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Investigation of the Nigerian Power Network with Solar Photovoltaic System

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Abstract: The demand for electric power is growing at a rapid rates in Nigeria, and the available conventional generation is not sufficient to meet this rising demand. Therefore, solar photovoltaic (PV) systems are been considered as alternative source of power generation. This paper presents a case study investigating the effect of solar PV on the Nigerian power system using power flow analysis method. Various solar PV penetration levels are connected to the network and the power flow results are presented. The results showed that before application of solar PV, there is under voltage in some of the buses of the system but were improved to safe operation values with the application of PV system. Also, the total system power loss was reduced by 19.26%. In this way, the power system becomes more secured and reliable.
Keywords: Network losses, Power flow, Renewable generation, Solar photovoltaic, Voltage profile

1. INTRODUCTION

Climate change and reduction of greenhouse gas emissions have become worldwide concerns[1]. Governments around the world are committed to tackling these issues using various measures. Currently Nigeria is facing challenges of reduction of greenhouse gas emission, insufficient power generation, under voltage, inadequate maintenance and occasional network collapse [2]. In Nigeria, the government has targeted 30% power generation from renewable sources by 2030 to overcome these challenges [2]. The government has targeted that majority of this generation will be solar photovoltaic systems. In 2005, the Federal Ministry of Power launched the Electric Power Reform Act 2005 [3], which introduces an attractive Feed-in-Tariff (FiT) scheme to encourage renewable energy in Nigeria [4],[5]. Previous studies have been carried out to evaluate the effect of solar PV on electricity distribution system. For example, these authors have evaluated the impact of solar PV in terms of voltage profile[6], line losses[7], [8], short circuit current [9], and harmonic [10]. However, these studies were conducted in UK and Germany power systems which are more sophisticated than the Nigeria power network. It is essential to perform these studies based on the Nigerian distribution network in order to understand the effect of integrating solar PV into the Nigerian distribution network. Therefore, this paper presents a case study investigating the effect of grid-connected solar PV on the Nigerian electricity distribution network.

2. RESEARCH METHOD

The model of the 33kV distribution system was developed using Neplan software. Power flow analysis is carried out using the Newton-Raphson solution with a standard load profile. The modeled network is simulated with and without solar PV generation. Power flow analysis provides the solution to the network under steady-state condition subject to certain inequality constraints such as nodal voltages, reactive power generation of the generators, and gives the voltage magnitude and angles at each bus in the steady-state. This is rather important as the magnitudes are required to be held within a specified limit.

2.1. Test system description

The existing 33kV power grid used in this study is located in Ekiti State. The power grid covers a total land area of 5887.89km^2[11]. Electricity supply to Ekiti State is unreliable and poor [12]. Currently, the demand for electricity in the state is far greater than available supply of less than 40 MW [12].

The population in the state has increased rapidly due to industrialization and economic growth. This increase in population has led to high demand for electricity in the state. Available statistics in the National Control Centre (NCC) in Osogbo, Nigeria , reveal occasional cases of systems collapse in the power system [13].The model of the 33kV power grid is shown in Fig 1.

The 33kV grid is fed from Akure, Ilorin, and Osogbo feeders. The network data for the analysis was obtained partly from [11], [14], and partly from Power Holding Company of Nigeria. Table1 shows the power injection to the 33kV power grid, and the network parameter for the analysis is as presented[16]. The limits for the distribution voltage in Nigeria are ±6% of nominal (11kV and 33kV) [15].

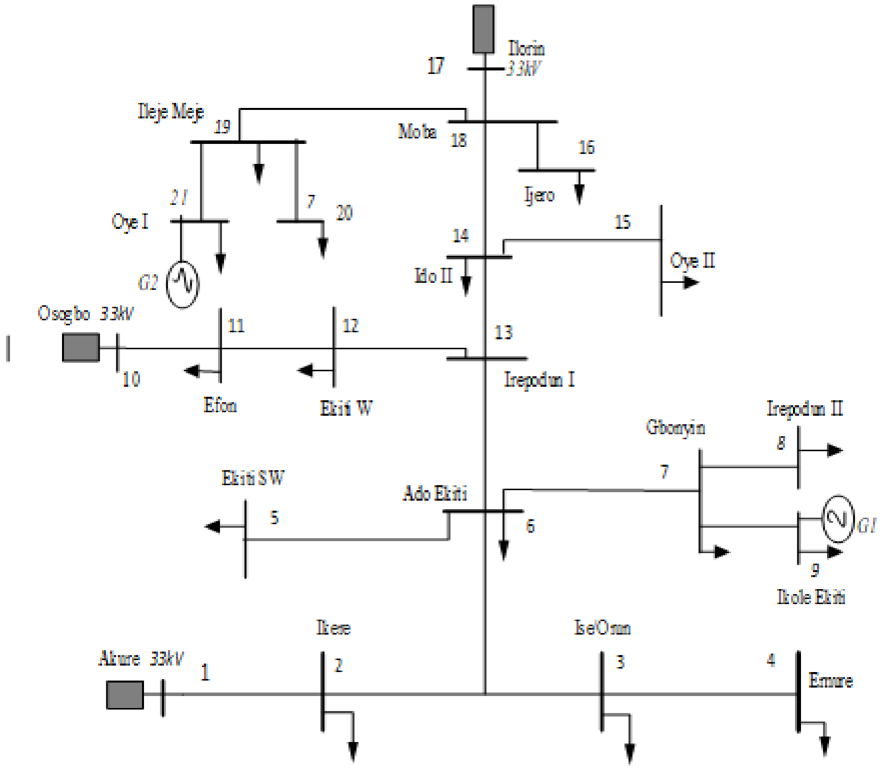

Fig.1. Ekiti-State 33kV power distribution network[16],[14]

One important obligation of the Distribution |Network Operators (DNOs) is to ensure that the voltage limits are not violated but strictly maintained. In Nigeria, less than 40% of the population have access to the power grid, and the remaining 60% are denied the benefits of reliable electricity supply [11], [17]. The power demand for Ekiti-state is 224MW [17].

Table 1 Injector- substation[16]

Substation	Power (MW)	Line Size (mm^2)	Thermal Capacity (A)
Akure	15.8	100	300
Osogbo	12.7	100	300
Ilorin	10	100	300

2.2 Power flow analysis

In Neplan software, the nodal equations used to analysed network are implemented using newton Raphson method. In the formulation, the nonlinear equation are solved by an iterative method. The power flow analysis calculates the power flows, voltage magnitude and phases for all nodes.

The current I_i entering into bus i is given as

$$I_i = V_i \sum_{j=0}^{n} y_{ij} - \sum_{j=1}^{n} y_{ij} V_j \qquad j \neq i \qquad (1)$$

The real and reactive power at bus i is

$$P_i + jQ_i = V_i I_i^*$$

$$I_i = \frac{P_i - jQ_i}{V_i^*} \qquad (2)$$

Substituting for I_i in (1) yields

$$\frac{P_i - jQ_i}{V_i^*} = V_i \sum_{j=0}^{n} y_{ij} - \sum_{j=1}^{n} y_{ij} V_j \qquad j =\neq \qquad (3)$$

From the above relation, the resulting algebraic non-linear equations must be solved by iterative techniques [28], [29].
Equation (3) above can be rewritten in terms of the bus admittance matrix as

$$I_i = \sum_{j=1}^{n} Y_{ij} V_j \qquad (4)$$

Fro equation (, j includes bus i. expressing this equation in polar form, we have

$$I_i = \sum_{j=1}^{n} |Y_{ij}|\,|V_j| < \theta_{ij} + \delta_j \qquad (5)$$

The complex power at bus i is

$$P_i - jQ_i = V_i^* I_i \qquad (6)$$

Substituting from (5) for Ii in (6),

$$P_i - jQ_i = |V_i| < -\delta_i \sum_{j=1}^{n} |Y_{ij}|\,|V_j| < \theta_{ij} + \delta_j \qquad (7)$$

Separating the real and imaginary parts,

$$P_i = \sum_{j=1}^{n} |V_i|\,|V_j||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \qquad (8)$$

$$Q_i = \sum_{j=1}^{n} |V_i|\,|V_j||Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) \qquad (9)$$

Expanding (8) and (9) in Taylor's series results in the following set of linear equations.

$$\begin{bmatrix} \Delta P_2^{(k)} \\ \vdots \\ \Delta p_n^{(k)} \\ \hline \Delta Q_2^{(k)} \\ \vdots \\ \Delta Q_n^{(k)} \end{bmatrix} = \left[\begin{array}{c|c} \begin{bmatrix} \frac{\partial P_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_2^{(k)}}{\partial \delta_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_n^{(k)}}{\partial \delta_n} \end{bmatrix} & \begin{bmatrix} \frac{\partial P_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_n^{(k)}}{\partial |V_n|} \end{bmatrix} \\ \hline \begin{bmatrix} \frac{\partial Q_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_2^{(k)}}{\partial \delta_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_n^{(k)}}{\partial \delta_n} \end{bmatrix} & \begin{bmatrix} \frac{\partial Q_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_n^{(k)}}{\partial |V_n|} \end{bmatrix} \end{array}\right] \begin{bmatrix} \Delta \delta_2^{(k)} \\ \vdots \\ \Delta \delta_n^{(k)} \\ \hline \Delta |V_2^{(k)}| \\ \vdots \\ \Delta |V_n^{(k)}| \end{bmatrix}$$

The element of the Jacobian matrix are the partial derivatives of (7) and (8), evaluated at $\Delta\delta_i^{(k)}$ and$\Delta|V_i^{(k)}|$. It can be re-written as

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \qquad (10)$$

ΔP andΔQ represents the difference between specified value and calculated value respectively.
ΔV and$\Delta\delta$ represents magnitude voltage and voltage angle respectively in an incremental form.

2.3 Flow chart for the Newton-Raphson method

The flowchart for power flow solution is presented in Fig. 2.

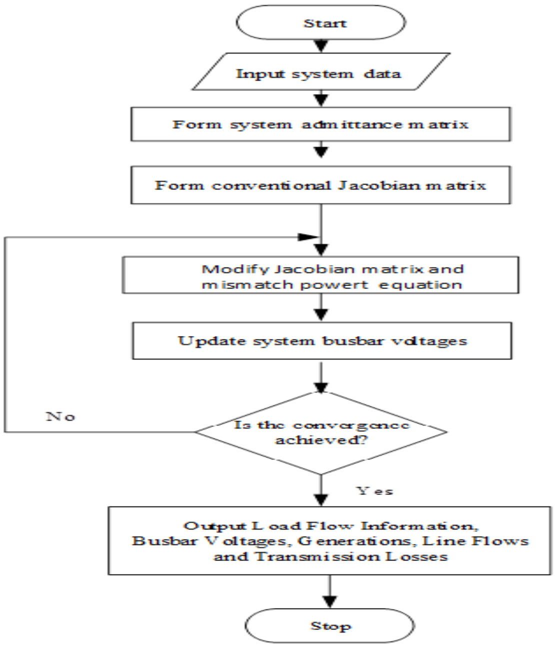

Fig. 2. Flowchart for power flow solution using Newton Raphson method

3. CASE STUDIES

Two case studies were carried out.

- The first case study investigated the Ekiti state 33kV grid in the year 2020.
- The second case study investigated the Ekiti state 33kV grid in the year 2030

In case study1, two simulations were performed. The first simulation was carried out without PV generation while the second simulation was performed with PV generation in the year 2020. In case study2, two simulations were also performed with and without PV generation in the year 2030. The aim is to investigate the effect of solar PV on the network with respect to network voltage and power losses. The simulations were conducted in the Neplan software environment. The solar PV generations were connected to the modeled network as illustrated in Fig 1. Two solar PV, G1 and G2, 5MW capacity each, were connected at node 9 and node 21 respectively in the year 2020. The total value of G1 and G2 were increased to 40MW in the year 2030. The PV system were located at the weakest parts of the network, towards the end of the feeder while the time-series load was connected at node 9.

3.1 Solar photovoltaic systems

The solar PV data was obtained from the Nigeria Meteorological Department. These data have been used in the previous article [18]. The PV generation profile is shown in Fig 3. These previous work [18], [19] established that global radiation in Nigeria can support any form of a solar energy system. In Nigeria, the mean annual average solar radiation varies from about 3.5kWhm^{-2}days^{-1} in the coastal latitudes to about 7 kWhm^{-2}days^{-1} in the far north [20], [21]. Solar PV was chosen because of global reduction in the cost of a solar panel and availability.

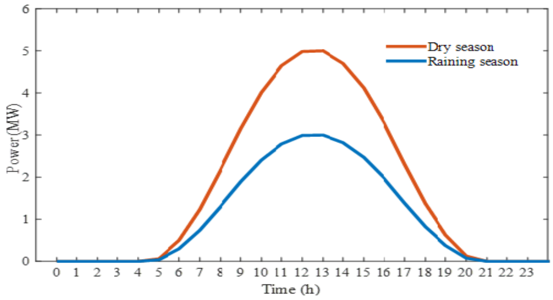

Fig. 3 Solar PV generation profile over 24 hours

3.2 Electricity demand

The electricity demand profile used in this study is shown in Fig 4. It is observed that the demand for electricity is lower in the dry season than in the raining season. The peak demands in the dry season are usually lower than the peak demands of the raining season when compared.

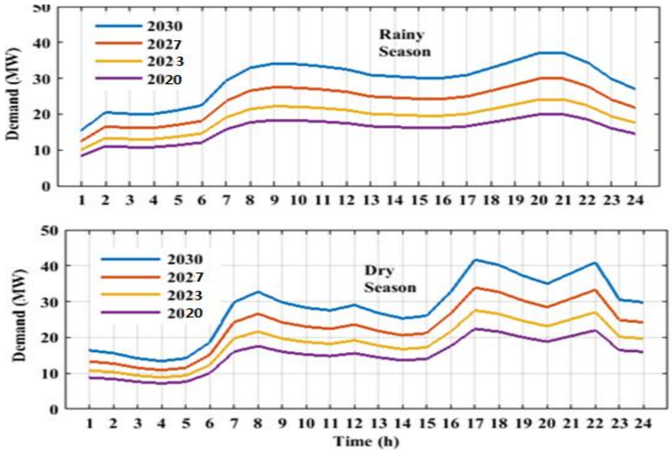

Fig. 4 Electricity demand over 24 hours

It is important to state that the demand for electricity tends to fluctuate over the course of the day, determined by human activity. The electricity demand used in this study (Rainy season: September 06, 2019, and dry season: October 26, 2019) is represented in 24 hourly load steps and was obtained by applying an annual increase rate of 0.3%. The demand projection is shown in Figure 4 [22]. This load demand is expected to increase yearly up to 2030 [22]. The two sets of simulations conducted on the test system are intended to demonstrate the benefits and future operation of the distribution network with solar PV systems. The energy losses in a PV system are assumed to be zero. The conversion efficiency of the PV generator is assumed to be 1 (n = 1)

4. RESULTS AND DISCUSSION

4.1 Case study 1

The results of the first simulation for the year 2020 with the time-varying load connected at node 9 of Fig 2 showed that during the peak hours(7:00 am to 9:00 am and 20:00 pm to 22:00 pm), the network voltage is low both in the rainy and dry season as shown in Fig 5. However, the lowest voltage permitted by DNO has not been exceeded in this case.

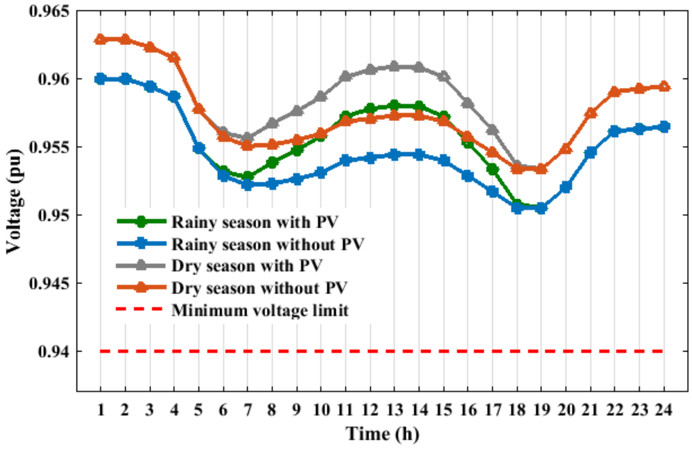

Fig. 5 Voltage profile at node 9 or case study 1

Therefore in the year 2020, only 10MW of PV generator was connected to the network to improve the bus voltage. The result shows that there are voltage increases during the day when the solar PV generation is active (between 7:00 am and 19:00 pm). The bus voltage rise by an average of 50.8V during the peak hours of the day. But the situation of the voltage is expected to be worse as the demand for electricity increase between year 2020 and 2030. Since more load is expected to be connected to the network between year 2020 and year 2030 due to growing demand for electricity as a result of rising population and industrialization. In Nigeria, the expected lower and upper voltage limits at 33 kV are 31.02kV (0.94pu) and 34.98kV (1.06pu) (+/- 6%) respectively [15].

4.2. Case study 2

The simulation results for the year 2030 showed that without solar PV generation, the network voltage during the afternoon peak load was below the minimum voltage limit line in the raining season day.

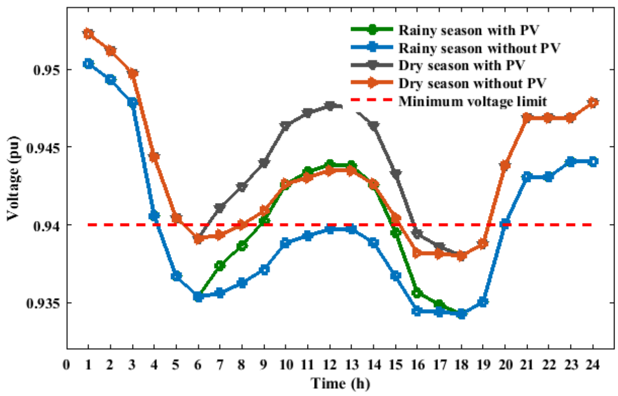

Fig 6 Voltage profile at node 9 for case study 2

The bus voltage reduced significantly at the connection node due to the size of the connected load. As shown in Fig.6, the bus voltage drop to 30.84 kV (0.934pu) in the raining season while in the dry season the bus voltage dropped to 30.96kV (0.938pu). In the second case study, during the raining season, due to high load demand, the bus voltage has fallen outside the permissible voltage limit.

In the second case study, 40MW solar PV generation was connected to the network due to high load demand. This increased power generation (PV) caused the bus voltage to rise by 136V. As shown in Fig 6, there was under voltage problem in early hours of the day (5:00 am to 8:00 am) and evening (16:00 pm to 19:00 pm) despite the inclusion of PV generation to the power network. This under-voltage problem is due to the intermittency of solar PV generation output during these hours. Therefore, the resident will need to purchase costly electricity during peak hours in the morning and in the evening.

It is important to state here the relevance of electrical storage system to perform the function of proper energy management during the peak and off-peak hours. The storage system is able to store excess electricity to be later released during the peak demand hours[25]. The storage system will help to overcome the intermittency problem due to solar PV generation and also improve power quality. However, the addition of storage will provide significant benefits to the system, but will incur additional costs to the system. The PV system must be properly sized to avoid energy wastage and to meet the load requirements[26]. That means, the battery state of charge must not exceeds its maximum allowable value, and load demand must not be less than the solar power output [27].

4.3 Network Power losses

The network active power losses in the test network with and without solar PV are shown in Fig7. In the cases studied, the addition of PV generation causes the total network losses to decrease. The loss reduction increased as more PV generation are integrated into the network.

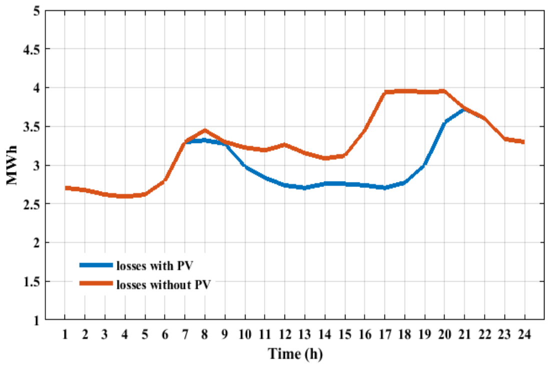

Fig. 7 Network losses over 24 hours

The results showed that in the year 2020, the addition of 10MW PV generation to the network resulted in losses reduction of approximately 3.73MWhr while in 2030, the network losses reduced by 10.03 MWhr. It is observed from the study that there are more losses in the raining season due to increased residential power demand. The summary of the results is shown in Table4. The penetration level of solar PV should be optimized and not maximized because, at a certain level, the network losses no longer decrease, but increase sharply, the cost-benefits ratio has the optimum value before having reached the minimum network losses.

Table 4 Summary of the results

	2020	2030
Voltage improvement	50.9V	135V
Loss reduction (%)	7.97	19.26
Annual savings due to loss reduction (US$)	203,308	545,096

5. CONCLUSION

This paper introduces the solar PV system as a tool to address the problem of unreliable electricity supply in Nigeria. Solar PV technology is currently in demand in both developed and underdeveloped economies. Countries with less access to quality and secure electricity must addressed their power problem with solar PV technology. In Nigeria, there is no tangible investment in the power sector over the years due to the economic recession. Lack of investment in power generation has caused low voltage and occasional system collapse. These challenges of insecurity and lack of sustainable as well as the needs to meet the carbon emission reduction target has prompted this study

This work presents an analysis of some of the advantages and disadvantages of solar PV systems in the electricity distribution systems. The results show that the integration of solar PV systems is able to improve the condition of the network voltage profile and losses. It is observed from the results that the integration of solar PV systems improves the voltage profile by 135V making the power system to be more secure and reliable.

The total network losses reduced by 19.26% which will lead to savings in the network cost. However, voltage rise problem could occur at higher penetration of PV systems which could affect standard operating limits and damage network equipment. The impact of solar PV is location-dependent, as such, PV generations were connected to the weak section of the distribution network to avoid unnecessary voltage rise. The intermittency of PV system could be addressed with energy storage technology as backup energy during peak demand hours and when solar irradiation is low. The results obtained from this study will provide valuable information to other researchers in their work and assist the Power Holding Company of Nigeria in network planning, operation, and maintenance.

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