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THE BEHAVIOURAL CHANGE OF DISTRIBUTION NETWORKS WITH INCREASING CIRCUIT LENGTH AND LOAD

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ABSTRACT

Purpose: This study investigated the behavioural change of distribution networks with increasing circuit length and load.

Design/Methodology/Approach: This study employed a simulation-based experimental design using OpenDSS to model and analyse the behaviour of the distribution network under different scenarios. A combination of varying network lengths and loading levels was chosen to determine the behavioural changes of a network. A total of 100 simulations were conducted, representing 10 different circuit lengths and 10 different loading conditions. Data collection on voltage levels at various points along the circuit, focusing on the voltage at the end of the circuit was carried out. Each scenario will be modelled and analysed to study the voltage drop and stability. The simulation results were validated by comparing them with theoretical calculations and real-world measurements from similar networks.

Findings: It has been shown that, for every circuit length there is a maximum load that will result in a linear relationship maintaining the correct energy balance to respond to voltage regulation and power flow. With circuit length increase, capacitive reactance reduces while resistance and inductive reactance increase leading to a more inductive circuit.

Research Limitation/Implications: The research considered only changes in circuit length and loading as it was based on a simplified source-load equivalent circuit.

Practical implication: It draws the attention of practising engineers and designers to be mindful of the implications of load increase and network expansions on system characteristics. It forms a guide to the limit a circuit could be extended or loaded if system balance is to be maintained.

Social Implication: A stable and reliable power supply supports economic growth, public health, and safety, leading to improved quality of life. Ensuring all communities have reliable electricity fosters social equity and inclusion, promoting fairness and improving the quality of life for disadvantaged groups.

Originality/Value: The novelty of this research lies in its comprehensive, realistic, and advanced approach to studying the behavioural changes in distribution networks with increasing circuit length and load. By addressing previously overlooked aspects and integrating modern computational and data analysis techniques, the study provides valuable new insights that can significantly improve the design, operation, and management of long distribution networks.

Keywords: *Circuit length. current. reactance. resistance. voltage*

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INTRODUCTION

The parameters of a distribution line that determines the characteristic of the network are largely dependent on the construction features (Alihodzic, Mujezinovic, Turajlic, & Dautbasic, 2022; Lu, Lang, Yang, Li, & Geng, 2023). The spatial arrangement does have some influence on per-phase voltage variation between phases. This is as a result of the difference in inductance and capacitance-induced parameters thus, phase conductor to ground distance, spacing between conductors of different phases and spatial orientation of phase conductors. These parameters are also proportional to the length of the circuit, the inductance 'L' and the capacitance 'C'.

Considering their electrical significance which is expressed as inductive and capacitive reactance, it is obvious that the effect of circuit length is not the same for both parameters thus, inductive reactance 'X_L' increases with an increase in circuit length while capacitive reactance 'X_C' decreases.

Recognising that inductive and capacitive reactance are responsible for the magnetic field and electric field respectively, it is imperative to investigate the characteristics of the network concerning the circuit length (Parsa Sirat & Parkhideh, 2023).

Voltage imbalance is defined, calculated and interpreted in various ways, it is defined as the ratio of the negative or zero sequence component to the positive sequence (Kini et al., 2007).

It is also defined as the ratio of the maximum deviation of the average of the three-phase voltages or currents to the average of the three-phase or current, expressed in percentage (Singh et al., 2007; Garcia et al., 2009).

Due to the effect of imbalance, ANSI standard requires that electric supply systems should be designed and operated at no-load condition with a voltage imbalance of not more than 3%. (Ciontea & Iov, 2021) concludes that the most widely used and recommended measure of voltage unbalance in the network is that of the ratio of the negative and positive sequence voltages which is expressed as (Gul 2008).

$$\%VUR = \frac{V_2}{V_1} * 100 \qquad (1)$$

Similarly, it can be expressed in terms of negative and positive sequence currents ratio or its percentage. Ideally, the ratio should be 1.3% or less, but normally 2% is acceptable (Rafi et al., 2020).

In developing countries, governments are busily expanding supply to the citizenry without taken note of the uncontrolled lengths of distribution feeders, especially the rural ones. This creates a serious challenge when it comes to voltage regulation and balancing. To investigate the issue, an equivalent 11KV rural feeder represented by a source, an overhead line and a load is modelled under graduated loading levels as a percentage of actual load and circuit length. Modelling is done in OpenDSS simulation software.

THEORIES UNDERPINNING THE STUDY

Voltage Drop and Regulation Theory

Voltage drop is considered one of the main issues relating to power quality users experience especially in the low voltage distribution network, (Zimann et al., 2019). Wires carrying current always have inherent resistance, or impedance, to current flow. Voltage drop is therefore defined as the amount of voltage loss that occurs through all or part of a circuit due to impedance (Zhu et al., 2020).

Kirchhoff's voltage law (KVL) is the algebraic sum of the voltage drops around a closed path that is zero (Sundararajan, 2020). Kirchhoff's voltage law (KVL) follows the more general physical principle that potential differences along a closed path in any conservative energy field must sum to zero.

Ohm's law also states that the current flowing through a conductor is equal to the ratio of the voltage applied across it and the resistance of the conductor (Raczynski, 2023).

Similar to voltage drop power losses is the difference between the input power and the power received at the customer end. Mathematically, it is expressed as:

$$Power\ Loss\ (P) = Inputpower - Outputpower = I^2R = IV = \frac{V^2}{R} \qquad (2)$$

Voltage drops and regulation theory is fundamental in electrical engineering, particularly for the design and analysis of power systems. Despite its robust foundation, existing models often do not account for all the variables affecting voltage drop over extensive circuit lengths, especially under dynamic loading conditions and there is a lack of effective strategies for reactive power compensation tailored to long distribution circuits, this requires further research or improved understanding.

Behavioural Theories

Behavioural theories in the context of distribution networks with increasing circuit length and load focus on understanding how various elements of the network interact and affect overall performance. These theories examine the behaviour of electrical parameters, network components, and their interdependencies under different conditions. Here are some key behavioural theories relevant to this context:

Load Flow Theory: Shows how increased circuit length and load can lead to higher losses and voltage drops, requiring more robust voltage regulation strategies (Visser et al., 2022). Existing load flow models may not fully capture the unique challenges posed by long distribution circuits, such as increased line losses and voltage drops.

Voltage Stability Theory: Highlights the risk of voltage collapse in long distribution networks, especially under high load conditions, necessitating effective voltage regulation mechanisms

(Adetokun et al., 2020). Traditional voltage stability analysis does not adequately incorporate real-time monitoring and control capabilities.

Power Quality Theory: Demonstrates the need for harmonic filters and other power quality improvement measures in long distribution networks to ensure stable voltage and reliable power delivery. The amount of power loss is dependent on the values of the current flowing and the voltage drop. Since the resistive value determines the current flow for any given voltage drop, any intervention to reduce R will lead to reduction in power loss (van der Horst et al., 2023). Resistance is a result of the characteristics of the material used, the cross-sectional area and the length. Because there are standard conductors, material and cross-sectional area could be considered as fixed hence, only length can be controlled. Ray (2023) revealed that to reduce power loss, the distance of the current flow could be shortened by bringing alternative sources closer to the customer.

NETWORK MODELLING PARAMETERS

For most of the rural feeders, circuit lengths between the source and the load located at the furthest distance are more than 80km therefore, a medium representation of the circuit could be used (García & Inga, 2023). The dependence of resistance, inductance and capacitance of circuit length are expressed as:

The total circuit resistance is expressed as; $R = \frac{\rho l}{A} \; = rl$ (3)

Where, ρ is the resistivity of the material used for the conductor. l is the length of the segment of the conductor, A is the cross-sectional area of the conductor and r is the per unit length resistance.

The inductance and capacitance are expressed as

$$L = 2 * 10^{-7} In\left(\frac{GMD}{GMR}\right) H/m \tag{4}$$

$$C = \frac{2\pi\varepsilon}{In\left(\frac{GMD}{r}\right)} F/m \tag{5}$$

Where ε is the permittivity, GMD is the geometric mean diameter, GMR is the geometric mean radius and r is the radius of the conductor.

The effect of inductance on the performance of an electrical circuit is expressed as;

$$X_L = 2\pi \mathrm{fL}l \;=\; X_L' l \tag{6}$$

$$X_C = \frac{1}{2\pi \mathrm{fC}l} = \; {X_C'}/{l} \tag{7}$$

Where, $X_L'\; and\; X_C'$ is per unit reactance, C and L are per unit capacitance and inductance respectively, l is the total circuit length and f is the system frequency.

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Therefore, considering a volt-drop expressed as;

$$\Delta V = \frac{RP + XQ}{V}$$

Then having

$$X = X_L + X_C$$

$$\Delta V = \frac{RP+XQ}{V} = \frac{rlP+\left(X'_L l - {X'_C}/{l}\right)Q}{V} \tag{8}$$

From equations (3), (6) and (7), it can be said that resistance and inductive reactance increase with a proportional increase in circuit length while capacitive reactance reduces with an increase in circuit length. The relationship is such that resistance and inductive reactance remains proportional to circuit length as capacitive reactance diminishes with a parabolic relation with increase in circuit length. The reduction in capacitive reactance could be zoned into three as represented in Figure 1 with the following characteristics.

Zone 1: Fast linear reduction rate

Zone 2: Reduction with parabolic nature

Zone 3: Slow linear reduction rate

It is therefore evident that as the length of the circuit increases, the capacitive reactance of the line approaches zero which means that energy storage of the circuit will be weaker while the magnetic characteristics of the line strengthen that opposing current flow.

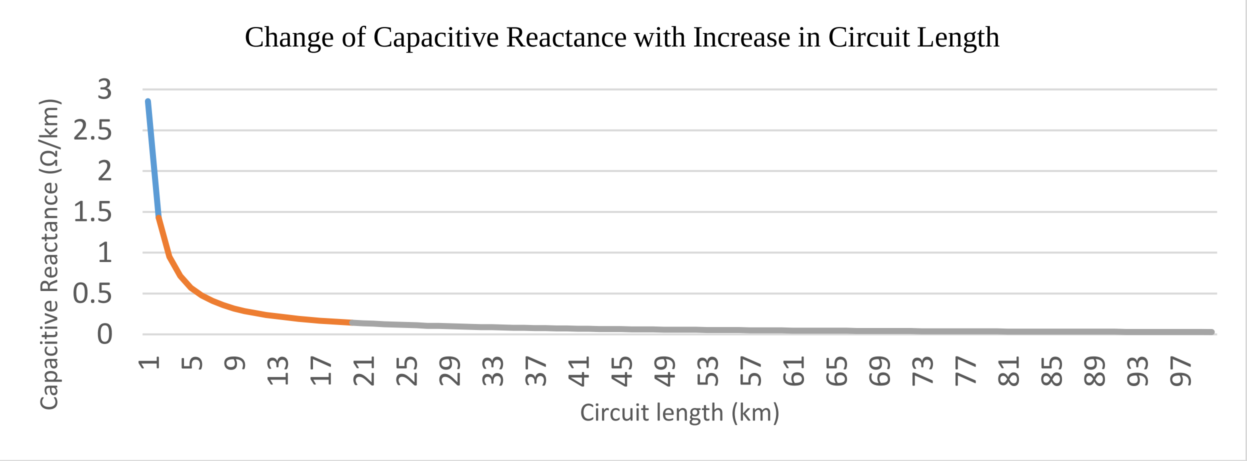

Figure 1: Change of Capacitive Reactance with Increase in Circuit Length

Considering that the total impedance of the line is expressed as:

$$Z = \sqrt{\left(R + j(X_L - X_C)\right)} = \sqrt{(R + jX)} \qquad (9)$$

and also having $R \ll X,$ the total impedance will exhibit a three-zone characteristic.

NETWORK REDUCTION

A typical rural feeder is made up of a main branch and some first-level, second-level, third- level and so on sub-branches. This type of network could be equivalent to a source-load type of network where the connected load at the end of the line will be the equivalent lump load L_L of the original network. The length of line is also the equivalent circuit length l_{eq} with correspondent R_{eq}, X_L, and B_L, as shown in Figure 2.

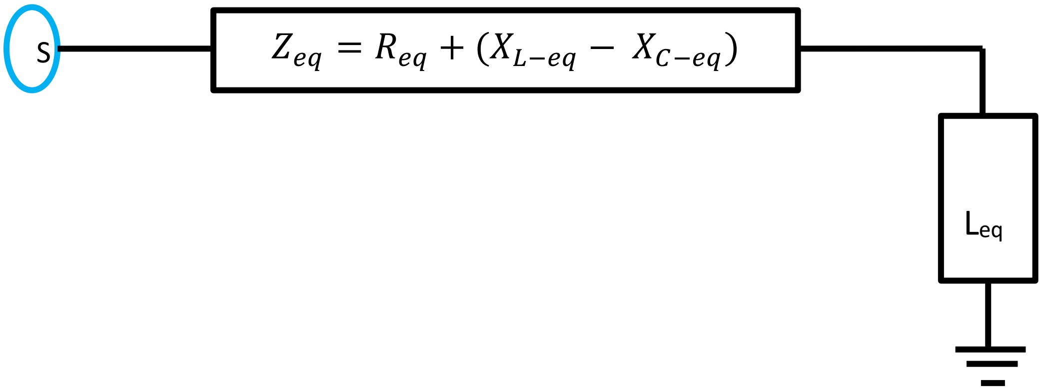

Figure 2: Equivalent of a Rural Distribution Feeder

To arrive at the equivalent circuit of Figure 2, several circuit reduction methods are given in the literature of which some are used (Shimada et al., 2000; Thant, 2008; Rodrigues et al., 2020).

The philosophy behind each method is dependent of the purpose for which circuit reduction is required. For a circuit to be a true equivalent of an existing one, flows to and through the retained buses and their voltages should be equal to those of the existing network associated with the same buses.

METHODOLOGY

This study employs a simulation-based experimental design using OpenDSS to model and analyse the behaviour of the distribution network under different scenarios. A combination of varying network lengths and loading levels was chosen to determine the behavioural changes of a network. The network is made up of an 11KV source, an overhead line of 120sqmm bare aluminium conductor of length ranging between 10km to 100km. A total of 100 simulations were conducted, representing 10 different circuit lengths and 10 different loading conditions. Whiles the ten modules stand for different loading starting from 480KVA to 4800KVA at steps of 480KVA. Data collection on voltage levels at various points along the circuit, focusing on the voltage at the end of the circuit was carried out. Each scenario will be modelled and analysed to study the voltage drop and stability. The module is modelled using OpenDSS software for different scenarios. Voltages, currents and losses were extracted from the simulation results and analysed. The simulation results were validated by comparing them with theoretical calculations and real-world measurements from similar networks.

RESULTS AND DISCUSSION

For a system to maintain some level of consistency concerning characteristics, there should be some degree of linearity in the relationship of its parameters. Whenever there is a deviation in linearity it signifies a change in system characteristics.

Voltage Profile

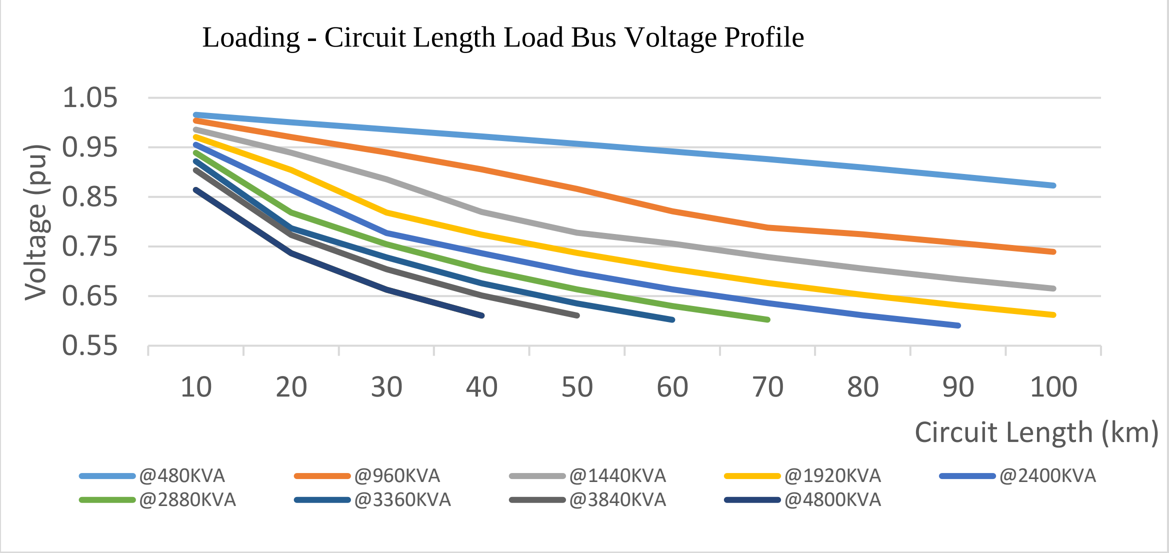

Figure 3: Load Bus Voltage Profile at Various Loading levels and Circuit lengths

From Figure 3, it can be seen that at low loading voltage drop seems to have some level of proportionality with circuit length, the finding is in agreement with Lai, et al. (2021) who disclosed that the change in linearity confirms the nature of the linearity of capacitive reactance concerning circuit length. Also as load increases and circuit length also increases there appear to be three zones of linearity that are the characteristics of the network changes with a combination of load and circuit length. The load leads to a reduction in voltage.

Line KW Losses

Active power losses associated with each circuit length and loading are shown in Figure 4. From this graph of Figure 4, it is evident that a similar characteristic change is exhibited by the network with the point of change of circuit behaviour being at the same circuit length and loading, this is also corroborated by Hua et al. (2021) noted that the power loss is proportional to both voltage and current, therefore as voltage decrease is less than the current increase, the resultant will be an increase in power loss with increase in both voltage drop and current flow. Also, the behavioural effect of the changes in capacitive reactance will feature in the behaviour of the power loss variation as evident in Figure 4.

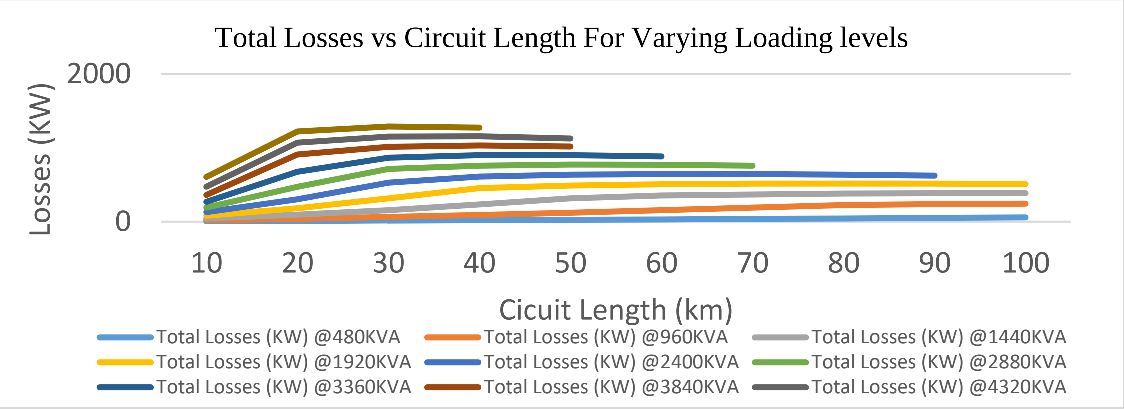

Figure 4: Total KW losses @ Various Loading levels and Circuit lengths

Served load

From Figure 5, it is shown that at a lower loading level, there seems to be higher circuit performance in that all the loads connected are served. On the other hand, if loading increases, there is a sharp decline in circuit performance. This is in alignment with Vliex (2021) revealed that as load increases, voltage drops and power loss increases hence, resulting in less power served and low voltage at the customers' end. It should be also noticed that the same three segmented characteristic zones are exhibited and the changing points are the same as mentioned earlier.

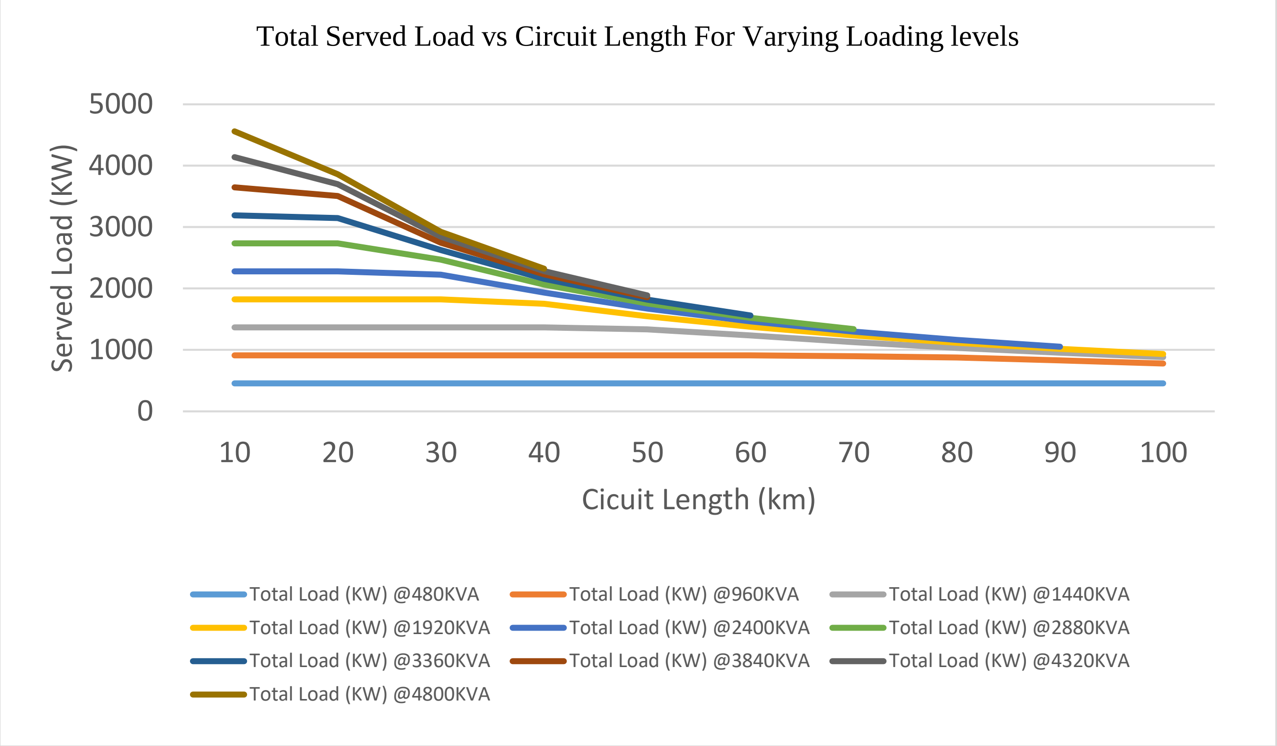

Figure 5: Total Served Load vs Circuit Length for Varying Loading Levels

System Imbalance

Although the circuit is made up of the same conductor in terms of material and size and also having a three-phase balanced load connected, there is still some level of imbalance in the results.

This could be associated with the geometry of the line concerning phase conductor location and its relation with other phase conductors and the earth. From Figure 6, it could be stated that with short circuit length, the percentage imbalance is small and also changes gradually with increase in circuit length. The finding agrees with Das et al. (2021) that noted that a suitable logic control is essential for this equalizer, especially to avoid short circuits. This could be attributed to the increase in capacitive area hence greater capacitive reactance which is not shared equally among the phases.

On the other hand, with an increase in load and for the same circuit length percentage imbalance sharply increases. Again, it is obvious that the points of change in characteristics of the circuit at different loading and circuit lengths are also the same as in other relationships. This can also be attributed to the fact that due to imbalance voltage as a result of unequal capacitive reactance, the current drawn per phase will not be equal and leads to further distortion of the three-phase system.

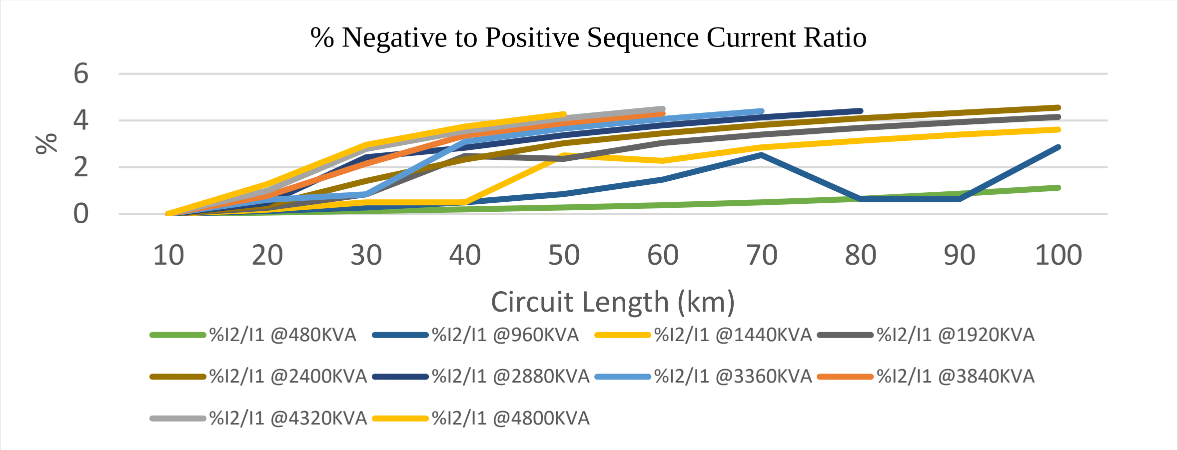

Figure 6: % Negative to Positive Sequence Current Ratio

Looking at the graph of Figure 7, it is clear that the relationship or ratio between the zero and positive sequence currents becomes larger as the load and current increase and follow the same characteristic change.

This means that for long lines, as the load increases there is associated deformation of the sine wave and also a zero-point displacement.

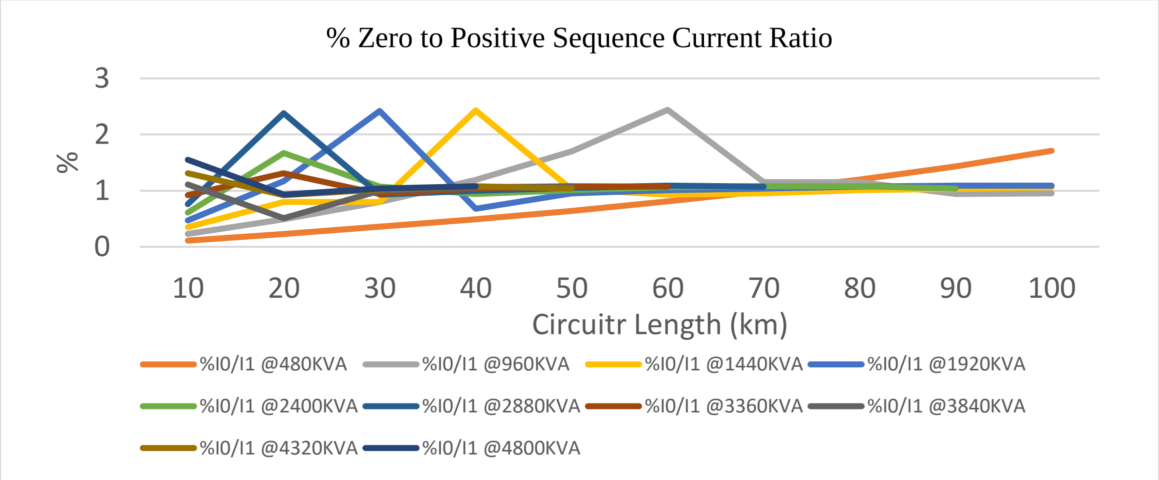

Figure 7: % Zero to Positive Sequence Current Ratio

Load Currents

From figure 8, it could be seen that the average phase load current of the connected three phase balanced load gradually increases with load increase but peaks at a point depending on the circuit length and the capacity of the load connected. It is also evident that the higher the load the shorter the circuit length that will result in peaking. Similarly to all the discussion made, there exist three characteristic zones which coincide with that of the others.

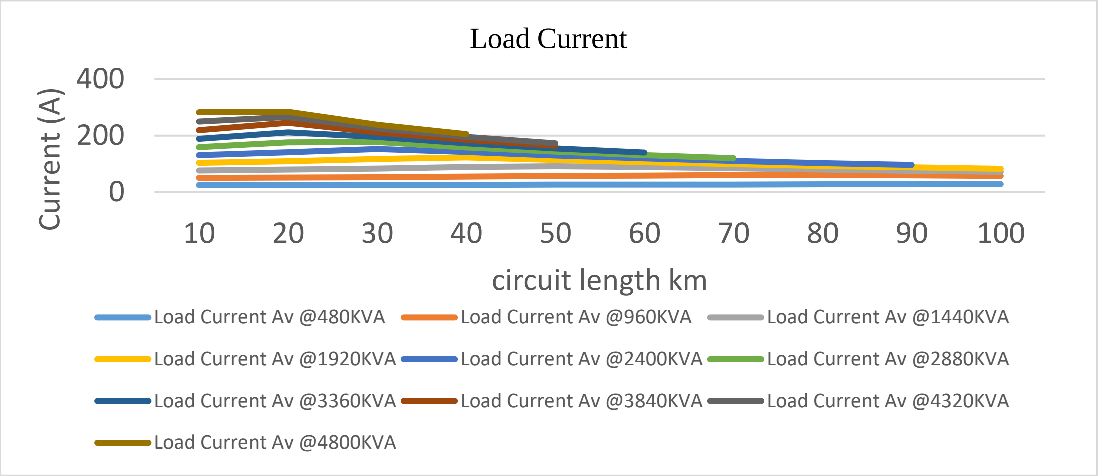

Figure 8: Load Current at Various Loading and Circuit Lengths

CONCLUSION

In this work the behaviour of network to changes in circuit lengths and load has been investigated. A conceptual equivalent circuit was used as the investigating network, and the network was modelled in OpenDSS for various scenarios. Circuit length ranging between 10km to 100 km was used and for each length load ranging from 480KVA to 4800KVA at intervals of 480KVA. The results obtained for voltage profile, load currents, system imbalance, line KW losses and served load indicate that for each loading, there is a maximum circuit length that will ensure the effective performance of the network.

The behaviour of the change in all the measured parameters follows the three zonal behavioural change in inductive reactance with a change in circuit length.

Going beyond the required loading level or over-extending the network too far, the electro-magnetic and electrostatic structure of the network deviates from the norm where the magnetic field increases while the electrostatic field far depreciates resulting in uncontrollable voltage collapse.

Practical implication

It draws the attention of practising engineers and designers to be mindful of the implications of load increase and network expansions on system characteristics. It forms a guide to the limit a circuit could be extended or loaded if system balance is to be maintained.

Social Implication

A stable and reliable power supply supports economic growth, public health, and safety, leading to improved quality of life. Ensuring all communities have reliable electricity fosters social equity and inclusion, promoting fairness and improving the quality of life for disadvantaged groups.

The novelty of this research lies in its comprehensive, realistic, and advanced approach to studying the behavioural changes in distribution networks with increasing circuit length and load. By addressing previously overlooked aspects and integrating modern computational and data analysis techniques, the study provides valuable new insights that can significantly improve the design, operation, and management of long distribution networks.

It is recommended that further investigation is made to ascertain the relationship between circuit length and its loading level that will respond linearly to reactive current compensation for voltage improvement and reduction in technical losses.

REFERENCES

Adetokun, B. B., Muriithi, C. M., & Ojo, J. O. (2020). Voltage stability assessment and enhancement of the power grid with increasing wind energy penetration. *International Journal of Electrical Power & Energy Systems*, *120*, 105988.

Alihodzic, A., Mujezinovic, A., Turajlic, E., & Dautbasic, N. (2022, June). Calculation of the Electric Field Intensity and Magnetic Flux Density Generated by High Voltage Overhead Transmission Lines. In *2022 XXVIII International Conference on Information, Communication and Automation Technologies (ICAT)* (pp. 1-6).

Ciontea, C. I., & Iov, F. (2021). A study of load imbalance influence on power quality assessment for distribution networks. *Electricity*, *2*(1), 77-90.

Das, U. K., Shrivastava, P., Tey, K. S., Idris, M. Y. I. B., Mekhilef, S., Jamei, E., ... & Stojcevski, A. (2020). Advancement of lithium-ion battery cells voltage equalization techniques: A review. Renewable and Sustainable Energy Reviews, 134, 110227.

García, J., & Inga, E. (2023). Georeferenced rural distribution network model considering scalable growth of users in rural areas. *Heliyon*, *9*(1).

Garcia, D. C., Anésio Filho, L. F., Oliveira, M. A., Fernandes, O. A., & do Nascimento, F. A. (2009). Voltage unbalance numerical evaluation and minimization. *Electric Power Systems Research*, *79*(10), 1441-1445.

Gul, O. (2008). An Assessment of Power Quality and Electricity Consumer’s Rights in Restructured Electricity Market in Turkey. *Electrical Power Quality and Utilisation. Journal*, *14*(2), 29-34.

Hua, X., Zhang, C., & Offer, G. (2021). Finding a better fit for lithium ion batteries: A simple, novel, load-dependent, modified equivalent circuit model and parameterization method. Journal of Power Sources, 484, 229117.

Kini, P. G., Bansal, R. C., & Aithal, R. S. (2007). A novel approach toward interpretation and application of voltage unbalance factor. *IEEE transactions on industrial electronics*, *54*(4), 2315-2322.

Lai, X., Jin, C., Yi, W., Han, X., Feng, X., Zheng, Y., & Ouyang, M. (2021). Mechanism, modeling, detection, and prevention of the internal short circuit in lithium-ion batteries: Recent advances and perspectives. Energy Storage Materials, 35, 470-499.

Lu, D., Lang, X., Yang, B., Li, Z., & Geng, H. (2023). Conductor Arrangement and Phase Sequence Optimization Scheme for 500 kV Four-Circuit Transmission Lines on Same Tower. *Energy Engineering*, *120*(10), 2287-2306.

Parsa Sirat, A., & Parkhideh, B. (2023). Current Sensor Integration Issues with Wide-Bandgap Power Converters. *Sensors*, *23*(14), 6481.

Raczynski, S. (2023). Electric Circuits and Devices. In *How Circuits Work: Amplifiers, Filters, Audio and Control Electronics* (pp. 1-24). Cham: Springer Nature Switzerland.

Rafi, F. H. M., Hossain, M. J., Rahman, M. S., & Taghizadeh, S. (2020). An overview of unbalanced compensation techniques using power electronic converters for active distribution systems with renewable generation. *Renewable and Sustainable Energy Reviews*, *125*, 109812.

Ray, S., Kasturi, K., Patnaik, S., & Nayak, M. R. (2023). Review of electric vehicles integration impacts in distribution networks: Placement, charging/discharging strategies, objectives and optimisation models. *Journal of Energy Storage*, *72*, 108672.

Rodrigues, R., Du, Y., Antoniazzi, A., & Cairoli, P. (2020). A review of solid-state circuit breakers. IEEE Transactions on Power Electronics, 36(1), 364-377.

Shimada, T., Agematsu, S., Shoji, T., Funabashi, T., Otoguro, H., & Ametani, A. (2000, July). Combining power system load models at a busbar. In *2000 Power Engineering Society Summer Meeting (Cat. No. 00CH37134)* (Vol. 1, pp. 383-388). IEEE.

Singh, A. K., Singh, G. K., & Mitra, R. (2007, September). Some observations on definitions of voltage unbalance. In *2007 39th North American Power Symposium* (pp. 473-479). IEEE.

Sundararajan, D. (2020). *Introductory circuit theory*. Cham, Switzerland: Springer.

Thant, A. P. (2008). Steady State Network Equivalents for Large Electrical Power System. *Polytechnic University*.

van der Horst, K., Diab, I., Mouli, G. R. C., & Bauer, P. (2023). Methods for increasing the potential of integration of EV chargers into the DC catenary of electric transport grids: A trolleygrid case study. *eTransportation*, *18*, 100271.

Visser, L. R., Schuurmans, E. M. B., AlSkaif, T. A., Fidder, H. A., Van Voorden, A. M., & Van Sark, W. G. J. H. M. (2022). Regulation strategies for mitigating voltage fluctuations induced by photovoltaic solar systems in an urban low voltage grid. *International Journal of Electrical Power & Energy Systems*, *137*, 107695.

Vliex, P. N. (2021). Modelling, implementation and characterization of an Bias-DAC in CMOS as a building block for scalable cryogenic control electronics for future quantum computers (Doctoral dissertation, Dissertation, RWTH Aachen University, 2021).

Zhu, J., Darma, M. S. D., Knapp, M., Sørensen, D. R., Heere, M., Fang, Q., ... & Ehrenberg, H. (2020). Investigation of lithium-ion battery degradation mechanisms by combining differential voltage analysis and alternating current impedance. *Journal of Power Sources*, *448*, 227575.

Zimann, F. J., Batschauer, A. L., Mezaroba, M., & Neves, F. A. (2019). Energy storage system control algorithm for voltage regulation with active and reactive power injection in low-voltage distribution network. *Electric Power Systems Research*, *174*, 105825.