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Low Voltage Distribution Network Simulation and Analysis for Electric Vehicle and Renewable Energy Integration

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***Abstract*—The continued dependence on fossil fuels which no doubts have negatively impacted on the climate has acted as a catalyst for the increasing deployment of distributed energy resources (DER). For most countries, the existing electricity structure was not designed to meet the increased deployment of renewable energy (RE), electric vehicles (EVs), hence the need for restructuring. Determining the existing operating conditions of a feeder and predicting the short, medium, and long-term scenarios is critical for the planning of distribution network (DN) expansion. Around the world, various timelines have been set for transitioning from high carbon emission conventionally fuelled vehicles to EVs. A typical Nigerian distribution network was modelled and the effect of implementing ultra-low carbon emission EVs in different parts of the network was studied. A PSCAD/EMTDC simulation tool was used to examine the operating conditions of distribution network parameters. Simulation cases show that EV fleet and their chargers can be integrated into the DN during minimum loading conditions but with local voltage control measures. The results of this study could be useful to both the electricity system operators and policy makers in planning future grid expansion projects.**

***Keywords*—Distributed Generation, Distribution Network, Electric Vehicle Integration, PSCAD/EMTDC**

I. INTRODUCTION

The average consumption of energy and electricity for transportation and domestic purposes are growing rapidly with an ever-rising increase in worldwide population. The concern of increased environmental pollution in the transport sector has led to growing interests towards the electrification of the sector. Recent figures show that the transportation sector is responsible for 25% and 20% of the global greenhouse gas emissions and global primary energy consumption, respectively [1], [2].

Nigeria with a population of about 200 million is one of the countries in Africa with the highest number of vehicles on roads. The Nigeria Bureau of Statistics [3] report shows that as at the second quarter of 2018, Nigeria had a vehicle population of 11,760,871 and the estimated vehicle per population ratio was 0.06. This is because road transportation is the most predominant means of transportation in the country and on the average consumes 90% of the energy used by the transport sector in Nigeria [4]. As noted in [12], the Nigerian transport sector energy consumption showed an increase at a Compound Annual Growth Rate (CAGR) of 3.68%, from 166 PJ in 1990 to about 368 PJ in 2012.

According to [5], the country's transport sector is mainly dominated by gasoline and diesel. With the increasing population vis-à-vis the vehicle per population ratio, the increase in fossil fuel demand is bound to grow leading to a resultant rise in the CO_2 and other related emissions. Although there are policies which aim at transitioning the nation's transport sector by the implementation of energy efficient and environmentally friendly technologies [6], specific timelines are yet to be assigned. However, developing such policies without duly considering the effects such transitioning would have on the energy system makes it worrisome.

A recent study on the sustainable energy pathways for land transport in Nigeria conducted by [7] deposited that achieving energy sustainability in Nigeria's transport sector requires structural and demand-side policies that would be capable of supporting technological innovations for improved fuel economy and alternative fuel development. Such structural policies and reduction in CO2 emission in the transport sector can only be achieved by transportation through electrification.

To reduce the over dependence on fossil fuels, as well as CO_2 emission, some countries are beginning to gradually decarbonize. In the transport sector, governments of different countries have introduced ultra-low carbon emission EVs. According to [8], the smooth and successful transition to EV technology could save up to 2.5 tons of carbon dioxide annually. The operation of EVs would also facilitate the formation of smarter grids by taking part in demand response programs and serving as controllable loads or storage systems to enable the integration of RE storage systems into DN and grids [9].

Despite the potential benefits of EV technology to both the people and the grid, the development of the EV industry in Nigeria is currently slow and the policies are at infancy stage. Also, there are some political concerns like the decline of accent by the President to the Nigerian Automotive Industry Development Plan (NAIDP) [13] and the rejection of a bill seeking the ban on the use of petrol vehicles by 2035 by the Nigerian senate. However, regardless of the challenges, efforts by both private individuals and foreign firms are on-going to enable the expansion of the EV market in Nigeria and other African countries [14].

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Other potential challenges associated with EV technology have been succinctly discussed in [10, 11]. These includes lack of EV charging infrastructures, high upfront cost of EVs, limited capacity of existing power networks and limited driving ranges and charging options. On the other hand, DN may be overloaded or congested at peak times resulting from large consumer consumption and demand, therefore, this introduces a question which this work aims to address the following question: "*Are the Nigerian electric grids capable of facilitating the integration of EVs and their sophisticated chargers, and what options are available for distribution network operators to maintain secure and safe network operation at all times*?"

To the best of the researcher's knowledge, there are currently no studies that have critically assessed the Nigerian LV network for DG and EV integration. The analysis in this paper is intended to fill this knowledge gap and aid in the development of an EV charging strategy which would enhance the DN resilience as well as minimise the charging time.

The main contribution of this paper is that a practical Nigerian distribution network is modelled, and the challenges introduced following the connection of different EV types are analysed. Small-scale wind turbines are modelled and implemented as distributed generation (DG) units with the intention to facilitate the connection of EVs during times when the network is heavily congested.

II. SYSTEM MODELLING

A. Network Modelling

The distribution network (see Fig. 1) is modelled using the network parameters from Kano central region, in Nigeria, using PSCAD/EMTDC.

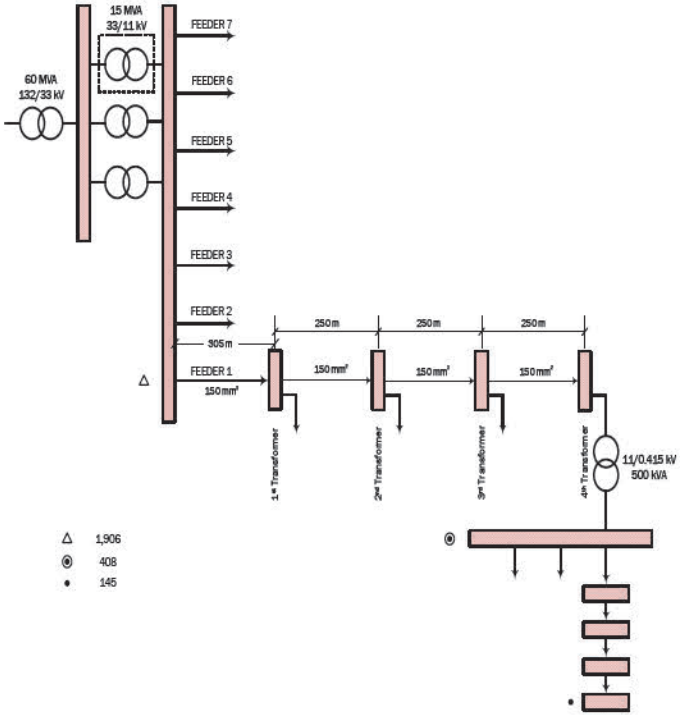

Fig. 1: Model of a typical low voltage (LV) DN in Nigeria

The model was built with the intention of performing some dynamic analysis. The club 33/11KV distribution injection substation receives supply from 132/33kV Dan Agundi transmission feeder. The distribution network has 7*11kV feeders which serve Kano central region namely, feeder 1 to feeder 7 with the actual feeder names anonymised at the point of data collection. This involves 35km of overhead conductors. Feeder 1(the test feeder) has a total of about 1,908 connected consumers with overhead lines stretch of up to about 1,055m.

B. LV Network Description

The 4th transformer 11/0.415kV, 500kVA transformer substation is one of the four substations being fed by the 11kV feeder 1. The LV supply is distributed in a radial manner through the three overhead up-riser lines to the different consumers. The substation has a total of about 408 connected consumers and the distance between each LV pole span is 45m on the average. The simplified nodal diagram of one arm of the LV network feeder under consideration indicating some of the highlighted parameters is shown in Fig. 2.

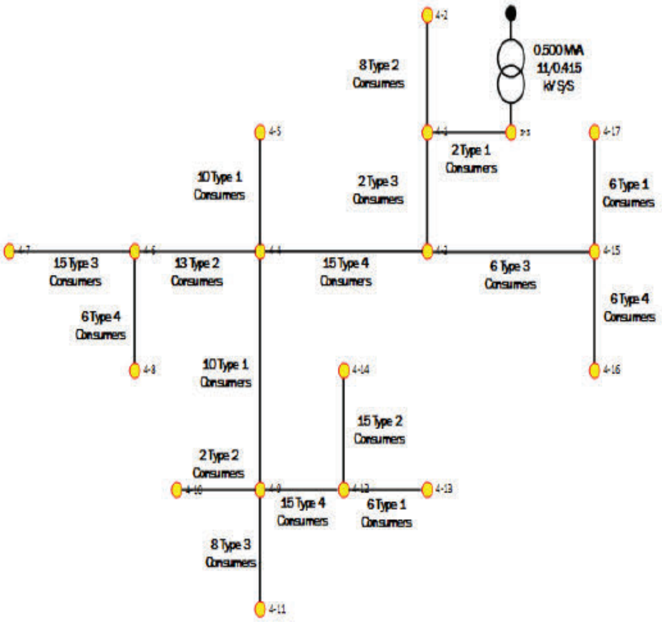

Fig. 2: Nodal representation of an arm of the studied LV network

The selected arm of the LV network from Fig. 2 is labelled from node 4-1 to 4-17, where 4-1 represents A and 4-17 represents Q. The various nodes have different numbers of consumers with varying load profiles. Different consumers were classified into different housing types namely: type 1 to type 4.

The loads were modelled using the 'lumped load model'. Each lumped load or group of consumers was modelled as a fixed PQ load due to the unavailability of the hourly load profile of the various consumers. In this method, a lumped load placed at the end of the line is considered while the exact equivalent demand for lumped loads is determined by taking into consideration a diversity factor. Using equation (1) along with relevant parameters, the equivalent lumped load demand for the various segments of the network under minimum and average loading conditions were determined, respectively.

$$PN + Q\sqrt{N} = LD \qquad (1)$$

where P, N, Q and LD represent active power, total number of consumers along a line, reactive power, and minimum and average lumped demands, respectively.

The results of the calculated equivalent lumped demand at minimum and average load is shown in Table I.

TABLE I. CALCULATED LUMPED DEMAND FOR EACH NODE

Nodes	Number of Consumers (N)	Min P & Q Avg P & Q (kW)	Min LD (kW)	Avg LD (kW)
S/S - 4.1	2	0.41 and 0.19 1.15 and 0.55	1.09	3.08
4.1- 4.2	8	0.60 and 0.29 3.15 and 1.52	5.62	29.50
4.1- 4.3	2	0.90 and 0.43 4.50 and 2.17	2.41	12.07
4.3- 4.4	15	0.90 and 0.43 5.00 and 2.42	15.17	84.37
4.4- 4.5	10	0.41 and 0.19 1.15 and 0.55	4.70	13.24
4.4- 4.6	13	0.60 and 0.29 3.15 and 1.52	8.85	46.43
4.6- 4.7	15	0.90 and 0.43 4.50 and 2.17	15.17	75.90
4.6- 4.8	6	0.90 and 0.43 5.00 and 2.42	6.45	35.93
4.4- 4.9	10	0.41 and 0.19 1.15 and 0.55	4.70	13.24
4.9- 4.10	2	0.60 and 0.29 3.15 and 1.52	1.61	8.45
4.9- 4.11	8	0.90 and 0.43 4.50 and 2.17	4.41	42.14
4.9- 4.12	15	0.90 and 0.43 5.00 and 2.42	15.16	84.37
4.12- 4.13	6	0.41 and 0.19 1.15 and 0.55	2.93	8.25
4.12- 4.14	15	0.60 and 0.29 3.15 and 1.52	10.12	53.14
4.3- 4.15	6	0.90 and 0.43 4.50 and 2.17	6.45	32.32
4.15- 4.16	6	0.90 and 0.43 5.00 and 2.42	6.45	35.49
4.15- 4.17	6	0.41 and 0.19 1.15 and 0.55	2.93	8.25

Using this method, the various customer loads were distributed amongst the lines across each feeder based on the ratio of the number of buildings per line segment and feeder, respectively. The network was modelled in PSCAD/EMTDC software.

III. RESULTS

The DN has been analysed during minimum and average loading conditions, respectively. For each of the loading condition, two different scenarios are used. In the basic scenario, the LV network is simulated using its original existing parameters. In the reinforced scenario, the network is modified and hence the impedance between each branch of the LV network was recalculated as an improvement for all the voltage profiles where the consumers are connected.

Figs. 3 and 4 illustrate how the network voltages would normally be affected when each consumer follows their daily average load profiles without introducing EVs into the network. For all scenarios and voltage results, the upper voltage limit of 1.1p.u is never reached, and thus, only the lower operating voltage limit of 0.94 is shown on the labels.

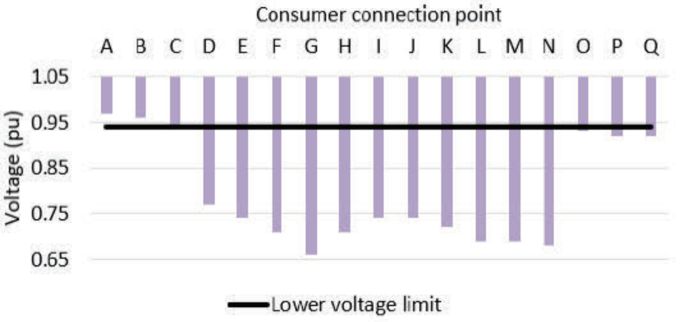

Fig. 3: Basic scenario average loading voltage profile

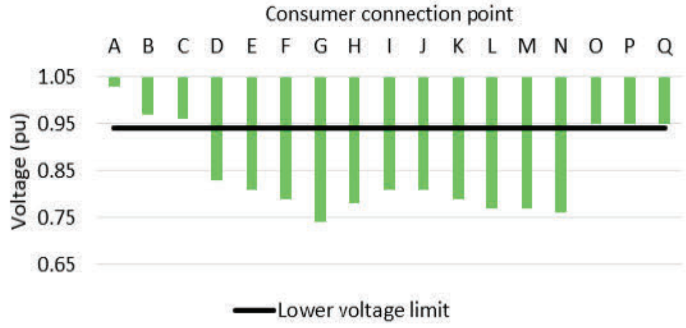

Fig. 4: Reinforced scenario average loading voltage profile

The results at average loading for both scenarios show that voltage profiles at points D to Q and D to N for basic and reinforced scenario respectively are exceeding the acceptable threshold range for this studied network. For LV network, the acceptable operating limit is within 1.1p.u (+10%) and 0.94p.u (-6%) of the declared nominal voltage. This is however typical for some of the LV networks in Nigeria due to network overloading. For instance, with the original network impedance in the LV network (see Fig. 3), the maximum voltage drop occurs at points G, L and N due to large number of consumers, and hence large consumption, and also due to the proximity of these points to the nearest 500kVA substation transformer. The 'G' point, for example, experiences a voltage drop of up to 35%; however, the results showed that the modification of cable impedances (see Fig. 4), results in a voltage improvement of up to 10% at these critical loaded points.

On the other hand, points A, B, C, O, P and Q manage to operate within the acceptable voltage limits since these are located closer to the main substation busbar where transformer is used, and possess the smallest number of consumers in the entire network with minimal consumption, as can be observed (see Fig. 2 and Table I).

Realistically, as a result insufficient power generation, most Nigerians experience long periods of outage with frequent load shedding arrangements. In view of this, the LV network is modified, with each consumer operating with minimum demand, which is a more likely scenario for a typical Nigerian case. Figs. 5 and Fig. 6 show how the same connection points are affected when each consumer has minimal demand in the LV network.

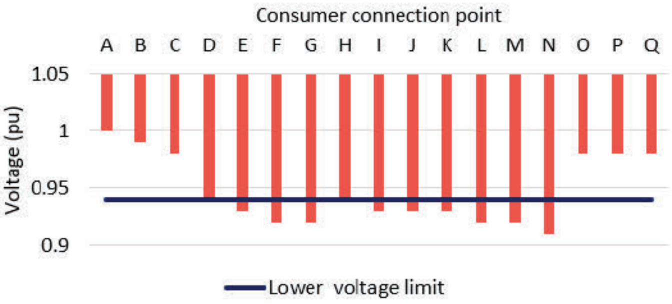

Fig. 5: Basic scenario minimum loading voltage profile

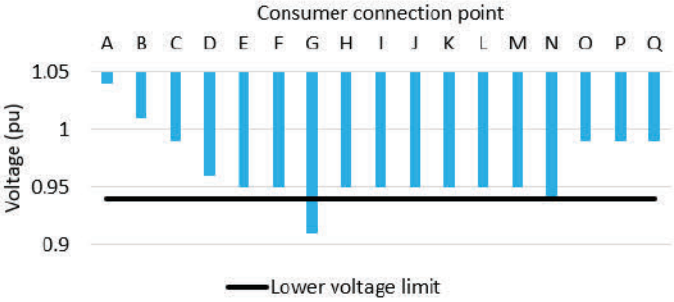

Fig. 6: Reinforced scenario minimum loading voltage profile

The results illustrate that the voltages at the LV network remained within acceptable operating voltage across most of the points, especially in the reinforced scenario. However, with the optimised cable impedances, the network shows that voltage profiles (see Fig. 6) are more stable except for point G. There is an improvement of up to 2-4% in most of the points.

In overall, the results show that with the modelling and inclusion of small-scale domestic wind turbines as a DG, local voltage control measures can be provided. Studies have shown that charging stations can be supported with small-scale wind/PV generation in the HV/MV side of the network. These DG units act as backup units to balance the generation and supply at the point of charging. However, for simplicity, this study only considers the charging of EVs, and therefore, small-scale wind turbines are used near the points of charging to provide local voltage control measures and facilitate the connection of EV and charger units near the congested and critical busbars in the LV network.

Small-scale wind turbine (Fig. 7) was modelled in PSCAD/EMTDC software based on induction machine and connected near the busbars where the EV charging units are connected. The parameters used for the simulation are based on that of an urban environment [15].

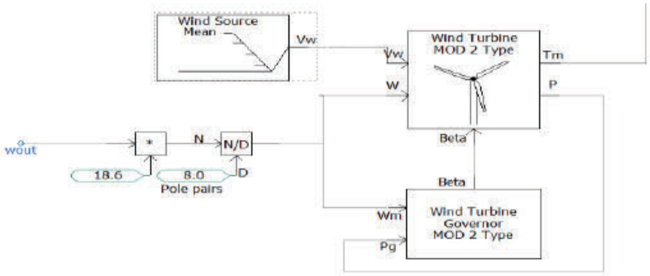

Fig. 7: Model of a small-scale domestic wind turbine using induction machine

In the next case, the LV network with the reinforced scenario is used. The feasibility of integrating a DG unit along with two different EV user types with their associated charging facilities is considered. Table II presents how the implementations of EVs are considered for the LV network.

TABLE II: ELECTRIC VEHICLE PARAMETERS USED IN THE NETWORK

Type of EV USERS	EV Type 1	EV Type 2
Type of charger	Slow speed chargers	Fast speed chargers
Charging power	10 kW at each station	50 kW at each station
Connection point	C, I, O	A and Q
EV penetration rate	30 kW	100 kW

The EV loads were also modelled as a constant PQ load in the network. As presented in Table II, two types of EV users and their associated chargers are implemented in the LV network. The first group of EV users represents people who charge their EVs using slow speed chargers at their residential outlets at points C, I and O. The second group of EV users represents business class (taxis, buses) that requires fast speed chargers due to their busy daily activities. The second groups of chargers are connected at points A and Q.

Moreover, this study assumes that at each of these connection points there are five vehicles. Thus, according to this assumption, each of the five vehicles in points C, I and O charge their vehicles at 2 kW, respectively, whereas at points A and Q the charging power per vehicle is 10 kW. Therefore, the total number and charging demand of EVs exerted due to the first group of EV users (points C, I and O) equal 15 cars and 30 kW, respectively. In addition, the total number and charging demand of EVs in the second group equal 10 cars and 100 kW, respectively. With these considerations, local voltage control measures by means of DG units are also implemented into the network near the charging stations to support and facilitate the connection of EVs and their associated chargers in the network.

The results in Figs. 8 and 9 compare the voltage profiles after the addition of two different EV user types with their chargers in the network with the proposed DGs. Points C, I and O had an additional total demand of 30 kW resulting from the charging of 15 vehicles altogether, whereas points A and Q had an additional total demand of 100 kW due to the charging of 10 vehicles simultaneously. These charging demands were exerted onto the base demand of the LV network.

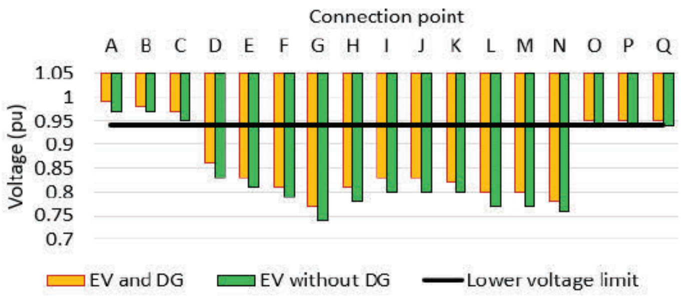

Fig. 8: Reinforced scenario average loading voltage profile with EV and DG

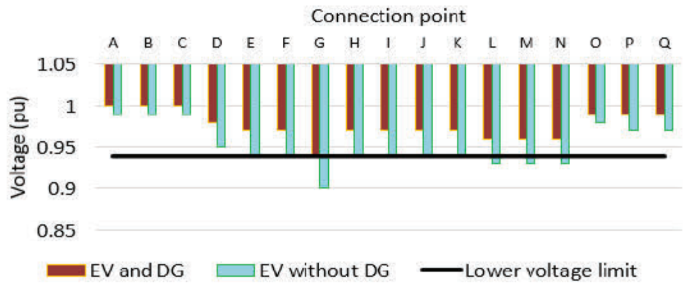

Fig. 9: Reinforced scenario minimum loading voltage profile with EV and DG

Fig. 8 shows that the implementation of EVs may not be a good idea during peak or average seasons; however, EVs can be used or charged in the network in the off-peak hours. Furthermore, the results, especially during minimum network loading, showed that EV charging stations with local DG units facilitate the connection of EVs and improve the stability of the system by keeping all busbars voltages within acceptable operating limits. The highest improvement during minimum network loading was observed at point G, where the voltage was improved by up to 4% after the connection of a 10-kW small-scale domestic wind turbine. The DG units were connected at points C, I, O, A, Q and G, with 5 of these points representing where the EVs were connected, whereas the 6th point (G) was chosen since the previous results (see Figures 4 and 6) showed high voltage violation at that point. The results showed the importance of connecting 20kW small-scale DG units at the points where the demand associated with the charging of vehicles is higher than the base network demand. Although, increasing the sizing and capacity of these wind turbines will allow for a further voltage improvement; however, this will increase the cost of the system.

IV. CONCLUSION

This paper analyses what the effect of EV deployment would have on the stability of a typical Nigerian distribution network. The paper also seeks to establish whether the existing network structures can receive EVs and their charging facilities. Besides these, the research aimed at ascertaining the state of readiness of the network for renewable and distributed energy technologies. A model of a typical distribution system in Nigeria was developed and analysed. Using the PSCAD/EMTDC software, the simulation was conducted. Two scenarios namely: the basic and reinforced scenarios were considered. Voltage profile results from both scenarios at minimum and average loading conditions indicated voltage violations at some specified nodes resulting from excessive load connection at those node points. However, with the introduction of DG units, significant improvements were observed across all nodes in the network.

Using the modified network scenario, two types of EV users with their associated charging facilities were introduced into the network. The results, especially during off-peak minimum network loading, showed that EV charging stations with DG units facilitate the connection of EVs and improve the stability of the system by keeping voltages within acceptable limit. Overall, it is hoped that the findings from this study would be useful to both the policy makers and network operators in Nigeria and other countries with similar network structure.

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