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Integrating Electric Vehicles into Electric Power Network

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ABSTRACT
Integrating electric vehicles (EVs) into the power grid will presents numerous opportunities and challenges. A high electric vehicles (EV) uptake may contribute to the reduction of CO2 emissions, but it could presents distribution network operators (DNOs) with a number of challenges. This paper present these challenges such as transformer and feeder loading, power quality and voltage unbalance that could hinder effective integration of electric vehicles. Possible solutions are suggested to address these challenges. A case study that investigates the impact of EVs charging on the network was studied to determine the capacity of three different networks to accommodate EVs charging without violating the permissible network voltage limit.

Keywords: *electric vehicles (EVs), smart charging, grid to vehicle, plug-in electric vehicles, renewable energy*

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I. INTRODUCTION

The development of electric vehicles (EVs) dates back to the 1800s. With growing concern of carbon emission and climate change countries around the world are rigorously investing in EVs. The integration of Electric vehicles (EVs) provides a clean alternative method of transportation to conventional gasoline vehicles. [1]. However, as more EVs are integrated into grid, they pose negative effects such as overloading the electric grid, which results in reduced reliability, higher system losses, and higher operational and charging cost. In Nigeria, there is growing interest in Electric vehicles integration. The rising interest in EV technology is that, it will not only help to increase generation but also help to mitigate Greenhouse gases (GHGs) emissions. The advancement in EV technology can lower the reliance on fossil fuels and leads to emission reduction [2]. Charging the EVs from a power grid will contributes more to decreasing pollutant emissions [3]. The United Nations has identified EVs as crucial for achieving their Sustainable Development Goals, which aim to create a cleaner and more sustainable future by 2030. In Nigeria, electric vehicle fleet accounts for around 8.4% of the total vehicles in use in the continent.

Forecasts suggest that Ethiopia, Kenya, Nigeria, Rwanda, and Uganda could potentially reach 4.0-5.0 million units in EV sales. The absence of government support, cost concerns, and insufficient infrastructure, particularly in the energy sector, present significant obstacles to the adoption of EVs in Nigeria. The lack of adequate infrastructure undermines the reliability and consistency of electricity distribution, which is crucial for the widespread acceptance of EVs. The erratic and unreliable energy supply diminishes the feasibility and appeal of EVs, which depend on a regular power supply for charging. The paper review electric vehicles types, charging technologies and benefits and challenges of EVs integration in Nigeria. A case study that investigates the impact of EVs charging on the network is also studied.

II. LITERATURE REVIEW

2.1 Electric Vehicles Technology

An EV is a vehicle that is powered or driven, at least in part by electricity such as trams, metros, electric cars, electric trains, trolleybuses, etc. Most of the mentioned technologies are mature and widely used, except the private EVs (i.e., electric cars), but they are getting huge attention in the last years. EV technology is not new as it appeared in the 19th century powered by lead–acid batteries and it was not used a lot because the fuel-powered cars, i.e., internal combustion engine vehicles (ICEVs), showed better performance at that time because the energy density of fuel was better than lead–acid batteries. Usually, EV terminology is widely used to refer to private electric cars and not to other electrified transportation methods like trams, metros, etc.

2.2 Electric Vehicle Types

There are many types of electric vehicles (EV), including the plug-in hybrid (PHEV), the all-battery vehicle (BEV), and vehicles powered by the hydrogen fuel cell. These different vehicles can feed the power grid, and also, utilised renewable energy sources which are free of CO2 emissions. There are many types of EVs categorized according to the energy converter (i.e., ICE or EM) used to propel the vehicle, the power source (i.e., battery, fuel cell, or gasoline), and if it charges from an external source (i.e., charging station or home charger) [4]. A brief explanation of those types is presented in the following subsections.

Battery Electric Vehicle (BEV)

A battery electric vehicle uses chemical energy stored in rechargeable battery packs for propulsion. BEVs use electric motors and motor controllers instead of internal combustion engines (ICEs). The main advantage of this type is that it produces no emissions locally, which is very crucial in big cities. There are many configurations of this type [5] depending on different companies' designs. The main challenge for BEV is the long charging period and limitation of public charging infrastructure. This issue will be tackled in the near future with the advancement in battery technology which will extend the electric range that the EV can drive before the need to be recharged.

Hybrid Electric Vehicle (HEV)

A hybrid electric vehicle (HEV) is a type of electric vehicle which combines a conventional IC engine and battery packs. Hybrid electric vehicle can be further classified based on the power trains used for propulsion such as series, parallel and series–parallel hybrids. HEV has lower GHGs emissions and fuel consumption than ICEVs. In this type, no charging from distribution network by EV charger is used [5,6]. Therefore, it does not result any negative impacts on the power system due to battery charging and cannot provide any electrical services. There are different structures of this type [5]: series, parallel, series/parallel, mild, and complex HEVs, in addition to series/parallel plug-in hybrid electric vehicle.

Plug-in hybrid Electric Vehicle (PHEV)

A plug-in hybrid electric vehicle also known as a plug-in hybrid is a hybrid vehicle with rechargeable battery packs that can be charged by plugging to an external power supply. A PHEV shares the characteristics of both a conventional hybrid electric vehicle and an internal combustion engine. Figure 1 showed the plug-in-hybrid electric vehicles.

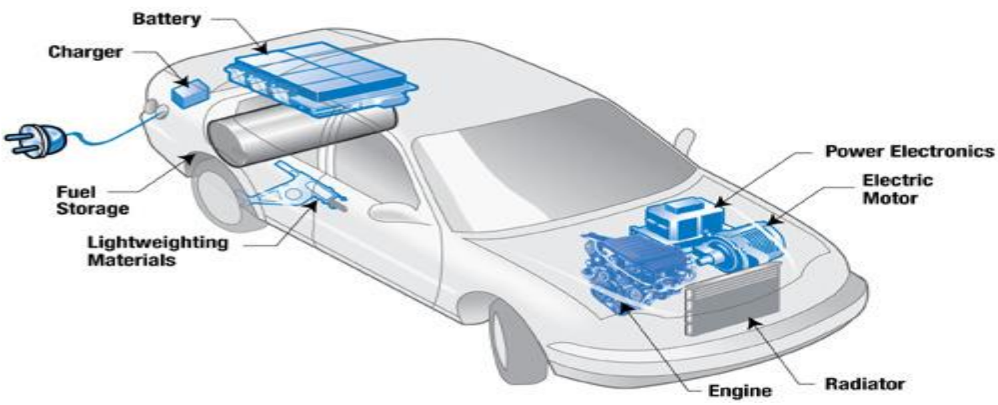

Figure 1: Plug-in hybrid electric vehicle (Source: Argonne National Laboratory)

It is characterized by larger EM power, smaller ICE, and larger battery capacity compared with HEV in order to extend the electric range. It can operate in all electric mode and use EM only which results in zero GHGs emissions. The capacity of the battery specifies the range of electric operation [5, 6]. This type usually has a small battery capacity. Therefore, it is expected that it has a limited negative impact on electric power system. Moreover, its ability to provide electrical services is limited. PHEV can be in any hybrid configuration.

2.3 Electric Vehicles Charging and Discharging

Each EV is characterized by its own charging and discharging characteristics due to different manufacturers. Few of the recent electric cars with their battery capacity are shown in Table 1.

Table 1: EVs storage capacity [7]

S/N	Product	Battery Capacity
1	Tesla Model 3	75kWh
2	Chevrolet Bolt EV	66 kWh

3	Nissan leaf	40kWh
4	Porsche Taycan	93.4kWh
5	Tesla Model S performance	85 kWh
6	Audi E-Tron	71kWh

It is to be noted that none of the EVs are using their full battery strength to increase the life span of the battery. The most of the manufacturers establish a working optimum range to be maximum up to 85% and minimum up to 20% [10].

2.4 Grid to Vehicle (G2V) AND Vehicle to Grid (V2G) Technologies

The power flow from grid to vehicle is G2V technology while that from vehicle to grid is V2G technology.

Grid-to Vehicle (G2V) Technology: The G2V technology is required for charging of electric vehicle whenever it is required through different charging stations. But to optimize the process of charging of EVs, it is required to incorporate a demand response strategy into Demand Side Management and also EV aggregator to increase the flexibility of distributed networks [9],[10],[11]. To complete this charging scheme it is necessary that EV aggregator calculate the initial SOC of EV batteries for every 24 hours in a day, time of connection, type of vehicle and mode of charging. Also 24 hour load demand profile and topology of a low voltage network are required as initial data for the system. While during the charging system, the EV is considered to be an electrical appliance consuming electric energy.

Vehicle to Grid (V2G) Technology: The bidirectional flow of power between smart grid and vehicle is the V2G technology. In the V2G technology power is flown out of vehicle to the main grid and EV act as a distributed energy source. Thus V2G technology permits EV for reverse power flow to fulfil the demand during peak hours of main grid. This technology also benefits to grid to improve its performance in terms of voltage and frequency and give assurance for vehicle to work on desired SOC on next time. Although the V2G technology is very expensive and complex to implement, but it helps to distributes load profile of community microgrid in a more efficient way.

2.5 Challenges of EV Charging on the Grid.

Electric vehicles (EVs) charging can cause operational challenges and require upgrades based on the power drawn from the system and the specific location from which the power is drawn. The impacts can be classified as those affecting the capacity limits of the different components of the network, those that affect the power quality for the end users and those that affect the larger power system. One of the most pressing concerns is ensuring that the national grid is stable enough to support the additional load from EV charging. Effect of EV on power system operation Incorporating Vehicle-to-Grid technology can yield advantages for electric vehicle users and electrical utilities. Electric cars and trucks supply it to the electrical grid during high demand. This functionality allows EVs to function as load requirements and as a means to combine distributed production and energy preservation [12]. Nevertheless, inadequate coordination of V2G incorporation into the electrical system may adversely affect operational effectiveness and reliability, particularly in widespread electric vehicle deployment [12]. Hence, the present section focuses on analyzing the challenges of EV charging on the grid.

Transformer and feeder loading: sustained loading beyond the physical capacity of the components of the grid can lead to premature ageing or permanent damage. Operating limits on current, voltage, frequency, temperature and losses are placed in order to reduce the likelihood of this problem. The components must be upgraded or reinforced if loading is expected to regularly exceed these limits. The effect of EVs at low EV penetrations are negligible on residential distribution transformer. But the effect is increased as no. of EVs increases. A high number of EVs leads to voltage limit violations, transformer overload & increase line losses [12].

Power quality: the current drawn for EV charging may lead to imbalances in the network voltage if EV charging is done on a single phase and may also lead to harmonic distortions. Lower power quality could lead to the eventual damage of other nearby electrical appliances, and hence distribution utilities are subject to power quality indicators, such as contractual voltage limits and harmonic distortion limits.

Voltage Unbalance

Voltage unbalance usually occurs in rural areas where the distribution lines are too long. It is mainly caused by uneven distribution of single phase loads over the three phase system. Uncoordinated charging of electric vehicles could significantly increase the voltage unbalance of the distribution system. The voltage unbalance has negative impacts on the power system and its equipment. The power system will have heating effects and more losses in case of unbalanced conditions. Moreover, temperature and machine losses will be increased which result in reduced efficiency and decreased life of the machines. National Electrical Manufacture Association (NEMA) defines the voltage unbalance in percent as the ratio of maximum voltage deviation from the average line voltage to the average line voltage (%LVUR). NEMA recommends that the maximum voltage unbalance of the electrical supply system must be restricted to 3%. According to the standers of "NEMA Motors and Generators" and International Electro technical Commission (IEC), the permissible maximum voltage unbalance for the induction motors is one percent [13].

2.6 Mitigating Challenges of EVs Charging on the Power Grid

In order to mitigate the challenges resulting from EVs charging on the power grid, the following methods should be employed.

Robust and Decentralized Grid: The current grid might not be able to handle a large influx of charging demand from electric vehicles without significant upgrades. Charging EVs would create additional demand on the national grid, especially if large numbers of vehicles are plugged in simultaneously, for instance, during evening hours when the grid is already under stress. A more robust and decentralized grid (possibly incorporating renewable energy sources like solar or wind) would be necessary to handle increased demand. Battery storage technologies could also help balance the supply and demand for electricity. EVs affect power, performance, or need grid power, especially when the vehicle is charged with restriction. When a basic recharge technique is applied [12], peak loads increase. It also calls for increased investment in capacity generation and transmission. When the vehicle uses an adaptive charging strategy, the vehicles raise the total load and use the base charging devices. And also it does not require any extra installed capacity [14, 15].

Smart Charging Infrastructure: A solution to the potential grid strain would be the deployment of smart charging stations. These stations can help manage charging times and distribute demand more evenly throughout the day. Also, vehicle-to-grid (V2G) technology allows EVs to send electricity back to the grid when needed, helping to stabilize the grid during high-demand periods. This could become a key feature of EV integration into Nigeria's grid, providing a resource for balancing supply and demand.

Renewable Energy Integration: Nigeria has abundant sunlight, making solar power a natural fit for EV charging stations, especially in off-grid or rural areas. Solar-powered EV charging stations could reduce the pressure on the national grid. In areas with unreliable grid access, solar-powered charging stations or mini-grids could offer a solution for EVs, contributing to both clean energy adoption and greater energy independence. While solar is prominent, wind energy could also support the power needs for EV charging in some areas, especially in coastal regions.

Charging Infrastructure Development: Building an extensive charging network across cities and major highways would be essential. In addition, rural areas could benefit from innovative charging solutions, such as mobile charging units or home-based solar charging setups. Private sector investment would be critical in developing this infrastructure, and public-private partnerships (PPPs) could help accelerate the rollout of charging stations across Nigeria.

Grid Modernization and Upgrades: For the seamless integration of EVs, Nigeria's grid needs modernization. This includes improving transmission lines, smart meters, and more efficient power generation methods. Incorporating large-scale energy storage solutions could help store excess power generated during low-demand periods (e.g., during the day with solar power) for use when demand peaks.

2.7 Benefits of Vehicle-to-Grid

Ancillary Services

In PG, supply & demand must be maintained, supply & demand regulated, and electricity transfer from the seller to the buyer provided via Ancillary services. The two-way V2G paradigm offers better quality ancillary services than those offered at current. More PEVs must be obtained by the transistors in the community to provide a greater and needed load for utilities [15, 16].

Voltage and Frequency Regulation

Regulation services represent the 1st phase for V2G since the vehicle power storage device is of high market demand and has low stress [17, 18]. To balance supply and demand, frequency regulation is used [19]. The frequency regulation is attained by cycling large generators that are expensive [20]. In its fast charging or discharging speeds, V2G is a good alternative to frequency change [21]. The voltage regulator is used for reactive power to balance supply & demand. PEV shave fast control signals that can be independently controlled for each PEV [22]. The charger will reduce inductive or reactive power by choosing the correct current phase angle [23]. If grid voltage decreases, the vehicle charging will be shut down as well as the vehicle charging will begin when the grid voltage becomes high [24]. By connecting multiple PEVs, transmission lines or voltage overloads, as well as stability issues, may occur in low voltage. The union controls the transfer of power by three steps to ensure a stable frequency in the delivery system. The primary, secondary & tertiary frequency control [25, 26]. By charging PEVs battery it can provide regulation down and if there is a need of the rule up then the battery will discharge in grid [27]. The control of secondary and tertiary frequency is based on the bid. The lower bid is activated first as the need for regulation increases. As the regulation is provided means a reduced cost fee and this is beneficial for PEVs [28].

Load Levelling
By charging during high demand or charging during low demand, V2G can level power load. Local & global smart charging monitoring approaches were described by K. Mets [29]. By doing the smart charging, the peak load, as well as the load curve, would be reduced. For leveling the grid, PEVs should be paid at night. The design of the battery charger is regulated to minimize the overall load and to increase energy demand [30].

III. MATERIAL AND METHODS

The research method involves two processes namely, data collection and system modelling. The system modelling consists of test system model without and with electric vehicles. A deterministic steady-state analysis was performed in order to assess a network's ability to accommodate electric vehicles technology. The method investigates the effects of increasing EV penetration, as well as the effect of the location on the network and is assessed in terms of the resulting network voltage levels and thermal loading of components. This is achieved by incrementally adding EV units to the network for a given time period. In order to perform this analysis, a model of a section of UK LV distribution network was developed using power system analysis software (NEPLAN). Steady-state analyses were performed using unbalanced load-flow calculations, with the changes in voltage and thermal loading levels at various parts of the network recorded. The load-flow solutions were calculated using the Newton-Raphson method employing 3-phase current injection equations [11].

Power Flow using Newton-Raphson Technique

The Newton-Raphson (NR) method has become one of the most effective techniques for solving power flow problems. The main advantage of this method is its faster convergence and higher accuracy, especially in larger or more complex power systems. The process begins with the initialization of system variables, including voltage magnitudes and angles for all buses. Power flow equations are then formulated, detailing the power balance at each bus by considering both real and reactive power. The special NR method involves the Jacobian matrix, which contains the partial derivatives of the power flow equations. The partial derivatives describe how small changes in voltage will influence the power at each bus. After the power mismatches are represented at any bus, the Jacobian matrix adjusts the voltages until the power mismatches are sufficiently small, and finally, the voltage values and power angles are updated.

Flow chart for the Newton-Raphson method
The flowchart for power flow solution is presented in Fig. 1.

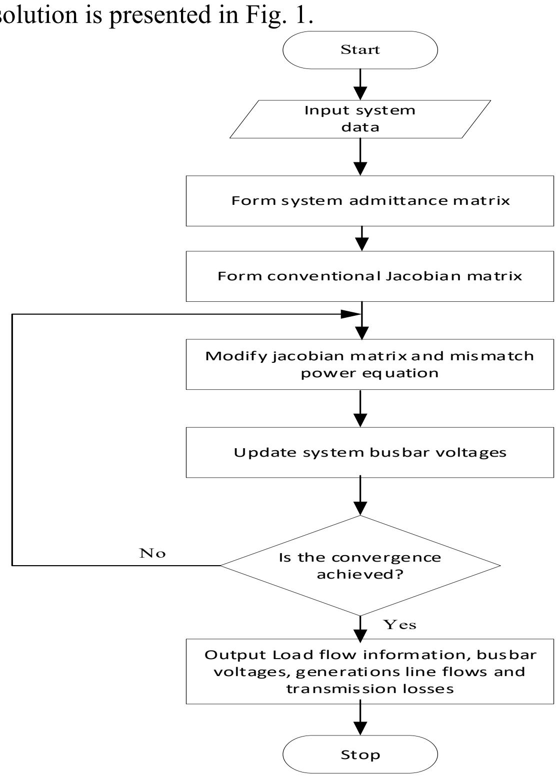

Fig. 2. Flowchart for power flow solution using Newton Raphson method

CASE STUDY

The case study aims to analyse the impacts of EVs charging on the low voltage UK generic distribution network with respect to the network voltage profile, network losses, transformer loading, maximum capacity (units) of EVs that could be connected by individual customers in the distribution system without violating the DNO permissible voltage limits by individual customers in the network. The test system shown in Fig 1 is the UK generic distribution network (UKGDN) model [31]. It consists of a 500 MVA three phase 33kV voltage source, connected to two 15MVA transformers, and eight 11kV outgoing feeder's substation. Each feeder supplies 11/0.433kV transformer which ultimately feeds the networks [32]. Three different networks namely N1, N2, and N3 were defined and modelled for this study. The first network, N1, is a residential distribution network with 384 homes with annual consumption of 4000kWh as shown in [33]. The second network, N2, is a commercial distribution network with sixteen offices with a maximum and minimum loading of 19.275kVA and 5kVA. The average office has a power factor of approximately 0.85 [31]. The third network, N3, is a housing estate, having 63 residential homes and 1 commercial building and is based on a real Cardiff network. It is an urban area, so the network was connected by underground cable. As shown in [33] the network consists of 15 nodes and a distribution transformer (500kVA). The commercial load in the network is represented by node 35

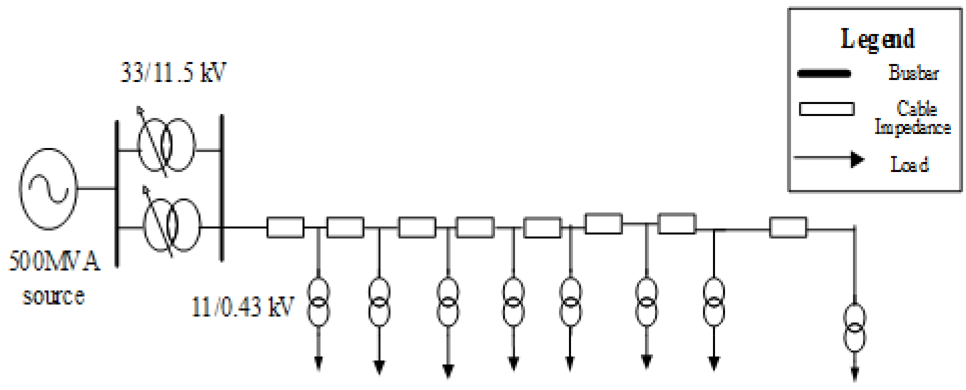

Fig 1 UK generic low voltage distribution network

IV. RESULTS AND DISCUSSION

In this case study the basic unit of EV is considered to be 6.6kW [33]. Thus for 100% penetration, each of the 24x4 residential customers have an EV with 6.6kW load. For commercial load, it is assumed for the purpose of this research study, a car park with 40 EVs.

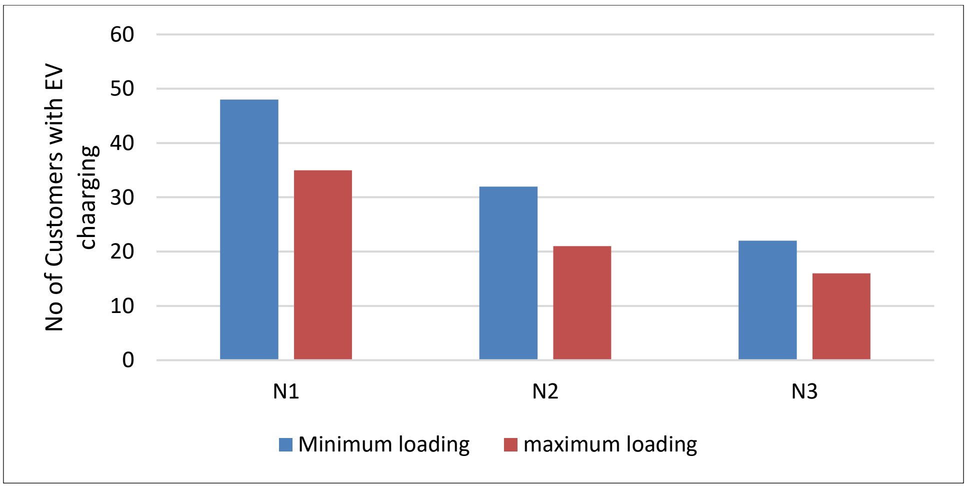

Fig 2. Electric Vehicles Charging on the Distribution Network

The EV is considered in Grid to Vehicle (G2V) mode. Load flow study was performed to determine network voltage changes with EV penetrations. In all the simulations and analysis, the statutory voltage limit of +10%and -6% was strictly maintained. Simulations in this case covers extreme condition at minimum load at both 50% and 100% EV penetration (charging mode) [34]. For residential customers, at 50% and 100% penetration of EV in charging mode, each load group is additionally loaded by 12x6.6 kW=79.2kW and 24 x 6.6 kW = 158.4 kW to an existing minimum load of 3.84 kW. At 50% penetration, the resulting voltage is within the limit (+10% and -6%) permitted by DNO. However, at 100% EV penetration, there is additional burden in the network, with effective loading of 6.6kW per customers. Since there is no power injected into the network by a DG source, the voltage of the networks drops below the normal operating limit. As shown in Fig 2. the results show that with minimum loading, a total of forty-eight (48) customers in N1, thirty two(32) customers in N2 and twenty-two (22) customers in N3 can charge their EVs without violating permissible voltage limit. In addition two simulations were conducted on N1, N2 and N3 with and without DG connected. Over the simulation time, the maximum network losses occurred in N3 which is 20.36 kWh at 12:00. With DG connected, the losses reduced to 15.31kWh at 12:00. Without DG, from Table1, it was shown that the total loss in the network was 834.1kWh. The losses reduced to 604.2kWh with DG connected to the distribution network. However, the lowest losses occurred at N2 as shown in Table 2. The value reduced to 604.3kWh with 100% DG added to the network. The total loss reduction is 113.9kWh (15.61%).

Table 2. Network losses with and without distributed generation

	Power losses over the day (kWh)		
	N1	N2	N3
Without DG	774.8	628.0	834.1
With DG	620.0	510.5	604.2

V. CONCLUSION

The power system capacity in the developing countries such as Nigeria is currently not sufficient to accommodate EVs integration, and then, as we get more EVs incorporated in the future, we should be able to assume more generation, which will most likely be renewables distributed generation.

However, future EV charging scenarios, if uncontrolled, could immediately affect the distribution system by causing thermal line overloading, high network losses, or voltage violations.

Also, EVs are expected to account for a significant portion of residential demand and annual energy. In distribution systems, the coincident EVs and household demand can result in technical difficulties in a network, if the original distribution network design parameters have been exceeded. For instance, if a residential low-voltage network has been designed considering an average peak demand of certain value per house, then adding an additional kW per house due to EV may lead to voltages below the acceptable limits and/or to asset (feeders, transformers, etc.) thermal overloads. It is, therefore, in the interest of the distribution system operator to evaluate how these networks will be affected by different numbers of EVs.

In addition, a case study that investigates the impact of EVs charging on the network was studied to determine the capacity of three different networks to accommodate EVs charging without violating the permissible network voltage limit. Otherwise voltage rise may occur in the network. This voltage rise may lead to the maximum voltage limits being violated which have adverse effects on consumer appliances. In order to mitigate this problem voltages control strategies such as, active power curtailment, smart grid design and implementation and reactive power compensation are employed. Therefore, prior to EV_S and DG integration, a comprehensive study must be carried out to determine the electricity consumption pattern of the customers for safe network

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