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The Impact of Solar Energy-Based Distributed Generation on Nigeria's Power Distribution Grid: An Analysis of the 11KV/415V Distribution System

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Abstract

Integrating distributed generation (DG) into electrical power systems can significantly enhance system performance by reducing wattage losses, improving voltage profiles, and boosting power quality, thereby cutting down the need for substantial transmission and distribution investments. This study analyzes the 11/415 kV Distribution Network of the World Bank in Aba, Nigeria, using ETAP 16.0 software. By comparing scenarios with and without DG, the study found that DG integration at specific buses improves bus voltages and optimizes power distribution, highlighting the practical benefits of DG in stabilizing and enhancing Nigeria's power distribution system. It also highlighted some drawbacks that comes with DG integration in single buses.

Keywords*: Renewable Energy, Solar Energy, Solar PV, DG Integration, ETAP.*

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1. INTRODUCTION

Energy policies worldwide are increasingly directed towards achieving higher energy security to address the rising demand, depletion of resources, and volatility in supply and prices (IRENA, 2015). The electricity market is transforming towards a competitive environment, prompting a renewed interest in distributed generation (DG) due to issues like price instability, ageing infrastructure, and changing regulations (Pepermans et al., 2003). DG offers advantages by positioning generation units at customer sites, reducing wattage losses, enhancing voltage profiles, and improving power quality.

Utility restructuring, technological advancements, and environmental policies are fostering DG's progress. This restructuring coincides with escalating electricity demand, improved DG technology performance, heightened environmental concerns, and reliability issues in power supply (EIA, 2020). DG refers to electric power production technologies integrated close to the point of use within distribution systems, typically smaller than 30 MW (Mohammad et al., 2017), and connected to medium or low voltage grids. It contrasts with traditional centralized generation, which involves large power stations transmitting electricity over long distances.

A distributed electricity system involves small generators directly connected to consumers and lower voltage networks, with excess generation fed into the active distribution network. Storage systems may be used to balance variable generation outputs. DG systems offer clean, efficient, reliable, and flexible on-site power alternatives, appealing for their market-driven, customer-oriented solutions.

In Nigeria, the power sector faces challenges such as inadequate generation capacity, undervoltages, overloaded transformers, and high transmission and distribution losses. These issues have led to poor and unreliable power performance, with significant investment barriers (Onyekwena et al., 2017). Increasing demand outstrips supply, overloading the system. Efforts to incorporate renewable energy aim to enhance energy security and reduce emissions.

This research examines the effects of distributed generation utilizing solar energy sources and enhancements to the distribution grid by simulating a Nigerian distribution system with integrated distributed power generation, specifically focusing on the 11kV distribution network.

2. REVIEW OF LITERATURES

The increasing global demand for electricity, coupled with challenges in generating and transmitting capacities, has spurred significant interest in Distributed Generation (DG) sources. Distributed generation is an electricity source that is linked directly to the distribution network or situated on the customer's side of the meter (Bollen & Hassan, 2011)

In Nigeria, universities and research centers are actively investigating DG, particularly through renewable energy, to tackle persistent power challenges. Ariyo & Omoigui (2013) provided the fundamental analysis done on the 330 kV electrical network in Nigeria with penetration of distributed generation (DG). Akpoviroro et al. (2021) examined the long-standing practice of a centralised system of energy production that generates and transmits electricity over long distances, resulting in enormous losses. Inyama, Onojo, Okozi, & Joe-Uzuegbu, (2023a) presented a review on the impact of distributed generation using solar sources. They discussed that Distributed Generation (DG), driven by rising power demand and ageing infrastructure, plays a vital role in modern grids, with solar energy gaining prominence due to its renewable nature. Replacing fossil fuels with renewable technologies can reduce CO2 emissions and mitigate the negative impacts of conventional energy production. Kelechi & Eberechi (2023) explored a method for integrating Distributed Generation (DG) at multiple stations to achieve the desired power transfer capability within the south-east transmission network in Nigeria. Their research involved analyzing the performance of wind and solar DG units integrated at the station buses in the selected locations. A strategy for integrating distributed generation in the post-deregulation age was presented by Odubiyi et al. (2003) along with an assessment of the practice of distributed generation in Nigeria. The solar energy potential for sustainable energy generation in Nigeria and the numerous issues involved in harnessing solar energy. He clearly articulated a road map to enable Nigeria tap into the huge potentials of solar energy

3. **METHODS**

It is crucial to accurately model the utility grid, focusing particularly on the integration of solar energy and photovoltaic (PV) systems within the distributed generation framework. The design will include the feeders connected to this DG, and a power distribution analysis will be conducted using ETAP software.

The methods involve the collection of power flow and load data's of distribution generation network in the study area. Figure 3.1 describes the methodology of the study to be undertaken.

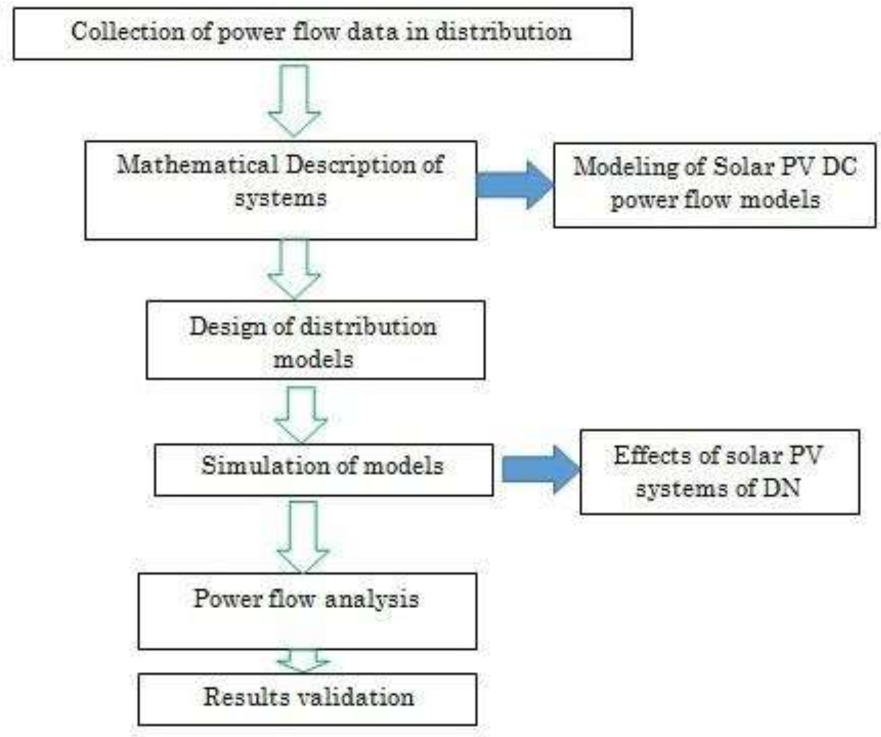

Figure 3.1: Block diagram showing methods. (Inyama, Onojo, Okozi, & Joe-Uzuegbu, 2023b)

3.1 Data collection

The data for this study will be derived through calculations utilizing data sheets and load flow information from the World Bank district in Aba, Abia State, Nigeria. The collected data will include details on power consumption, availability, and load ratings measured in kW, kVar, and amperes.

3.2 Mathematical Models

Analyzing power flow on transmission lines, reactive power on generator buses, and consumer bus voltages is crucial. The Newton-Raphson (NR) method, an iterative technique using Taylor series expansion, approximates nonlinear simultaneous equations into linear ones for load flow analysis. These equations as descried in (Inyama et al., 2023b) will not be used in this investigation, it does provide a mathematical explanation of the flow of power in slack buses.

3.2.1 Solar PV DC power model

The DC output power of a solar PV cell can generally be calculated for specific weather conditions using data provided by the module manufacturer and the solar cell's diode model. The solar panel's DC output power is expressed as follows

$$I = I_l - I_o\left(e^{\frac{q(V+R_sI)}{mKT}} - 1\right) \qquad (3.1)$$

$$\boldsymbol{P} = IV \qquad (3.2)$$

Where R_s is the series resistance, I_o the diode's reverse saturation current, $V\ and\ I$ the operating voltage and current of the PV system, I_l (the luminous flux) and, and a (the diode ideality factor). The parameters I_l, I_o and mKT and thus the actual operating voltage and the current of a solar module), are influenced by the cell temperature T_c and the irradiation level G_{POA}. The following relationships serve as reliable approximations for many PV modules.

$$a = a_{ref}\frac{T_c}{T_{c,ref}} \qquad (3.3)$$

$$I_l = \frac{G_{POA}}{G_{POA,ref}}\left[I_{Iref} + \mu I_{sc}.\left(T_c - T_{c,ref}\right)\right] \qquad (3.4)$$

$$I_o = I_{o,ref}\left(\frac{T_c}{T_{c,ref}}\right)^3 exp\left[\frac{\varepsilon N_s}{a_{ref}}\left(1 - \frac{T_{c,ref}}{T_c}\right)\right] \qquad (3.5)$$

The subscript ref in equations 3.3 to 3.5 gives the magnitude at standard reference conditions (STC), denoted as solar irradiance of $G_{POA,ref} = 1000\frac{W}{m}$ and ambient temperature of $T_{amp,ref} = 298K$.

3.2 The distributed generation model

Adopting an appropriate injection architecture that leverages the distributed controllability of converters ensures reliability, reconfigurability, and self-backup in such setups. While DG influences Distribution Networks both positively and negatively depending on various factors, this study focuses on the backup capabilities of solar PV-based DG installed at specific feeders within the World Bank Distribution Network (DN).

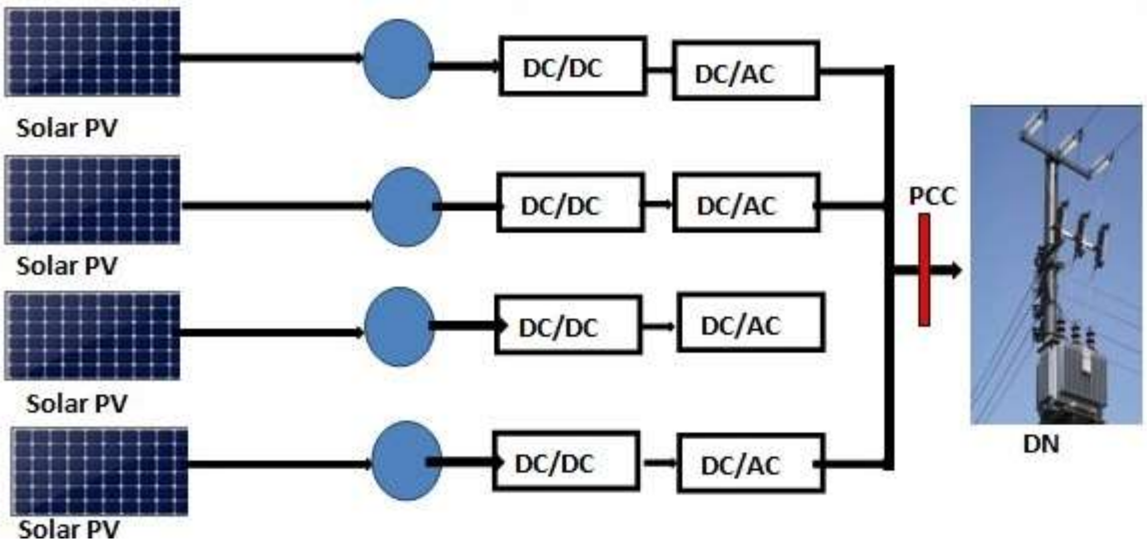

Figure 3.2: Block diagram of the PV array interfaced with the DN

3.4 Implementation of the World Bank 11kV/415V Distribution Network on ETAP

The collected data on load distribution across the World Bank distribution network, aligned with predefined distances and line specifications, will enable accurate modeling and implementation of the network structure in ETAP software as shown in Figure 3.3.

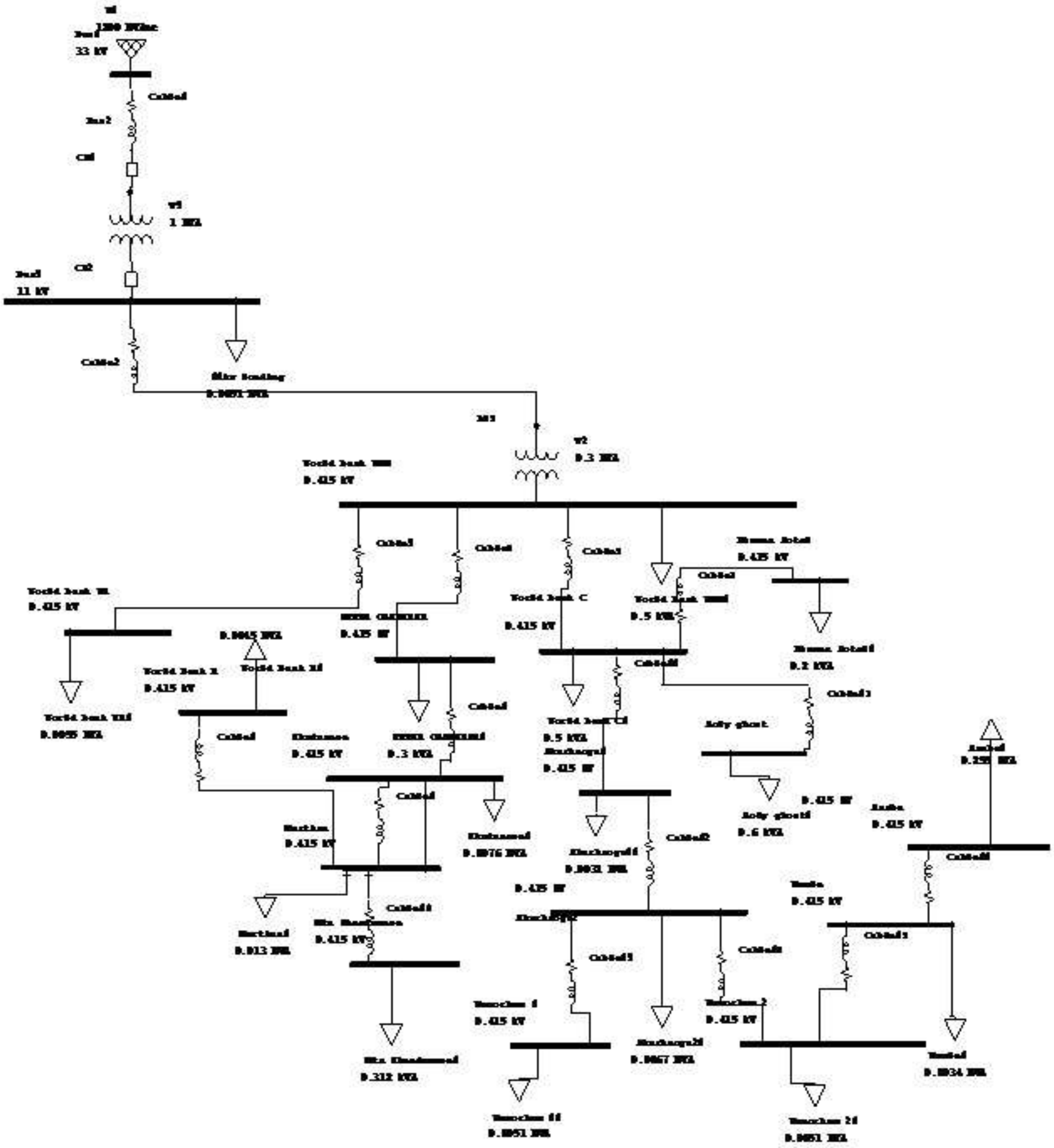

Figure 3.3: Implementation of the World Bank 11 kv/415 V DN on ETAP

The outcomes of the simulation are shown in Table 4.2. The voltage levels at each bus were observed and the corresponding data was gathered. The simulation was rerun under different scenarios, with power being injected at various buses through the PV system DG. Notable improvements in the voltages at different buses were also recorded.

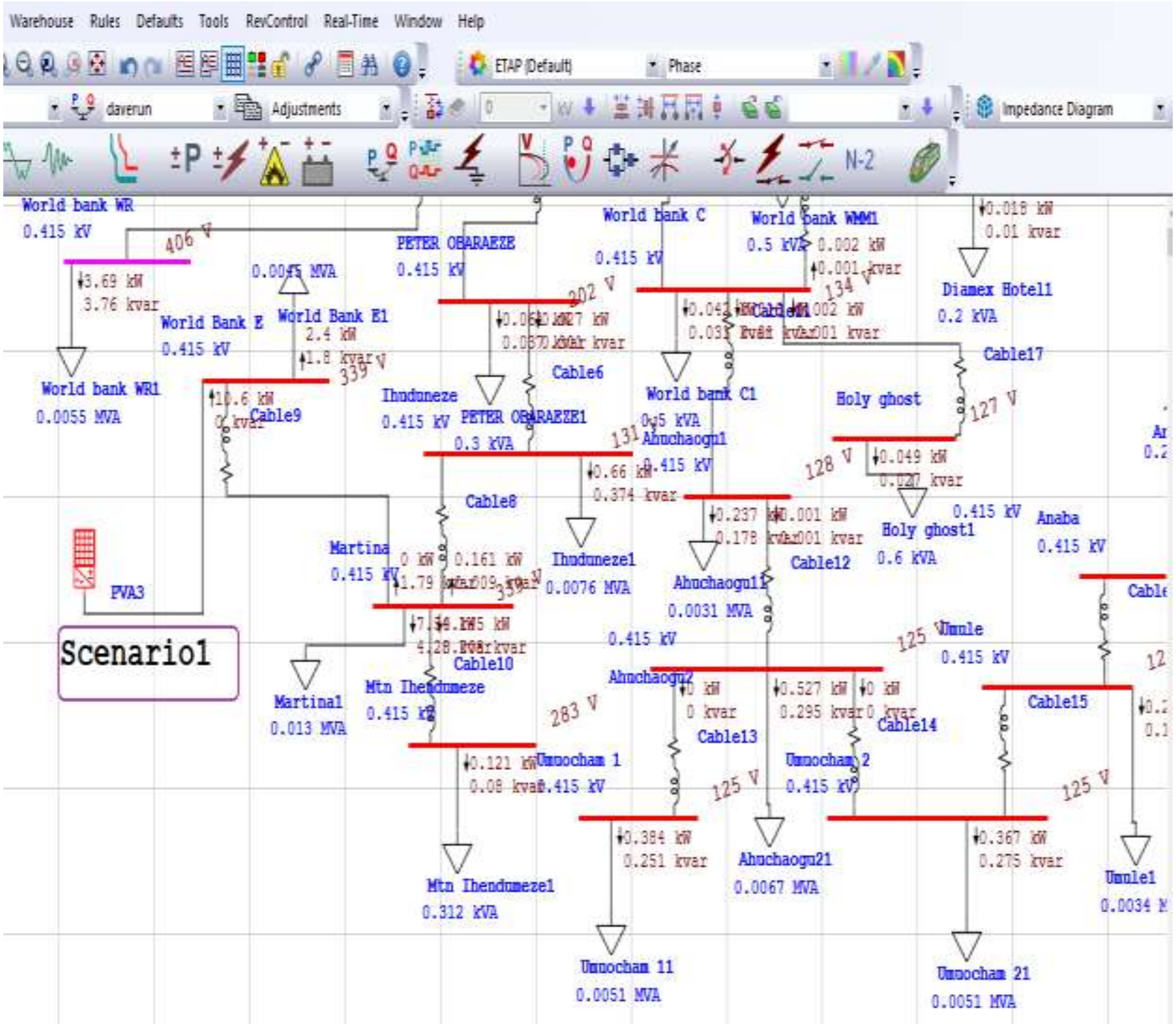

Figure 3.4 DG integration at World Bank east.

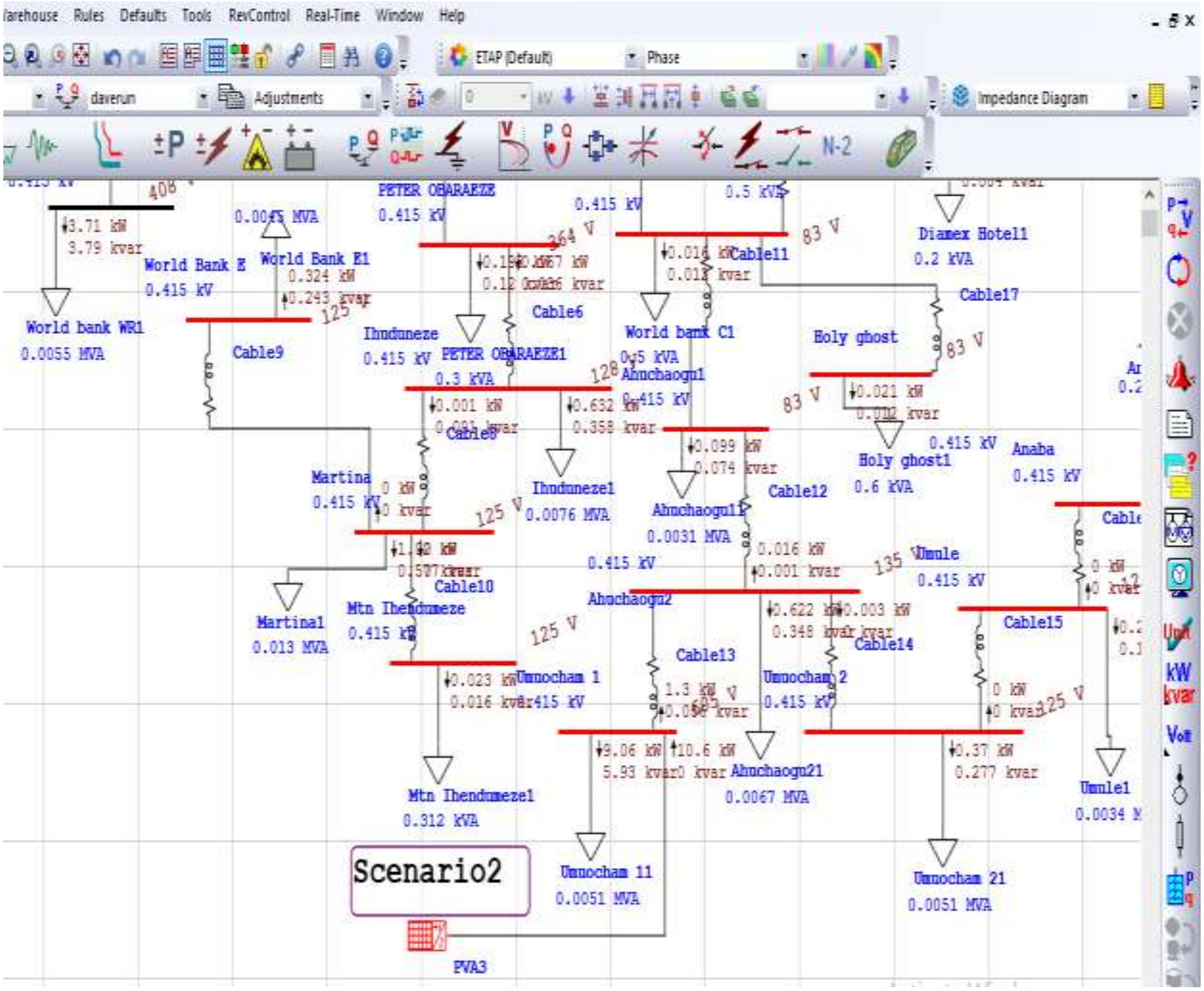

Figure 3.5: DG integration at Umuocham 1

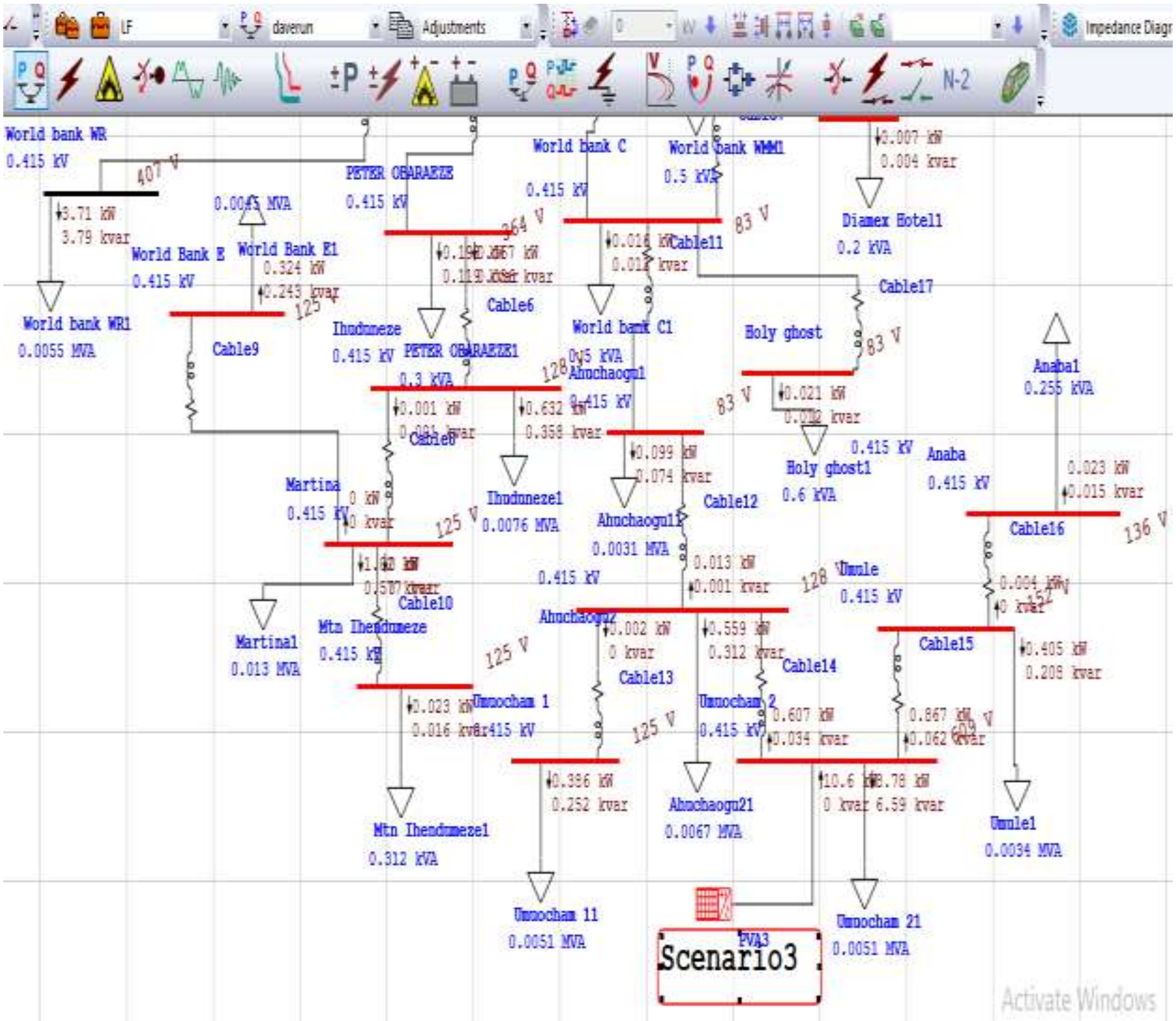

Figure 3.6: DG integration at Umuocham 2

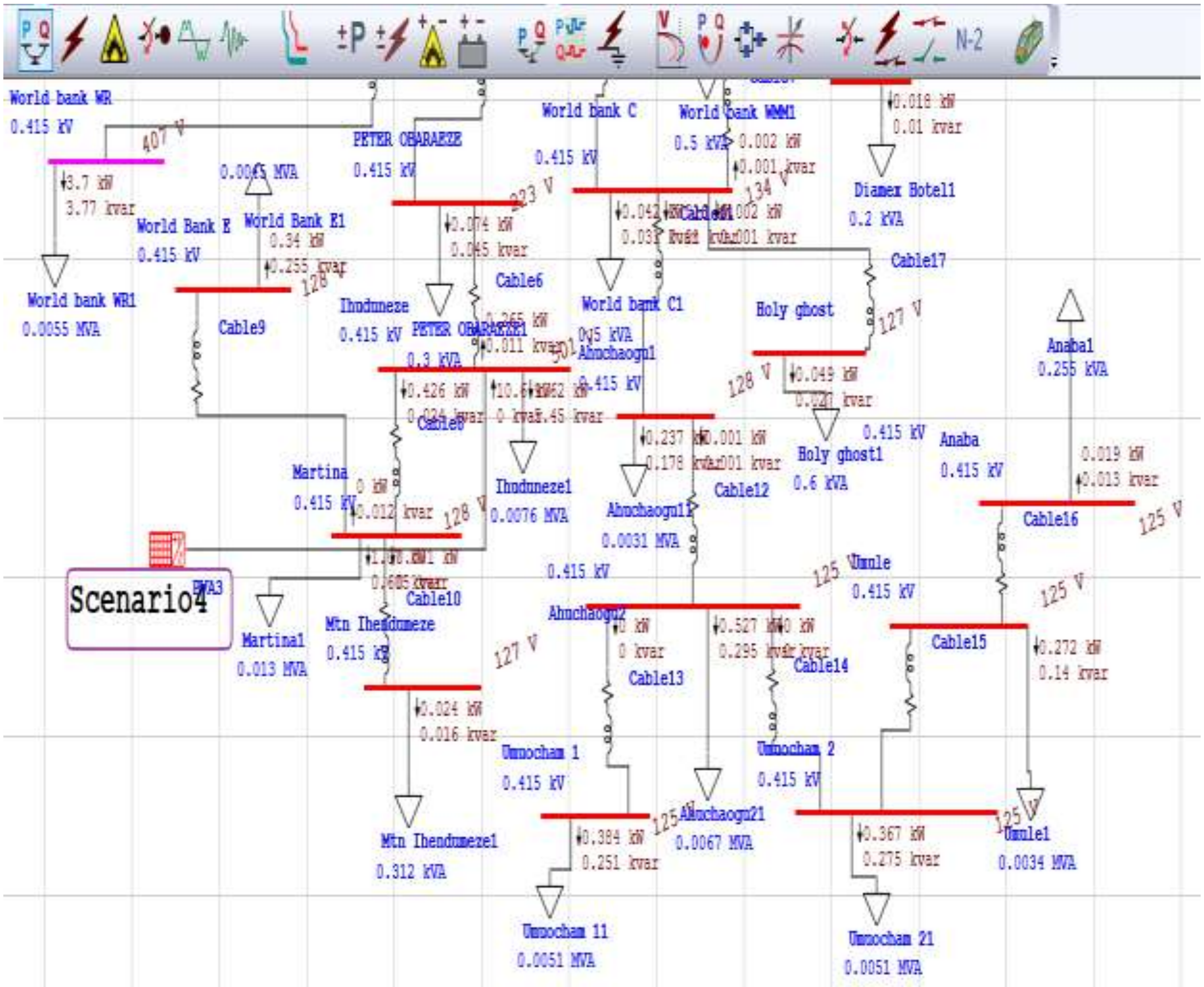

Figure 3.7: DG integration at Ihendumeze

4. RESULTS AND DISCUSSIONS

The presented results will encompass power flow data from ETAP, gathered across four distinct scenarios following the integration of solar PV systems into regions with low voltage levels

4.1 Results

The results will showcase power flow data from ETAP, obtained from four specific scenarios following the integration of solar PVs into low-voltage areas. The necessary data for designing and simulating the solar DG unit and the World Bank distribution network in ETAP has been provided. Table 4.1 outlines the simulation data for the PV unit.

Table 4.1: solar PV rating chosen for DG integration

PV panel	Values

Power	400 watt/panel
Temp.	-40 ~+85degree C
DC volts	1000V/1500V/DC
Number of Panels	100

Table 4.2 presents the flow data for various buses before the integration of solar PV systems into the feeders. It highlights the nominal values at each bus, with 0.415 kV buses linked to the 11 kV bus via step-down transformers. The flow data indicates the need for solar PV integration at the Umuocham 1 & 2, World Bank East, and Ihuduneze buses.

Table 4.2: Bus data of the distribution network

Bus ID	Nominal kV	Type	Voltage (V)	kW Loading	kvar Loading
Ahuchaogu1	0.415	Load	128.4	0.239	0.179
Ahuchaogu2	0.415	Load	124.6	0.527	0.295
Anaba	0.415	Load	124.5	0.0192	0.0126
Bus3	11	Load	10983.7	8.36	7.95
Diamex Hotel	0.415	Load	132	0.0176	0.01
Holy ghost	0.415	Load	126.7	0.0488	0.0273
Ihuduneze	0.415	Load	128.3	0.634	0.359
Martina	0.415	Load	124.5	1.02	0.578
Mtn Ihendumeze	0.415	Load	124.5	0.0234	0.0156
PETER OBARAEZE	0.415	Load	366	0.37	0.168
Umule	0.415	Load	124.5	0.272	0.14
Umuocham 1	0.415	Load	124.5	0.384	0.251
Umuocham 2	0.415	Load	124.5	0.367	0.275
World bank C	0.415	Load	134	0.0624	0.0434
World Bank E	0.415	Load	124.5	0.324	0.243
World bank WMM	0.415	Load	411.6	4.75	4.31
World bank WR	0.415	Load	409.5	3.75	3.82

4.1.1 PV Integration Scenarios

To facilitate the effective integration of solar PV into the World Bank distribution grid, the following scenarios will be analyzed:

I. Power flow data without solar PV integration.

II. Power flow data with solar PV integrated at the World Bank East bus.

III. Power flow data with solar PV integrated at Umuocham 1.

IV. Power flow data with solar PV integrated at Umuocham 2.

V. Power flow data with solar PV integrated at Ihuduneze.

When solar PV was integrated at the World Bank East bus, the bus voltage experienced a significant increase from 124.5V to 239.01V (see Figure 4.1). Martina also observed a substantial voltage improvement, rising from 124.5V to 339V, while MTN Ihendumeze saw a notable increase from 124.5V to 282.8V.

Table 4.3: Bus Data for DG integration at World Bank east Bus

Bus ID	Nominal kV	Type	Voltage	kW Loading	kvar Loading
Ahuchaogu1	0.415	Load	128.4	0.238	0.179
Ahuchaogu2	0.415	Load	124.6	0.527	0.295
Anaba	0.415	Load	124.5	0.0192	0.0126
Bus3	11	Load	10972.2	13.05	14.24
Diamex Hotel	0.415	Load	131.9	0.0176	0.01
Holy ghost	0.415	Load	126.7	0.0488	0.0273
Ihuduneze	0.415	Load	131.2	0.66	0.374
Martina	0.415	Load	339	7.85	6.09
Mtn Ihendumeze	0.415	Load	282.8	0.121	0.0804
PETER OBARAEZE	0.415	Load	201.7	0.317	1.36
Umule	0.415	Load	124.5	0.272	0.14
Umuocham 1	0.415	Load	124.5	0.384	0.251
Umuocham 2	0.415	Load	124.5	0.367	0.275
World bank C	0.415	Load	133.9	0.062	0.0432
World bank E	0.415	Load	239.01	1.4	0.8
World bank WMM	0.415	Load	408.1	9.26	10.56
World bank WR	0.415	Load	406.1	3.69	3.76

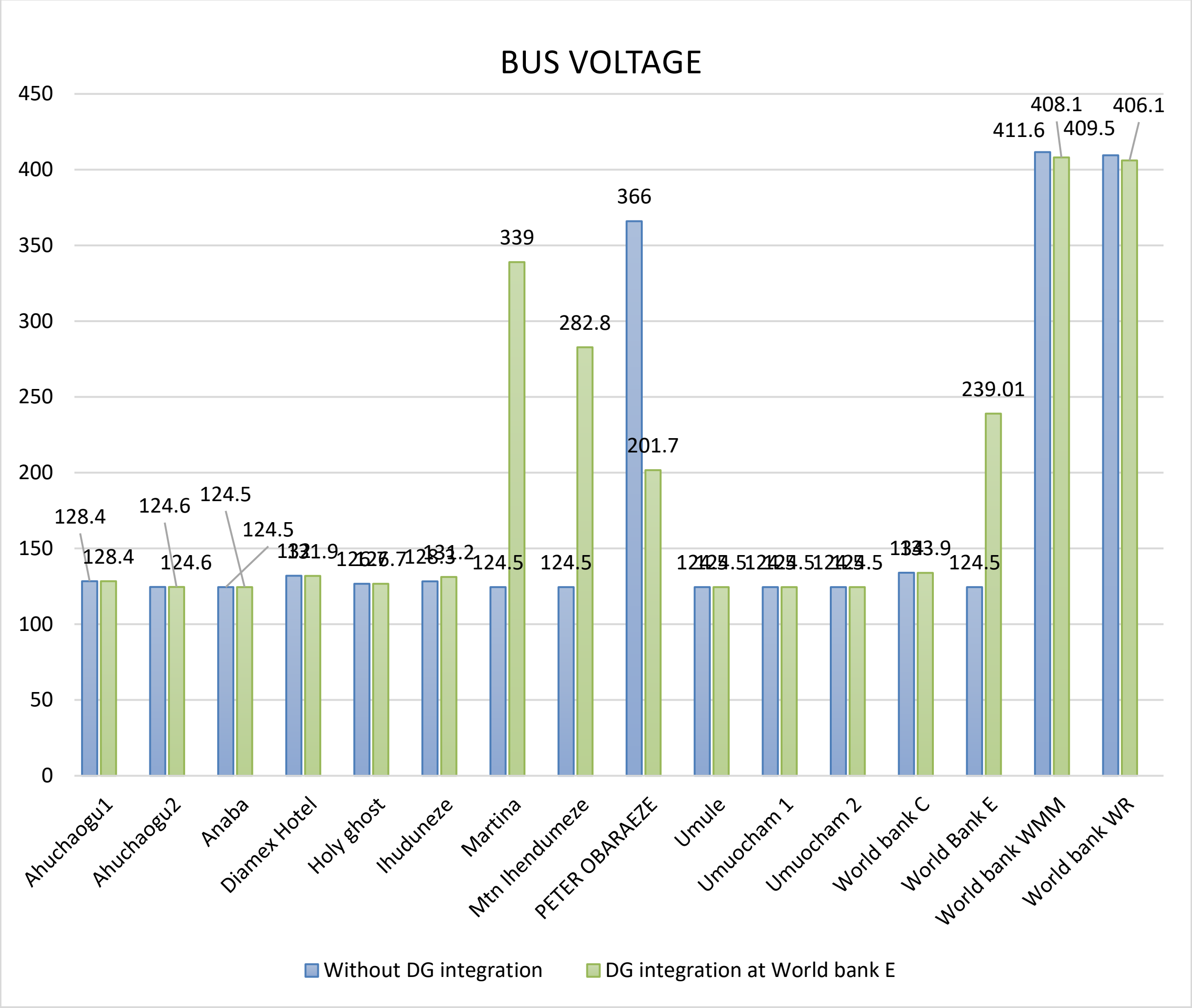

Figure 4.1: Bus voltage world bank east DG integration

The integration of solar PV at the Umuocham 1 bus led to a substantial increase in bus voltage, rising from 124.5V to 213V (refer to Figure 4.2). However, a slight decline in voltage was observed at the World Bank Central bus, decreasing from 134V to 83V. Meanwhile, the Ahuchaogu 2 bus experienced a modest voltage increase from 124.5V to 235.3V

Table 4.4: Bus Data for DG integration at Umuocham 1 Bus

Bus ID	Nominal kV	Type	Voltage	kW Loading	kvar Loading
Ahuchaogu1	0.415	Load	83	0.0992	0.0744
Ahuchaogu2	0.415	Load	135.3	0.641	0.349
Anaba	0.415	Load	124.5	0.0192	0.0126
Bus3	11	Load	10975.9	10.38	12.92
Diamex Hotel	0.415	Load	83	0.007	0.0039
Holy ghost	0.415	Load	83	0.021	0.0117
Ihuduneze	0.415	Load	128.3	0.633	0.359
Martina	0.415	Load	124.5	1.02	0.578
Mtn Ihendumeze	0.415	Load	124.5	0.0234	0.0156
PETER OBARAEZE	0.415	Load	364.3	0.366	0.166
Umule	0.415	Load	124.5	0.272	0.14
Umuocham 1	0.415	Load	233	1.93	2.06
Umuocham 2	0.415	Load	124.9	0.37	0.277
World bank C	0.415	Load	83	0.0182	0.0285
World Bank E	0.415	Load	124.5	0.324	0.243
World bank WMM	0.415	Load	409.7	6.67	9.26
World bank WR	0.415	Load	407.6	3.71	3.79

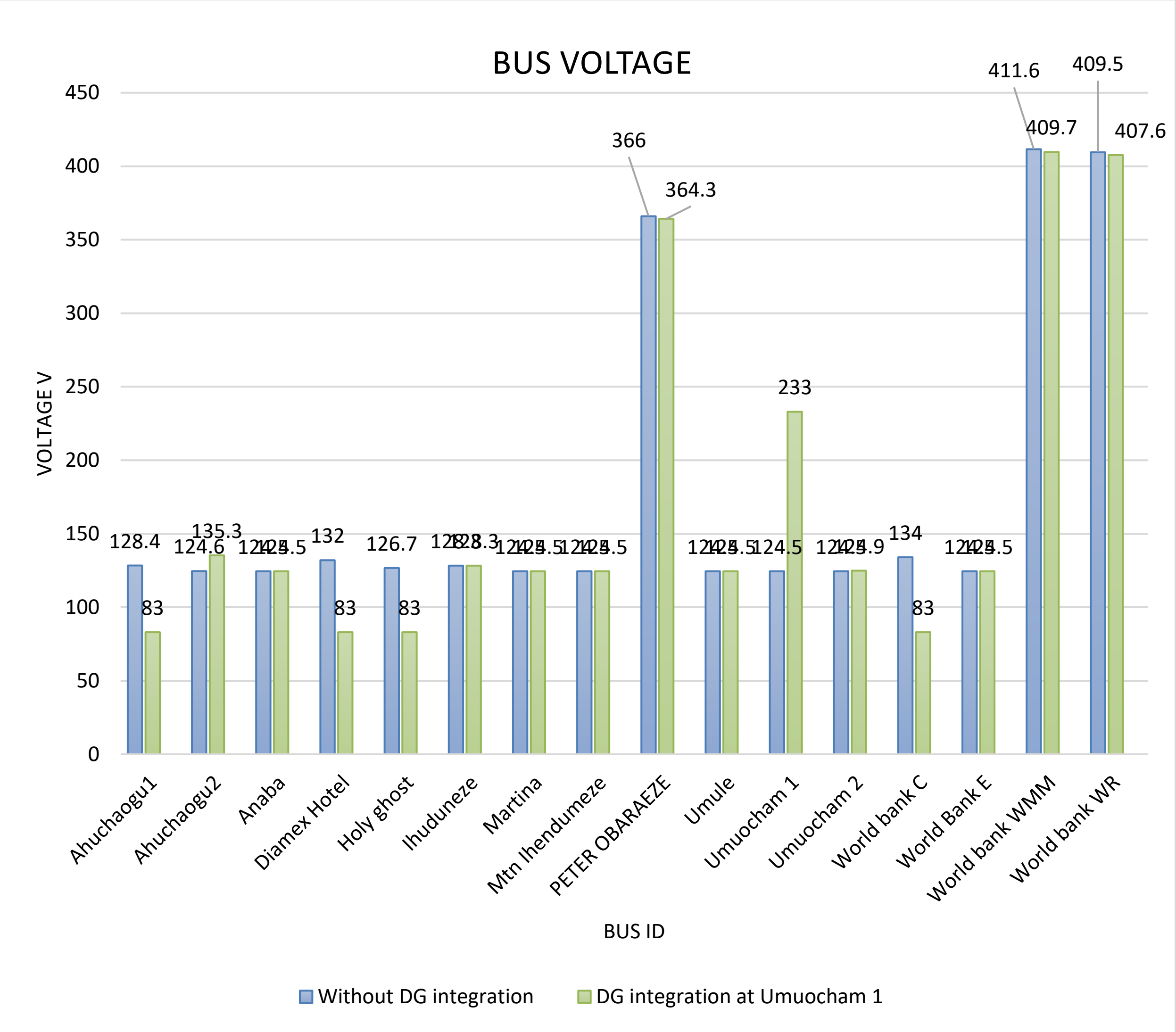

Figure 4.2: bus voltage Umuocham 1 DG integration

At the Umuocham 2 bus, the integration of solar PV resulted in a significant increase in bus voltage, rising from 124.5V to 206V (see Figure 4.3). The Umule bus also experienced a considerable voltage improvement, increasing from 124.5 to 132V. However, the bus voltages at Ahuchaogu 1, Holy Ghost, and Diamex Hotel dropped substantially, decreasing from 124.5V to 83V.

Table 4.5: Bus Data for DG integration at **Umuocham 2** Bus

Bus ID	Nominal kV	Type	Voltage	kW Loading	kvar Loading
Ahuchaogu1	0.415	Load	83	0.0992	0.0744
Ahuchaogu2	0.415	Load	128.3	0.574	0.313
Anaba	0.415	Load	135.9	0.0229	0.015
11 KV bus	11	Load	10975	10.62	13.53
Diamex Hotel	0.415	Load	83	0.007	0.0039
Holy ghost	0.415	Load	83	0.021	0.0117
Ihuduneze	0.415	Load	128.3	0.633	0.359
Martina	0.415	Load	124.5	1.02	0.578
Mtn Ihendumeze	0.415	Load	124.5	0.0234	0.0156
PETER OBARAEZE	0.415	Load	364.1	0.366	0.166
Umule	0.415	Load	151.8	0.41	0.208
Umuocham 1	0.415	Load	124.8	0.386	0.252
Umuocham 2	0.415	Load	206	3.79	2.59
World bank C	0.415	Load	83	0.0183	0.0285
World Bank E	0.415	Load	124.5	0.324	0.243
World bank WMM	0.415	Load	409.5	6.9	9.86
World bank WR	0.415	Load	407.4	3.71	3.79

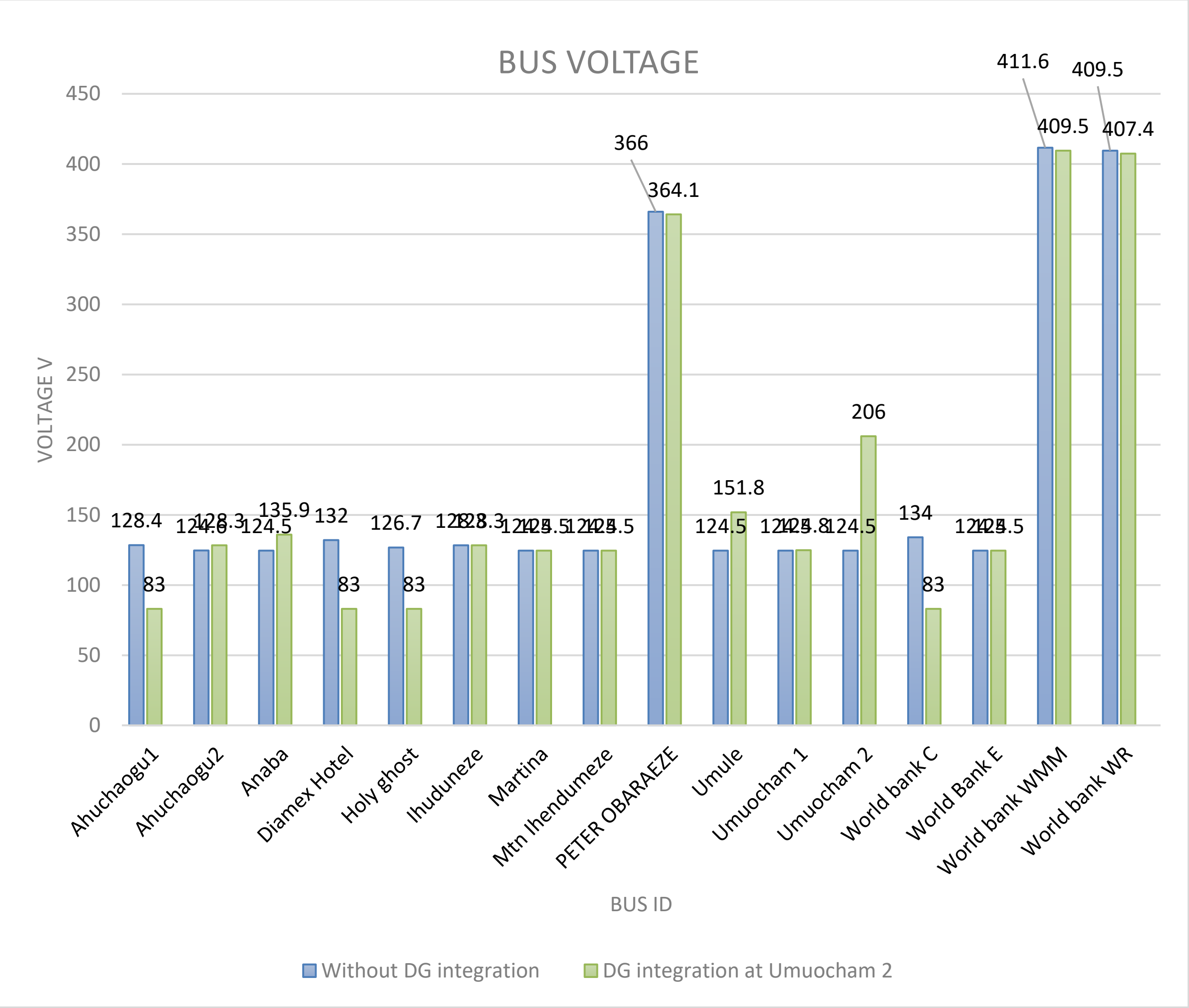

Figure 4.3: bus voltage Umuocham 2 DG integration

Integrating solar PV at the Ihuduneze bus led to a notable increase in bus voltage, from 128.3V to 210.23V (refer to Figure 4.4). In contrast, the Peter Obaraeze bus experienced a significant voltage drop, decreasing from 366V to 223.2V. Additionally, the Martina bus showed a slight improvement in voltage.

Table 4.6: Bus Data for DG integration at Ihenduneze bus

Bus ID	Nominal kV	Type	Voltage	kW Loading	kvar Loading
Ahuchaogu1	0.415	Load	128.4	0.238	0.179
Ahuchaogu2	0.415	Load	124.6	0.527	0.295
Anaba	0.415	Load	124.5	0.0192	0.0126
Bus3	11	Load	10973.8	12.05	13.54
Diamex Hotel	0.415	Load	131.9	0.0176	0.01
Holy ghost	0.415	Load	126.7	0.0488	0.0273
Ihemduneze	0.415	Load	210.23	2.62	1.45
Martina	0.415	Load	127.5	1.07	0.618
Mtn Ihendumeze	0.415	Load	126.7	0.0242	0.0161
PETER OBARAEZE	0.415	Load	223.2	0.36	1.51
Umule	0.415	Load	124.5	0.272	0.14
Umuocham 1	0.415	Load	124.5	0.384	0.251
Umuocham 2	0.415	Load	124.5	0.367	0.275
World bank C	0.415	Load	133.9	0.062	0.0432
World Bank E	0.415	Load	127.5	0.34	0.255
World bank WMM	0.415	Load	408.7	8.3	9.88
World bank WR	0.415	Load	406.7	3.7	3.77

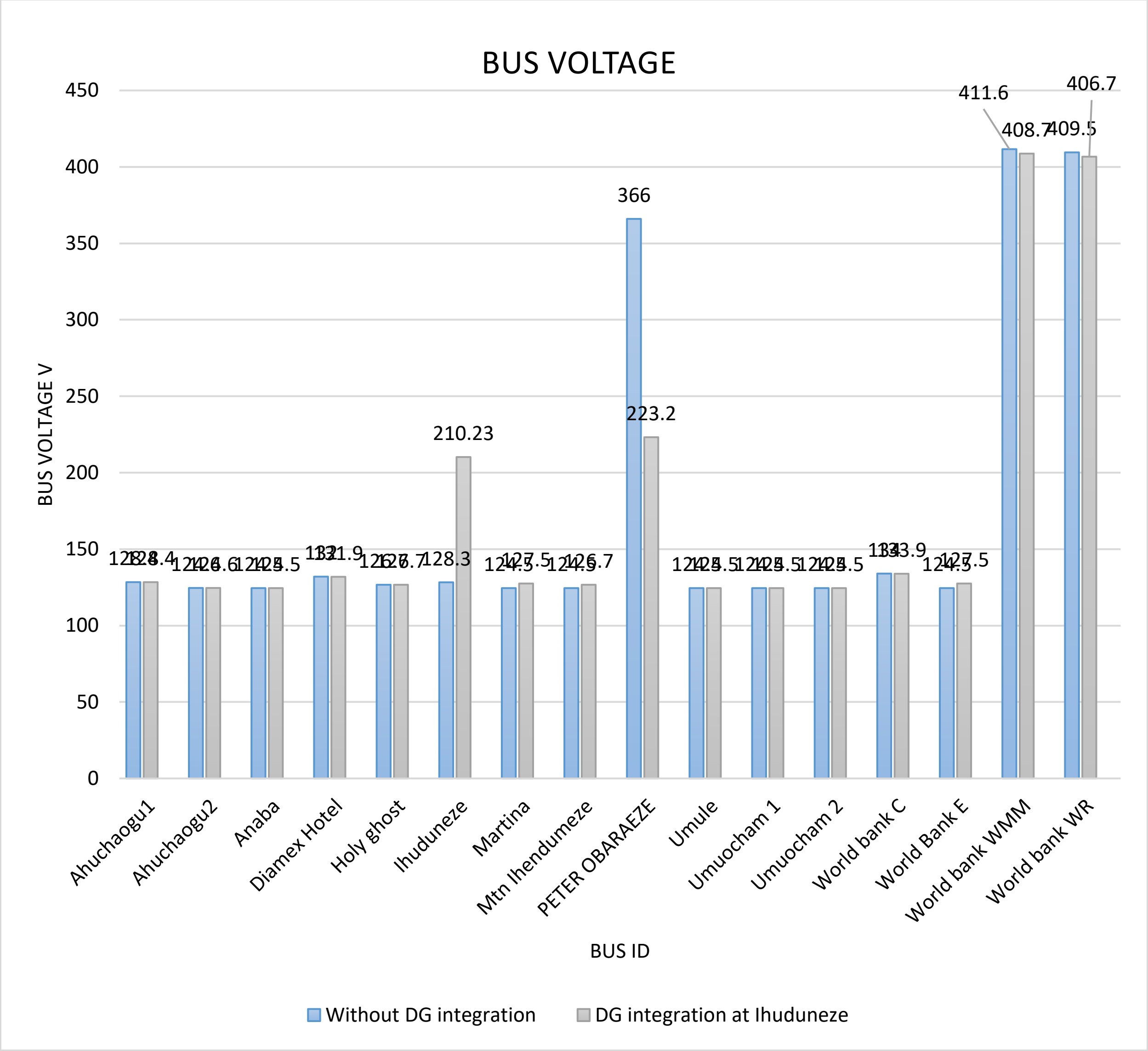

Figure 4.4: bus voltage Ihuduneze DG integration

4.2 Discussion

After integrating DG at the World Bank East bus, significant voltage improvements were observed at World Bank East, Martina, and Ihenduneze, while a slight voltage drop below nominal value occurred at Peter Obaraeze.

Similarly, DG integration at Umuocham 1 resulted in notable voltage improvement at that bus, but slight voltage drops below nominal values were recorded at Holy Ghost and Diamex Hotel buses.

At Umuocham 2, significant voltage differences were noted before and after DG integration, with improvements at Umuocham 2 and Umule buses, though Holy Ghost and Diamex Hotel buses experienced minor voltage reductions.

DG integration at Ihenduneze improved voltages at Ihenduneze and World Bank East buses, but a voltage reduction was observed at Peter Obaraeze.

5. CONCLUSION

The study highlights the significance of renewable energy sources for power integration. It demonstrates how integrating Solar PV DG systems into distribution grids and buses can enhance voltage profiles and wattage flow, thereby facilitating the delivery of high-quality power.

It also emphasized a drawback, noting that voltage can drop below nominal levels in some buses when DG is integrated into a bus located far from them.

5.1 Probable causes of Voltage reduction in some buses

Power Flow Direction: Uneven power distribution or reverse power flow caused by the solar source can create imbalances, leading to voltage reductions in distant buses.

Load Variations: High or fluctuating loads on distant buses can exacerbate voltage drops, especially if the solar source cannot supply sufficient power during peak demand (Iioka et al., 2019).

Impedance of Distribution Lines: High impedance in lines connecting the buses can increase voltage drops, especially under heavy load or high power transfer conditions.

Intermittent Solar Generation: Fluctuations in solar output due to weather conditions can lead to inconsistent voltage levels, causing drops in buses not directly supported by the solar source.

Inadequate Network Design: A network not optimized for distributed generation integration may face power flow constraints or imbalances, leading to voltage drops in some areas.

Harmonics and Power Quality Issues: Solar inverters can introduce harmonics into the network, potentially degrading voltage levels in some buses.

5.2 Recommendations

Mitigating these issues requires proper network planning, harmonics compensation, and load balancing to ensure consistent voltage levels throughout the distribution network.

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