UNIVERSITY of RWANDA COLLEGE OF SCIENCE AND TECHNOLOGY ACE-ESD AFRICAN CENTER OF EXCELLENCE IN ENERGY FOR SUSTAINABLE DEVELOPMENT

Title of the Project: **IMPACT OF GRID-CONNECTED PV SYSTEM ON POWER QUALITY: RWANDA'S ELECTRIC GRID CASE**

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Kigali-Rwanda

DECLARATION

I, the undersigned, declare that dissertation titled **Impact of Grid-Connected PV System on Power Quality: Rwanda's Electric Grid Case** is my original work, and has not been presented for a degree in University of Rwanda or any other universities. All sources of materials that will be used for the thesis work will have been fully acknowledged in the correct academic format.

Names: MUKAKAMANA Valentine

Signature

APPROVAL

Date of Submission: 19 /10/2022

This dissertation work has been submitted for examination with my approval as a universityadvisor.

Dr. Mulugeta GebreHiwot GebreMichael

Dissertation supervisor: Signature

DEDICATION

To my beloved husband UWITONZE Anastase

To my beloved son MANZI Jaspin

To my beloved father BIZIMANA Martin

To my mother BANYANGABOSE Beatrice

To my lovely brothers and sisters

To my supervisor

To my friends and colleagues

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I would want to use this opportunity also to thank my beloved husband UWITONZE Anastase, my beloved son MANZI Jaspin, my lovely father BIZIMANA Martin, my lovely mother BANYANGABOSE Beatrice, my sisters and brothers for their unconditional love and attention.

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ABSTRACT

Clean energy, in general, and solar PV systems, in particular, offer excellent solutions to challenges that people confront in their daily lives. When compared to the use of fossil fuels, energy generation with solar PV systems is less expensive and more environmentally friendly. Apart from its benefits, this technology still has numerous problems when connected to electric grid. Data were collected using appropriates methods and other are gathered from Meteo Rwanda by use of Homer software. In this work a Grid-connected PV systems was modelled and analysed using ETAP. It was seen that when PV power plant is connected to the electric network, it generates harmonics which exceeds the allowable limits. The analysis was done at different buses and at the output of inverters.

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ABBREVIATIONS

PV: Photovoltaic

SPV: Solar Photovoltaic

DC: Direct Current

AC: Alternating Current

I_{ph}: Photocurrent

I_s: Saturation current

R_s: Series resistance

R_{sh}: Shunt resistance

m: Diode quality factor

rms: root mean square

MPPT: Maximum Power Point Trucker

MPP: Maximum Power Point

PCC: Point of Common Coupling

CSP: Concentrated Solar Power

THD: Total Harmonic Distortion

CHAPTER I. INTRODUCTION

1.1. Background

The energy paradigms in many countries have experienced tremendous shift in the two last decades from dirty fossil based resources to clean renewables like wind turbines and photovoltaics. Among recently commissioned plants, the global weighted average levelized cost of electricity (LCOE) of utility-scale solar PV fell by 85 percent between 2010 and 2020, from USD 0.381/kWh to USD 0.057/kWh. This is a significant decrease in value. Renewable energy's contribution of electricity generation has likewise steadily increased. The global market for new electricity generation capacity is now dominated by renewable energy technologies. Despite the pandemic's negative effects on most global supply chains, over 260 gigawatts (GW) of renewable power capacity was built globally in 2020. In 2020, 111 GW of wind energy was installed, up from 60 GW in 2019, and 127 GW of solar PV was added. The share of renewables in electricity generation has increased from 20% to nearly 28% in the years 2010-2020 as renewable electricity generation capacity grows[1].

In Rwanda particular; the overall installed capacity rose from 228.418MW to 238.368MW by the end of June 2021. In Rwanda particular; by the end of June 2021, the total installed capacity increased from 228.418MW to 238.368MW. This installed capacity is composed by hydropower plants which have 104.628 MW equivalent to 44%, thermal power plants which have 58.8MW equivalent to 25%, solar power plants which have 12.05MW equivalent to 5%, methane gas power plants which have 29.79MW equivalent to 12%, import and shared which have 18.1MW equivalent to 8% and peat fired power plants which have 15MW equivalent to 6%. By the end of June 2021, the electricity access rate countrywide had increased from 55.41% to 64.53% [2]. In 2024, the government plans to have 52% of the population on the grid and 48% off, with universal electrification. The nation has chosen a novel approach to achieve this objective, choosing to electrify a sizable portion of the population (48%) off grid in order to achieve universal electrification as quick and cheap as possible. Solar home systems (SHS) and solar micro grid will make up this off grid electrification [3]. For this reason, great care must be taken to guarantee that the electric grid’s power quality complies with all necessary standards while integrating renewable energy into the system.

1.2. Statement of the problem

The global demand for electricity is increasing, and a dependence on fossil fuels is has lost its viability. Several countries in world are expanding their use of renewable energy as a percentage of overall electricity generation. Renewable energy adoption is growing as associated costs continue to fall, making renewable energy cost-competitive with conventional electricity in many regions of the world. As a result, the steady expansion on the proportion of energy from renewable resources in the world's mix of energy necessitates a change in the energy structure and operation. When compared to other renewable energy generating technologies, solar PV power generating technology has maintained an exceptional annual growth rate. However, because renewable energy is intermittent, connecting it to the grid is difficult. Existing electrical systems should be able to handle power from renewable energy generators as demand for electricity grows[4]. In Rwanda, the total electrical power generated is 238.368MW where solar power plants have 12.05MW equivalent to 5% [2]. Solar PV arrays in solar PV systems convert incident solar energy into DC electricity, necessitating the need of a power electronic-based DC-to-AC converter between the PV generator and the AC grid. This power generated from PV systems depends on the weather condition or the climate and the change of weather or climate causes the output power to fluctuate.

Small scale PV system known as PV mini grids are generally connected to the grid at the primary or secondary distribution and are considered as distributed generation (DG). Integration of PV systems into the grid can also be done at the transmission level depending on the scale of generation. All those types of interconnection present different issues and challenges that must be carefully analysed before grid interconnection [5]. One of the issues encountered while integrating PV mini grid to the electric grid is the issue of power quality. This is a technical concern for utilities, customers and PV generators as the power should be supplied at standard voltage and frequency because devices and appliances are designed to receive power at or near specified voltage and frequency. For example, in Rwanda for AC mini grid the nominal voltage at customer should be 400V line to line and 230V line to neutral. The operating voltage should not vary beyond ± 10% of the nominal voltage for both the transmission and the distribution. The operating frequency of the mini grid should be 50Hz. The allowed operating range should be within +6% (53Hz) and -6% (47Hz) beyond which the protection relay at generation should operate to shut the mini grid after a time delay of 500ms from the time the frequency crosses the allowed boundaries [6] [7]. Voltage and current harmonics should be also in acceptable limit [7].

So; the deviation beyond the acceptable limit of one of those parameters may cause appliances and devices malfunction or damage. In this research the common power quality issues encountered while PV mini grid is integrated to the electric grid will be highlighted and the possible solutions will be suggested.

1.3. Objectives

1.3.1. Main objective

The main objective of this research work is to analyse the impact of grid-connected PV system on power quality of electric grid.

1.3.2. Specific **objectives**

The specific objectives of this research are:

(i) To model a grid-connected PV array

(ii) To assess and analyse power quality issues when a PV system is integrated to the electric grid.

(iii) To suggest possible solutions to the issues encountered by an electric grid when PV mini grid is integrated to the grid.

1.4. Research questions

- What are the impact of grid connected PV system on power quality of electric grid?
- What are the effects of power quality problems on electric grid and consumers?
- How power quality problems can be mitigated?

1.5. Scope of the study

This research is restricted on highlighting power quality issues arisen when PV mini grid is connected to the grid and the proposed solutions of those issues.

1. 6. Expected outcomes and significance of the study

1. 6.1. Expected outcomes

The expected outcomes of this research are:

(i) Power quality issues related to the connection of PV power system on electric grid will be analysed and this will help the utility grids to take decision in connecting PV mini grid to the electric grid.

(ii) Possible solutions to the power quality problems caused by grid-connected PV system will be proposed and this will help to reduce the utility cost related to the poor power quality.

1. 6.2. Significance of the study

The Rwandan government is already encouraging different stakeholders to participate in the development of on-grid and off-grid connected PV systems. Some PV systems are already deployed, some are under construction and many are in plan. The output of this research work can be used as a useful input in decision makings and as a reference for number of technical issues when it comes to the development of PV systems integrated to the grid.

1.7 Outline

This research details the impact of grid connected PV system on power quality. Hence, the work is organized as follows:

Chapter 2 provides a brief literature review about grid connected PV system.

Chapter 3 describe research methodology for this research which contain research procedure, research method, and research tools.

Chapter 4 describe the modal, simulation and results analysis of grid connected PV power system. A model and simulation of PV power system connected to grid with case study of Rubona Solar power plant was done using ETAP 19.0.2 software. Results from simulation are discussed.

Chapter 5 summarizes the conclusions from this research, and gives suggestions for better future work. Finally, appendices and list of bibliography used.

CHAPTER II. LITERATURE REVIEW

2.1. Introduction

The demand for electrical energy is gradually increasing, and as a result, the integration of photovoltaics systems into electric network is rapidly increasing as well, despite the impact that it has a substantial impact on the network power quality.

2.2. Description of PV system

2.2.1. Overview of a PV system

PV system is a widely used renewable energy source that convert solar energy by using photovoltaic effect into useful electricity. Based on their applications PV system in power networks are split into two classifications: Stand-alone and grid connected. The applications of grid connected is that they can supply both local loads and interchange power with the utility grid, whereas stand-alone PV systems can supply electric power energy for local loads where there is no any source of power [8]. In grid connected PV systems, an inverter converts DC current from the PV panel into AC current. When a PV system is connected to the grid, it can send excess electricity to the grid after meeting the demand and when the demand is higher than its generation, the additional energy is obtained from the grid [9].

2.2.2. Components of PV system

Depending on the type of system, location and applications, several components can be found in a solar PV system. Panel/module, charge controller, battery, inverter and load are the major components that can be connected together to create a system that can give electricity to a typical load.

- **PV module**

PV module transforms solar radiation into direct current electricity by means of semiconductors that uses the photovoltaic effect to generate electricity. It is made by a large number of PV cells. Many PV modules can be connected together to producer more power, the connection can be series or parallel depending on to amount of output power needed [10].

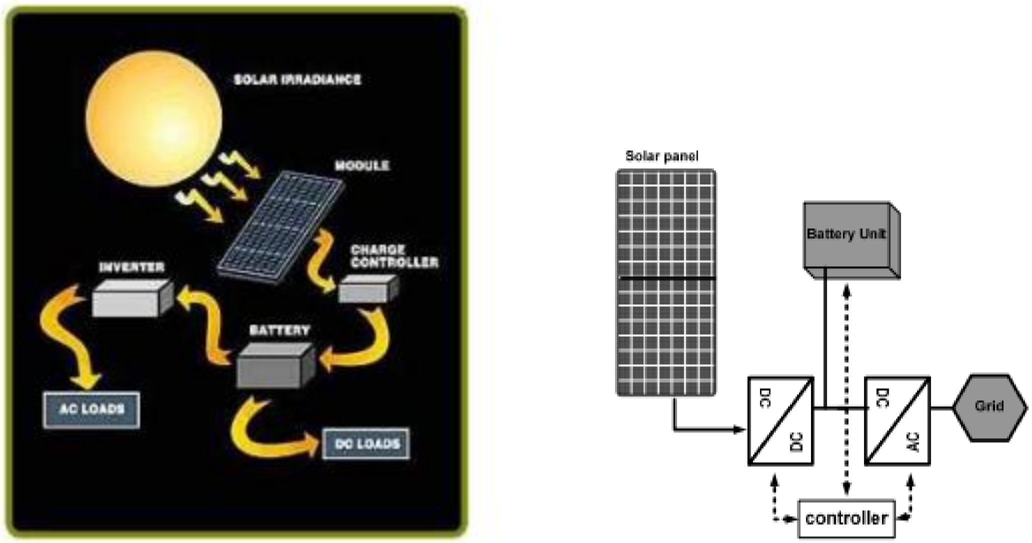

Figure 2.1 Diagram of PV system and grid connected PV system [11] [12]

- **Charge controller**

The role of charge controller in the system is to keep battery from being destroyed by regulating the charging and discharging cycles. It also used as a connection between the other components of the system by making certain the voltage and current flow remain within permissible limits. It plays a critical function in the system because the cost of energy produced is highly dependent on its quality.

- **Battery**

Batteries are used to store excess energy that will not be used immediately. They have the ability to withstand a certain amount of charging and discharging depending on their capacities.

- **Inverter**

The role of inverter in solar PV system is to transform the DC current into AC current needed at the grid, which is used, by most of consumer's appliances [13]. Inverters are required to supply constant voltage and frequency, regardless of varying load conditions, and needed to either supply or absorb reactive power when dealing with reactive loads [14].

➢ **DC-DC Converter**

The application of DC-DC converter known as chopper is to transform a variable solar panel voltage to a constant DC voltage.

➢ **Load**

It refers to any electrical devices that must be powered by electricity in order to operate and can be either an AC or DC load.

2.2.3. Model of Solar PV system

PV cells are used to convert energy from solar into electric energy. PV generators are made up of several strings of solar cells coupled in series and parallel to give the desired output voltage and current. The equivalent circuit of photovoltaic generator is demonstrated in figure 2.2 [12] [15].

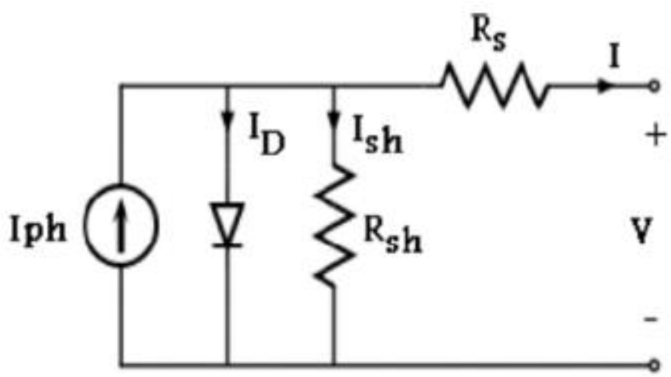

Figure 2.2 Equivalent circuit of Solar PV cell or generator [15]

The PV panel's generated voltage and current are expressed as follows:

$$V_{pV} = -I_{pV}R_s + \frac{nkT}{q}\ln\left(1 + \frac{I_L + I_{pV}}{I_O}\right) \tag{2.1}$$

$$I_{pV} = I_L - I_O\left[e^{q\left(\frac{V_{pV}+I_{pV}R_s}{nkT}\right)} - 1\right] \tag{2.2}$$

The relationship of current and voltage is expressed as:

$$I = I_{ph} - I_s\left[\exp\left(\frac{V+IR_s}{mV_t}\right) - 1\right] - \frac{V+IR_s}{R_{sh}} \tag{2.3}$$

Where:

I: PV Panel current

V: PV Panel voltage

$V_t = \frac{KT}{e}$, K is the Boltzmann constant ($1.38*10^{-23}$), T is the temperature of the solar cell (IN Kelvin) and e is the charge of the electron ($1.6*10^{-19}$C), V_{pV} is the output voltage of the cell, I_{pV} is the output current of the cell, q is the charge of electron, I_L is the light generated current, I_O is the saturation current of diode, n is the ideality factor and R_s and R_{sh} is the series and shunt resistors.

2.2.4. Characteristics of PV system

One of the essential characteristic of solar PV system is current-voltage (I-V) and power-voltage (p-v) curves of PV cell, module or array. As shown in figure 2.3 the photovoltaic power characteristic is nonlinear. Several methods for obtaining maximum power have been presented to solve this challenge [14] [15].

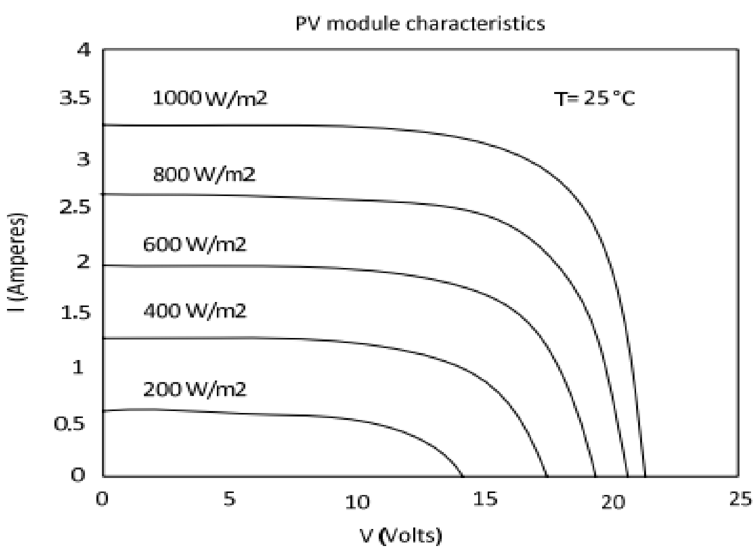

Figure 2.3 current-voltage (I-V) Characteristic of a SPV system at 25°C [10]

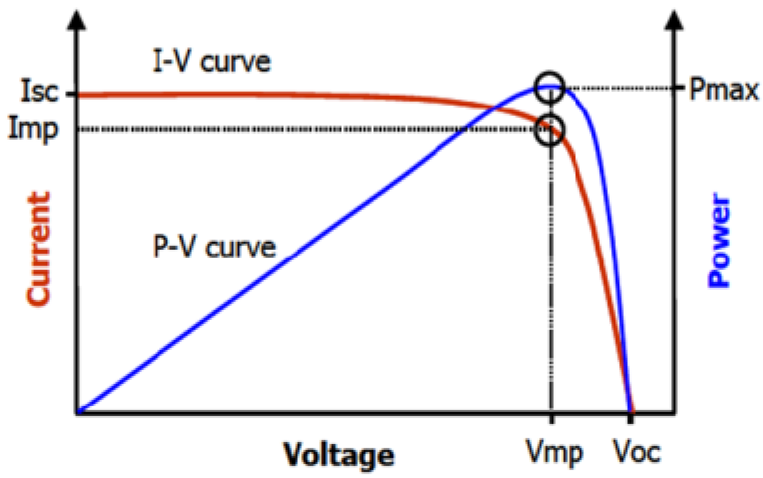

Figure 2.4 current-voltage (I-V) and power-voltage (P-V) Characteristic of SPV Cell/ Module [16]

Figure 2.3 shows the range of voltage and current at which the module can operate in the case of constant inputs and figure 2.4 shows how a PV cell or module generates energy based on inputs such as solar irradiation, cell temperature, and module orientation.

2.2.5. MPPT techniques of PV array

The main MPPT techniques used are: Fixed Duty Cycle, Constant Voltage, Perturb and Observe (P&O) and Modified (P&O), Incremental Conductance (IC) and Modified IC, Ripple Correlation, and System Oscillation [17] [18].

- **Fixed Duty Cycle**

This is the easiest of the approaches used in MPPT which does not necessitate any feedback; the load impedance is changed once for the maximum power point and there is no need of other adjustment.

- **Constant Voltage**

In Constant Voltage technique, the PV array's operational point is retained within close proximity to the MPP by adjusting the array voltage and matching it to a reference voltage equal the voltage at the maximum power point of the typical PV module [19]

- **Perturb and Observe (P&O)**

This method compares the power obtained at the current circle to the power obtained in the previous cycle by regularly increasing or decreasing the PV's output terminal voltage. If the voltage varies and the power increases, the control system adjusts the operating point in that direction otherwise the operating point is changed in other direction. In modified P&O, steps are adjusted according to the MPPT's distance and this result in high efficiency [18].

- **Incremental Conductance (IC)**

The IC technique is predicted on the fact that at MPP, The PV's power slope is zero; the MPP may be found in terms of the increase in array conductance. This method searches the MPP in the same way that the P&O does but it does not require the calculation of power and has excellent transient performance when exposed to rapid changes in atmospheric conditions [17].

- **System Oscillation**

The system oscillation approach is based on the maximum power transfer concept and employs oscillations to discover the operating point. The ratio of oscillation voltage to the average voltage is constant at the MPP [19].

- **Ripple Correlation**

In order to determine the optimal point, the ripple correlation employees power oscillations pass filters, which is likewise based on maximum power transfer principles.

[17].

2.3. Power quality of electric grid

Power quality of electric grid can be defined as a set of values for factors such as service continuity, voltage amplitude and frequency variation, transient voltages and currents, and harmonic content [14]. Any divergence in the amplitude, frequency, or waveform shape of the voltage and current that causes customer equipment to fail or malfunction is referred to as a power quality problem [20]. Many power quality challenges arise as the percentage of renewable energy systems integration in the power grid grows. Therefore, as the percentage share of PV systems increase in the power grid, it results in the increase of PQ issues [21]. This increase of PQ problems is due to the variation of solar irradiance, cloud shadow and the non-linear performance of power electronic modules like inverters and filters [22] [23]. The minimum global horizontal solar irradiation in Rwanda varies from 4.2 up to 5.8KWh/m^2 and has 5 daily peak sun hours [24] [25].

There are two different power quality issues that have to be taken into consider:

A) Power quality issues initiated by the variating nature of energy resource

- Over voltages during feed-in

  PV systems are often built to run at or near power factor which is equal to 1 in order to maximize the utilization of solar energy. PV systems only inject active power into the utility grid in this situation, which may modify the system's flow of reactive power. As a result of the absence of reactive power, the adjacent buses' voltage can be increased [26]. This overvoltage may have a detrimental influence on the utility and customer's ability to operate in a stable manner.

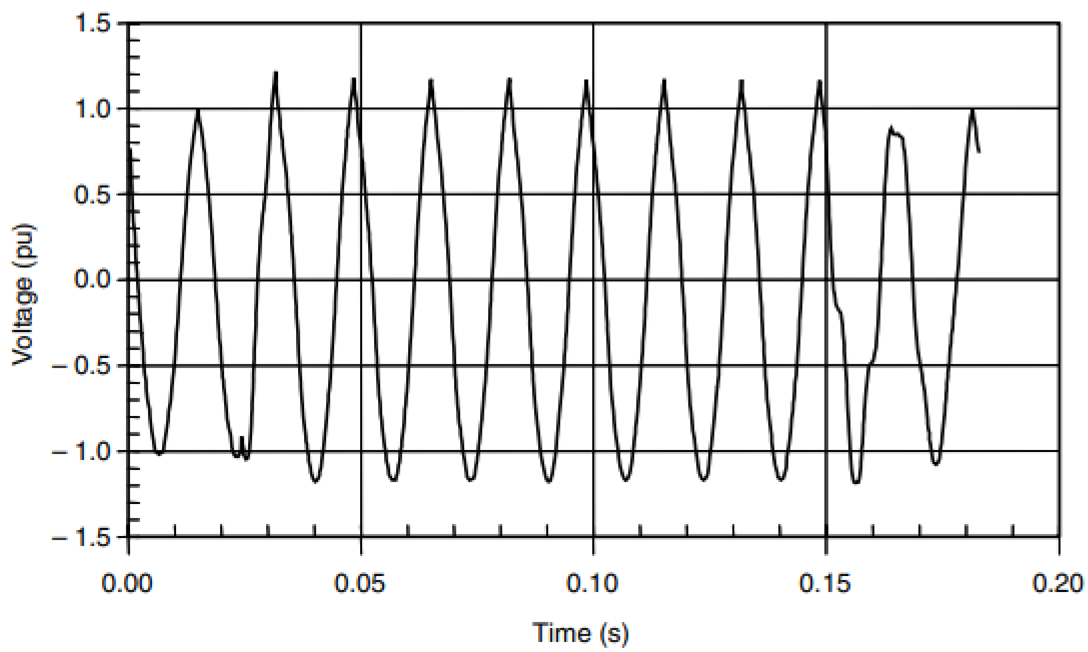

Figure 2.5 Waveform of voltage swell [25].

- Under voltage or Voltage sag

A voltage sag refers to a decrease of rms value of voltage for the power frequency for periods ranging between 0.5 cycles to 1 minute to value between 0.1 and 0.9.Voltage sags can be brought on energization of high loads or the starting of powerful motors, even if they are typically related to system breakdowns [25].

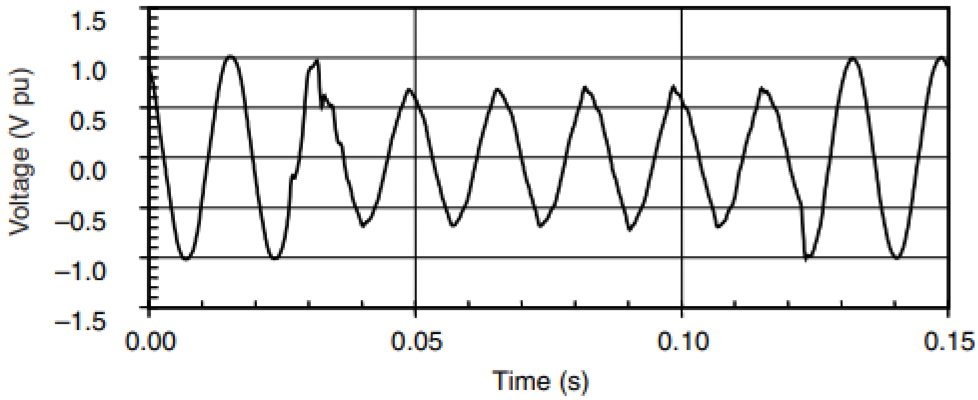

Figure2.6 Waveform of Voltage sag [25].

- Output power fluctuations

The variation of PV system output power is one among the significant factors that might lead to severe operational issues for the utility such as line power swings, over and under loading, undesirable voltage fluctuations and voltage flicker. The fluctuation of output power results from solar irradiance variation which is also caused by cloud movement and this could remain from less minutes to many hours with relation of wind speed, the type and size of clouds passing, and the area covered by PV system [26].

- Unbalance

When the line voltage or phase deviates from the normal balancing condition, a voltage unbalance occurs in the electrical system [27]. Voltage unbalance can occur in supply system for a variety of reasons [13].

- Frequency deviations

The reaction of PV system to grid frequency fluctuation requirements has received a lot of consideration in latest years, as frequency is one among the utmost essential variables in ensuring that power systems are of excellent quality. As a result, certain recent standards require the PV system to run under frequency control, which requires the PV system to work at a nominal frequency with a specified margin; otherwise, rapid disconnection is necessary [9].

B) Power quality issues caused by power electronic interface with the power system

- Harmonic injection

Voltage/ current harmonics comes from devices made by electronic components mainly inverters and loads that are nonlinear [27]. Harmonics are also generated by some loads that introduce frequencies that are multiple of fundamental frequency [8] [27]. Harmonics have impact on the system such as equipment overheating that leads to equipment failure, increased power losses, system malfunction, equipment protection and operation failure and voltage fluctuation [20] [28].

Harmonics are measured in percentages as THD which is the total harmonic ratio to the fundamental component.

$$THD_v = \frac{\sqrt{{V_{2rms}}^2 + {V_{3rms}}^2 + \cdots + {V_{h\,max,rms}}^2}}{V_{1\,rms}} \tag{2.4}$$

$$THD_i = \frac{\sqrt{{I_{2rms}}^2 + {I_{3rms}}^2 + \cdots + {I_{h\,max,rms}}^2}}{I_{1\,rms}} \tag{2.5}$$

Where$V_{1\,rms}$, V_{2rms}, V_{3rms} ,……, $V_{h\,max,rms}$ and $I_{1\,rms}$, I_{2rms}, I_{3rms}, ……, $I_{h\,max,rms}$ are the first order, 2nd order, 3rd order and higher order of voltage and current root mean square correspondingly.

Table 2.1 and table 2.2 shows the limits of current and voltage distortion according to IEEE standards respectively [28].

Table 2.1 limits of current distortion

I_{sc}/I_L	$3 \leq h \leq 11$	$11 \leq h \leq 17$	$17 \leq h \leq 23$	$23 \leq h \leq 35$	$35 \leq h \leq 50$	THD (%)
< 20	4	2	1.5	0.6	0.3	5
20 < 50	7	3.5	2.5	1	0.7	12
50 < 100	10	4.5	4	1.5	0.7	12
100 < 1000	12	5.5	5	2	1	15
> 1000	15	7.0	6	2.5	1.4	20

Table 2.2 limits of voltage distortion at PCC

Bus voltage at PCC	Total harmonic distortion, THD (%)
V ≤ 1.0Kv	8
1 kV< V ≤ 69 kV	5
69 kV < 20 ≤ 161 kV	2.5
161kV < V	1.5

Inrush currents

Due to the small dissimilarity among the utility and the PV system, the inrush currents flow between the utility and the PV system when the connection is being done and then decline to zero exponentially. The inrush currents could result in aggravation tripping and thermal overheating [26].

2.4. Related works

Abdullah Ali Alhussainy, et al (2020) [28] **,** renewable energy integration is the one method used to increases the power demand to satisfy the load demand. When large scale photovoltaic system with full converter are integrated, power quality is a serious challenge. A power system with poor connection of big solar PV-based generating may experience power quality issues which may cause power disturbances and economic losses. When the network is off, the solar PV system tries to deliver reactive power on the load. However, due to insufficient generated power capacity, the load cannot be met. Furthermore, when the connection of electric grid is re-established, the active and reactive powers oscillate. As a result, when the load exceeds the capacity of the solar PV, eventually, it can no longer support the load.

They have failed to control the phase angle because there was a jump of phase angle which affected the IGBT's firing angle position, the Voltage harmonic distortion and voltage imbalance.

Qianjin Zhang, **et al (2018)**[29]**,** Large-scale renewable power plants were connected to the electric power grid due to the rapid development of renewable energy. Meanwhile, for delivering with appropriate service to the consumer, the electric grid requires a solar photovoltaic system to have high power quality and stability. In PV stations, however, paralleled voltage source converters (VSCs) have a significant impact on system stability. Non-linear factors in large scale PV systems can be a source of additional issues and should be investigated. Dead time is critical in the normal operation of VSCs because it prevents short circuits in the inverter bridge. It does, however, reduce the fundamental component of the inverter's output voltage and introduce harmonics of low order to the system. The voltage phase information for inverter current management is provided by the PLL, which is also another non-linear element in the inverter system. Voltage fluctuations can influence the PLL'S function, as well as the system's stability and power quality.

The system phase margin and system power quality are both reduced when the dead time increases and the influence of dead time on grid connected power quality can be mitigated by large PV capacity.

Salah Kamal EL-Sayed, et al (2017) [10]**,** solar energy consumption is rapidly increasing as a result of rising in energy demand, as well as issues with fossil fuel such as depletion and CO2 emissions. Photovoltaic is a method of producing electricity that implicates transformation of solar radiation into electric current which is direct by means of semiconductors. The output of photovoltaic is dc power and need to be transformed into ac power needed to the grid, this need the inverter. The output of inverter contains many voltage or current harmonics; the filter is needed to reduce those harmonics to the acceptable level. They are numerous experiments of using central and string inverters utilizing pulse width modulation to describe the power quality which occur in

PV grid integrated systems. However, using space vector modulation to compare the performance of the central and string inverters, it was discovered that the central inverter has less total demand distortion and total harmonic distortion than the string inverter and that the string inverter performs better under changing of weather conditions than the central inverter.

This research focused only on reduction of voltage and currents harmonics by using SPWM ANS SVM controlling methods.

Abdulhakim Khalaf Alsaif (2017) [30]**,** the procedure of transferring power from renewable energy sources into the system grid of utility is known as integration of Renewable Energy. For meeting the parameters of integration, the Renewable Energy output must be converted to AC power. Renewable Energy sources are uncontrollable due to the fact that they are produced from natural resources for example sunshine, wind and ocean waves because they are intermittent and inconstant.

It is a difficult mission to integrate power generated from renewable energy technologies into the AC grid. There are numerous issues with this integration, including power quality, cost, availability of power, location of renewable energy resource, power variation, pace of power variation, and power forecast.

Power quality is critical in the power system to ensure grid system stability and efficiency, therefore optimum Power quality leads to a system that works well with high dependability and low cost. However, poor power quality can have grave consequences for the electrical grid, as well as industrial operations, extreme costs, and failure of equipment. Frequency disorder, current and voltage harmonics, low power factor, voltage volatility, and transmission line transits are all examples of PQ issues. Because the power production from renewable energy technology varies, most power quality issues exist, whether on or off the grid. As a result, when the integration is constructed, these considerations will have a negative impact on the grid. For example, if the system's power factor falls below a certain level, equipment will be damaged. Furthermore, due to the quantity of irradiance in solar energy, voltage and frequency are not constant, resulting in voltage and frequency deviations, which are important obstacles in integrating Renewable Energy.

This research proposed the use of micro grids and smart grid as one of the solutions to the power quality issues because smart grid has more advanced monitoring and management of any change in power level.

N.B.G. Brinkel, et al (2019) [31]**,** PV generation's intermittent nature is a cause of power quality difficulties. Light flicker and voltage oscillations, both of which are caused by voltage variations, are the principal problems of power quality related with rapid PV output swings. Electrical appliances which uses electricity when connected to the electric grid may be damaged by voltage fluctuations and flicker, and persons exposed to light flicker may experience discomfort and health risks. To ensure upcoming compliance with power quality principles, solutions for mitigating power quality issues caused by rapid PV output variations must be installed as PV penetration levels increase. It was shown that this power quality can mitigated by means of electric vehicles.

Various studies have examined the costs and prospects for mitigation potential of various methods; however, further study is required to identify the ideal mitigation solution because this studies looked at unrelated systems with various pricing methods.

Hagumumana Noel et al (2021) [32]**,** in their research "Concentrated Solar Power and Photovoltaic Systems: A New Approach to Boost Sustainable Energy for All (Se4all) in Rwanda", they have displayed the current position of SCP and photovoltaics systems in Rwanda where only PV are being used with total on-grid installed capacity of 12.08MW and there is no implementation of CSP being used. The techno-economic analysis of CSP and PV systems was conducted and it have been seen that PV systems is more economic than CSP because CSP necessitates significant financial investment to be bankable or implemented. Due to the availability of solar energy in Rwanda PVs are promoted as means of providing people with affordable electricity. This is because the time it takes to build a power plant that uses solar as energy resource is shorter and faster compared with other energy resources. This could help the Rwandan economy by lowering energy prices and making it easier to obtain it. The technical and financial viability of PV and CSP micro-grid systems in Rwanda's off-grid sites have been evaluated using the system advisor model.

Nsengimana Cyprien et al (2020) [24]**,** in their research on "Comparative Analysis of Reliable, Feasible, and Low-Cost Photovoltaic Micro-grid for a Residential Load in Rwanda" have used homer software and they have demonstrated that the LCOE of grid-integrated PV battery system is less than that of other forms of off -grid PV systems such as Diesel Genset-PV-Batteries and PB Batteries systems. They have demonstrated that when PV-battery systems are used and connected to the grid, electricity costs are four times less than they are under the current national tariff. Due to this, they encourage to use Grid connected PV with Battery energy storage.

The usage of renewable energy, particularly solar PV systems, is rapidly increasing in Rwanda as it is in many other areas throughout the world. Hence, people must have sufficient information to positively influence its use and take into account the challenges that may arise when the SPV system is connected to the grid. Many researches about the impact of grid tied PV system on the power quality of electric grid were done in different countries of the world but no research was done in Rwanda.

This study will help Rwandans, particularly Rwanda Energy Group, comprehend the effect of PV installations on the reliability of the Rwanda grid and provide mitigation measures.

CHAPTER III. RESEARCH METHODOLOGY

3.1. Introduction

To achieve successfully main objective and specific objectives of this research; the detailed methodology has been developed. This chapter includes techniques and methods that have been used for conducting this research. It includes research design, research procedure, baseline survey undertaken to collect data. Information on the impact of grid integrated PV system on power quality has been gathered and thoroughly assessed through a review of the literature.

3.2. Documentation

Through different researches like published papers, conference articles, renewable energy integration books and scientific reports have been used in literature review in order to get information about Impact of Grid-Connected PV System on Power Quality.

3.3. Data collection

A baseline survey has been undertaken at PV power plant connected to grid in Rwanda (Rubona Sloar Power Plant). This is the first step a researcher takes to determine the current state of affairs at the location of his research study before implementing the project. This is the primary research in which information is acquired directly from sources by asking people questions in person, on paper, over the phone, or online. Face-to-face interviews, online and questionnaires have been employed in this study's survey. Other ways of data collection approaches that have been employed include literature reviews on Impact of PV System Grid-Connected on Power Quality, questionnaires, interviews and observation. Questionnaires, interviews and observation were used for collection of primary data. Secondary data had been gathered from literature reviews of books, journals/articles and websites as well as data from Rwanda Energy Group (REG).

3.4. Area of the study

Rubona PV power plant is a solar power plant connected to grid that was constructed by Gigawatt global Rwanda and it is located in Rwamagana district/ Eastern province. This plant is constructed on 17ha and it has the maximum power generation of 8.5MW. Its daily power generation varies from 0.1 MW to 6.94 MW.

The table 3.1 shows the variation of power generated by Rubona solar power plant fed into the grid in 2021.

Table 3.1 Vatiation of power fed to the grid

MONTH	VARIATION OF POWER GENERATION	
	Minimum Power (MW)	Maximum Power (MW)
January	0.393	6.81
February	0.247	6.94
March	0.244	6.79
April	0.3	6.4
May	0.8	6.7
June	0.7	6.4
July	0.4	6.4
August	0.4	6.4
September	0.4	6.4
October	0.4	6.8
November	0.2	6.9
December	0.1	6.6

The frequency varies between 49.05 Hz to 50.51Hz, and the output voltage used in transmission line 15kV.

Table 3. 2 shows the solar radiation on PV panels. It indicates the minimum and the maximum received by the PV panel every month in 2021.

Table 3.2 solar radiation that arrives on PV panels

MONTH	SOLAR RADIATION (W/m^2)	
	Minimum	Maximum
January	76.47	1148.23
February	62.56	1137.37
March	39.43	1248.54
April	81.25	1167.55
May	60.13	1138.57
June	39.03	1019.1
July	54.04	967.08
August	22.01	1026.18
September	54.36	1099.34
October	51.37	1333.10
November	71.23	1124.89
December	50	1099.39

This area has the average sun Global irradiance (GHI) of 4.88kWh/m2 as shown on table 3.3

Table 3.3 Monthly average solar Global irradiance for Rwamagana (Rubona) from Homer tool

Month	Clearness index	Daily radiation
January	0.480	4.930
February	0.497	5.220
March	0.472	4.970
April	0.478	4.830
May	0.497	4.710
June	0.531	4.830
July	0.557	5.140
August	0.520	5.090
September	0.492	5.070
October	0.448	4.680
November	0.442	4.540
December	0.451	5.570
Annual Average:		4.88

3.5. Data collection Methods

For conducting this research, different data collection approaches were engaged, including literature reviews on grid connected pv systems, interviews and observations. Interviews and observations were used to collect primary data while literature reviews from papers/articles/ journals, websites and Meteo Rwanda were used to collect secondary data. The data collected was used to model and simulate a PV connected to the system grid.

CHAPTER IV. RESULTS AND DISCUSSIONS

4.1. Model of grid connected PV system

The PV system connected to grid was modelled, simulated and analysed in ETAP 19.0.1 software. Therefore, RUBONA solar power plant was taken as case study; and generates 8.5MW peak power from 28306 PV modules with 8 inverters and four step up transformers which directly coupled to 15KV RUBONA-MUSHA feeder. The 28306 PV modules were arranged on 1418 strings laid at 709 tables; where by each string is made by 20 PV modules and 50 string combiners [1]. The PV system which is connected to grid has inverters which are the source of harmonic. The accepted harmonics can't exceed 5% from the fundamental voltage and frequency [2]. The inverters affect the quality of Grid system by injecting the harmonics because of the power electronics components inside them. The impact of Grid connected PV system was analysed through the increase of voltage, and frequency fluctuation results from harmonic. Figure 4.1 shows the complete model RUBONA solar power plant from RUBONA up to MUSHA substation. From figure 4.1, RUBONA –MUSHA feeder starts from B4 up to B1 buses and it has three distributed transformers which supply power to the secondary consumers. The distribution transformers step down the voltage from 15KV to 0.415kV as fundamental voltage. Bus16 is 15KV bus from solar PV transformers and cables which connect RUBONA solar power plant to grid system.

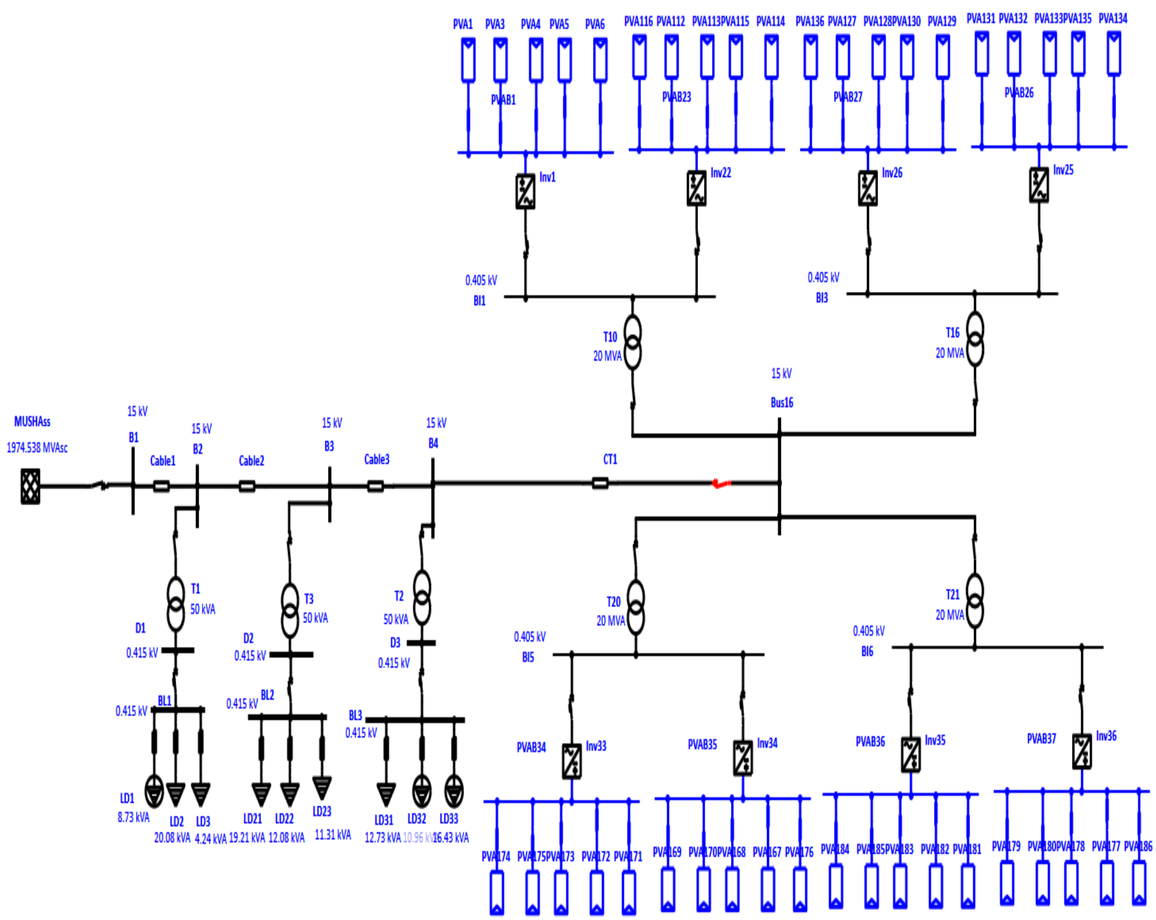

Figure 4.1 Model RUBONA PV power plant grid connected system

4.2. Simulation and Results analysis

4.2.1. Simulation of Rubona Solar Power plant before integrated on the grid

Figure 4.2 demonstrates the power consumed, line voltage drops and the terminal voltage before connecting RUBONA solar power plant to the grid system. The power are real power, reactive power and apparent power. The figure4.2 shows that real power at bus B1 is 95.5KW with reactive power of 58.7Kvar, at B2 bus the power consumed is 67.7KW with 42.6KVAR, at B3 the power consumed is 32.3KW with 24.5KVAR. Hence, the power factor of MUSHA substation becomes 0.852.

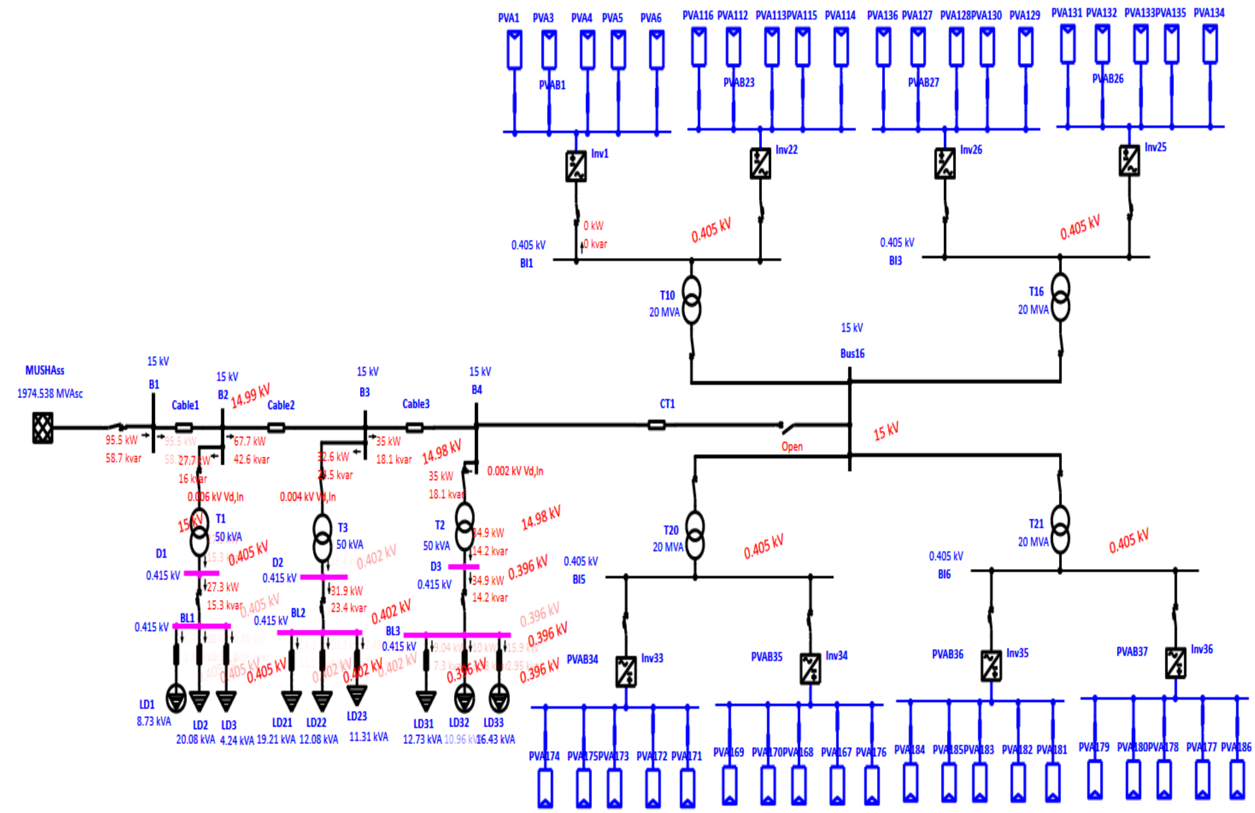

Figure 4.2 Load flow of Rubona-Musha feeder

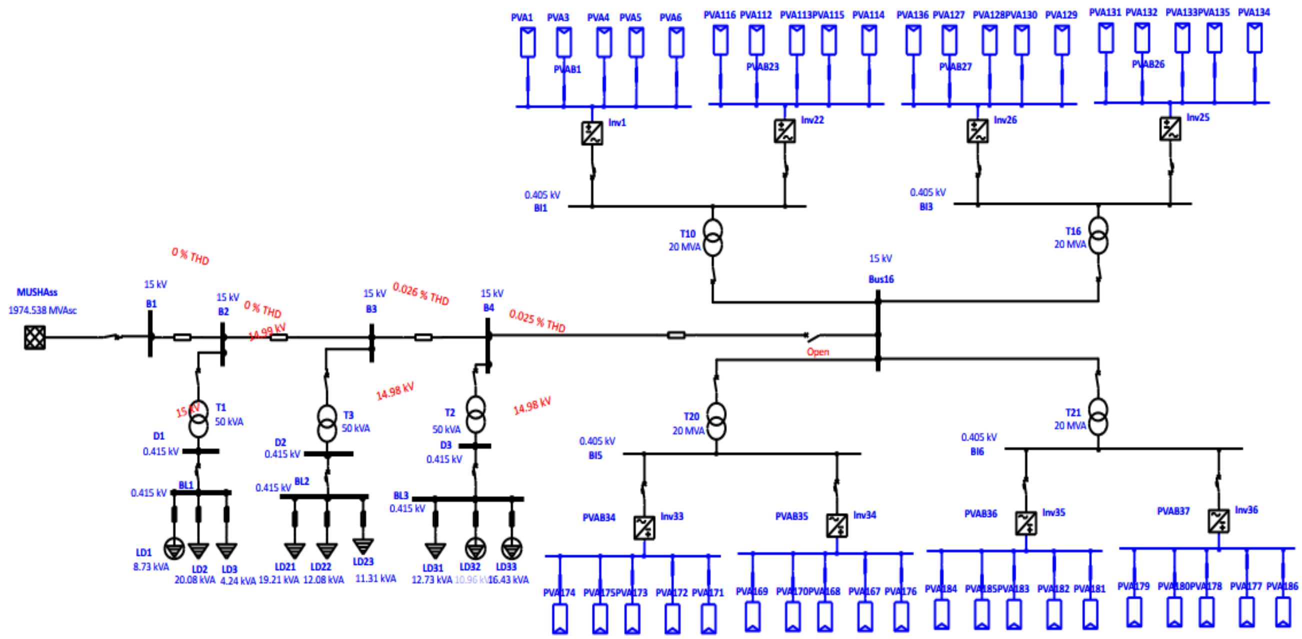

Figure 4.3 Harmonic on RUBONA-MIUSHA feeder when RUBONA solar power plant is not connected

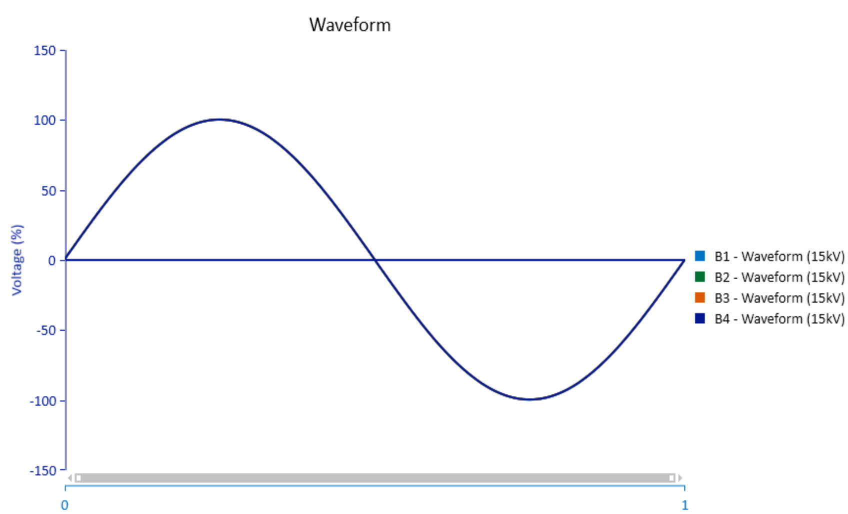

Figure 4.4 Voltage characteristics obtained on RUBONA-MUSHA feeder when RUBONA solar power is not connected

From Figure 4.3, it can be observed that the quality of power is good due to the fact that harmonic was very low as the THD was not exceeding the accepted value and therefore, these harmonics come from the static loads as they are sources of harmonic. For instance, at B1, THD is 0% with 15KV as fundamental voltage. However, when RUBONA solar power plant is connected to grid, the harmonic was generated too and the harmonic at bus BI1 becomes 5.33% with increase of 11.11 % from fundamental voltage. Figure 4.4 shows that the output signal is good as there is no voltage fluctuation available on buses (B1, B2, B3, and B4) and the loads get power from Grid. Table 4.1 gives more information about the power quality when RUBONA photovoltaic power plant is not integrated to the Grid system.

Table 4.1 Bus harmonic distortion information

Bus		Voltage Distortion								
ID	kV	Fund. %	RMS %	ASUM %	THD %	TIF	TIHD %	TSHD %	THDG %	THDS %
B1	15.000	100.00	100.00	100.09	0	1.51	0.00	0.00	0.02	0.02
B2	15.000	99.93	99.93	100.04	0	1.51	0.00	0.00	0.03	0.03
B3	15.000	99.88	99.88	100.00	0.03	1.52	0.00	0.00	0.03	0.03
B4	15.000	99.86	99.86	99.97	0.03	1.52	0.00	0.00	0.03	0.03
BI1	0.405	111.11	111.27	133.24	5.33	151.03	0.00	0.00	5.33	5.33
BI3	0.405	111.86	111.88	120.69	2.01	73.62	0.00	0.00	2.01	2.01
BI5	0.405	111.86	111.88	120.69	2.01	73.62	0.00	0.00	2.01	2.01
BI6	0.405	111.86	111.88	120.69	2.01	73.62	0.00	0.00	2.01	2.01
BL1	0.415	97.53	97.57	106.41	2.88	98.30	0.00	0.00	2.88	2.88
BL2	0.415	96.65	96.71	109.40	3.34	187.91	0.00	0.00	3.34	3.34
BL3	0.415	95.30	95.37	103.37	4.01	46.20	0.00	0.00	4.01	4.01
Bus16	15.000	111.67	111.68	118.18	1.69	83.57	0.00	0.00	1.69	1.69
D1	0.415	97.53	97.57	106.41	2.88	98.30	0.00	0.00	2.88	2.88
D2	0.415	96.65	96.71	109.40	3.34	187.91	0.00	0.00	3.34	3.34
D3	0.415	95.30	95.37	103.37	4.01	46.20	0.00	0.00	4.01	4.01

* IndicatesTHD (Total Harmonic Distortion) Exceeds the Limit.
\# Indicates IHD (Individual Harmonic Distortion) Exceeds the Limit.

Table 4.1 shows bus information and total harmonic of both power plant and Musha-Rubona feeder when the plant is not connected to the grid. It seems that the voltage fluctuation becomes less 100% due to losses and the bus with low voltage is D3 because it is quite away from Musha (nearby Rubona).

4.2.2. Simulation of Rubona - Musha feeder when Rubona Solar Power plant is integrated on the grid

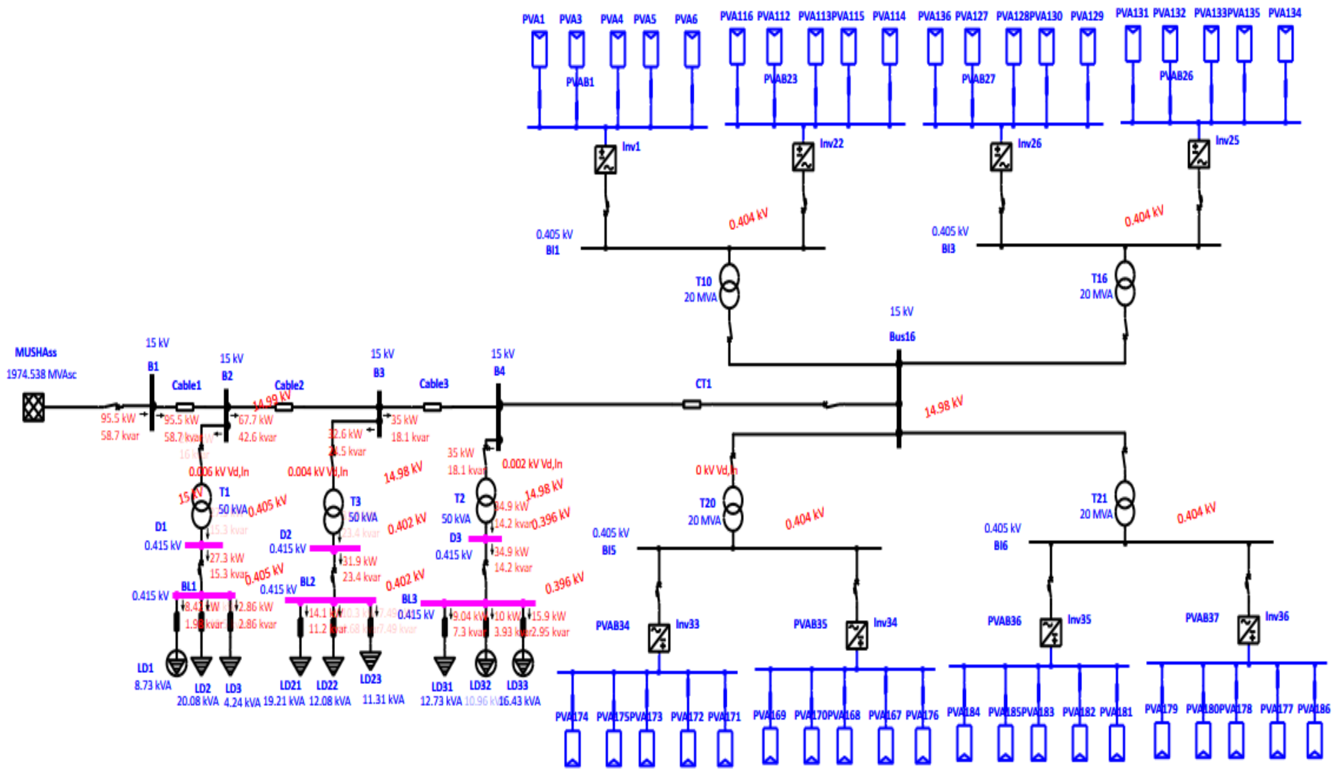

Figure 4. 5 Simulation of Rubona - Musha feeder when Rubona Solar Power plant is integrated on the grid

Figure 4.5 shows the situation of loads at Rubona-Musha feeder when Ruboner solar power plant is connected to the grid system. Furthemor, it demonstrates the ampere of each connected load with its corresponding power factor.

Table 4.2 load flow result when RUBONA solar power plant is connected to grid

Bus		Voltage		Generation		Load		Load Flow					XFMR
ID	kV	% Mag.	Ang.	MW	Mvar	MW	Mvar	ID	MW	Mvar	Amp	%PF	%Tap
*B1	15.000	100.000	0.0	0.095	0.059	0.000	0.000	B2	0.095	0.059	4.3	85.2	
B2	15.000	99.930	0.0	0.000	0.000	0.000	0.000	B1	-0.095	-0.059	4.3	85.2	
								B3	0.068	0.043	3.1	84.6	
								D1	0.028	0.016	1.2	86.6	
B3	15.000	99.881	0.0	0.000	0.000	0.000	0.000	B2	-0.068	-0.043	3.1	84.6	
								B4	0.035	0.018	1.5	88.9	
								D2	0.033	0.025	1.6	79.9	
B4	15.000	99.856	0.0	0.000	0.000	0.000	0.000	B3	-0.035	-0.018	1.5	88.9	
								Bus16	0.000	0.000	0.0	0.0	
								D3	0.035	0.018	1.5	88.9	
BI1	0.405	99.856	0.0	0.000	0.000	0.000	0.000	Bus16	0.000	0.000	0.0	0.0	
BI3	0.405	99.856	0.0	0.000	0.000	0.000	0.000	Bus16	0.000	0.000	0.0	0.0	
BI5	0.405	99.856	0.0	0.000	0.000	0.000	0.000	Bus16	0.000	0.000	0.0	0.0	
BI6	0.405	99.856	0.0	0.000	0.000	0.000	0.000	Bus16	0.000	0.000	0.0	0.0	
BL1	0.415	97.638	-0.7	0.000	0.000	0.027	0.015	D1	-0.027	-0.015	44.6	87.2	
BL2	0.415	96.804	-0.6	0.000	0.000	0.032	0.023	D2	-0.032	-0.023	56.8	80.6	
BL3	0.415	95.532	-5.2	0.000	0.000	0.035	0.014	D3	-0.035	-0.014	54.9	92.7	
Bus16	15.000	99.856	0.0	0.000	0.000	0.000	0.000	B4	0.000	0.000	0.0	0.0	
								BI1	0.000	0.000	0.0	0.0	
								BI3	0.000	0.000	0.0	0.0	
								BI5	0.000	0.000	0.0	0.0	
								BI6	0.000	0.000	0.0	0.0	
D1	0.415	97.638	-0.7	0.000	0.000	0.000	0.000	B2	-0.027	-0.015	44.6	87.2	
								BL1	0.027	0.015	44.6	87.2	
D2	0.415	96.804	-0.6	0.000	0.000	0.000	0.000	B3	-0.032	-0.023	56.8	80.6	
								BL2	0.032	0.023	56.8	80.6	
D3	0.415	95.532	-5.2	0.000	0.000	0.000	0.000	B4	-0.035	-0.014	54.9	92.7	
								BL3	0.035	0.014	54.9	92.7	

* Indicates a voltage regulated bus (voltage controlled or swing type machine connected to it)

\# Indicates a bus with a load mismatch of more than 0.1 MVA

Table 4.2 is the report of figur5 obtained by using ETAP software. It shows that the highest power factor is 92.7%.

4.2.2.1. Harmonics from Rubona power plant

Figure 4.6 shows how solar power plant increases the THD when it is integrated to the grid. At B4, the harmonic rises from 0.03(table5.1) % to 6.88% with fundamental voltage 16.11KV. At B3, the harmonic rises from 0% to 5.01% with fundamental voltage 16.92KV.

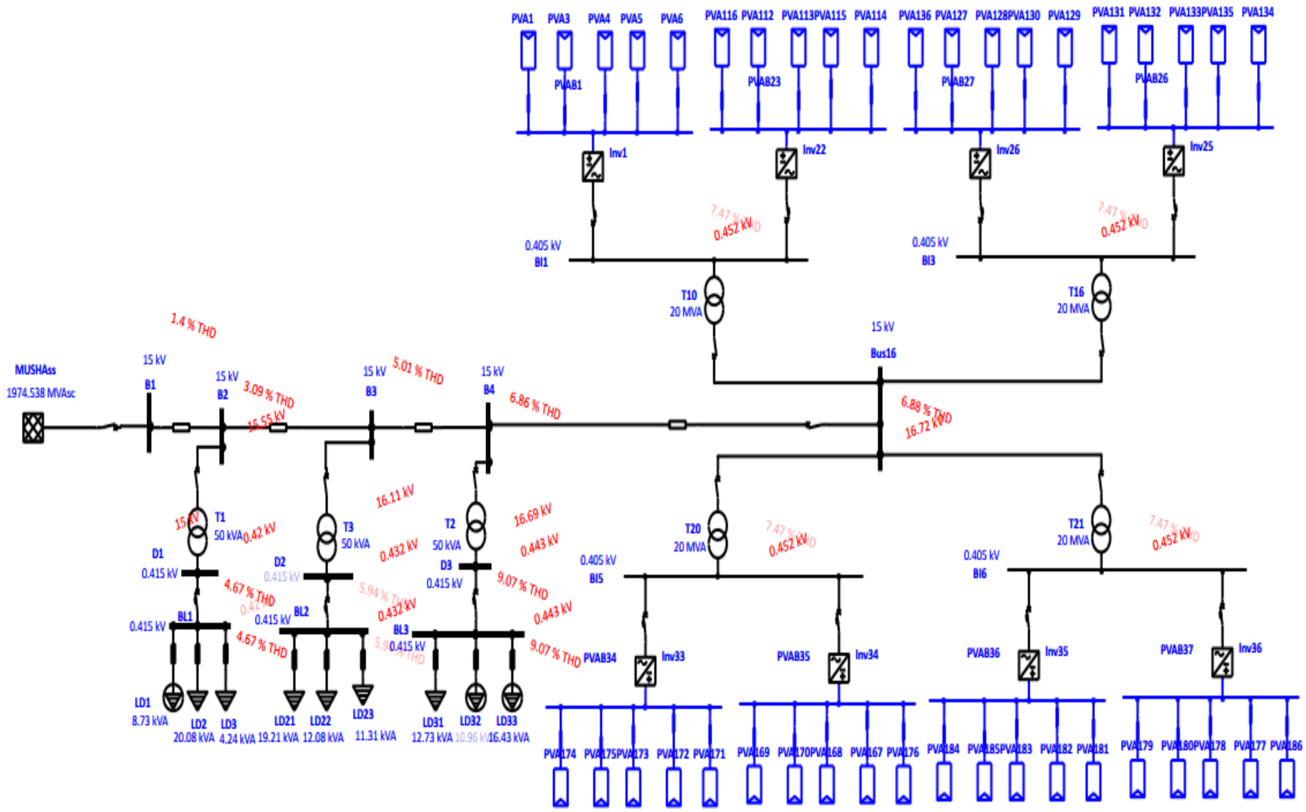

Figure 4.6 TDH including harmonics from RUBONA power plant

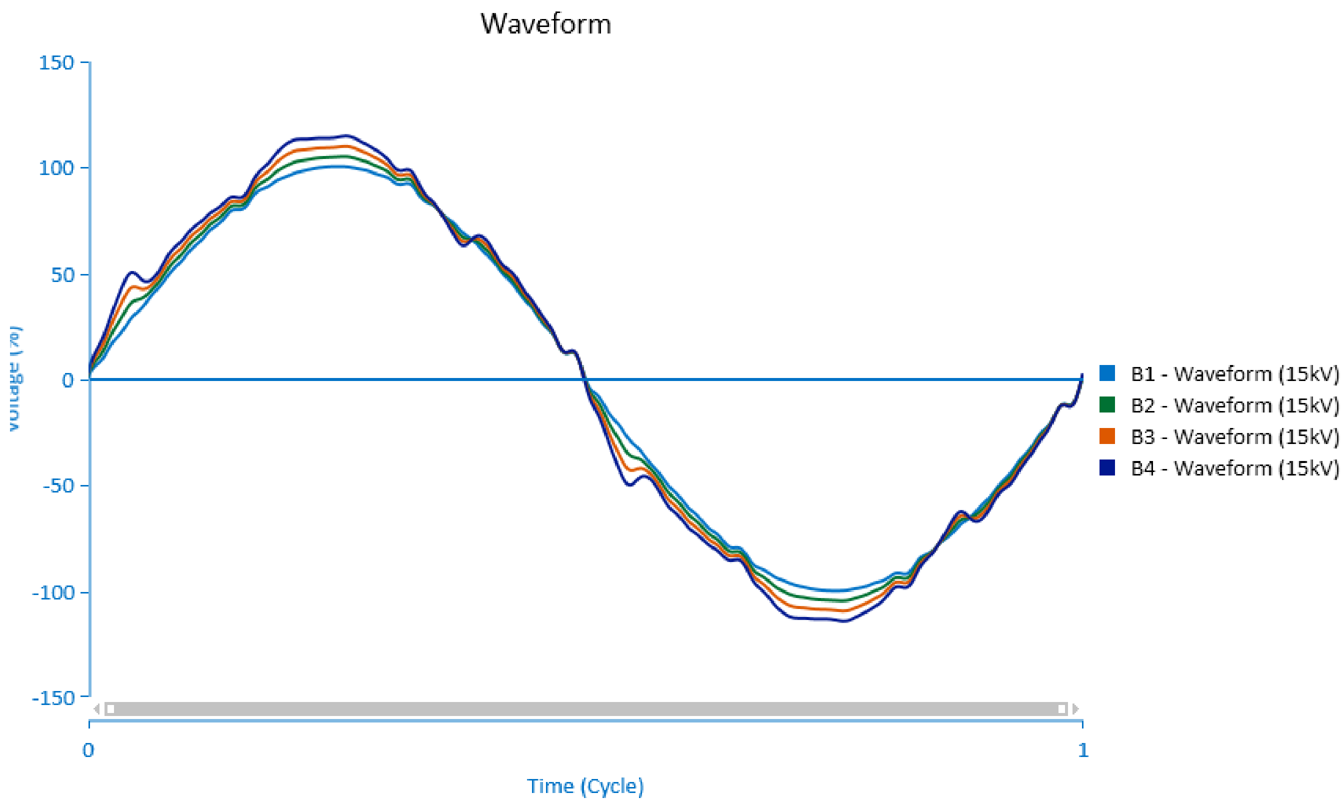

Figure 4.7 graphs of TDH including harmonic from RUBONA power plant

The harmonic exceeds the limit because the solar power plant is connected to the grid system. For instance, the harmonics at Bus B3 is 5.01% with the voltage rise of 22.1 % from fundamental voltage. Hence, to minimize the harmonics it will be needed to protect the loads before connected to grid system and therefore, it will not affect the power quality of electrical network.

4.2.2.2. Harmonic analysis at the buses of inverters

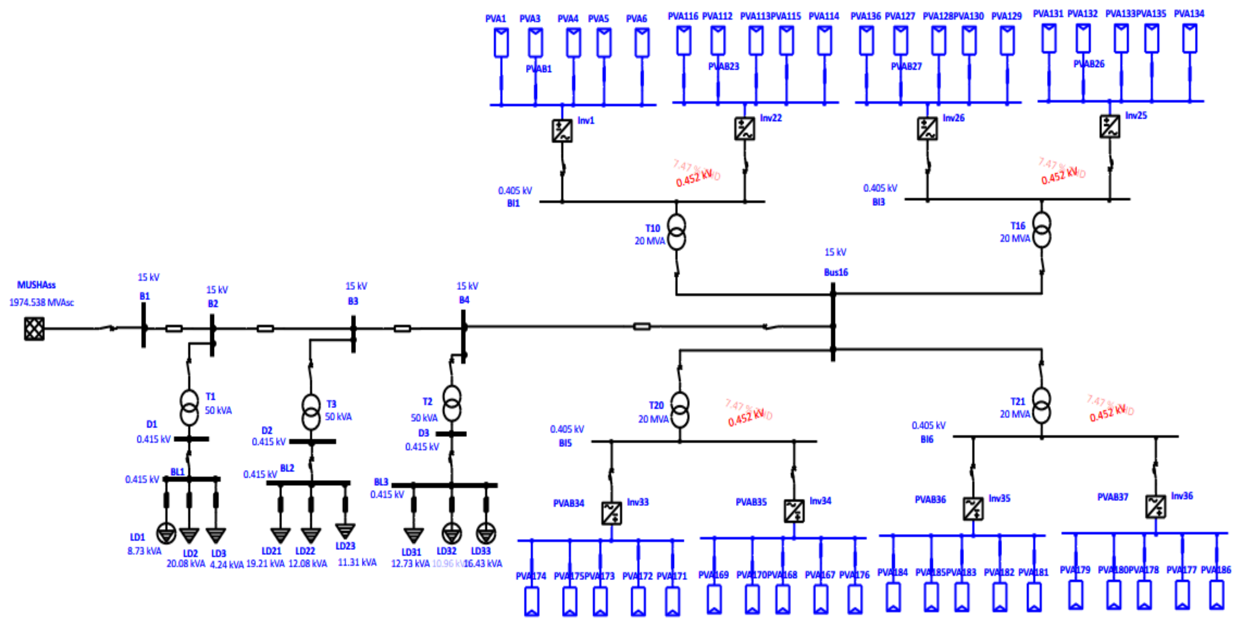

Figure 4.8 Harmonic analysis at the buses of inverters

Figure 4.8 indicates that the harmonics at the inverter buses IB1, IB3, IB5 and IB6 are 7.47% with fundamental voltage of 452V for two inverters. The THD of 7.45% of two inverter is beyond the limits that are accepted in the electrical network system. Due to the harmonic from inverters, the solar grid system needs filter for reducing the harmonics before connecting to the grid system. In addition to that, Figure 4.9 proves that the inverters are the source of harmonics that affect the power quality of electrical system.

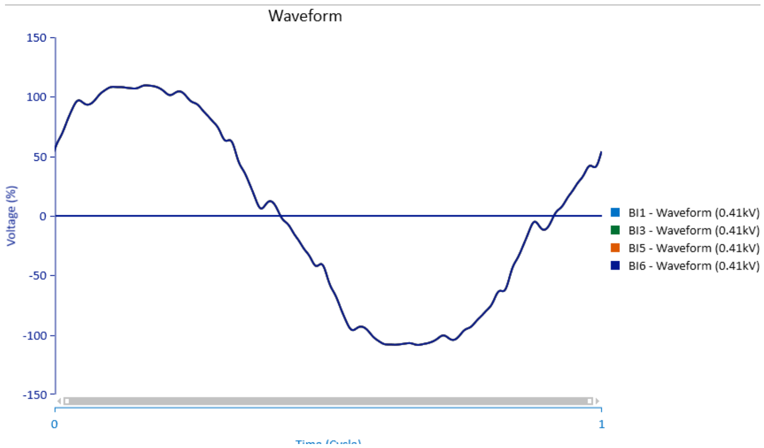

Figure 4.9 Curves of Harmonic analysis at the buses of inverters

The figure 4.9 shows that the inverters are the main sources of harmonic which tends to affect the quality of electrical network. The curves shows that the characteristics for all 8 inverters are similar with harmonics that affect the loads.

4.2.2.3. Harmonic analysis at the buses of the loads

Figure 4.10 demonstrates the THD at the consumers where at BL1, TDH is 4.67KV with 420V, at BL2 bus, TDH is 5.9% with 432V and At BL3, THD is 9.07% with 443V. At BL1, the harmonic is below limit that cannot affect the power quality while for BL1 and BL2 the power quality was not good due to the rising of harmonic.

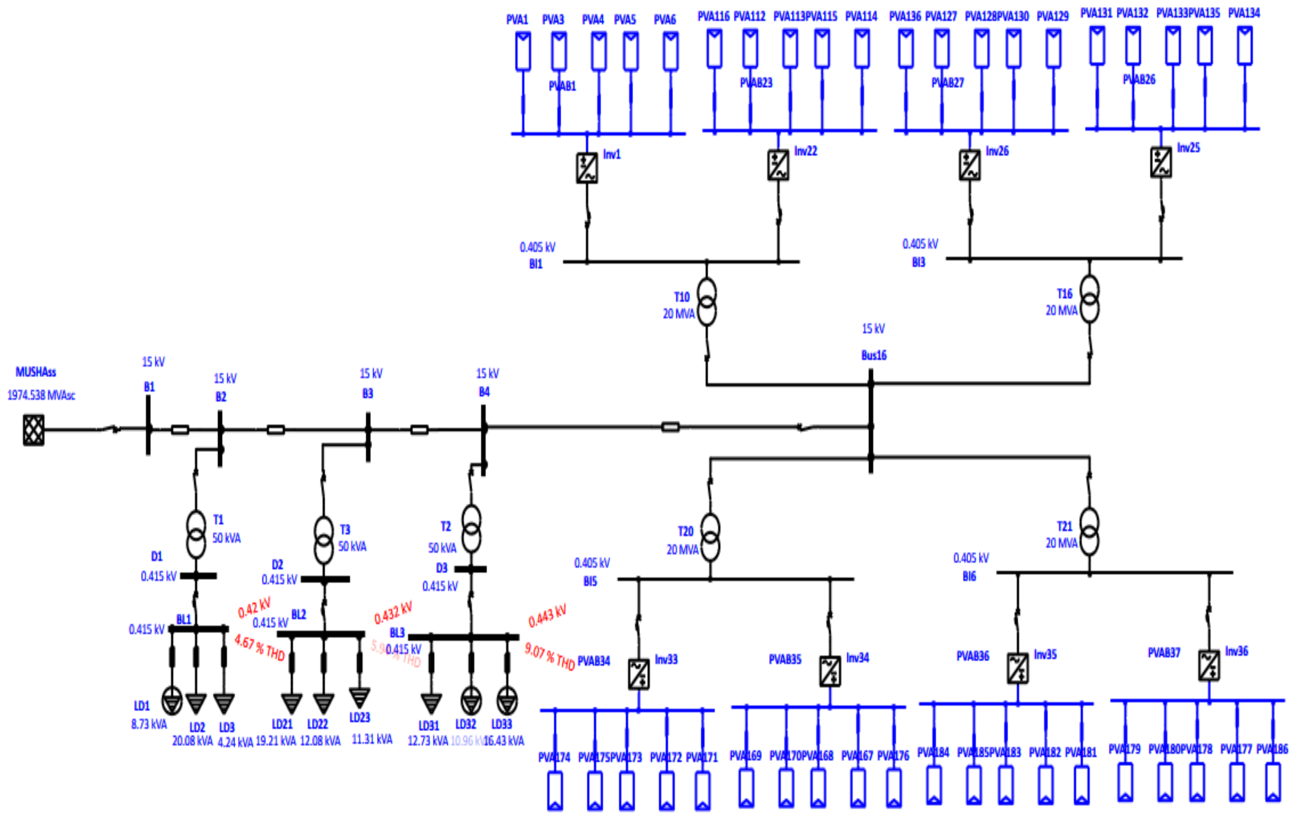

Figure 4.10 Analysis at the load buses

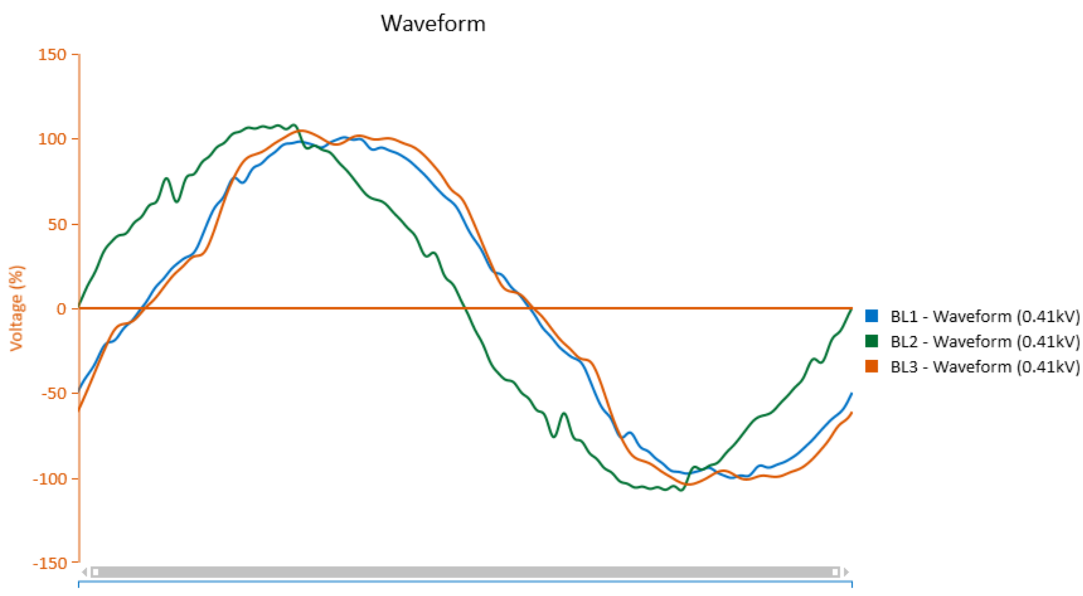

Figure 4.11 curves of harmonic analysis at the load buses

4.2.2.4. Overall harmonic of the Rubona solar power plant

The figure 4.12 shows how the PV grid connected affect the power quality through the harmonics generated from inverter. The total harmonics is of the plant is 6.88% that is greater than 5% which is accepted on grid and though, this percentage result to voltage fluctuation and affect the characteristics of electrical signal.

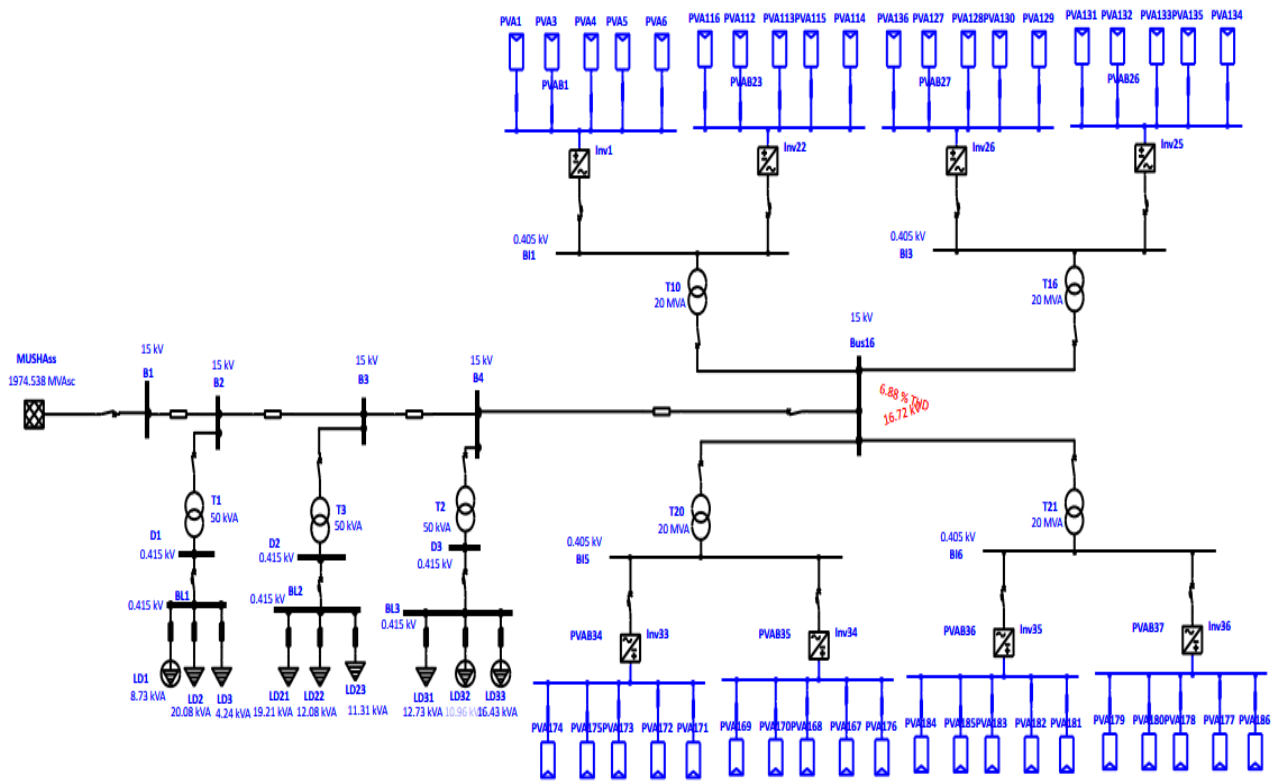

Figure 4.12 total harmonic at plant bus

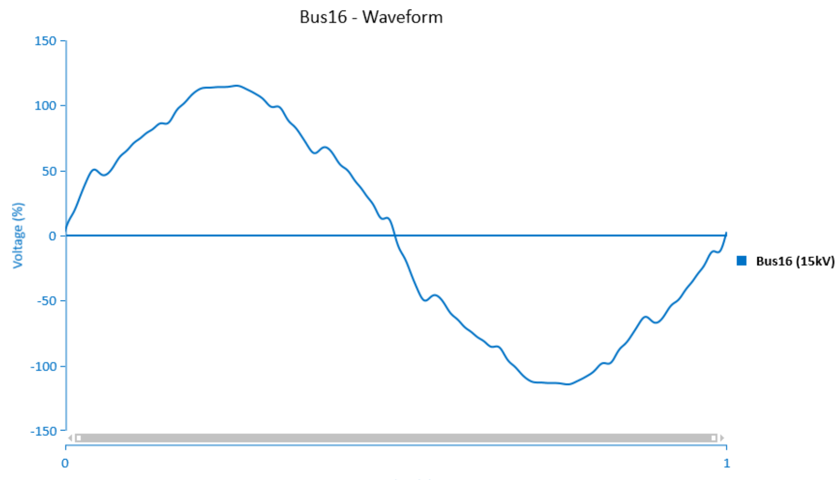

Figure 4.13 characteristic of total harmonic at plant bus

Figure 4.13 indicates the voltage fluctuations caused by connecting PV plant to the grid where by the behaviour or characteristics of AC electrical network is changed due to this plant. The change in voltage can be under or over voltage which affects the loads and mostly affected, are the loads that are connected near by the plant.

4.2.2.5. System buses information of rubona pv plant-musha substation

Table 4.3 demonstrates the bus information concerning the power quality and it shows that the most critical bus are the inverter buses (IB1, IB2,IB3,IB4 and bus 16) with 111%vof fundemental voltage. The terminal voltage exceeds 11% at these buses and total harmonic distortion became 7.47%.

Table 4.3 System buses information of RUBONA PV PLANT-MUSHA substation

Bus		Voltage Distortion								
ID	kV	Fund. %	RMS %	ASUM %	THD %	TIF	TIHD %	TSHD %	THDG %	THDS %
B1	15.000	100.00	100.01	105.55	1.40	84.43	0.00	0.00	1.40	1.40
B2	15.000	103.62	103.67	113.66	3.09	96.10	0.00	0.00	3.09	3.09
B3	15.000	107.29	107.42	122.45	5.01	116.46	0.00	0.00	5.01	5.01
B4	15.000	111.01	111.27	131.43	6.86	140.12	0.00	0.00	6.86	6.86
BI1	0.405	111.39	111.70	136.28	7.47	150.01	0.00	0.00	7.47	7.47
BI3	0.405	111.39	111.70	136.28	7.47	150.01	0.00	0.00	7.47	7.47
BI5	0.405	111.39	111.70	136.28	7.47	150.01	0.00	0.00	7.47	7.47
BI6	0.405	111.39	111.70	136.28	7.47	150.01	0.00	0.00	7.47	7.47
BL1	0.415	101.16	101.27	113.48	4.67	104.55	0.00	0.00	4.67	4.67
BL2	0.415	103.82	104.01	122.61	5.94	191.51	0.00	0.00	5.94	5.94
BL3	0.415	106.40	106.83	124.84	9.07	85.16	0.00	0.00	9.07	9.07
Bus16	15.000	111.20	111.46	131.70	6.88	140.14	0.00	0.00	6.88	6.88
D1	0.415	101.16	101.27	113.48	4.67	104.55	0.00	0.00	4.67	4.67
D2	0.415	103.82	104.01	122.61	5.94	191.51	0.00	0.00	5.94	5.94
D3	0.415	106.40	106.83	124.84	9.07	85.16	0.00	0.00	9.07	9.07

* IndicatesTHD (Total Harmonic Distortion) Exceeds the Limit.
\# Indicates IHD (Individual Harmonic Distortion) Exceeds the Limit.

CHAPTER V. CONCLUSION AND RECOMMENDATION

5.1. Conclusion

The impact of PV grid connected on power quality is inspected through total harmonic distortion injected in grid from inverters. Study case is taken at RUBONA solar power plant . The simulation results were carried out on 16 buses using etap19.0.1 software. The results show the effect of harmonics from RUBONA PV plant on electrical grid .

The harmonics from inverter imposes a great problem on the power qaulity through over voltage ,under voltage,overfrequency and under frequency that could damage the loads which are connected to grid system and their effects are different due to harmonics order. These results help outhor to know the harmonic filters that will be installed to minimize the harmonics distortion to the accepted level.

A complete design of RUBONA PV power plant to MUSHA substation has been done including the transformers that are attached to this feeder. The design is carried out through etap software and simulation of the results is shown in this work.

Finally. Suitable filters have to be identified from the total harmonic distortion of the system through change in volatge and change in frequency for improving the quality of electrical grid.

5.2. Recommendation

The results shown indicate that, the harmonics from PV plant is exceeding the accepted level where by it becomes 6.86% ; this requires to install a suitable harmonic filter on inverters output before connecting to pv system to grid system to ensure the power quality of the ystem will no be affected.

In addition to that, the harmonics cause the change in voltage and change in frequency that could affect the electrical equipment nearby the plant . Harmonic filtering devices such as SCs and hybrid devices made by RHS and SCs are recommended to install in electrical network to handle the effects produced by harmonics. This would result to the reduction in size of transformers and distribution cables.

Finally, the author suggests a further research work on the impacts of the grid connected pv system to have a better and improved power quality.

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