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Impact Assessment of Increasing Solar PV Penetrations on Voltage and Total Harmonic Distortion of a Distribution Network

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***Abstract*—This paper presents a study on the impact of increasing PV integration on voltage profile and total harmonic distortion of the electrical distribution sub-network that supplies the Professorial and Lecture Theatre Blocks of the College of Engineering of the Kwame Nkrumah University of Science & Technology (KNUST). Real-time power quality (PQ) data were captured at 10 minute intervals using CA 8335 PQ analyzer as well as a Sunny Webbox solar PV data logger, whilst simulations were undertaken using the Open Distribution System Simulator (OpenDSS) software. The simulated results were compared with ground data measurements by the power quality analyzer for purposes of validation.**

PV integration generally improved the voltage profile by as much as 15 %. Simulation results also showed that voltage limits would be exceeded at a PV penetration level of more than 140 %, corresponding to158 kWp PV injection. The 3 % total harmonic distortion (THD) limit set by the Ghana Grid Code was found to be exceeded at 169 % or more PV penetration. The 169 % penetration level, which corresponds to a PV installed capacity of 18.73 MW, is not likely to be attained for the distribution system used for the study. *Hence total voltage harmonic distortion is not a major concern with increasing penetration level for the case study distribution network.*

Keywords—PV system; penetration level; total harmonic distortion (THD); OpenDSS; distribution network

I. INTRODUCTION

High growth in population, increased industrialization and modernization has given rise to increased demand on the existing exhaustible fossil fuel-based energy sources. The need for other renewable and non-polluting sources to complement the existing power supply has thus become imperative because, these renewable energy sources (RES) are abundantly available, clean and environmentally friendly.

In the drive for renewable energy resources, solar energy and hence solar PV systems are currently featuring prominently because PV modules prices are gradually becoming cheap with improved technology. According to [1], solar photovoltaic module prices have fallen by around 80% on average since the end of 2009, while electricity costs from large-scale solar PV plants halved between 2010 and 2014, according to IRENA's Quarterly Update published in October.

In Ghana, with the promulgation of the Renewable Energy Law 2011, Act 832, the integration of solar generation systems into the grid is being vigorously promoted as a way of supplementing the traditional electrical energy sources to meet the increasing demand. But the high integration of solar photovoltaic resources into the distribution grid presents a number of technical challenges, and changes the normally expected network behavior [2]. These include power quality-related issues like voltage rise/variation from the nominal value, frequency deviations [2], [3], [7], [9], network instability [3], harmonic injections and associated protection coordination issues [4], [5], unintentional islanding [6], system loss with increased PV penetration [8] and reverse power flow [10]

Various impact studies have been conducted to quantify the negative effects and challenges of high PV deployment. In a study by Velasco et al [7], simulations were undertaken in a South African LV network with the Diligent Power Factory software. Up to 120 kW PV representing 480 % penetration, the voltage was within acceptable range but with 170 kW representing 680 % penetration level, the voltage rose by 7 % above the acceptable ± 5 % deviation. Both real and reactive power loss also increased as penetration increased. A 120 kW penetration caused a real power loss of 0.5 % and reactive loss of 0.7 %, while an increased penetration of 240 kW caused a real power loss of 1.6 % and reactive loss of 2.8 %. Another study by [8] on a UK LV distributed system using MATLAB/SIMULINK registered a voltage level of 1.12 p.u. at 100 % penetration at peak irradiation and low load.

This paper presents findings of a study sponsored by the Energy Commission of Ghana to assess the impact of increasing solar PV integration on the voltage profile and total harmonic distortion (THD) of the electrical distribution sub-network that supplies the Professorial and Lecture Theatre Blocks of the College of Engineering of the Kwame Nkrumah University of Science & Technology (KNUST), Kumasi, Ghana. Real-time power quality (PQ) data were captured at 10 minute intervals using a CA 8335 PQ analyzer as well as a Sunny Webbox solar PV data logger, whilst simulations were undertaken using the Open Distribution System Simulator (OpenDSS) software. The simulated results were compared with ground data measurements by the power quality analyzer for purposes of validation.

II. INTEGRATION IMPACTS OF SOLAR PV GENERATION ON THE POWER GRID

The integration of renewable energy technologies has unique characteristics in terms of generation, transmission and operational technology, and while they can have positive impacts on that network, they can also have negative impacts at high penetrations if appropriate measures are not implemented [11], [13]. There are two main types of PV system integration technical challenges [3].

1. The first is distribution-network-level PV impacts, which includes impacts that are isolated to localized LV networks (such as voltage imbalance, voltage instability, voltage rise and reverse power flow, etc.) and do not translate into problems for the entire network

2. The other has to with the whole system network-level PV impacts, which includes system instability due to frequency deviations that occasion inverter switching offs as well as cloud fluctuations.

The impacts and challenges of large-scale photovoltaic (PV) distributed generation on the power grid are treated below.

A. Voltage imbalance

Voltage imbalance is when the amplitude of each phase voltage is different in a three-phase system or the phase difference is not exactly 120°. Single phase systems installed disproportionately on a single phase may cause severely unbalanced networks leading to damage to controls, transformers, and distributed generators (DG), motors and power electronic devices [11].

B. Voltage Instability

Inverters are responsible for keeping the power factor of the PV system at unity. When the power factor is at unity there is no exchange of reactive power between the inverter and the grid. This becomes problematic when solar PV is connected to a weak grid and the capacity is large, static voltage instability problems will occur since the PV system will draw reactive power [14]

C. Voltage Rise

Voltage rise is caused by high penetration of solar PV into the utility grid. It is the situation when there is an increase in voltage at the inverter side or load end relative to the utility voltage [15]. Such voltage rise can cause overvoltage tripping at the inverter and this will affect the overall performance of the grid. Besides having negative impacts on end-use equipment, voltage rise can also have negative customer equity impacts for system owners towards the end of the line as the voltage rise will be greater at that point [11].

Neutral voltage rise can also occur when there is an imbalance of loads and high PV generation on three phase power system [16]

D. Reverse Power Flow

With significant levels of PV on feeders, localized overvoltage can occur, and this can result in reverse power flow. The most common technical impact of reverse power flow is activation of network protection devices designed to stop ‘upstream’ current flow. Destabilization of voltage regulators’ control systems can also occur - because they are not designed for both forward and reverse power flow [11]

E. Losses

With the introduction of utility-scale PV generation (PVG), the network is being utilized in a different way with more variable and bidirectional power flows. The level of losses is closely linked to the power flows. Therefore the deployment of PVGs and the altered power flows that result may have a significant impact on losses [12].

F. Protection Issues

A number of different aspects of DG protection can be identified, namely, protection of the generation equipment from internal faults; protection of the faulted distribution network from fault currents supplied by the DG; anti-islanding or loss-of-mains protection (islanded operation of DG will be possible in future as penetration of DG increases) and impact of DG on existing distribution system protection [24].

G. Impact on system stability due to anti-islanding protection feature

Networks isolated from the main grid are more susceptible to frequency deviations than large interconnected grids. If a system disturbance occurs, such as a fault on the network, it is likely that an excursion will occur in either frequency or voltage, resulting in disconnection of PV systems from the network. Some customers with PV systems are reported to have experienced disconnection of their inverters from the network due to network frequency/voltage fluctuations [3].

But of particular concern for network stability is the frequency anti islanding protection. This is because voltage excursions are more likely to be localized, they only affect a small number of inverters and thus won't show as a large load fluctuations from the perspective of the power station. Conversely, the frequency is constant throughout the network and as such a frequency excursion will be visible to all inverters connected to the network. This has implications for network stability as there will be simultaneous disconnection of all inverters on the network [3]

H. Impact on system stability due to cloud fluctuations

Multiple numbers of solar PV units connected to the same distribution feeder in a small area resulting in a high density of PV installations is typically defined as a PV "cluster" [2].The output of PV systems is subject to variability with changes in solar irradiation. When the systems are highly clustered together, it is possible that large clouds can effectively reduce a large proportion of PV generation in a short period of time. Also due to the so-called cloud edge effect, the power output from PV can increase when cloud is approaching the system as solar irradiation can be increased by reflection and refraction from the approaching cloud [3].

The combination of these effects is that passing cloud cover has the potential to cause large and rapid variation in PV system output. When this effect is aggregated on a clustered network, the PV output variation appears as rapid load variation to the central generator, and depending on generator ramp rates and spinning reserve, there will be implications for system stability. This effect is also known as cloud shear [3]

III. VOLTAGE REGULATION VIA REACTIVE POWER CONTROL BY SOLAR PV INVERTERS

The interconnection standards for grid-connected PV distribution systems require that the terminal voltage be maintained within 0.95 to 1.05 p.u. of rated voltage and operate at or near unity power factor. To maintain the terminal voltage within the stipulated range, PV systems will have to either inject or absorb reactive power. Current inverters in a solar PV system have that reactive power control capability. If the voltage happens to be within the statutory limit, the PV inverter injects only active power. If the bus voltage rises above the maximum threshold, the inverter absorbs reactive power and acts like an inductor load. However, if the terminal voltage falls below the minimum value, the inverter injects reactive power like a capacitive load to boost the voltage [10].

Solar PV inverters typically operate at unity power factor and therefore the reactive power capability is kept ideally at *zero* so that whole capability of the inverter can be used for real power generation. However, if the PV inverters are allowed to inject reactive power, the capability has to be increased in such a way that the inverters are capable of injecting a certain amount of reactive power even at the time of maximum real power generation. The rating of the PV inverter needs to be increased to supply this additional output [2].

The power flow and voltage equations at a node or point of common coupling (PCC) in a radial circuit have been deduced by [9] as:

$$P_{k+1} = P_k - R_k\left(\frac{P_k^2 + Q_k^2}{V_k^2}\right) - p_{k+1} \quad (1)$$

$$Q_{k+1} = Q_k - X_k\left(\frac{P_k^2 + Q_k^2}{V_k^2}\right) - q_{k+1} \quad (2)$$

$$V_{k+1}^2 = V_k^2 - 2(R_k P_k + X_k Q_k) + (R_k^2 + X_k^2)\left(\frac{P_k^2 + Q_k^2}{V_k^2}\right) \quad (3)$$

Where $P_k + jQ_k$ is the complex power complex power flowing away from node k towards node $k+1$, V_k is the voltage at node k, $R_k + jX_k$ is the complex impedance of the link between node k and $k+1$, and $p_k + jq_k$ is the complex power extracted at node k. Both p_k and q_k are composed of local consumption minus local generation due to the PV inverter [9]

For a linearized model, the rate of energy dissipation (losses) L in the distribution circuit is given as

$$L = \sum_{k=0}^{n-1} R_k\left(\frac{P_k^2 + Q_k^2}{V_0^2}\right) \quad (4)$$

Where V_0 is the voltage set-point. The voltage variations must be within the statutory limits, and must obey equation (5) [9]:

$$\delta V = \max\left|\frac{V_k - V_0}{V_0}\right| \angle \varepsilon \quad (5)$$

where $\varepsilon \approx 0.05$ in normal operation.

The voltage regulation approach is akin to what happens in conventional power generating plants where voltage control is achieved by the manipulation of reactive power output within the reactive capability limits of the plant. The amount of reactive power generation or consumption will depend on the voltage set-point [2].

The inverter reactive power injections at a node or point of common coupling (PCC) in a radial circuit have also been deduced by [2] as:

$$S^k{}_{NI} = P^k{}_{NI} + jQ^k{}_{NI} = \left(P^k{}_{PV} - P^k{}_L\right) + j\left(Q^k{}_{PV} - Q^k{}_L\right) \tag{6}$$

Where $S^k{}_{NI}$ is the net PV injection at the k-th node, $P^k{}_L + jQ^k{}_L$ is the load connected at the k-th node and $P^k{}_{PV} + jQ^k{}_{PV}$ is the power injection by the solar PV inverter.

If the reactive power production is higher than the reactive power demand, this will create **reverse reactive power** flow in the feeder. Solar PV inverters provide maximum reactive power based on their remaining capability after generating active power [2]

IV. HARMONICS AND INTERCONNECTION STANDARDS

The deployment of large-scale solar PV inverters in the LV distribution networks leads to harmonic injection. From the manufacturer's specification sheets, the total harmonic distortions of SMA single-phase inverters employed in this research are less than 3 % [5]. Moreover, the predominant harmonics that emanate from power inverter outputs are the odd harmonics [6]. The total voltage harmonic distortion (VTHD) values were computed from the odd harmonics up to 13th considering both solar PV system harmonic contribution and background (load) harmonic contribution.

Thus the VTHD given as the ratio of the root of the square sum of the 3rd, 5th, 7th, 9th, 11th and 13th harmonics to the fundamental is expressed as (7):

$$VTHD = \frac{\sqrt{V_3^2 + V_5^2 + V_7^2 + V_9^2 + V_{11}^2 + V_{13}^2}}{V_1} \tag{7}$$

The regulating standards on harmonics and voltage in the distribution network used in this research are respectively IEEE Standard 519-1992: *Recommended Practices and Requirements for Harmonic Control in Electric Power Systems* [11], and ANSI C84.1-2006: *Voltage Levels of Electric Power Systems and Equipment* [12], and are found in Table 1 and Table 2.

TABLE I. VOLTAGE DISTORTION LIMITS FOR DIFFERENT VOLTAGE LEVELS [11]

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
69 kV and below	3.0	5.0
69.001 kV through 161 kV	1.5	2.5
161.001 kV and above	1.0	1.5

TABLE II. UTILIZATION VOLTAGE RANGES [12]

Nominal service voltage	Range B minimum	Range A minimum	Range A maximum	Range B maximum
Single-phase				
120/240, 3-wire	104/ 208	108/ 216	126/252	127/254
Three phase				
240/120, 4-wire	208/ 104	216/ 108	252/126	254/127
208Y/277, 4-wire	180/ 104	187/ 108	218/126	220/127
480Y/277, 4-wire	416/ 204	432/ 249	504/291	508/293
1.4 - 34.5 kV % of nominal Above 34.5 kV	86.7%	90%	105%	105.8%

V. CASE STUDY SYSTEM

The KNUST radial distribution sub-network used as case study is shown in Fig. 1. The network consists of underground copper and aluminum cables spanning a total length of 715 meters. The points of common coupling (PCC) of the 24 kWp solar PV system are two of the six load buses in a distribution pillar located at the Pharmacy Block and supplied by a 11/0.433 kV, 500 kVA transformer at the Agricultural Science Substation of KNUST. The total measured peak load was 113.382 kVA (110.846 kW and 16.743 kVAr). The source voltage varied between an average value of 0.9988 *pu* (10.98 kV) and 0.8 *pu* (9.8 kV).

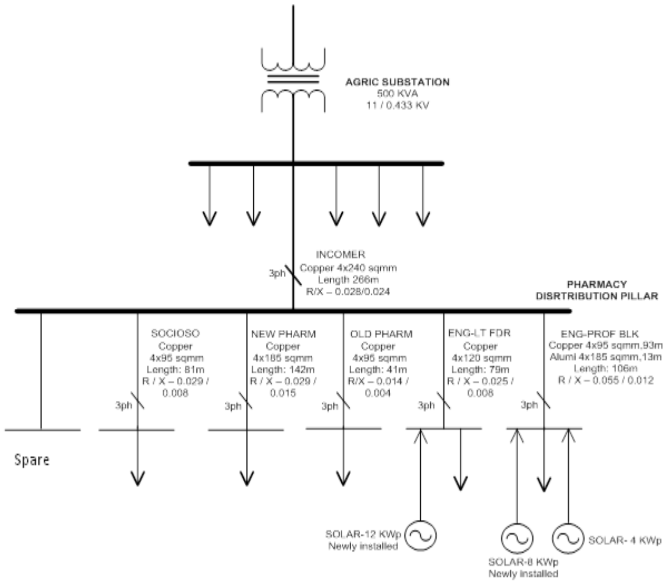


Fig. 1. *LV distribution system sub-network used for study*

The distribution system feeder underground cable parameters are given in Table 3.

TABLE III. BASIC UNDERGROUND CABLE PARAMETERS OF DISTRIBUTION SYSTEM SUB-NETWORK

Line / Feeder	Type & Dimension	R/m	X/m	Length (m)
Incomer	Copper, 4×240 mm2	0.028	0.024	266
Engineering PB	Copper, 4×95 mm2	0.055	0.012	93
	Aluminum, 4×185 mm2			13
Engineering LT	Copper, 4×120 mm2	0.025	0.008	79
Old Pharmacy	Copper, 4×95 sq. mm	0.014	0.004	41
New Pharmacy	Copper, 4×185 mm2	0.029	0.015	142
Social Science	Copper, 4×95 mm2	0.029	0.008	81

The 24 kWp solar PV system of the College Engineering (made up of different PV technologies, namely, amorphous silicon, polycrystalline and hybrid panels) is installed on the roofs of its Professorial and Lecture Theatre Blocks (Figs. 2 and 3). It has monitoring equipment that takes readings at hourly intervals. The energy from the PV arrays is supplied to the two load points through 7 single-phase inverters.

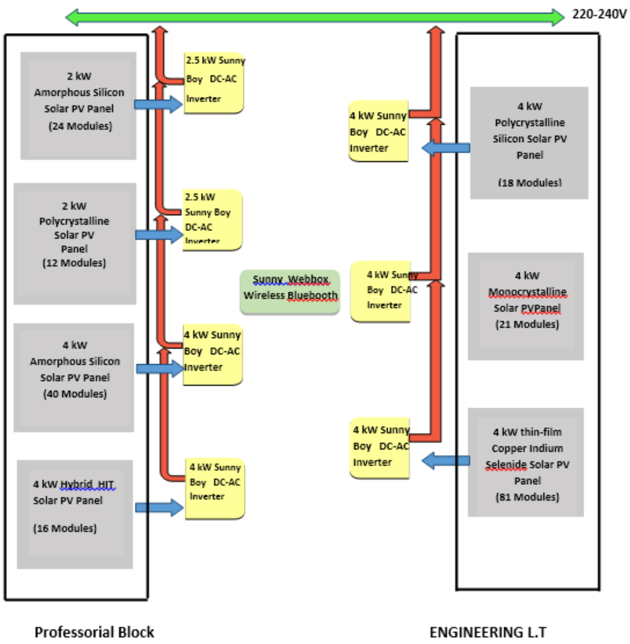
Currently, the percentage penetration level defined as rated output of solar PV system per peak feeder active power (8) [21] is 22 %.

$$\text{Penetration level} = \frac{\text{Rated output of solar PV } (kW)}{\text{Peak feeder real power } (kW)} \qquad (8)$$

Fig. 2. *12 kWp solar panels at the Engineering Professorial Block (PB)*

Fig. 3. *12 kWp solar panels at the Lecture Theatre (LT) Block*

Provided in Fig. 4 is information on the types of PV arrays and other solar PV technologies used for the installation.



Professorial Block Lecture Theatre Block

Fig. 4. *Configuration of installed PV system showing inverter ratings, types of PV technologies and module numbers*

VI. METHODOLOGY ADOPTED

The following procedures were adopted in the implementation of the research:

1. Capture of 24-hr solar irradiance and average ambient temperature data from an Automatic Weather Station (AWS) at the KNUST Solar Energy Applications Laboratory (SEAL)
2. Modeling of the LV distribution sub-network and the 24 kWp solar PV system in the Open Distribution System Simulator (OpenDSS)

3. Simulation of electrical impact of solar PV integration on the distribution sub-network using OpenDSS.
4. Simulation of PV penetration levels of 30 %, 50 %, 70 %, 100 %, 120 % and 200 **%** of the peak load to investigate the maximum penetration levels in the distribution network. The pyranometer data used for the simulation consisted of Global Horizontal Irradiance (GHI) and Average Temperature (AvgT) captured on 18th October, 2013.
5. Simulation of the voltage rise having regards to ANSI voltage range A, as well as the total voltage harmonic distortion (VTHD) having regards to IEEE 519-1992.
6. The source voltage was held constant at 0.99 p.u for the simulation, because it could not be varied in the OpenDSS. However, the actual source voltage was not constant, but varied
7. Capture of real-time power quality (PQ) data at 10 minute intervals using the Chauvin Arnoux CA 8335 power quality analyzer (PQA)
8. Analysis of PQ data captured and solar PV data monitored
9. Validation of simulated results with measured data

The tools used are shown in Figs. 5, 6 and 7.

Fig. 5. *Pyranometer at SEAL lab at KNUST*

Fig. 6. *Chauvin Arnoux CA 8335 power quality analyzer (PQA) used for data measurement*

Fig. 7. *SMA solar PV data logger*

VII. RESULTS AND ANALYSES

In this section, the results of some measured data using the CA 8335 PQA will be presented, followed by simulation results from the OpenDSS and assessment of impacts of increasing PV penetration on voltage and harmonic profiles. The results will be presented under the following headings:

1. Measured impact on voltage profile
2. Measured impact on reverse power flows
3. Measured impact on harmonic distortions
4. Comparison of simulated voltages with measured voltages, and their validation
5. Impact of increasing PV penetration on distribution system performance

VIII. MEASURED IMPACT OF PV INTEGRATION ON VOLTAGE PROFILE

Voltages measured at the points of common coupling (PCC) of the 24 kW solar PV and the grid are presented in this section. The analyses are made for all phases.

A. Phase-1 Voltages Measured at the Professorial Block

Fig. 8 shows voltage profiles for Phase-1 WITH and WITHOUT PV injection at the ***Professorial Block***. The data WITH PV were recorded on Friday, 18th October, 2013 and that WITHOUT PV recorded on Thursday, 24th October, 2013.

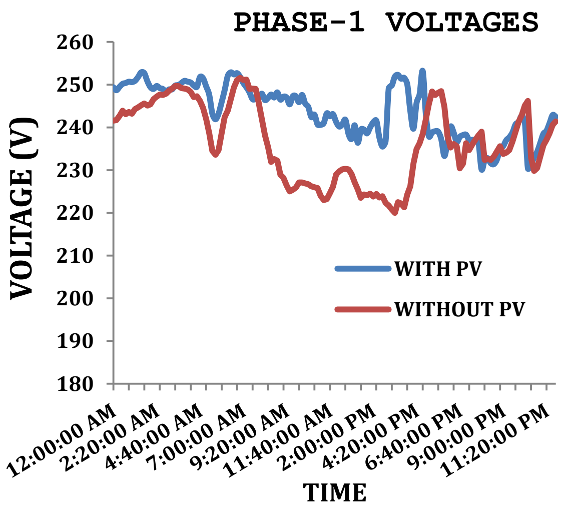


Fig. 8. *Comparison of measured voltage profile WITH and WITHOUT PV at the Professorial Block*

Observations/Analyses of Fig. 8:

1. It is observed that there was voltage improvement WITH PV injection during the active PV injection period.
2. From 6:00 AM to 6:00 PM when there was active PV injection, the voltage varied from 220 V to 245.5 V WITHOUT PV injection and from 235.5 V to 253.2 V WITH PV injection.
3. The highest voltage rise was 15 % and this occurred at about 3:00 PM.
4. Similar voltage profiles were observed on Phase-2 and Phase-3.

B. Phase-1 Voltages Measured at Lecture Theatre Block

Fig. 9 shows voltage profiles for Phase 1 WITH and WITHOUT PV at the ***Lecture Theatre Block*** recorded on Monday, 18th November, 2013, and Friday, 8th November, 2013 respectively.

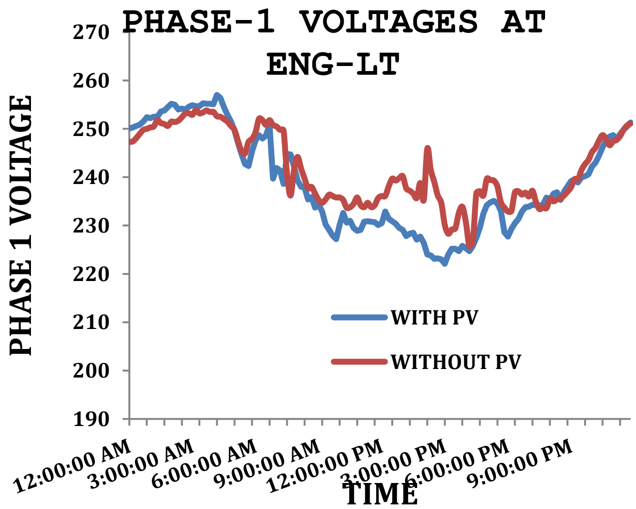


Fig. 9. *Comparison of measured voltage profile WITH and WITHOUT PV at the Lecture Theatre (LT) Block*

Observations/Analyses of Fig. 9:

1. For the case WITHOUT PV, the voltages fell in the range of 252.1V and 225.7 V, while for that WITH PV the voltages fell in the range of 250.9 V and 222.1 V between 6:00 AM to 6:00 PM.
2. Contrary to expectation, the voltages for the case WITHOUT PV were found to be slightly higher between the hours of 8:50 AM to 8:00 PM.
3. This can be attributed to the main supply voltage being lower than expected value of 11 kV (or 1.00 p.u).
4. The highest percentage difference between the two profiles was 11.90 % with respect to the case WITHOUT PV.
5. *Because of the low source voltage, the impact of PV generation cannot be easily deduced when compared with the absence of solar PV*.
6. This phenomenon was also observed on the other phases

IX. MEASURED IMPACT OF PV INTEGRATION ON REVERSE POWER FLOW

Reverse power flow measured at the PCC of solar PV and the grid is presented in this section. The measurements were made for all phases. However, only that for Phase-3 is being presented. The results of the other phases were similar.

A. Phase-3 Reverse Power Flow at the Professorial Block WITH PV injection during WEEKDAY and WEEKEND

Data for the reverse power flow at the ***Professorial Block*** for the case WITH PV WEEKDAY were recorded on Wednesday, 18th October, 2013. Data for the case WITH PV WEEKEND were recorded on Sunday, 13th October, 2013. The two are compared in Fig. 10.

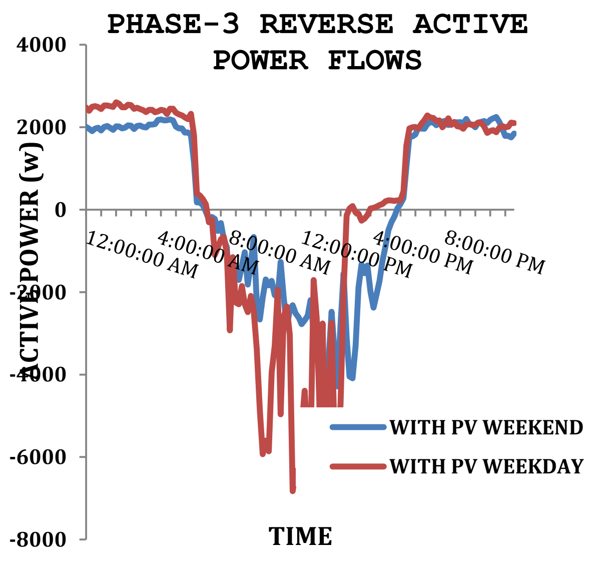


Fig. 10. *Comparison of reverse power flow on WEEKEND and WEEKDAY at the Professorial Block*

Observations/Analyses of Fig. 10:

1. The phenomenon of reverse (excess) power flow to the substation, *indicated by the negative sign of the power,* can generally be observed between the hours of 6:00 AM and 5:30 PM when active power generation of solar PV is high.
2. Outside these periods when there is a gradual reduction in active power generation from the solar PV, the grid rather complements the active power supply to the load, indicated by the positive sign of the power.
3. There was no reverse power flow on the other two phases.
4. The profiles of the other two phases (Phase-1 and Phase-2) were similar.

B. Phase-2 Reverse Power Flow at the Lecture Theatre Block WITH PV injection during WEEKDAY and WEEKEND

Data for reverse power flow for the ***Lecture Theatre Block*** for the case WITH PV WEEKDAY were recorded on Wednesday 2nd October, 2013. Data for the case WITH PV WEEKEND were recorded on Sunday, 6th October, 2013. The two are compared in Fig. 11.

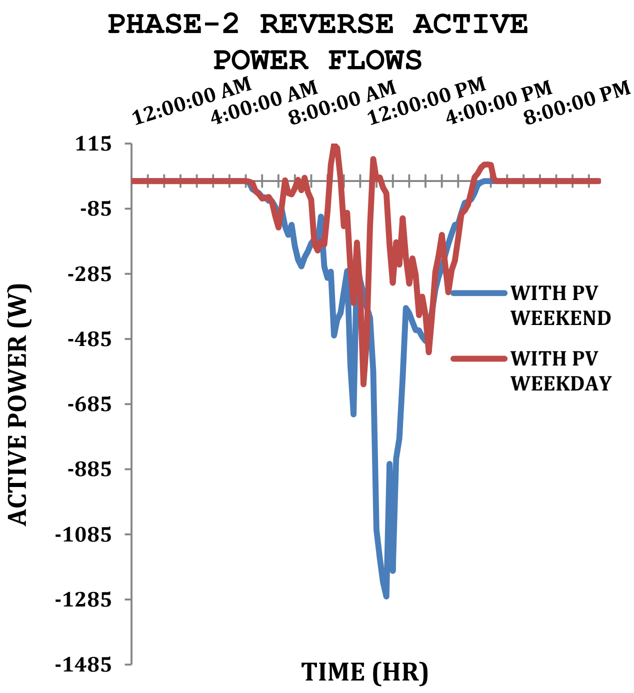


Fig. 11. *Comparison of reverse power flow on WEEKEND and WEEKDAY at the Lecture Theatre Block*

Observations/Analyses of Fig 11:

1. At the LT Block, the reverse (excess) power flow to the substation can also be observed between the hours of 7:00 AM and 6:00 PM on Phase-2.
2. The reverse power flow is higher during the WEEKEND when activities at the College of Engineering were low.
3. The maximum active reverse power flow of 1.28 kW occurred at 1:00 PM during the WEEKEND with PV integration. During the WEEKDAY, however, the maximum active reverse power flow of 624.23 W occurred at 11:50 AM.
4. Reverse power flow occurred also on Phase-3 of LT Block but not on Phase-2.

X. MEASURED IMPACT OF PV INTEGRATION ON TOTAL VOLTAGE HARMONIC DISTORTION

Voltage total harmonic distortion measured at the PCC of solar PV and the grid is presented in this section.

A. Phase-1 Voltage THD at the Professorial Block WITH and WITHOUT PV injection

Voltage THD WITH and WITHOUT PV at ***Professorial Block*** is compared in Fig. 12. Data for the case WITH PV were recorded on Friday, 18th October, 2013 and that WITHOUT PV were recorded on Thursday, 24th October, 2013.

Similar profiles were observed for Phase-2 and Phase-3.

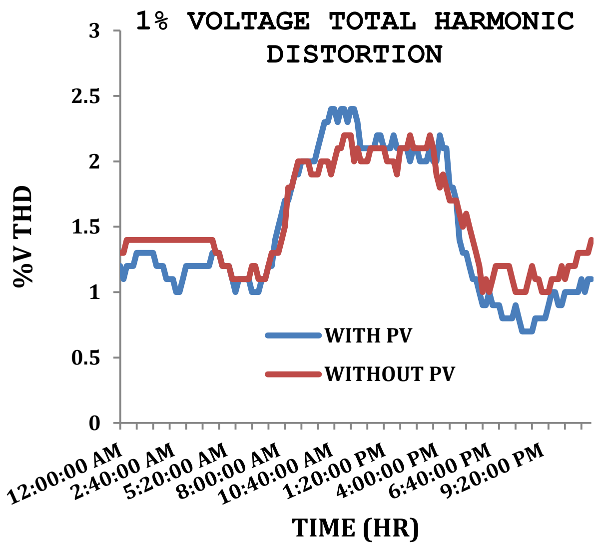


Fig. 12. *Comparison of voltage THD WITH and WITHOUT PV injection at the Professorial Block*

Observations/Analyses of Fig 12:

1. Voltage total harmonic distortions are seen to *increase marginally* with active PV injection.
2. At 9:40 AM voltage harmonic distortion begins to increase gradually from 2.0 % to peak value of 2.4 % at 11:40 AM.
3. This reduces gradually to 1.7 % from 5:10 PM to midnight.
4. *At the penetration level of 22 % (base case scenario), it is observed that the 3 % VTHD limit set by the Ghana Grid Code [23] is not exceeded.*

B. Phase-2 Voltage THD at the Lecture Theatre Block WITH and WITHOUT PV injection

Voltage THD WITH and WITHOUT PV at Professorial Block is compared in Fig.13. Data for the Lecture Theatre Block for the case WITH PV were recorded on Monday, 18th November, 2013, and that WITHOUT PV were recorded on Friday, 8th November, 2013. Similar profiles for Phase-1 and Phase-3 were observed.

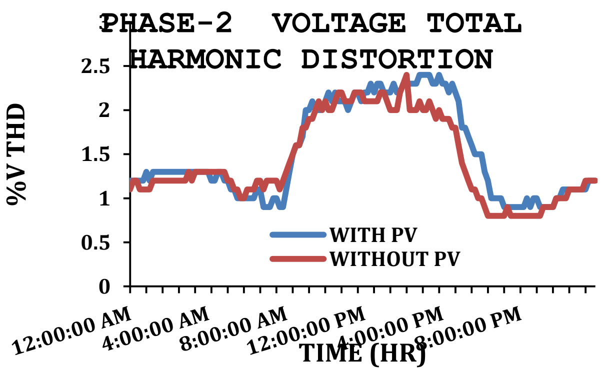


Fig. 13. *Comparison of voltage THD WITH and WITHOUT PV injection at the Lecture Theatre Block*

Observations/Analyses of Fig 13:

1. The voltage total harmonic distortion increased marginally with PV active generation at 12:00 PM from 2.1 % to a peak value of 2.4% at 2:50 PM.
2. This gradually reduced to a minimum value of 1.2 % in the evening.
3. The 3 % limit set by Ghana Grid Code is not exceeded at this point as well.
4. It is noted that the harmonic voltage distortions WITH and WITHOUT PV are higher at the Professorial Block than at the Lecture Theatre Block.
5. *This is because there are more non-linear loads at the Professorial Block than at the Lecture Theatre Block.*

XI. COMPARISON OF SIMULATED VOLTAGES WITH MEASURED VOLTAGES , AND THEIR VALIDATION

Fig. 14 compares simulated and measured voltages WITH PV injection at the ***Professorial Block***. The voltages were measured with the CA 8335 power quality analyzer.

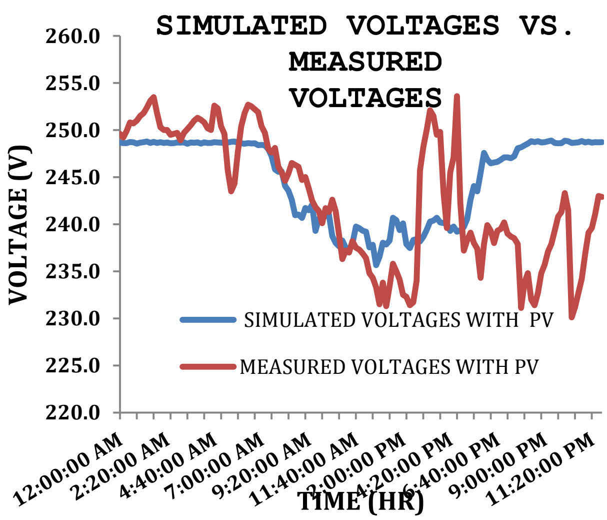


Fig. 14. *Comparison of measured voltages with simulated voltages WITH PV injection at the Professorial Block*

Observations/Analyses of Fig 14:

1. The source voltage was held constant at 0.99 p.u. for the simulation, because it could not be varied.
2. However, the actual source voltage was not constant. For instance, in the evenings it could be far below 0.99 p.u.
3. This explains the wide variation between the simulated and measured values after 5:00 PM and other peak times, when the supply voltage tends to drop.
4. Ignoring the data for the period after 5:00 PM, the root-mean-square error (RMSE) was found to be 4.31.

A scatter diagram plot of the simulated and measured voltages is shown in Fig. 15.

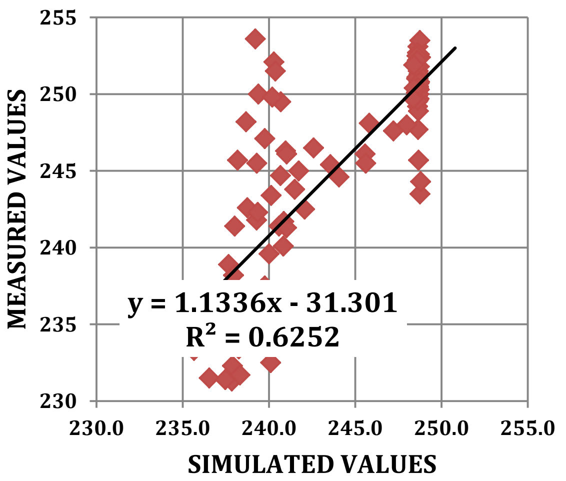


Fig. 15. *Scatter diagram plot of simulated and measured voltages WITH PV injection at the Professorial Block*

Observations/Analyses of Fig 15:

1. Using the Least Square Method, the relation between the measured values and the simulated values was found to be (8)

2. Measured value = 1.1xSimulated value – 31.3 (8)

3. The R^2 value found to be 0.63**,** giving a coefficient of correlation R=0.8, signifying a good correlation between measured and simulated values.

4. *Hence the system has been well modeled, and hence the simulation can be used to make a fairly good prediction of actual values***.**

XII. IMPACT OF INCREASING PV PENETRATION ON DISTRIBUTION SYSTEM PERFORMANCE

The simulation results obtained at the ***Professorial Block*** load bus under maximum load conditions and at peak active power generation from the solar PV system (worst case scenario) are presented here.

A. Impact of increasing PV penetration on voltage profile at the Professorial Block

Fig. 16 shows how the voltages vary with increasing percentage penetration at the Professorial Block.

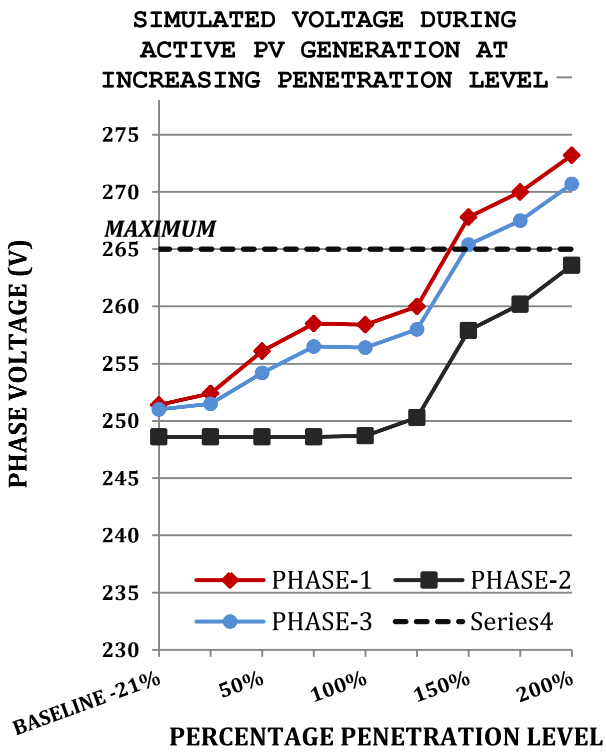


Fig. 16. *Simulated voltage for increasing PV penetration at the Professorial Block*

Observations/Analyses of Fig 16:

1. According to ANSI C84.1-2006, voltage limits for a system between 120 V and 600 V are 0.92 p.u. and 1.06 p.u. when measured at the utilization point, that is, the load point [22].

2. This represents a voltage range of 230 V to 265 V for the network under study.

3. From Fig. 16, the upper voltage limit of 265 V is exceeded at about 140 % penetration level (representing 158 kWp) on Phase-1.

4. *Hence the allowable penetration level should be 140 %.*

B. Impact of increasing PV penetration on total voltage harmonic distortion at Professorial Block

Fig. 17 shows simulated results of total voltage harmonic distortion (VTHD) at increasing penetration levels at the Professorial Block.

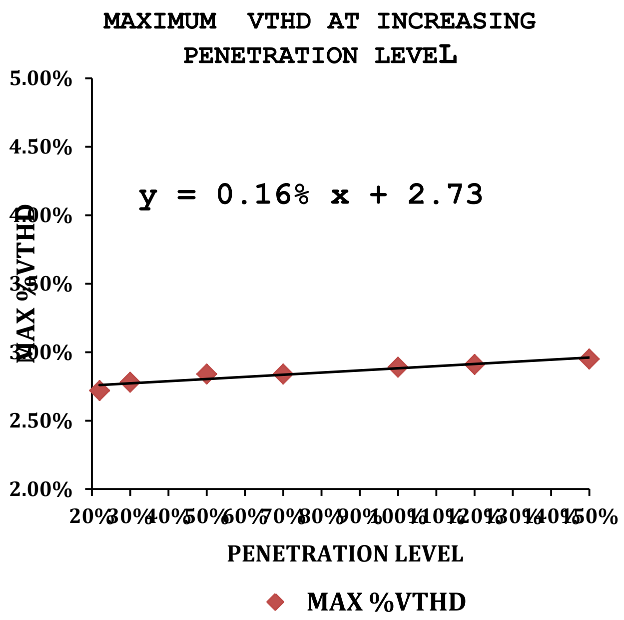


Fig. 17. *Simulated total voltageharmonic distortion (VTHD) increasing PV penetration at the Professorial Block*

<u>Observations/Analyses of Fig. 17:</u>

1. The VTHD increased from 2.55 % to 2.95 % as the penetration level was increased from 22 % (base case) to 150 %.
2. For penetration level up to 150 %, the VTHD was found to be within the 3 % limit specified in the Ghana Grid Code [23].
3. The curve may be approximated by the equation (9)

VTHD = 0.16 % x Penetration level +2.73 (9)

4. From equation (9), the *3 % VTHD limit set by the Ghana Grid Code will be exceeded at 169 % penetration level.*
5. This value, representing an equivalent PV installed capacity of 18.73 MW, is not likely to be attained for the distribution system used for the study.
6. Total harmonic distortion is thus not a concern for the distribution network under study.

XIII. CONCLUSIONS

In this paper, the 24 kWp solar PV systems and distribution sub-network they supply have been modeled using the Open Distribution System Simulator (OpenDSS).

Solar PV injections generally gave rise to an improved voltage profile.

Reverse power flow occurred when the PV generation exceeded the demand at the PCC, and was more pronounced on weekend (with light loading) than on weekdays.

From the simulation results, the maximum voltage limit of 265 V for the case study network would be violated at a PV penetration level of more than 140 %, corresponding to158 kWp PV injection. It is therefore not recommended to go beyond 140 % penetration level for the case study system.

The 3 % total harmonic distortion (THD) limit set by the Ghana Grid Code was found to be exceeded at 169 % or more PV penetration. The 169 % penetration level, which corresponds to a PV installed capacity of 18.73 MW, is not likely to be attained for the distribution system used for the study.

Hence total voltage harmonic distortion is not a major concern with increasing penetration level for the case study distribution network.

XIV. RECOMMENDATIONS

From the study, the following recommendations are made for integration codes for voltage and total voltage harmonic distortion:

Integration code for voltage profile:

The ANSI C84.1 code on voltage limits can be ADOPTED, with a 140 % penetration level limit placed on solar PV integration into distribution sub-systems.

Integration code for total voltage harmonic distortion:

The integration code prescribed in the Ghana Grid Code on VTHD should be ADOPTED for the distribution level. If this code is adopted, the total voltage harmonic distortion will not be a major concern since the 3 % total voltage harmonic distortion limit set by the Ghana Grid Code will not be exceeded by realistic and practical PV injection at the distribution level.

XV. SUGGESTED FUTURE WORK

- Further work must be done to ascertain the allowable penetration level beyond which *current harmonics limits* are violated for the LV distribution network.
- "Voltage dips" due to cloud transients/partial shading might be an issue at high PV penetration levels and might violate minimum acceptable voltage limits. A further study of this will be useful.
- Further work must be done to ascertain the allowable penetration level beyond which protection system coordination will be affected for distribution network.
- The penetration levels beyond which transformer and feeder transmission capacities are violated needs to be determined.

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