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# Minimization of Total Harmonic Distortion Introduced by Distributed Generation in a Distribution Network using Unified Power Quality Conditioner

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## ABSTRACT

**Distributed generation (DG) systems have become very popular in recent times as à solution to the ever-increasing demand for more energy caused by man's continuous quest for a better life. This is due to the obvious advantages of distributed generation, which include the elimination of the time and cost associated with the building of transmission systems. Regardless of the advantages of distributed generation, they still introduce some power quality problems into the network, of which harmonics appear to be the most prevalent. In this paper the level of harmonics introduced by solar (DG) sources is investigated and the unified power quality conditioner (UPQC) is proposed as a means of reducing these harmonics introduced by the presence of distributed generation sources. From IEEE 519 standard, the Voltage Total Harmonic Distortion (VTHD) should not exceed the 5% limit, but the VTHD obtained from Otovwodo network without the introduction of DG and UPQC was 13.09% – 22.59%. Also, Voltage Individual Harmonic Distortion (VIHD) should not exceed 3% as per IEEE 519 standard but was found in the range 10.79% - 17.45% in Otovwodo network before the introduction of DG. Harmonic load flow results of DG integrated network in the ETAP 16.0 software environment indicate an increase in Voltage Total Harmonic Distortion (VTHD) to values within the rang 15.60% - 24.37%. However, when the UPQC was introduced into the DG integrated network VTHD was found to reduce drastically to values within the range 1.81% - 4.86%. Thus, significantly improving the power quality of the Otovwodo Distribution Network.**

## 1. INTRODUCTION

The changes currently being observed, the world over, in power systems is driven by two major forces. One is the ever-increasing demand for electrical energy and the other is the demand for cleaner, greener, more environment friendly sources of power generation. Power industries, the world over, are thus driven by the need to expand capacity rapidly and at the same time come up with ways of doing so with minimal pollution and damage to the environment. The use of distributed generation is one method of connecting the gap between supply and demand for electrical energy. Distributed generation (DG), also known as

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decentralized generation, embedded generation, or dispersed generation, is any small-scale source of electrical energy that is directly connected to a power network's distribution system (Garipelly, 2012) . DG can come in different forms such as photovoltaic or solar systems, mini-hydro generation plants, or wind systems. Other forms include fuel-based systems, such as, fuel cells and micro-turbines. The numerous advantages of DG notwithstanding its introduction into the network comes at a cost. One of the cost implications of DG integration is the introduction of power quality (PQ) problems into the network. In renewable energy DG systems, we can identify two major types of PQ problems. These are problems involving voltage and frequency fluctuations and then problems of harmonics. Of these PQ Problems harmonics appear to be most prevalent. Harmonics refer to waveforms whose frequency are integral multiples of the original waveform and whose presence in the system create a distortion in the waveform of current and voltage from the usual sinusoidal shape (Pandya and Patel, 2018). In DG integrated systems harmonics are produced by power electronic converters which are used in renewable energy generation and integration. Some major effects of harmonics include; transformer saturation, equipment overheating, mains voltage flickering, incorrect operation of voltage sensitive devices, false tripping of protective relay systems, shorter life of organic insulation and audible noise in power system equipment (Olatunde and Awofolaju, 2016) . By using the proper custom power device (CPD) PQ problems, including harmonics, introduced by DG can be minimized. Hossain and Tür, (2018), enumerates the more common CPDs to include distributed static compensator (D-STATCOM), unified power quality conditioner (UPQC), static VAR compensator (SVC), uninterrupted Power Supply (UPS), and dynamic voltage restorer (DVR). The UPQC is a combination of a D-STATCOM and DVR. Combining both the qualities of D-STATCOM and DVR makes the UPQC more robust and desirable compared to other PQ minimization techniques (Khadkikar, 2011).

This research paper is divided into five sections. The first section discusses the concept of embedded power generation and its effect on the distribution system. It also mentions some power quality problems introduced by embedded power generation sources along with some existing mitigation techniques. In the second section the harmonics in the distribution system is discussed along with its effect on power equipment and consumer appliances. The third section introduces the unified power quality conditioner as a technique for the reduction of harmonic level in the power distribution system. The fourth section presents the materials and methods while in the fifth section, results are provided and the performance of the UPQC is discussed.

### 1.1 Harmonics in Power Distribution Systems

Harmonics in the distribution system refer to a distortion in the waveform of original system currents and voltages as a result of the presence of signals having frequencies that are integral multiples of the frequency of the fundamental or original current or voltage. Harmonics in power distribution systems are introduced by a number of factors one of which is the presence or existence of devices and equipment such as power electronic equipment used to integrate solar DG sources into the distribution system, which draw non-sinusoidal currents from the supply (Corasaniti et al., 2009). When these non-linear currents flow through the network they in turn give rise to non-sinusoidal harmonic voltages in network components.

Distortion in voltage creates a lot of issues for power providers at the distribution level as well as power consumers. Problems related to voltage harmonics include flickering, noise in power system components, incorrect operation of voltage sensitive devices, overheating of equipment, improper function of protective relays, transformer saturation and electromagnetic interference. Also the stability of the power system may be compromised when there is harmonic interaction between utility system and load (Gorantla et al., 2016). The presence of harmonics in the distribution system is measured in terms of total harmonic distortion (THD) and individual harmonic distortion (IHD). The total harmonic distortion (current or voltage) is defined as the ratio of square root of the sum of the squares of all harmonic components to the fundamental component (equation 1) while individual harmonic distortion (IHD) is defined as the ratio RMS value of individual component to RMS value of fundamental component (equation 2).

$$THD = \frac{\sqrt{\sum_{h=2}^{\infty} X_h^2}}{X_1} \quad (1)$$

Where $X_1$ is the RMS value of the fundamental current or voltage and $X_h$ is the RMS value of the $h^{th}$ harmonic

$$IHD = \frac{X_h}{X_1} \quad (2)$$

Although passive filters consisting of inductors and capacitor banks can be tuned to eliminate particular harmonics from the system, they may however result in resonance with line shunt capacitance and series inductance which pose a threat to system stability. For this reason research into the use of active filters like the dynamic voltage restorer (DVR), the distribution static compensator (D-STATCOM) and the unified power quality conditioner has gained relevance (Said and Nor, 2008).

### 1.2 Design of UPQC

The unified power quality conditioner (UPQC) employs series and shunt active filters that are linked back-to-back. Typically, these two filters are connected at the DC side and share a DC capacitor. By supplying voltage to maintain the load voltage at the desirable size, the series component shrinks supply side problems such as voltage sags/swells, flicker, voltage unbalance, and harmonics. The shunt component on the other hand takes care of issues such as poor power factor, load harmonic currents, and load unbalance by injecting currents in the system to make the source currents balanced sinusoids in phase with the source voltages (Bhatt and Vora, 2016). Figure 1 shows the structure of the UPQC and figure 2 shows the internal parts.

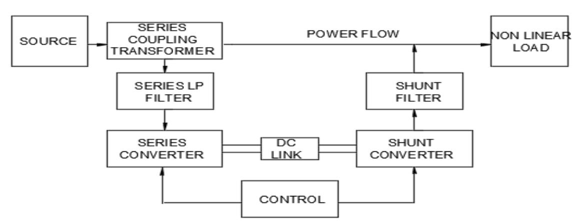


***Figure 1.*** *Block diagram of UPQC structure*

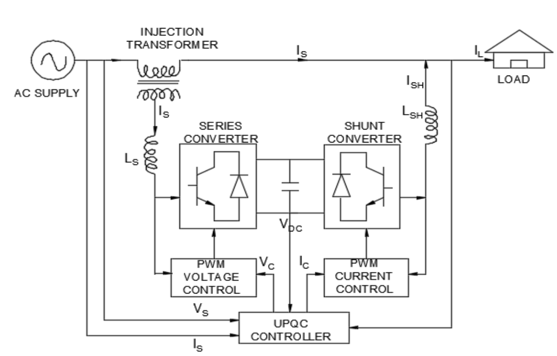

***Figure 2.*** *Parts of the UPQC*

With regards to function, the UPQC design has two distinct parts. The first is the power circuitry part which is made of the shunt and series Pulse Width Modulators (PWM) converters and the second part is the control part as seen in figure 2. The series PWM converter provides a source of voltage which is controlled, whereas the shunt PWM converter provides a source of current that is controlled. One distinguishing feature of the UPQC is that no power supply is connected at the common dc link, which can be either a capacitor or an inductor depending on the converter configuration (Sharma et al., 2017). The main function of the UPQC controller is to provide the compensating reference voltage $V_C$ and compensating reference current $I_C$ to the series and shunt converters respectively which is synthesized by using PWM voltage and current control technique. The shunt active filter can eliminate all unwanted current components, including harmonics and unbalances in the system (Singh and Arora, 2016). To cancel the harmonics produced by a solar embedded power generation source, the shunt converter would need to inject a current given by the equation 3:

$$I_C(\Theta) = I_S(\Theta) - I_L(\Theta) \qquad (3)$$

Where, $\Theta = \omega t$, $I_C(\Theta)$, $I_S(\Theta)$ and $I_L(\Theta)$ represents the shunt compensating current, source current, and load current respectively. By incorporating voltage in series with the line to achieve distortion-free voltage at the load terminal, the series active filter can eliminate supply voltage problems. The series converter should inject a voltage given by the expression:

$$V_C(\Theta) = V_L(\Theta) - V(\Theta) \qquad (4)$$

Where, $V_C(\Theta)$, $V_L(\Theta)$ and $V_S(\Theta)$ represents the series inverter injected voltage, load voltage, and actual source voltage, respectively. The control strategy should be capable of computing the three-phase reference voltage at the load terminal. The series active filter founded on Synchronous Reference Frame method (SRF) method can be used to solve the voltage related power quality problems such as, voltage sag, voltage swell and voltage harmonics. The SRF method in series active filter is used for generating reference voltage signal. The supply voltages are transformed into d-q-0 using the matrix (equation 5) below (Pavani and Sreelatha, 2018);

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = \sqrt{2/3}\begin{bmatrix} \sin(\Theta) & \sin(\Theta - 2\pi/3) & \sin(\Theta + 2\pi/3) \\ \cos(\Theta) & \cos(\Theta - 2\pi/3) & \cos(\Theta + 2\pi/3) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix}\begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \qquad (5)$$

Where, $\Theta = \mathrm{wt}$ is the transformation angle and V is voltage. The inverse park transformation is used for generating reference voltage signal through the equation below;

$$\begin{bmatrix} V'_{La} \\ V'_{Lb} \\ V'_{Lc} \end{bmatrix} = \sqrt{2/3}\begin{bmatrix} \sin(\Theta) & \cos(\Theta) & 1/\sqrt{2} \\ \sin(\Theta - 2\pi/3) & \cos(\Theta - 2\pi/3) & 1/\sqrt{2} \\ \sin(\Theta + 2\pi/3) & \cos(\Theta + 2\pi/3) & 1/\sqrt{2} \end{bmatrix}\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} \qquad (6)$$

Figure 3 shows the control block diagram of d-q theory for generating voltage reference signal using SRF. To implement the SRF method and for reference voltage calculation the phase locked loop (PLL) is used to generate the transformation angle (ωt) which presents the angular position of the reference frame. The low pass filter is used to obtain the reference source voltage in d-q coordinates.

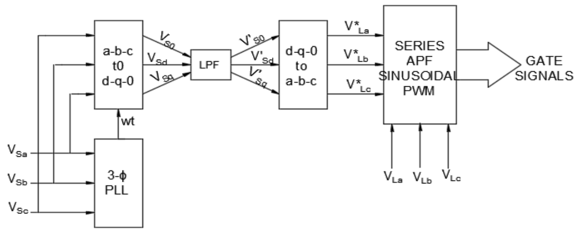


***Figure 3***. *Control block diagram of d-q theory of series APF*

The shunt active filter makes use of SRF method to solve the current related power quality problems including harmonic current. The SRF method is used for generating reference current signal (Pavani and Sreelatha, 2018). To achieve this the source currents are transformed into d-q-0 domain using the equation 7 matrix below;

$$\begin{bmatrix} I_d \\ I_q \\ I_0 \end{bmatrix} = \sqrt{2/3}\begin{bmatrix} \sin(\Theta) & \sin(\Theta - 2\pi/3) & \sin(\Theta + 2\pi/3) \\ \cos(\Theta) & \cos(\Theta - 2\pi/3) & \cos(\Theta + 2\pi/3) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix}\begin{bmatrix} I_{sa} \\ I_{sb} \\ I_{sc} \end{bmatrix} \quad (7)$$

The inverse park transformation is used for generating reference current signal as given in the matrix equation 8 below;

$$\begin{bmatrix} I'_{La} \\ I'_{Lb} \\ I'_{Lc} \end{bmatrix} = \sqrt{2/3}\begin{bmatrix} \sin(\Theta) & \cos(\Theta) & 1/\sqrt{2} \\ \sin(\Theta - 2\pi/3) & \cos(\Theta - 2\pi/3) & 1/\sqrt{2} \\ \sin(\Theta + 2\pi/3) & \cos(\Theta + 2\pi/3) & 1/\sqrt{2} \end{bmatrix}\begin{bmatrix} I_d \\ I_q \\ I_0 \end{bmatrix} \quad (8)$$

For reference current calculation the SRF based method uses source voltages, source currents and dc link voltages as shown in fig. 4. The phase locked loop (PLL) is used to generate the transformation angle (ωt) which presents the angular position of the reference frame (Kesler and Ozdemir, 2011) .

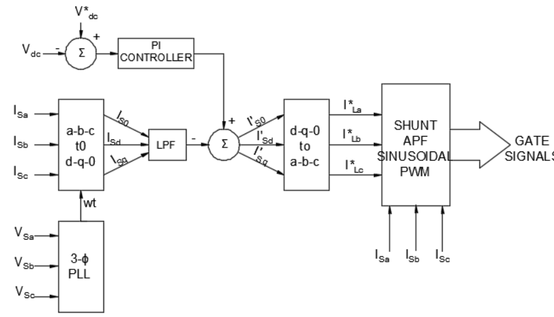


***Figure 4***. *Control block diagram of shunt active filter based on d-q theory*

The UPQC as a CPD is introduced at the point of common coupling (PCC). It can be placed before or after the DG unit in the distribution network, which makes for four possible placement positions. Figures 7 to 10 illustrates the four possible UPQC positions (Khadem et al., 2010). Each of these positions presents different dynamics with regards to sensing of the load current. However, position 3 is most common as this position allows the real value of the load current to be sensed.

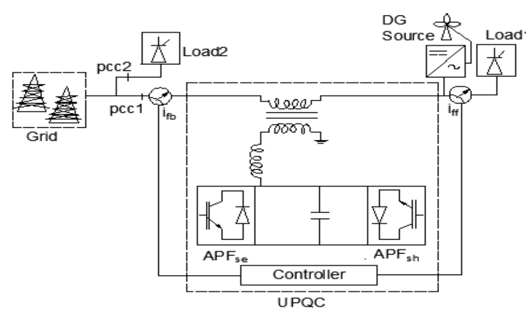


***Figure 5***. *UPQC placement position 1*

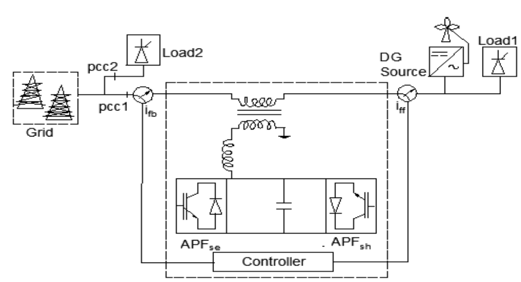

***Figure 6.*** *UPQC placement position 2*

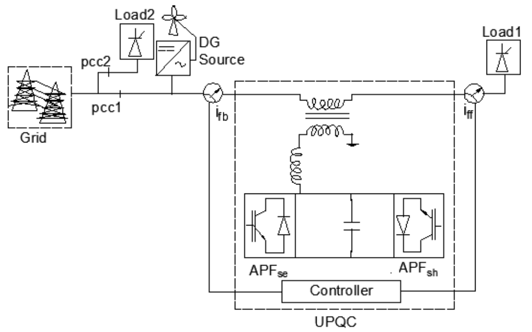


***Figure 7.*** *UPQC placement position 3*

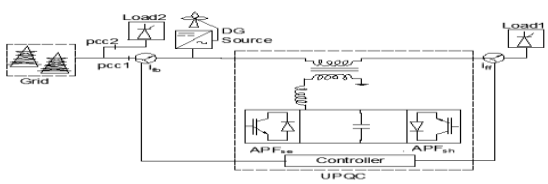


***Figure 8***. *UPQC placement position 4*

## 2. MATERIALS AND METHOD

The materials used in this research paper consist of data obtained from the Otovwodo distribution network in Ughelli, Delta state. Data on the 85 substations in the distribution system were obtained from daily activities as well as physical measurements and interaction with station staff. The network modelling and simulation was done using ETAP 16.0 power system simulation software using Newton Raphson method. The following sections present a discription of the network and data obtained as well as the different models and simulations that were done.

### 2.1. Otovwodo Distribution Network Description

The network under review is the 15 MVA, 33/11 kV Otovwodo distribution network, located at Otovwodo in Delta State, Nigeria. To supply its customers the Otovwodo distribution network gets supply from Transmission Company of Nigeria (TCN) through its 30MVA, 132/33kV injection substation. This is stepped down at Otovwodo 15MVA, 33/11kV injection substation and supplied to two 11kV feeders, Isoko Road feeder and Dumez Road feeder. Between both feeders the network has 85 active distribution transformers that feed the different consumers. Figure 9 shows Otovwodo 15 MVA injection transformer and switchyard and figure 10 shows part of network model in Electronic Transient Analyzer Program (ETAP 16.0). Table 1 and 2 presents some information from the two feeders used in the simulation exercise

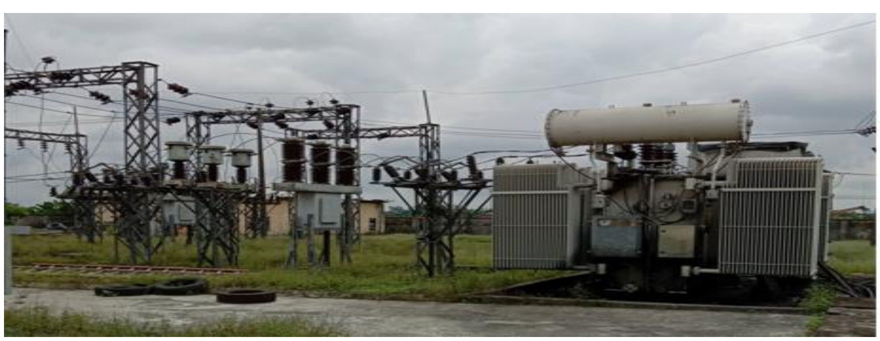

***Figure 9***. *Otovwodo 15 MVA injection transformer and switch yard*

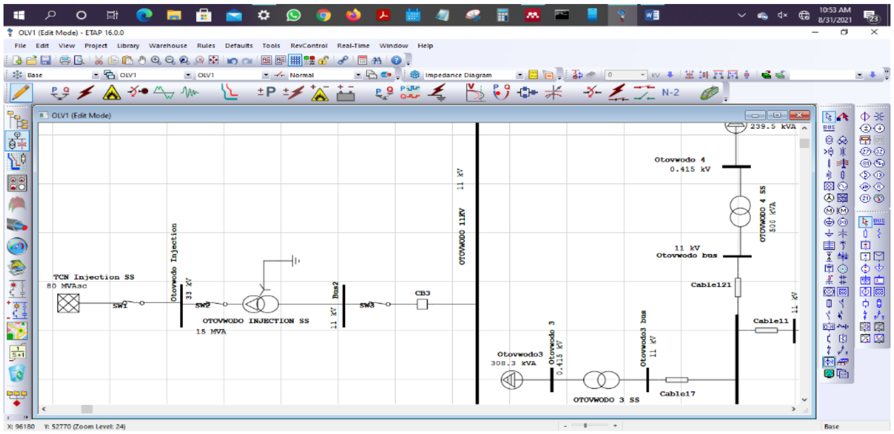


***Figure 10**. One-Line Model of Otovwodo 15MVA injection substation in ETAP 16.0 Environment*

***Table 1.** Average peak and off-peak loads on distribution transformers attached to Isoko road feeder.*

| SN | Substation | Rating (kVA) | Distance (km) | Ave. Peak Load | | | Ave. Off-Peak Load | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | kW | P.F | kVA | kW | P.F | kVA |
| 1 | Upper Agbarho 5 | 300 | 1.84 | 151.2 | 0.95 | 159.2 | 54.7 | 0.91 | 60.1 |
| 2 | D'Roseville Hotel | 100 | 3.14 | 18.7 | 0.88 | 21,25 | 5.2 | 0.94 | 5.5 |
| 3 | Onogharigho | 300 | 1.90 | 240.0 | 0.92 | 260.9 | 173.8 | 0.96 | 181.0 |
| 4 | Oviri-Ogor 1 | 200 | 3.01 | 134.5 | 0.90 | 149.4 | 57.8 | 0.93 | 62.2 |
| 5 | Ogbalor Cold Room | 300 | 0.86 | 38.5 | 0.68 | 58.6 | 28.9 | 0.71 | 40.7 |
| 6 | Cassidy | 500 | 2.72 | 342.5 | 0.92 | 372.3 | 196.2 | 0.95 | 206.5 |
| 7 | Ufor 1 | 500 | 3.10 | 275.3 | 0.92 | 299.2 | 149.2 | 0.92 | 162.2 |
| 8 | Utoro | 300 | 2.43 | 216.3 | 0.94 | 230.1 | 101.4 | 0.89 | 113.9 |
| 9 | Ufor 2 | 300 | 3.29 | 184.6 | 0.94 | 196.4 | 108.8 | 0.93 | 117.0 |
| 10 | Makolomi | 500 | 1.43 | 313.5 | 0.91 | 344.5 | 158.0 | 0.94 | 168.1 |
| 11 | Marvel Schools | 100 | 3.24 | 23.3 | 0.89 | 26.2 | 10.7 | 0.90 | 11.9 |
| 12 | Oviri-Ogor 2 | 300 | 2.67 | 47.6 | 0.95 | 50.1 | 28.5 | 0.82 | 34.8 |
| 13 | Daniel Umukoro | 300 | 4.79 | 101.3 | 0.95 | 106.6 | 64.6 | 0.96 | 67.3 |
| 14 | Dortie | 500 | 4.45 | 284.3 | 0.94 | 302.4 | 176.6 | 0.92 | 192.0 |
| 15 | Uduophori | 300 | 0.86 | 198.4 | 0.89 | 222.2 | 110.8 | 0.93 | 119.1 |
| 16 | Ikprukpru 2 | 300 | 4.21 | 176.4 | 0.94 | 187.7 | 119.5 | 0.96 | 124.5 |
| 17 | Robert Allor | 300 | 4.11 | 221.5 | 0.95 | 233.2 | 172.8 | 0.97 | 178.1 |
| 18 | Oviri Cold Room | 300 | 1.93 | 72.1 | 0.80 | 90.1 | 44.5 | 0.75 | 59.3 |
| 19 | Shell | 300 | 2.12 | 89.5 | 0.91 | 98.4 | 77.4 | 0.91 | 85.1 |
| 20 | Ovie | 500 | 0.49 | 393.5 | 0.90 | 437.2 | 248.2 | 0.95 | 261.3 |

***Table 2.** Average peak and off-peak loads on distribution transformers on Dumez road feeder.*

| SN | Substation | Rating (kVA) | Distance (km) | Ave. Peak Load | | | Ave. Off-Peak Load | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | kW | P.F | kVA | kW | P.F | kVA |
| 1 | Uduere 1 | 100 | 3.23 | 63.2 | 0.95 | 66.5 | 49.4 | 0.98 | 50.4 |
| 2 | Etefe | 300 | 10.11 | 58.4 | 0.82 | 71.2 | 37.6 | 0.83 | 45.3 |
| 3 | Otovwodo 4 | 500 | 1.58 | 203.7 | 0.86 | 236.9 | 190.7 | 0.86 | 221.7 |
| 4 | Awirhi | 200 | 12.43 | 44.8 | 0.93 | 48.2 | 13.0 | 0.96 | 13.5 |
| 5 | Agbarha Junction | 300 | 0.33 | 197.4 | 0.76 | 259.7 | 113.3 | 0.98 | 115.6 |
| 6 | Oteri | 200 | 9.25 | 75.1 | 0.97 | 77.4 | 35.3 | 0.93 | 38.0 |
| 7 | Olori Estate | 500 | 1.32 | 415.6 | 0.90 | 461.8 | 262.1 | 0.96 | 273.0 |
| 8 | Uduere 2 | 300 | 3.61 | 98.3 | 0.86 | 114.3 | 60.2 | 0.86 | 70.0 |
| 9 | Grubs | 100 | 1.34 | 37.3 | 0.84 | 44.4 | 28.3 | 0.97 | 29.2 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 10 | Olori Road | 300 | 2.13 | 244.0 | 0.88 | 277.3 | 110.2 | 0.97 | 113.6 |
| 11 | Agbarha Road | 500 | 0.48 | 134.1 | 0.73 | 183.7 | 46.6 | 0.97 | 48.0 |
| 12 | Mudi 1 | 300 | 2.30 | 183.0 | 0.77 | 237.7 | 97.2 | 0.91 | 106.8 |
| 13 | Mudi 2 | 300 | 2.56 | 254.2 | 0.91 | 279.3 | 139.5 | 0.89 | 156.7 |
| 14 | Slaughter House | 300 | 1.25 | 85.7 | 0.94 | 91.2 | 79.2 | 0.98 | 80.8 |
| 15 | Omonemu | 500 | 2.82 | 134.3 | 0.92 | 137.0 | 109.3 | 0.98 | 111.5 |
| 16 | Otovwodo 3 | 500 | 1.31 | 277.4 | 0.91 | 304.8 | 166.8 | 0.97 | 171.9 |
| 17 | Opherin | 200 | 6.46 | 95.2 | 0.87 | 109.4 | 68.9 | 0.87 | 79.2 |
| 18 | Bishop Emuobor | 500 | 1.64 | 295.3 | 0.95 | 310.8 | 181.8 | 0.98 | 185.5 |
| 19 | Owevwe | 200 | 5.82 | 78.4 | 0.82 | 95.6 | 36.6 | 0.92 | 39.8 |
| 20 | Otovwodo 2 | 500 | 0.77 | 259.4 | 0.72 | 360.3 | 160.3 | 0.98 | 163.6 |

## 2.2. Research Method

In this section the research method is presented. To begin, the data required for simulation in ETAP 16.0 was taken from the necessary locations on the network. The data gathered including injection substation rating, numbers of distribution substations on the two 11kV feeder along with their ratings and distance from the injection substation (for estimation of cable length) was subsequently used to generate models of the distribution network which were used to run harmonic simulations in ETAP. Also, the peak and off-peak loads on each distribution transformer was also gathered. The research method therefore flows like this;

- Collection of necessary network data. The network data collected include injection substation rating, number of feeders attached to the injection substation, number of distribution transformers on each feeder. Data was collected through interaction with distribution network staff as well as adoption of already existing data from daily logs. Tables 1 and 2, presented earlier, summarize data from part of the network.
- The data collected is used to model the distribution network in ETAP 16.0 software environment (figure 10). Three different models are required. The first model is of the distribution network without DG. The second is of the distribution network with DG and the third is of the distribution network with DG and UPQC.
- The three models developed, of the distribution network, are used to run harmonic load flow of Otovwodo distribution network. Three harmonic load flow simulations are required. The first simulation which is of the network prior to DG integration is done to determine the harmonics present in the network before introduction of DG (figure 11).
- The second simulation is of the network model with photovoltaic (PV) DG power sources present in ETAP 16.0. This gives a measure of the percentage of distortion put into the system due to integration of PV sources into the network (figure 12).
- Finally, a third harmonic load flow of the network with photovoltaic DG sources and UPQC is done in ETAP 16.0. This simulation provides an insight into the usefulness of UPQC in reducing percentage of harmonics (figure 13).

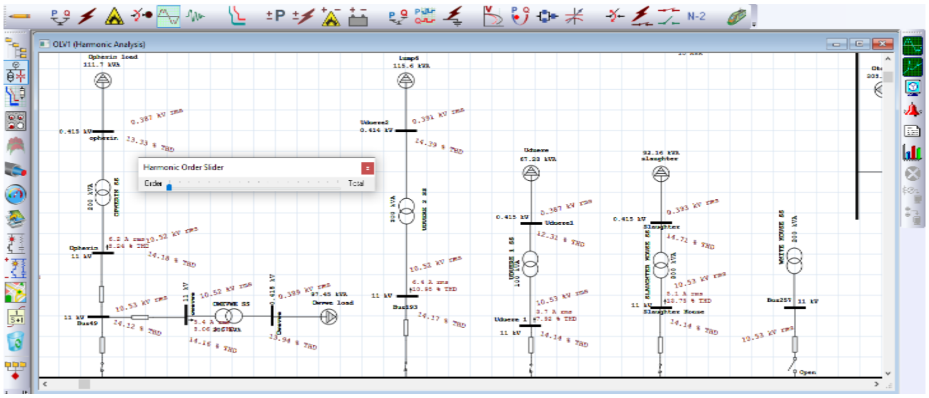

***Figure 11.*** *Harmonic load flow of distribution network without photovoltaic DG sources showing percentage of harmonics present at some buses*

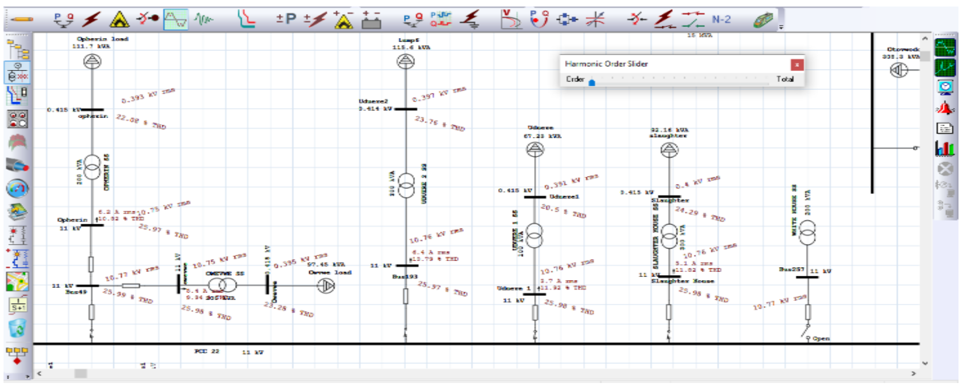

***Figure 12.*** *Harmonic load flow of distribution network after integration of photovoltaic DG sources showing percentage of harmonics present at several buses*

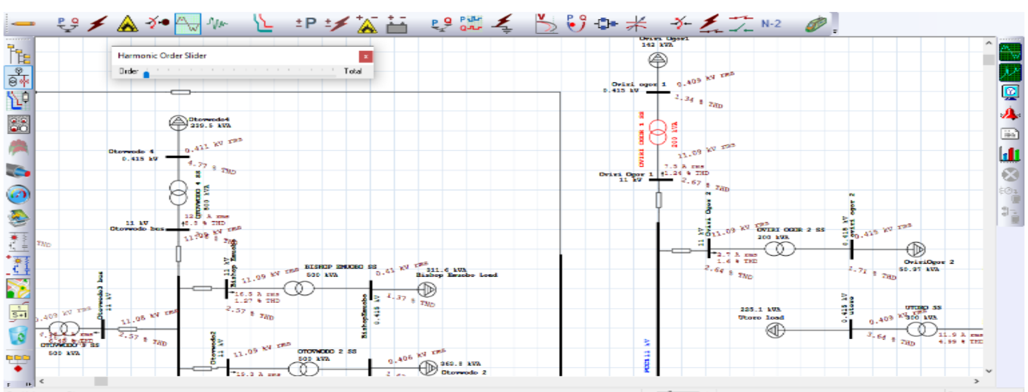

***Figure 13.*** *Harmonic load flow of distribution network after integration of photovoltaic DG sources and UPQC showing percentage of harmonics present at several buses*

## 3. RESULTS AND DISCUSSION

This section presents the results of the different simulations carried out in ETAP 16.0 of the Otovwodo 11kV distribution network. In line with the aim of this research which is to reduce the level of harmonics introduced by the presence of DG three harmonic load flow simulations have been carried out. For simplicity the simulation results from 20 buses are presented. However, the results can be extended to other buses in the network. The percentage of voltage total harmonic distortion (VTHD) and voltage individual harmonic distortion (VIHD) from the first simulation, which is without the inclusion of photovoltaic DG sources in the system is presented in table 3 (WODG). The percentage increase in harmonics caused by integration of photovoltaic DG sources, gotten from the second simulation is also available in table 3 (WDG). The percentage of harmonics present in the system after addition UPQC is also in table 3 (WUPQC).

***Table 3**. VTHD and VIHD for selected buses obtained from ETAP 16.0 simulations (Isoko road feeder)*

| **SN** | **Bus** | **Rating (kV)** | **VTHD (%)** | | | **VIHD (%)** | | |
|---|---|---|---|---|---|---|---|---|
| | | | **WODG** | **WDG** | **WUPQC** | **WODG** | **WDG** | **WUPQC** |
| 1 | Upper Agbarho 5 | 0.415 | 19.70 | 21.78 | 3.29 | 14.09 | 15.79 | 1.20 |
| 2 | D'Roseville Hotel | 0.415 | 22.59 | 24.92 | 4.76 | 17.45 | 19.32 | 1.22 |
| 3 | Onogharigho | 0.415 | 13.09 | 15.60 | 2.88 | 10.79 | 12.15 | 0.89 |
| 4 | Oviri-Ogor 1 | 0.415 | 14.81 | 16.54 | 2.26 | 11.04 | 12.85 | 0.98 |
| 5 | Ogbalor Cold Room | 0.415 | 20.70 | 24.37 | 4.33 | 17.15 | 18.99 | 2.60 |
| 6 | Cassidy | 0.415 | 16.80 | 18.51 | 3.79 | 13.50 | 14.88 | 1.99 |
| 7 | Ufor 1 | 0.415 | 17.73 | 19.55 | 4.21 | 14.15 | 15.66 | 2.17 |
| 8 | Utoro | 0.415 | 16.13 | 17.81 | 3.59 | 11.77 | 13.80 | 1.95 |
| 9 | Ufor 2 | 0.415 | 16.91 | 18.68 | 3.94 | 12.29 | 13.77 | 2.14 |
| 10 | Makolomi | 0.415 | 15.01 | 16.76 | 3.76 | 11.55 | 13.01 | 1.87 |
| 11 | Marvel Schools | 0.415 | 20.91 | 23.08 | 4.54 | 16.39 | 18.18 | 2.47 |
| 12 | Oviri-Ogor 2 | 0.415 | 18.13 | 20.31 | 2.68 | 13.80 | 15.55 | 0.99 |
| 13 | Daniel Umukoro | 0.415 | 19.35 | 21.38 | 4.65 | 13.38 | 15.54 | 2.44 |
| 14 | Dortie | 0.415 | 17.58 | 19.38 | 4.22 | 14.04 | 15.55 | 2.18 |
| 15 | Uduophori | 0.415 | 16.91 | 18.65 | 3.91 | 13.52 | 14.97 | 2.04 |
| 16 | Ikprukpru 2 | 0.415 | 17.12 | 18.92 | 4.80 | 12.45 | 13.94 | 2.18 |
| 17 | Robert Alor | 0.415 | 18.33 | 20.25 | 4.51 | 13.22 | 14.82 | 2.36 |
| 18 | Oviri Cold Room | 0.415 | 20.70 | 22.84 | 4.49 | 16.25 | 18.00 | 2.47 |
| 19 | Shell | 0.415 | 20.02 | 22.07 | 4.04 | 15.79 | 17.47 | 2.36 |
| 20 | Ovie | 0.415 | 16.64 | 18.19 | 3.96 | 12.59 | 13.96 | 1.67 |

***Table 3**. VTHD and VIHD for selected buses obtained from ETAP 16.0 simulations (Dumez road feeder)*

| SN | Bus | Rating (kV) | VTHD (%) | | | VIHD (%) | | |
|---|---|---|---|---|---|---|---|---|
| | | | WODG | WDG | WUPQC | WODG | WDG | WUPQC |
| 1 | Uduere 1 | 0.415 | 14.98 | 16.73 | 1.81 | 11.53 | 12.99 | 0.75 |
| 2 | Otefe | 0.415 | 21.43 | 23.65 | 4.72 | 16.79 | 18.59 | 2.62 |
| 3 | Otovwodo 4 | 0.415 | 18.98 | 20.94 | 4.70 | 15.06 | 16.67 | 2.29 |
| 4 | Awirhi | 0.415 | 24.04 | 26.70 | 4.69 | 18.42 | 20.44 | 2.55 |
| 5 | Agbarha Junction | 0.415 | 17.55 | 19.21 | 4.21 | 13.30 | 14.76 | 1.78 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 6 | Oteri | 0.415 | 19.21 | 21.20 | 4.86 | 15.23 | 16.86 | 2.35 |
| 7 | Olori Estate | 0.415 | 15.82 | 17.42 | 3.53 | 12.69 | 14.04 | 1.90 |
| 8 | Uduere 2 | 0.415 | 17.23 | 19.29 | 2.99 | 13.18 | 14.85 | 1.27 |
| 9 | Grubs | 0.415 | 19.26 | 21.25 | 4.80 | 15.25 | 16.89 | 2.31 |
| 10 | Olori Road | 0.415 | 15.94 | 17.55 | 3.55 | 12.78 | 17.46 | 1.90 |
| 11 | Agbarha Road | 0.415 | 20.12 | 22.50 | 4.45 | 14.35 | 16.08 | 2.47 |
| 12 | Mudi 1 | 0.415 | 17.39 | 19.18 | 4.09 | 13.89 | 15.38 | 2.11 |
| 13 | Mudi 2 | 0.415 | 15.37 | 23.28 | 3.37 | 15.49 | 12.59 | 1.87 |
| 14 | Slaughter House | 0.415 | 17.59 | 19.70 | 2.18 | 13.43 | 15.13 | 0.92 |
| 15 | Omonemu | 0.415 | 17.75 | 19.88 | 2.89 | 13.54 | 15.26 | 0.76 |
| 16 | Otovwodo 3 | 0.415 | 17.39 | 19.22 | 4.10 | 12.61 | 14.14 | 2.19 |
| 17 | Opherin | 0.415 | 18.06 | 23.21 | 4.37 | 13.05 | 14.64 | 2.29 |
| 18 | Bishop Emuobor | 0.415 | 15.27 | 17.07 | 2.53 | 11.75 | 13.23 | 1.11 |
| 19 | Owevwe | 0.415 | 19.11 | 21.08 | 4.78 | 15.16 | 16.78 | 2.32 |
| 20 | Otovwodo 2 | 0.415 | 15.84 | 17.71 | 2.56 | 12.17 | 13.79 | 0.85 |

WODG – without distributed generation
WDG – with distributed generation
WUPQC – with universal power quality conditioner

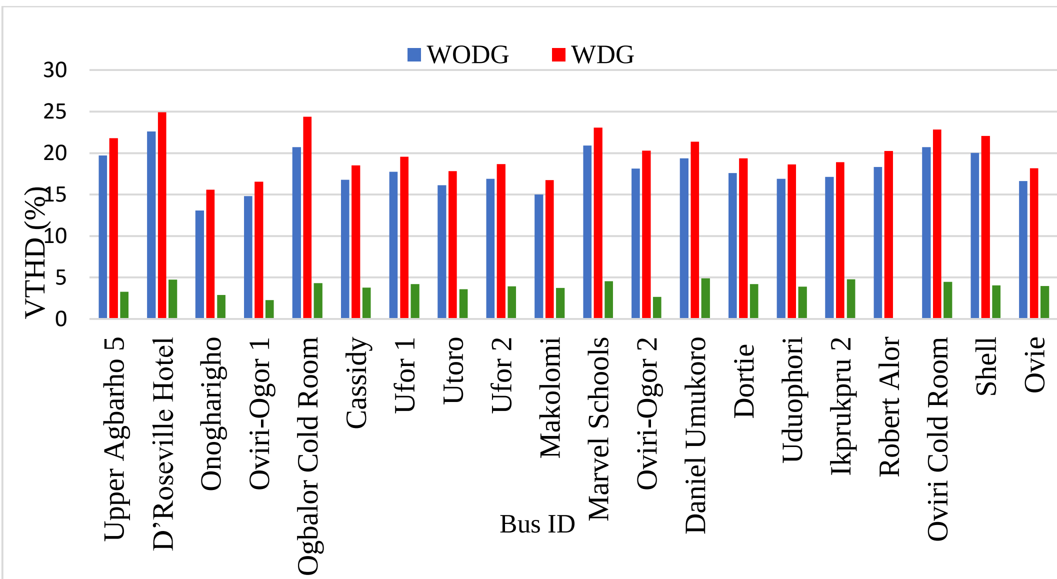


***Figure 14.*** *Bar chart showing the increase in VTHD and subsequent decrease after introduction of UPQC into the network for buses on Isoko road feeder*

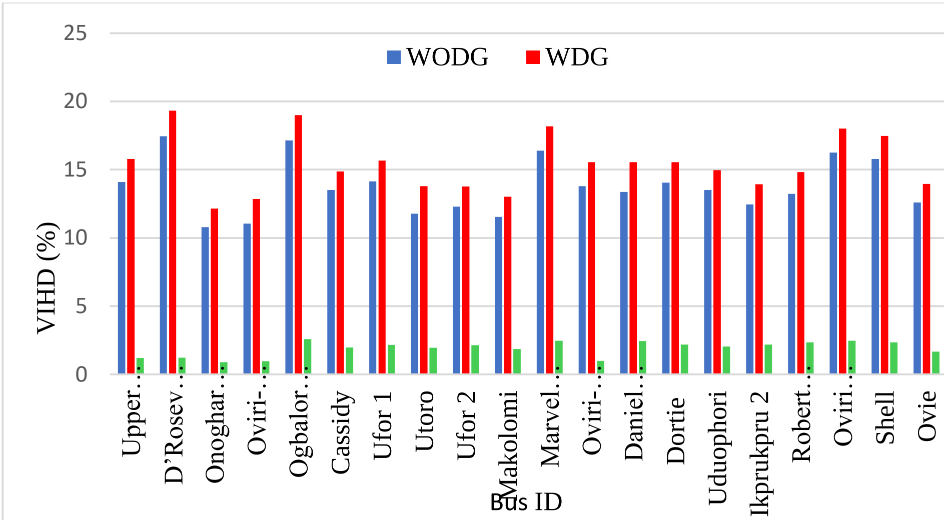


***Figure 15.*** *Bar chart showing the increase in VIHD and subsequent decrease after introduction of UPQC into the network for buses on Isoko road feeder*

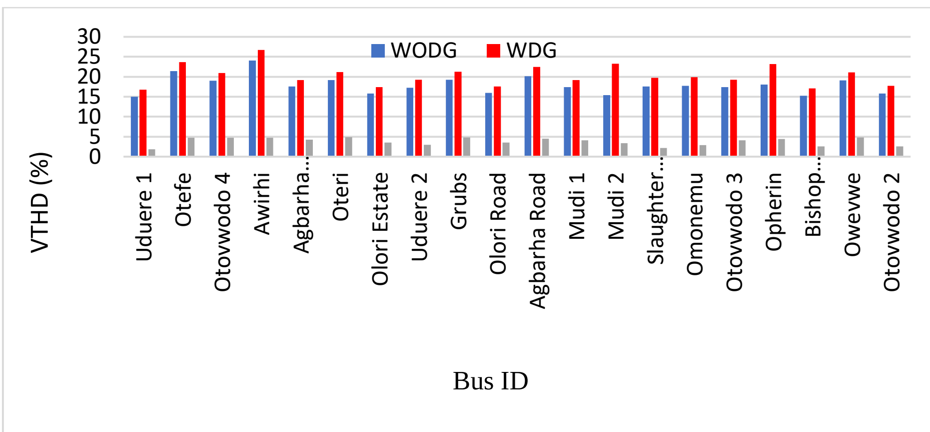


***Figure 16.*** *Bar chart showing the increase in VTHD caused by DG and subsequent decrease after introduction of UPQC into the network for buses on Dumez road feeder*

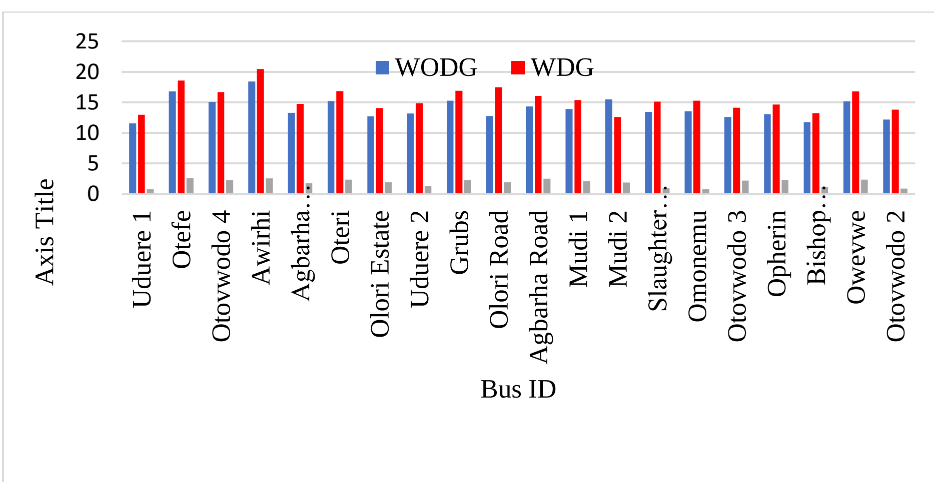


***Figure 17.*** *Bar chart showing the increase in VIHD and subsequent decrease after introduction of UPQC into the network for buses on Dumez road feeder*

Figures 14 to 17 show bar chart representations of the results obtained from ETAP simulations for the three study cases. Figure 14 and 15 show the effect, in terms of increase and decrease in VTHD and VIHD, caused by introduction of DG and subsequent introduction of UPQC on the buses attached to Isoko road feeder while figures 16 and 17 show the effect on the buses attached to Dumez road feeder. From figures 14 to 17 and tables 2 and 3 it is seen that integration of DG into the network increased both VTHD and VIHD. For the buses on Isoko road VTHD increased by 11.3% while VIHD increased by 11.9%. For the buses on Dumez road feeder VTHD increased by 13.5% while VIHD increased by 11.0%. Also referring to tables 2 and 3 for harmonic levels after integration of UPQC it can be seen that the VTHD reduced by 80.4% while VIHD reduced by 87.6% for the buses on Isoko road feeder. However, for the buses on Dumez Road it is observed that VTHD is reduced by 81.5% while VIHD is reduced by 88.2%. This reduction of harmonic level to values within IEEE 519 standards, which is attributed to the effect of the UPQC, have greatly improved the performance of the network.

**Conflicts of Interest**

No conflict of interest was declared by the authors.

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