for electric power, severe constraints on land availability, environmental effects, etc., it is essential to use right-of way (ROW) efficiently, Barnes and Barthold (1972).

The flow of electromagnetic power at any point in space can be universally described by the Poynting vector as:

$$S = E \times H. \qquad (9)$$

Where:

S' = Power density [Watts/m^2]

E = Electric field intensity [V/m]

H = Magnetic field intensity [A/m]

and the total power flowing through some plane (say for instance, the plane perpendicular to the transmission line) is:

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$P = \int x \int y\ S\ dx\ dy$ ----with x and y extending to infinity in both negative and positive directions.
Now, E and H are related by the impedance of free space Z_o (377Ω), and the electric field intensity E has a natural limit at the electric breakdown strength of air, approximately 3MV/m. This implies that H is also limited and thus there is only a limited amount of power that can be sustained by the air medium, under standard conditions.
This is:

$$|S| = |E \times H| = E.E/Z = (3 \times 10^5)^2 / 377\Omega = 9 \times 10^{12} / 377$$
$$= 24\ GW/m^2 \text{ peak}$$
$$= 12\ GW/m^2 \text{ RMS}$$

The entire width of the right-of-way (ROW) should have power density at, or very near this limit to make optional use of the available transmission corridor. Densities of this magnitude are approached only very close to the surface of conductors in traditional transmission line construction, Barnes and Barthold (1972). Hence, to increase the power transferred in a given transmission corridor, it is logical to fill that space with as many conductors - placed as closely together as possible. This is precisely what forms the logical basis for HPO transmission.

3.2 Materials

Bus 1 - Ibom Generation Power Station Plant in Ikot-Abasi, Akaw Ibom State.
Bus 2 - Afaha-Ube Transmission Substation in Uyo, Akwa Ibom State.
Transmission lines - 73Km, 132kV transmission line connecting Bus 1 and Bus 2.
Substation - Ibom Generation Power Plant & Afaha-Ube Transmission Substation.
MATLAB 2015a (PSAT10.1verson, PSCAD),

3.3 Methodology

The transient stability of a 73Km, 132Kv 6-phase transmission line with its right-of-way was modeled and compared with an existing 73Km, 132kV 3-phase transmission line (case study) located in Akwa Ibom State. Power System Analytical Toolbox (PSAT) and Power System Computer Aided Design (PSCAD) were used to simulate both lines. PSAT was utilized to simulate the transient stability (current, voltage stability & the load flow analysis) of both 3-phase and 6-phase lines. PSCAD was used to simulate the magnetic & electric field effect of both lines to determine the right-of-way. The comparison of both lines showed a better outcome for the 6-phase line in terms of reduced power loss, improved voltage and current reliability, limited right-of-way, better critical clearing time (CCT), and critical clearing angle (CCA) with better stability.

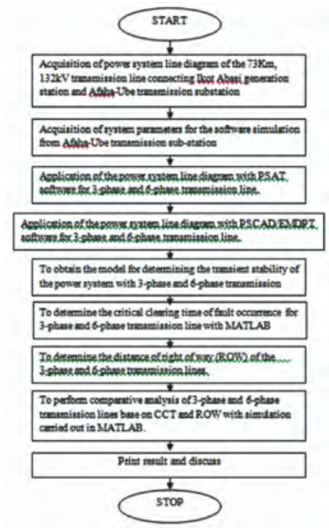

Fig. 3.6 Research methodology flow diagram

Prior to this procedure, research on 6-phase transmission was done for broader perspective and contributions of other researcher in this field was noted. Then, transmission line data and bus information and the required data was obtained from Afaha-ube Transmission Substation in Akwa-Ibom State. The data obtained was implemented with two softwares namely; Power system analytical tool (PSAT) and Power system computer aided design - PSCAD/ EMTP. This is to ensure that the result presented by each software coincides with the other. MATLAB software was needed in determining the right-of-way, the fault critical clearing time & angle for both lines for power system network connected with 3-phase line and six-phase line. This was necessary to determine the line with the shortest path (right-of-way) and the power system that best detects and clears fault in power system machines. The summary of the research procedure was summarized in the flow diagram shown in figure 3.6

3.4 Description of Case Study Cite

The case study of this study is the 73Km, 132kV transmission line connecting the Ibom Generation Power Station Plant in Ikot-Abasi (bus 1) and the Afaha-Ube Transmission Substation in Uyo (bus 2) all in Akwa Ibom State. The design capacity of the generation gas power plant in Ikot-Abasi was 190MW. The transmission line is a three-phase, as such during the implementation of the power system with computer application, a six-phase transmission with 132kV voltage was introduced. The line diagram of the power system of the transmission line connecting Ibom Generating Station and Afaha-Ube Substation is shown below in figure 3.7.

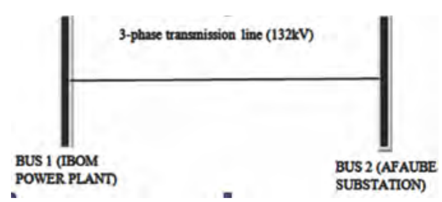

Fig. 3.7 Single line diagram of the power system.

3.5 Data Acquisition

The data for the single line diagram shown in figure 3.7 was collected in the Afaha-Ube transmission substation. This Afaha-Ube Substation represents the control station of Akwa Ibom State where all the power system data were obtained. The parameters and the values of the generation plant and the transmission substation and the transmission line parameters obtained to aid in further studies are as outlined below.

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- Power rating of the Ibom Generation Power Station Plant; 190MW.
- Partially operated with power generated being 90MW
- Transmission line distance; 73km
- Voltage transmitted; 132kv.

3.6 Modeling with Power System Analytical Tool (PSAT)

Power System Analytical Tool (PSAT) is an electrical power system software used in power system modeling. The simulation of steady state and dynamic nature of several types of machines are carried in this software. Also, Flexible Alternating Current Transmission System (FACTS) applications (models) are available for minimizing the steady state instability. For this study, PSAT10.1verson of the PSAT software was used for the simulation of both 3-phase and 6-phase transmission lines using line diagram shown in figure 3.7. The PSAT environment library is shown below in figure 3.8. To call up the library, PSAT command was typed at the command window of MATLAB 2015a, the first icon in the figure contains the buses with links. The second icon contains some power system static components namely; slack bus, icons for different types of power generations, different types of power system transformers, cables and transmission lines. The third icon comprises of the components necessary for continuous power flow and optimal power flow simulations. The fourth icon comprises of the fault icon and the circuit breaker icon. The fifth icon comprises of various types of load buses. The sixth contains the synchronous and induction machine. The seventh is made of several types of controls models. The eight icon contains various components of regulating transformers.

Fig. 3.8 Power system environment library in PSAT

The ninth icon is made up of different icon for flexible alternating current transmission system (FACTS).

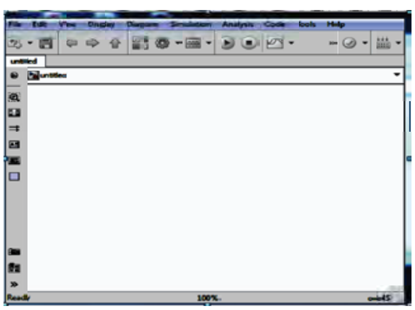

Fig. 3.9 Model Environment of the PSAT.

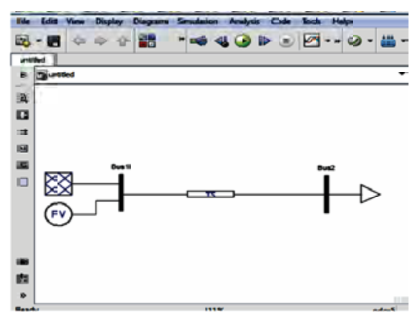

Fig. 3.10 Model environment with a three phase transmission line power system.

The tenth icon comprises of several wind turbine plants. The eleventh icon comprises of several energy storage models and the twelfth icon is made of frequency and phasor measurement units. For this study, the PV generation bus with the slack bus and PV load were used for the generation station and the sub transmission station. The model environment for the insertion of the required power component in PSAT for the simulation is shown in figure 3.9

In the environment shown in figure 3.9, all the power system parameters need for the simulation of the line diagram are imported to this figure where the line connections were made to enable uninterrupted simulation. The model environment with the necessary power system blocks is displayed in figure 3.10.

Figure 3.10 is the implementation of the power system line in figure 3.7. Bus 1 is the generation bus at Ikot-Abasi (Ibom Power Plant) and bus 2 is the load bus which represents the Afaha-Ube Transmission Substation. The parameters utilized for each component is displayed in the following figures.

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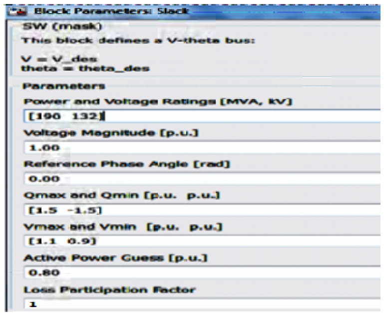

Fig. 3.11 Parameters for the slack bus.

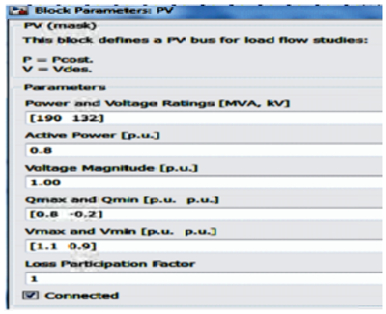

Fig. 3.12 Parameters for the PV generation bus

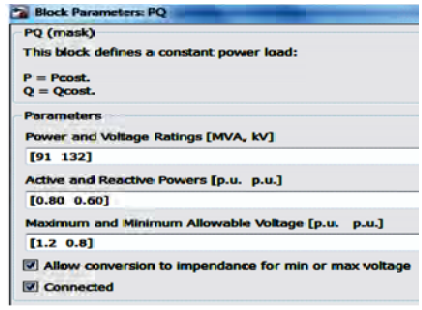

Fig. 3.13 Load bus indicating the Afaha-Ube transmission substation.

The parameters in figure 3.11, figure 3.12 and figure 3.13 are the necessary parameters for actualizing the dynamic nature of the power system simulation of the line diagram obtained from the case study cite. The PSAT for the six-phase line is shown in figure 3.14.

Fig. 3.14 Six-phase transmission line model.

The outcome of the simulation of the power system was presented in chapter 4.

3.7 Modeling with Power System Computer Aided Design (PSCAD)

Power system computer aided design (PSCAD) is used for the design and simulation of electrical power systems. This software generally increases the productivity, efficiency and effectiveness of electrical system designers by providing a design foundation that allows power systems to be created quickly and enabling the power engineers to test the safety and integrity of their design concept. Power system computer aided design (PSCAD) is much advanced than any other power software as such is used in the modeling of the power system line diagram shown in figure 3.7., the PSCAD library environment is shown below in figure 3.15.

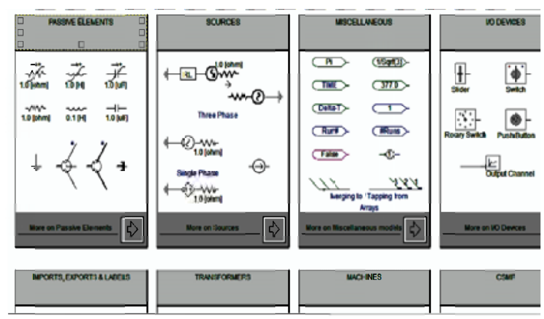

Fig. 3.15 Part of the PSCAD library.

The power system computer aided design (PSCAD) software comprises of advanced power system components that depict the actual power system scenario. The model environment of the power system PSCAD is shown below in figure 3.16.

Table 3.1: Transmission line Parameters

From	*To*	*Resistance (pu)*	*Reactance (pu)*	*Line length (km)*
Ibom power plant	*Transmission sub-station Afaha-ube*	*0.12*	*0.24*	*72*

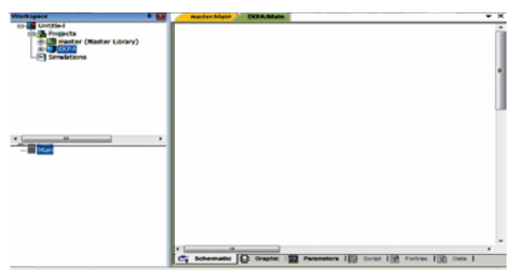

Fig. 3.16 PSCAD modeling environment.

The power system blocks/models are assembled in the environment shown above in figure 3.16. The environment with the power system block parameters are shown in figure 3.17. The difference between the 3-phase transmission line and the six-phase transmission is the selection in the transmission line. Other power system parameters as shown in the line diagram are presented in the PSCAD figure.

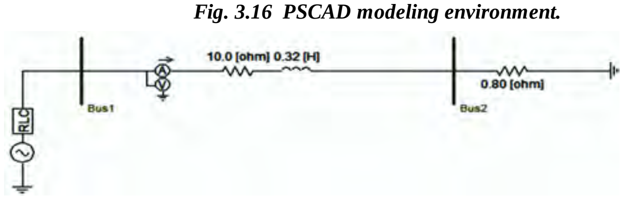

Fig. 3.17 Power system model with PSCAD

The PSCAD with 6-phase transmission line is shown below in figure 3.18. The model for the three-phase transmission line impedance and resistance was replaced with six-phase model as shown above in figure 3.18., this was done to determine the effectiveness of the 6-phase line in terms of system stability and right-of-way distance to magnetic field.

3.8 Transmission Line Right-of-Way Model

The main purpose for determining right-of-way is to elimination human and property risk from electric and magnetic fields of a transmission line. For this study, the magnetic field and the electric field of the transmission line model was obtained and the right-of-way of the 6-phase lines to achieve the same field strength was calculated and the comparison was made between the line distance of 3-phase line and the 6-phase lines. The magnetic field data was obtained with PSCAD software. The line data for the 132Kv line connecting Ibom power station and Afaha-Ube transmission line was obtained and modeled with the power system computer aided design (PSCAD) software were several magnetic field values and electric field was obtained at various heights (0.5m, 1m, 1.5m & 2m) of the transmission line. The three-phase line was replaced with a six-phase line where the electric and magnetic fields were obtained at various heights of the six-phase line. The line distance connecting Afaha-Ube and Ibom power station was 73km. The lateral distance considered was between 10m apart (-10 to 10m) with the zero point being the center of the tower.

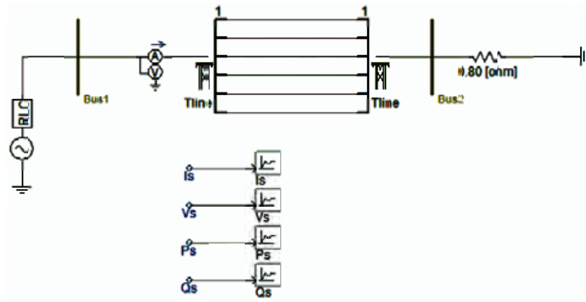

Fig. 3.18 6-phase power system with PSCAD

3.9 Power Losses

The model for determining the line losses between the generating station (Ikot-abasis Generating Station) and Afaha-ube Transmission Substation is given as;

$$P_l - I^2R \quad (10)$$

For 3-phase line loss it becomes

$$P_l = 3I^2R \quad (11)$$

For 6-phase line loss it becomes

$$P_l = 6I^2R \quad (12)$$

Where:
R is the resistance of the transmission line in ohms per phase,
I is the current signal and
P_l represents the power losses.
The current signal can be obtained as;

$$|I| = \frac{P_{gen}}{3\, V_{gen} \cos\infty_{gen}} \quad (13)$$

Where:
P_{gen} is the generated power,
V_{gen} is the magnitude of the generated voltage (line-to-line) and
$\cos\infty_{gen}$ is the generator power factor.
Combining equations 3.2 and 3.4, we obtain the power loss for three—phase;

$$P_L = \frac{RP_{gen}^2}{V_{gen}^2 \cos\infty_{gen}} \quad (14)$$

And combining equations 3.4 and 3.3 gives the power loss for 6-phase line.

$$P_L = \frac{2RP_{gen}^2}{V_{gen}^2 \cos\infty_{gen}} \quad (15)$$

The power loss for 3-phase and 6-phase were obtained with power system analytical toolbox with results presented in chapter four.

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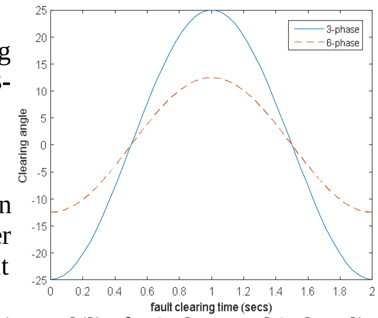
4.0 Results And Discussion

Two power system computer aided software was used to obtain the results of this study; Power System Analytical Toolbox (PSAT) and Power System Computer Aided Design (PSCAD). PSAT was utilized to simulate the transient stability performance, current reliability, voltage stability, and the load flow analysis of both 3-phase and six-phase transmission lines while power system computer aided design (PSCAD) was utilized to simulate the right-of-way of both 3-phase line and six-phase lines in terms of effect of magnetic and electric field.

4.1 Transient Stability results showed that 6-phase line had a reduced critical clearing time (CCT) of 0.97secs and critical clearing angle (CCA) of 12.47^0 as against that of 3-phase whose (CCT) is 1.32secs and (CCA) of 24.95^0, indicating that six-phase line had a better performance of fault clearing than 3-three phase despite having a higher number of fault occurrence. Figure 4.1 shows a comparative analysis of the critical clearing angle (CCA) and the critical clearing time (CCT) of the 3-phase transmission line and 6-phase transmission line. The plots in figure 4.1 indicates that the power system with the six-phase transmission line had a better performance in terms of fault clearing than the 3-three phase line despite having a higher number of fault occurrence.



4.1 Transient stability for 3-phase and 6-phase line

4.2 Current Reliability results shows the current analysis for 3-phase is 85Amps while that of 6-phase is 168.29Amps, meaning that 6-phase line can travel longer distance and is more reliable. The graph of comparative analysis of the three-phase line and six-phase line in figure 4.2 shows that the 6-phase line is more reliable because the current signal can last in longer distance than the 3-phase line.

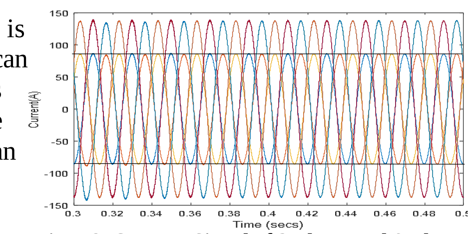
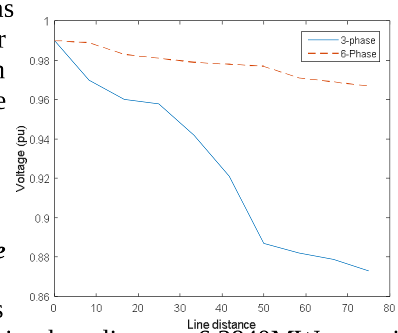


Fig. 4.2 Current Signal of 3-phase and 6-Phase

4.3 Voltage Stability showed that the receiving end voltage for 3-phase was 0.87pu as against 0.968pu for 6-phase; meaning that 6-phase line is more reliable with better power distribution ability. Figure 4.3 below shows the comparative performance in terms of voltage stability of the 3-phase line and six-phase line. It can be seen from the figure that the power system from the six-phase transmission line had a higher voltage signal received than that of the 3-phase transmission line.

__Fig. 4.3 Transmitted Voltage Signal of 3-phase and 6- Phase line__



4.4 Load Flow of 3-phase line is 147.3120MW while that of the six-phase line is 153.6160MW, showing that 6-phase line had a better performance. The power loss in six-phase line was 6.3840MW as against 12.688 MW of three-phase, showing 50% reduction of power loss on the six-phase line. Figure 4.4 below shows the comparative performance of the 3-phase and the 6-phase transmission lines. It can be seen from the figure that 6-phase line had a better performance than the 3-phase transmission line. The powers losses on 3-phase line and six-phase line are shown as a barchart in figure 4.5. the chart shows that the power loss on the six-phase transmission line was 50% less than that of the three-phase transmission line (loss in 3-phase was 12.688 MW and loss in 6-phase line was 6.3840MW).

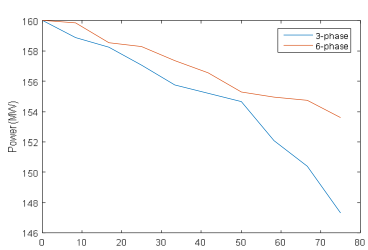


__Fig. 4.4 Quantity of Power transmitted by 3-phase &6-phase transmission line__

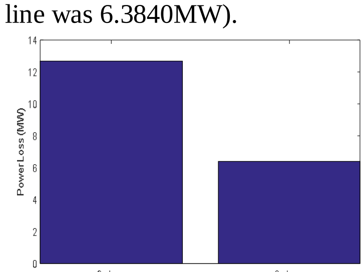


__Fig. 4.5 Power losses on 3-phase &6-phase transmission lines__

4.5 Right-of-Way - from the line tower center of the 3-phase line, the tolerable electric field was 6.735m wide and that of the 6-phase line were 5.51m wide; implying that 6-phase has reduce right-of-way from 6.735m apart (13.4700m) to 5.51m apart

(11.02m). The distance covered by the magnetic field for the 3-phase line is 16m while that of 6-phase line was 14.286m as such, the effect of the magnetic field was limited by 1.714m. Six-phase line had a better limited magnetic and electric filed effect (limited right-of-way) with improvement from 3-phase being 1.714m for magnetic field and 2.45m for electric field. The simulated electric field at 0.5m high with PSCAD and edited with MATLAB is shown in figure 4.6.

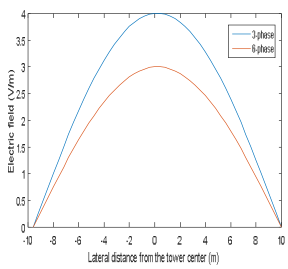


Fig.4.6 Electric field at 0.5m high

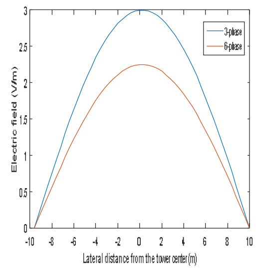


Fig.4.7 Electric field at 1m high

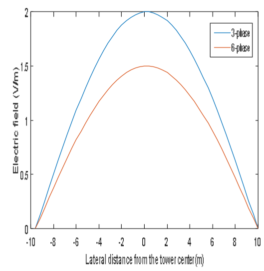


Fig.4.8 Electric field at 2m high

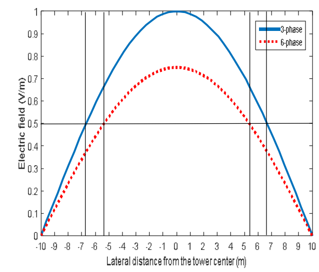


Fig. 4.9 Electric field at 2m high with right of way values.

To determine the right-of-way of 3-phase and 6-phase transmission lines, The acceptable tolerance value of the electric field was 0.5V/m (Ukhurebor,2018) and lines where inserted to indicate the right-of-way for 3-phase and six-phase lines after re-plotting with MATLAB 2015a as displayed in figure 4.9.

It can be seen from figure 4.9 that the right-of-way for the 3-phase transmission line for a tolerable electric field was 6.735m wide from the line tower center and that of the 6-phase line were 5.51m wide from the tower center. This implies that the introduction of the 6-phase will reduce the right-of-way from 6.735m apart (13.4700m) to 5.51m apart (11.02m).

The plots for the magnetic field against the lateral distance is shown in figure 4.10 to 4.13.

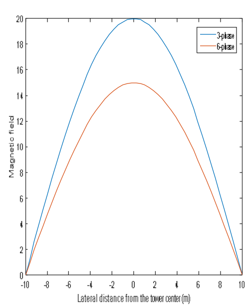


Fig.4.10 Magnetic field at 0.5m high

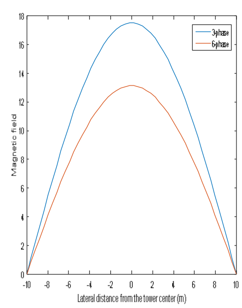


Fig.4.11 Magnetic field at1m high

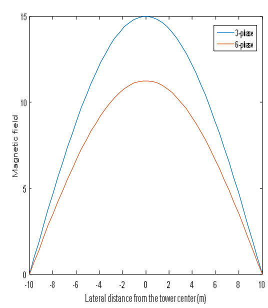


Fig.4.12 Magnetic field at 1.5m high

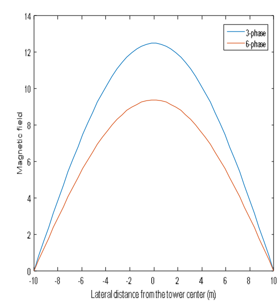


Fig. 4.13 Magnetic field at 2m high

The edited magnetic field for 2 meters high with MATLAB 2015a to determine the limited right-of-way with respect to magnetic field is shown in figure 4.14. The distance covered by the magnetic field for 3-phase transmission line is 16m. On introducing 6-phase transmission line, it can be seen from figure 4.23 that new distance covered was 14.286m as such, the effect of the magnetic field was limited by 1.714m.

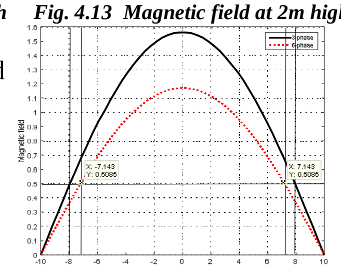


Fig. 4.14 Limited right-of-way for Magnetic field.

5.0 Conclusion

The result of the comparative analysis of the modeled six-phase transmission line with the existing 73Km, 132kV three-phase transmission line (case study) using power system analytical softwares (PSAT) and Power system computer aided design (PSCAD) showed that the 6-phase line has better outcome with reduced power loss, improved voltage and current reliability, limited right-of-way, better critical clearing time (CCT) and critical clearing angle (CCA) with better stability. It is recommended that the 73Km, 132kV transmission line that connects Ibom generation plant (source) and Afaha-Ube transmission substation (load) be replaced with 6-phase transmission line for optimum power transfer as a means of providing uninterrupted power supply with limited right-of-way.

5.1 Recommendation

Based on the limited right-of-way results presented in this study for 3-phase transmission lines and 6-phase lines, it is recommended that the case study area should be replaced with 6-phase transmission line for efficient power transmission. 6-phase transmission technique should be extended to the Nigerian 31 Bus 330kV National Grid transmission network to eradicate its frequent collapse. This will ensue that the power production and subsequent supply is available, reliable and affordable for the common good (Christie Etukudor, Ademola Abdulkareem, Olayinka Ayo, 2015).

5.2 Contribution to knowledge

The knowledge contributed as a result of embarking on this research is the determination of limited right-of-way as it relates to magnetic and electric field intensity on the 3-phase and 6-phase transmission line connected between Ibom power plant and Afaha-Ube transmission station via computer aided design.

5.3 Suggestion for further Research

The following suggestions were made for the further research.

1. **"Performance Evaluation Of 9 & 12phase Power Transmission Lines With Limited Right-Of-Way"**. The same performance evaluation done on 6phase should be extended to 9 & 12phases to see it's effect.
2. **"Fault Analysis On Six-Phase Transmission Network For Increased Fault Detection And Critical Clearing Time (CCT)".** Out of 120 types of possible fault combinations, 23 are significant faults in six-phase transmission line whereas, out of 11 types of fault combinations, 5 significant faults can occur in three-phase double circuit transmission line. Hence fault detection and CCT of six-phase is necessary.
3. "**Detailed Study On The Various Types Of Faults On Six-Phase Transmission Line**". The types of faults, its occurrence and combination in six-phase line will be known.
4. "**Six-Phase Power Transmission Line Tower Design And Optimization**". Transmission line configuration, especially on the position of transmission line conductors is necessary. More research should be conducted on optimizing towers of six-phase transmission lines.

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