

ANALYSIS OF POWER QUALITY ISSUES DUE TO THE PROPOSED SOLAR POWER PLANTS IN HAMBANTOTA

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Department of Electrical Engineering

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Sri Lanka

December 2014

DECLARATION

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(Prof. J. P. Karunadasa)

ABSTRACT

Solar power plants, despite their high initial investment are fast spreading in Asian countries owing to the availability of higher solar radiation throughout the day time. In Sri Lanka, two grid connected small scale solar power plants of 737 kW, 500 kW are already in operation located in Baruthankanda, Hambantota.

Three private developers have made proposals for another 30 MW solar plants, (each 10 MW) near the existing plants which would be directly connected to 33kV Bus at Hambantota GSS. However, unpredictable variations in the source of energy and power electronic converters of such a large solar power plant can create a significant impact on the existing power system in power quality point of view.

This thesis describes the details of a study carried out on the probable impacts on power quality at the GSS due to random fluctuation of solar radiation level for different system-design options of the proposed 30 MW plant. Standards IEEE 519-1992 and IEEE 1547-2003 were used in the power quality check-up.



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LIST OF ABBREVIATIONS

Abbreviation	Description
CEB	Ceylon Electricity Board
SEA	Sustainable Energy Authority
PSCAD	Power Systems Computer Aided Design
P&D	Planning & Development
EE	Electrical Engineer
ES	Electrical Superintendent
IEEE	Institute of Electrical & Electronic Engineers
TDD	Total Demand Distortion
NCRE	Non- Conventional Renewable Energy
GSS	Grid Sub Station
PV	Photo Voltaic
DC	Direct Current
AC	Alternative Current
STC	Standard Test Conditions
MPPT	Maximum Power Point Tracking
IC	Incremental Conductance
P&O	Perturb & Observe
THD	Total Harmonic Distortion
PCC	Point of Common Coupling
DR	Distributed Resource
RMS	Root Mean Square
DDLO	Drop Down Lift Off
ABS	Air Break Switch
EMTDC	Electro Magnetic Transients including DC
IGBT	Insulated gate Bipolar Transistor
PWM	Pulse Width Modulation



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1.1 Background

Electricity generation in Sri Lanka is mainly dependent on conventional energy sources (i.e. petroleum, coal, hydro) based power plants owned by Ceylon Electricity Board and a few private power generation companies. However, the government of Sri Lanka has declared by the Gazette published on “National Energy policy and Strategies of Sri Lanka” in June, 2008 that the government endeavor for minimum level of 10% of electrical energy supplied to the grid to be from Non -conventional Renewable Energy (NCRE) by 2015 [01]. In order to achieve above target, all the responsible authorities in state sector such as Ministry of Power & Energy, Ceylon Electricity Board, Sri Lanka Sustainable Energy Authority, and Public Utilities Commission of Sri Lanka worked together & took appropriate measures to encourage private developers to invest on NCRE based embedded generators. Therefore, in recent past, several wind power plants, dendro power plants, bio mass power plants, solar power plants were added to the national grid.



By 2013, the NCRE based power plants reached up to 18 nos. with installed capacity of 96 MW which is 2.9 % of total installed capacity [02]. Contribution of such plants to the annual energy generation was 262 GWh in 2013 which is about 2.0 % of gross generation [02]. Growth of installed capacity and contribution to the energy generation over last few years by NCRE based power plants are indicated in Figure 1.1 & Figure 1.2 respectively.

With the addition of these power plants, impact to the system power quality was one of the key aspects that the professionals involved in Power & Energy Sector were keen to investigate and research on. Therefore, several studies and researches had been carried out in relation with wind power penetration to the national grid mainly because of the complaints raised by the consumers regarding power quality issues.

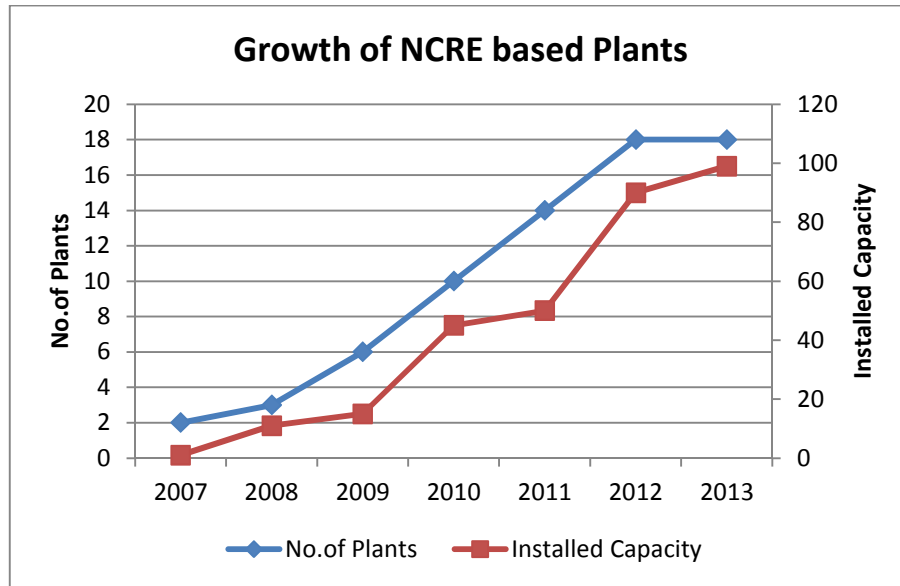


Figure 1.1: Growth of installed capacity by NCRE based power plants

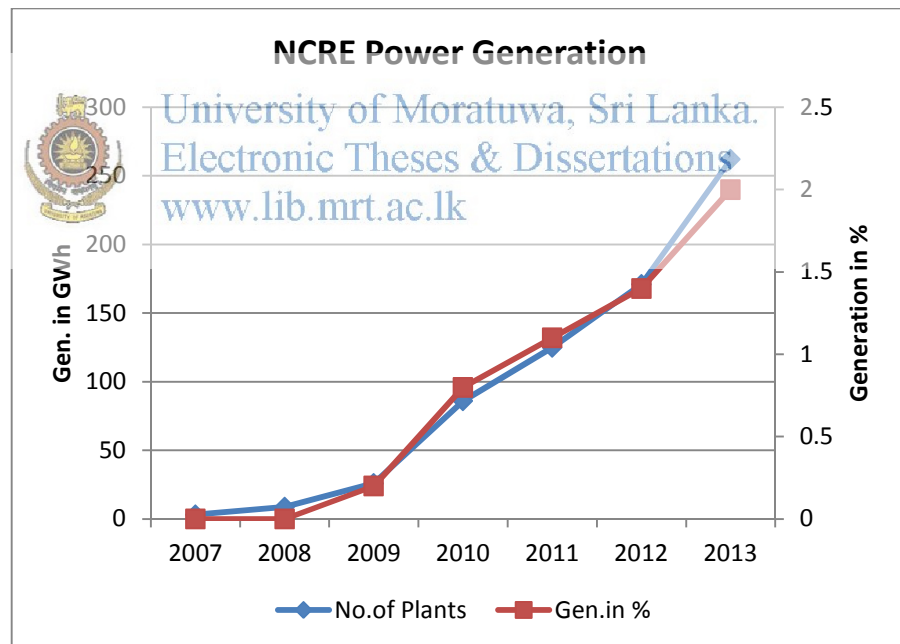


Figure 1.2: Contribution to the generation by NCRE based power plants

Solar power plants are also an emerging trend in Asian countries since solar radiation is adequately available throughout the day time, although the initial investment is high. Two grid connected small scale solar power plants of 737 kW, 500 kW put up with the

aids of Japanese and Korean grants and owned by Sri Lanka Sustainable Authority are in operation at Baruthankanda, Hambantota. In addition, there is another solar plant of 0.123 MW in Tirappane. Table 1.1 shows their annual generation in last three years.

Table1.1: Annual generation of existing solar plants

Project Name	Capacity (MW)	Annual Generation (kWh)		
		2011	2012	2013
Gonnoruwa SPP - II	0.500	510,900	701,800	658,600
Tirappane SPP	0.123	6,122	9,375	4,493
Gonnoruwa SPP - I	0.737	475,957	1,112,024	1,017,897

However, the unpredictable variations in source of energy and power electronic based controlling & conversion creates big impact to the existing power system in power quality point of view. Also, the Sri Lankan government is of the concept called “Solar Parks”, to be implemented especially in Hambantota so that more solar penetration to the national grid is assured in future.

Therefore, the necessity of carrying out researches on solar penetration & impact to the power system was very vital.

1.2 Importance of analysis of power Quality issues due to the Solar Penetration.

Quality of power supply is to determine its basic parameters like, voltage, frequency, phase are compatible with the customer loads, equipment. CEB itself has clearly stated in the mission statement, the “Quality” as its first core value.

The quality of electrical power could be described as a set of values of parameters, such as;

- Variation in voltage magnitude

- Transient voltages and currents
- Harmonic content in the waveforms for AC power

Through the literature review, it was realized that large solar penetration can create harmonics problems in the power system. Further, intermittent nature of the solar energy can also lead variations in system voltage. Therefore, these issues should be investigated, analyzed in order to assure quality supply within the limits stipulated in national and international standards, especially as harmonics can form following issues.

- Limitations on supply and network utilization
- Increased losses
- Increased transformer, motor and cable heating
- Reduced equipment life time
- Control system malfunctions
- Pulsating and reduced motor torque
- Audible noise
- Insulation degradation



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1.3 Motivation

Three private developers have made proposals for another 30 MW solar plants, (each 10 MW) nearby existing plants which will be directly connected to 33kV Bus at Hambantota GSS through 33kV, Lynx Double Circuit line. Names of those three developers are given below.

- M/s Saga Solar power (Pvt) Ltd
- M/s Anorchi lanka (Pvt) Ltd.
- M/s Iris Eco power lanka (Pvt) Ltd.

Since this a large power injection to a single point of supply, as an Electrical Engineer working for Ceylon Electricity Board and currently involving in embedded generation interconnections in Distribution Division 4, I was very much interested to study &

investigate the impact to power system by above three proposed power plants in power quality point of view which was a new area that no one in Sri Lanka has touched on and ought to be done. On the other hand this research would be more beneficial in future applications as well.

1.4 Objectives of the study

Main objective of this research is to analyze the power quality issues such as voltage harmonics, current harmonics, voltage fluctuations created by proposed solar power plants and check whether they satisfy the stipulated standards like IEEE 519-1992, IEEE 1547-2003.

It is expected to ascertain the effect of environmental conditions to the power quality by Photovoltaic system through measurements and simulation. Results of this research will also be very much important for future applications in other part of the country as well specially for solar parks. Results of the research and PSCAD model can be used for finding out solutions to mitigate those issues.

1.5 Methodology

- Obtain power quality measurements and environmental conditions data of existing solar power plant & analyze the results.
- Obtain the design of existing solar plant & model it in PSCAD software & compare it with measurements in order to validate the model.
- Scale up the PSCAD model to proposed solar power plants & analyze the power quality through simulation results.

2.1 Energy from the Sun

Solar energy is a form of radiant energy that travels to the earth as electromagnetic waves that covers the full breadth of the electromagnetic spectrum. The earth receives 174 petawatts of incoming solar radiation at the upper atmosphere [3]. Approximately 30% of it is reflected back to space while rest is absorbed by the clouds, oceans and land masses. Breakdown of reflected and absorbed amounts of incoming solar energy by different forms are shown in Figure 2.1 [4].

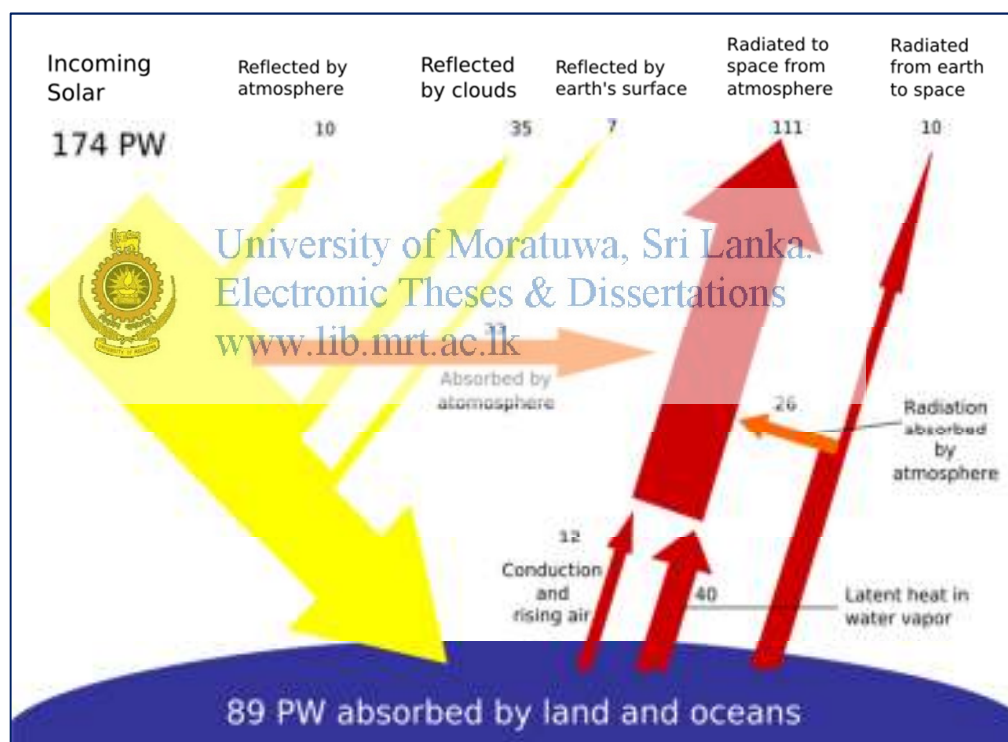


Figure 2.1: Overview of a typical solar power plant

The total solar energy absorbed by the earth's atmosphere, oceans and land masses is approximately 3,850,000 exajoules per year which is about 70% of total incoming energy [3]. This is a massive figure compared with the total annual energy obtained from non-renewable energy sources like coal, oil, natural gas, mined uranium.

2.2 Physics of solar generation

Solar cells are physically made of p-n junctions. Hence, it is important to refresh the knowledge on p-n junction, its characteristics and operation. Figure 2.2 shows an overview of a p-n junction.

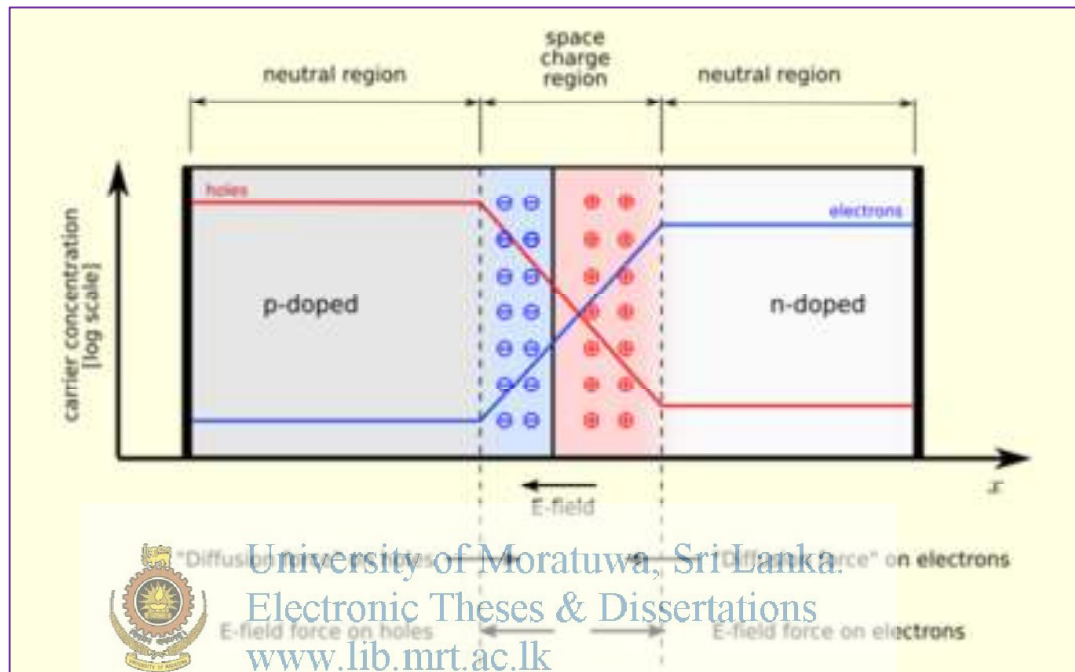


Figure 2.2: Overview of a p-n junction

2.2.1 Production of p-n junction

There are several ways to make p-n junction industrially. Simply, it is made by using a single wafer of Si or Ge. First, a silicon (pure, intrinsic) wafer is converted to a p-type semiconductor by doping it with a trivalent impurity (Boron or Indium) on one side. Then, this p-type semiconductor is doped with a pentavalent impurity (Phosphorous or Arsenic or Antimony) to form an n-type region on the same wafer, resulting in formation of a junction (between p-type and n-type semiconductors) on the same silicon wafer.

2.2.2 Formation of p-n junction

There are three important phenomena in formation of a p-n junction as explained below.

2.2.2.1 Diffusion

In an n-type semiconductor, the majority carriers are negative charge carriers or electrons. In a p-type semiconductor, majority carriers are holes or positive charges. When a junction is formed in a silicon wafer by doping, a concentration gradient occurs between p-type and n-type materials. This results in electrons moving from n side to p side and holes moving from p side to n side through the junction (call it as “initial movement”). When an electron leaves the n-side region, it leaves behind an ionized donor (a positive charge) at the n-side. Similarly, when a hole is diffused to n-side, it leaves behind an ionized acceptor (a negative charge) at the p-side. This movement of electrons from n-side to p-side and the movement of holes from p-side to n-side is called “diffusion” and it results in a current named as “diffusion current”.

2.2.2.2 Depletion region

When more and more electrons leaves the n-region & more and more holes leaves the p-region, a region of positive and negative charge is formed at the junction. positive charges get accumulated near the n-side junction and negative charges get accumulated near the p-side junction. This region is known as “depletion” region.

2.2.2.3 Drifting

The -ve & +ve charges accumulated in the depletion region results in the formation of an electric field directed from positive charge to negative charge. This electric field causes electrons to move from p-side to n-side and holes to move from n-side to p-side. This motion of charge carriers due to electric field is known as “drift”, the current is known as “drift current”. Drift current is opposite in direction to the diffusion current.

2.2.2.4 Equilibrium of p-n junction

Initially, diffusion current will be the highest and drift current will be very small. gradually as the depletion region formation continues, drift current builds up and

diffusion current falls down. When diffusion current is exactly equal and opposite to drift current, the junction comes to a state of equilibrium. At this state, there is no net current and hence the formation of p-n junction is complete.

2.2.3 Overview of a typical solar power plant

A typical grid-connected solar power plant (without battery back-up) mainly consists of photovoltaic array, inverter with AC/DC disconnects, AC panel, utility energy meter, step-up transformer, and connection to the national grid as shown in Figure 2.3.

2.2.4 Solar Cell characteristics & PV array

Solar cell is the smallest building block of PV array. PV module is made by connecting appropriate no. of solar cells in series, creating a string. No. of these cell strings are connected in parallel to form a solar module of required power output. Similarly, PV array is built by connecting no. of module strings in parallel as shown in Figure 2.4.

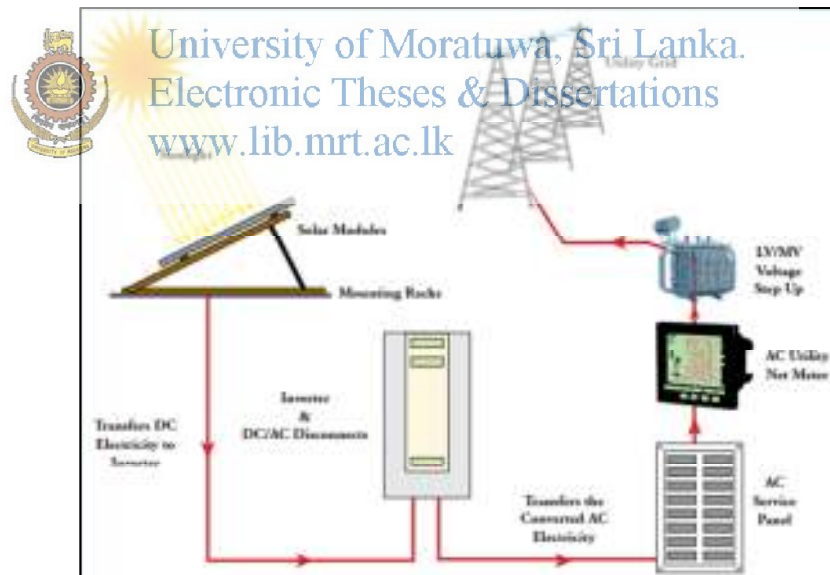


Figure 2.3: Overview of a typical solar power plant

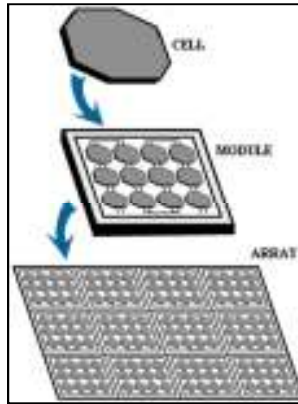


Figure 2.4: Building of a PV array

2.2.4.1 Working principle of a PV cell

A solar cell is made by joining a p-type semiconductor and n-type semiconductor. The p-type will make up the bottom layer of the solar cell and the n-type will make up the top layer. The two layers form an electric field between them which only allows electrons to flow from the p-type semiconductor to n-type semiconductor.

Sunlight consists of little particles of solar energy called photons. As a PV cell is exposed to sunlight, many of photons are reflected, pass right through or absorbed by the solar cell. When enough photons are absorbed by the negative layer of the photovoltaic cell, electrons are freed from the negative semiconductor material. Due to the manufacturing process of the positive layer, these freed electrons naturally migrate to the positive layer creating a voltage differential, similar to a household battery. When these two layers are connected to an external load, the electrons flow through the circuit creating electricity.

2.2.4.2 Main components of a solar cell

Main components of a typical solar cell are indicated in Figure 2.5, such as front contact, anti-reflective coating, n^+ region, p^- region, back surface p^+ field, back contact. Functionality of each above component is self-descriptive.

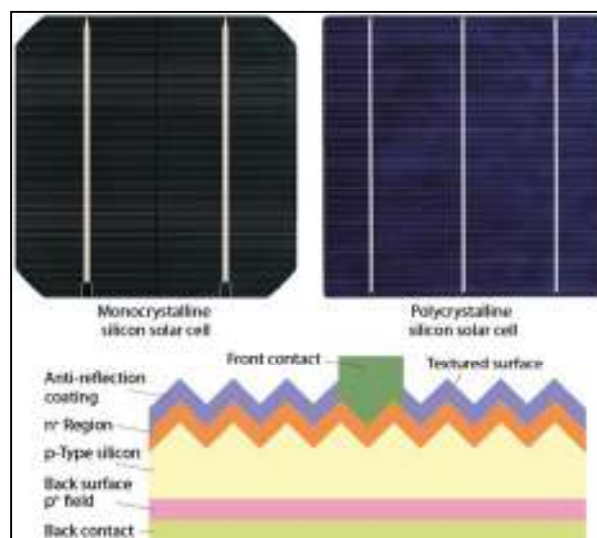


Figure 2.5: Main components of a PV cell

2.2.4.3 Technology wise categorization of solar cell

Type of solar cells can be categorized as shown in Figure 2.6.

- Crystalline Silicon cells makes up around 86% of present PV market and are very stable with module efficiencies in the range of 10-16%. The mono crystalline PV cells are made using saw-cut from single cylindrical crystal of Si & operating at efficiency up to 15%. Multi Crystalline PV cells are casted from ingot of melted and recrystallized silicon & operating at efficiency up to 12%. This covers 90% of crystalline Si market.
- In this technology, Silicon is deposited in continuous on a base material such as glass, metal, or polymers. Thin-film crystalline solar cell consists of layers about 10 μm thick compared with 200-300 μm layers for crystalline silicon cells. This production is low cost but, not very stable.

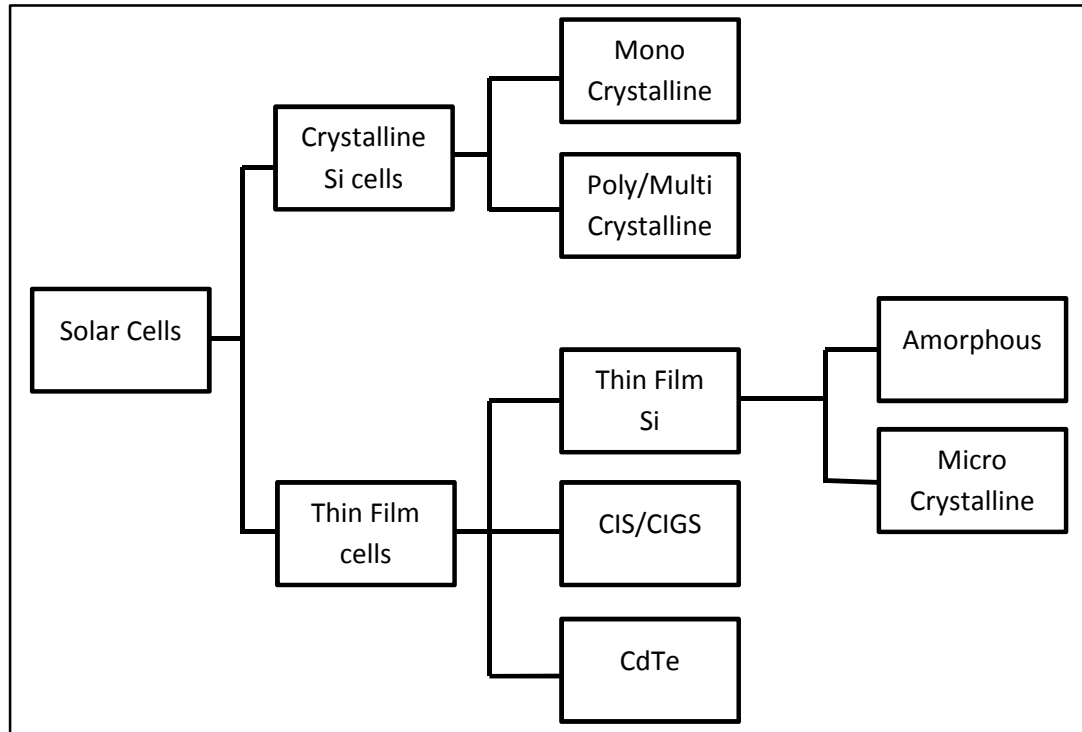


Figure 2.6: PV cell categorization

2.3 Equivalent circuit of a solar cell

A solar cell can be modeled using an electrical equivalent circuit that contains a current source anti-parallel with a diode, a shunt resistance and a series resistance. An example of solar cell's electrical equivalent circuit model is shown in Figure 2.7 [5].

The DC current that is generated when the cell is exposed to light varies linearly with solar irradiance. Solar cells are characterized by their nonlinear V-I curve as shown in Figure 2.8 [6].

The basic equation that characterizes the solar cell V-I relationship can be derived considering the equivalent circuit shown in Figure 2.7. Kirchhoff's current law of the circuit provides the following equation [6].

$$I = I_{sc} - I_d - I_{sh} \dots\dots\dots (A)$$

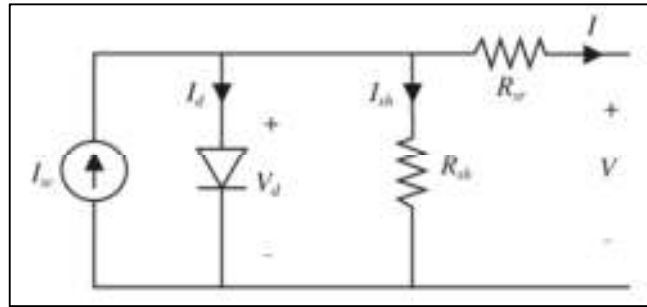


Figure 2.7: PV cell equivalent circuit

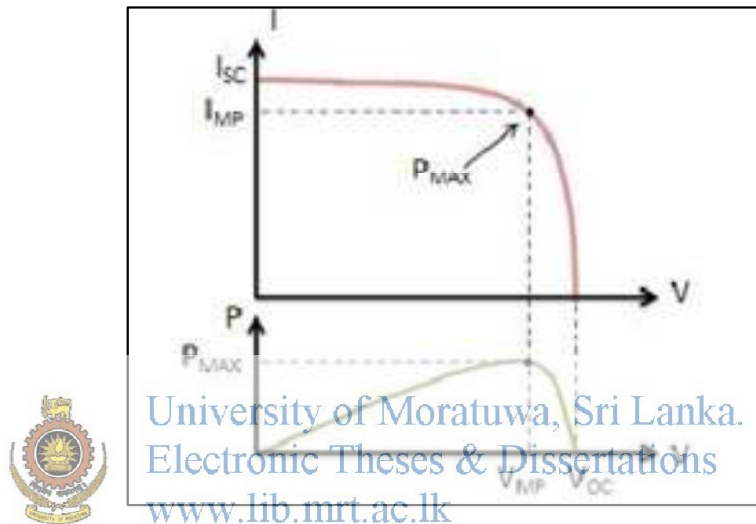


Figure 2.8: V-I & P-V characteristics of a solar cell

After substitution of the equivalent diode current expression for I_d and shunt branch current I_{sh} , above equation (A) becomes following equation [6].

$$I = I_{sc} - I_o \left\{ \exp \left(\frac{V + IR_{sr}}{\eta k T_c / q} \right) - 1 \right\} - \left(\frac{V + IR_{sr}}{R_{sh}} \right) \quad \text{..... (B)}$$

I_{sc} is the photo current and it is a function of the solar radiation on the plane of the solar cell G and the cell temperature T_c . The photo current equation is as follows.

$$I_{sc} = I_{scr} \frac{G}{G_R} \left[1 + \alpha_T (T_c - T_{CR}) \right] \quad \text{.....(C)}$$

I_{scr} is the short circuit current at the reference solar radiance G_R and the reference cell temperature T_{CR} . The parameter α_T is the temperature coefficient of photo current.

The current I_o in equation (B) is called the dark current. It is a function of cell temperature & is given by following equation [6].

$$I_o = I_{oR} \frac{T_C^3}{T_{CR}^3} \left[e^{\left(\frac{1}{T_{CR}} - \frac{1}{T_C} \right) \frac{q e_g}{nk}} \right] \dots\dots\dots (D)$$

I_{oR} is the dark current at the specified reference temperature. Other parameters used in above equations are n , k , e_g , q which is diode non-ideality factor, the Boltzmann constant, the band gap energy, and charge of an electron respectively.

2.4 V-I characteristics & P-V characteristics

Electrical performance or behavior of a solar cell is very important & specific as shown in Figure 2.8. It can act as a constant current source and constant voltage source as well. However, there are several important parameters to be identified as given below.

- Open circuit voltage - Voltage at current, $I = 0$
- Short circuit current - Current at Voltage, $V = 0$
- Maximum Power, P_{max} - Maximum cell operating power, Power at knee Point of the curve.
- Current, I_{max} - Current at maximum power point, P_{max}
- Voltage, V_{max} - Voltage at maximum power point, P_{max}
- Efficiency - P_{OUT} / P_{IN}
- Fill Factor - $P_{max} / P_{theoretical}$, $(V_{max} * I_{max}) / (V_{oc} * I_{sc})$

2.4.1 Effect of Solar radiation on V-I characteristics & P-V characteristics

Standard Test Conditions (STC) are conditions under which a module is typically tested in a laboratory under an irradiance intensity of 1000 W/m^2 , AM 1.5 solar reference spectrum and cell/module temperature of $25 \pm 2 \text{ }^\circ\text{C}$.

The Figure 2.9 clearly indicates the behavior of V-I characteristics & P-V characteristics of a solar cell under different solar radiation levels [7]. When solar radiation level

increases, short circuit current, open circuit voltage & power generation increases resulting higher maximum power point.

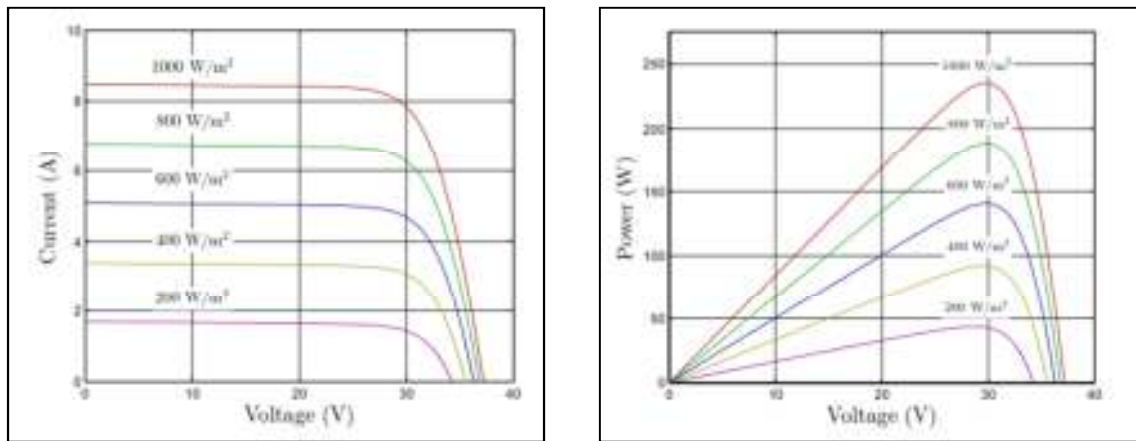


Figure 2.9: Effect of solar radiation on V-I & P-V characteristics

2.4.2 Effect of cell temperature on V-I characteristics & P-V characteristics

When cell temperature increases, short circuit current also increase while open circuit voltage decreases as shown in Figure 2.10 [7]. However, maximum power point decreases resulting poor performance of the cell.

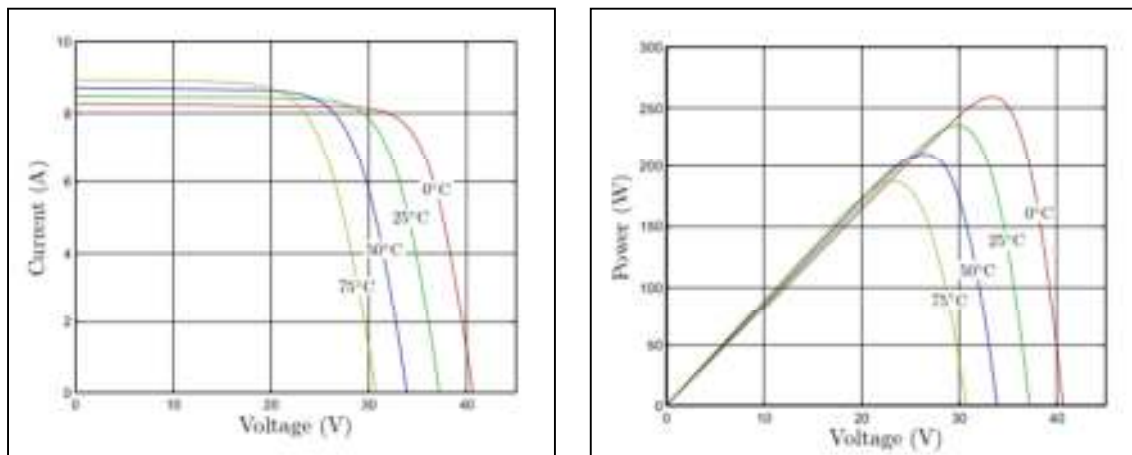


Figure 2.10: Effect of solar radiation on V-I & P-V characteristics

2.5 Maximum power point algorithms

Due to the non-linear I-V characteristics of a solar cell, their power output varies greatly depending on the voltage in which it is operating at. In order to fully utilize any solar system, the voltage across the solar panel terminals needs to be monitored and controlled in such a way that it is always at the maximum power point voltage.

The two most commonly used Maximum Power Point Tracking (MPPT) Control algorithms are Perturb and Observe (P&O) and the Incremental Conductance (IC) method.

- The P&O method calculates the present output power of the solar panel. From this, it “perturbs” the terminal voltage of the solar panel by incrementing or decrementing it and compares the new calculated output power to the previously calculated one. If this new value is larger, then the terminal voltage continues in the direction it was incremented or decremented. The algorithm is operated in this fashion until the maximum power point is achieved.
- IC algorithm finds the MPP based on the slope of the power curve for a solar cell. At the MPP, the slope of the power curve is zero, to the left of the MPP the slope is positive and to the right of the MPP, the slope is negative. By sampling the current and voltage of the solar cell and computing the incremental and instantaneous conductance, the MPP voltage can be determined. A detailed flow chart is shown in Figure 2.11[8]. Further, at the MPP the incremental conductance is equal to the negative value of instantaneous conductance as the derivation is shown in Figure 2.12 [8].

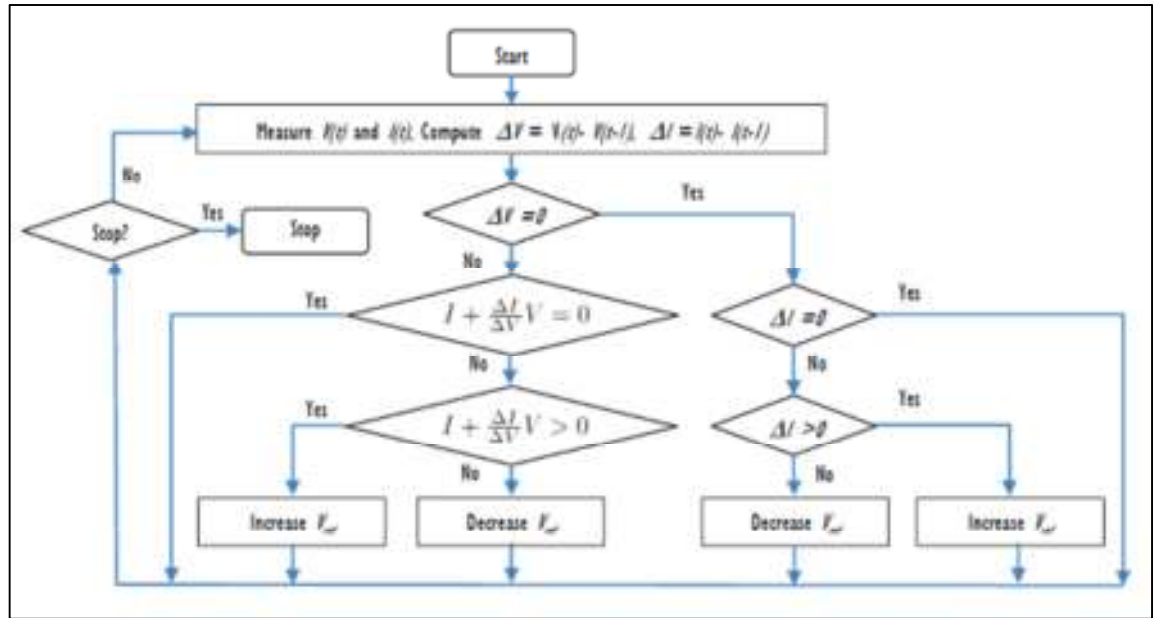


Figure 2.11: Flow Chart of the IC algorithm



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$$\frac{\partial P_{pv}}{\partial U_{pv}} = 0$$

$$\frac{\partial (U_{pv} \cdot I_{pv})}{\partial U_{pv}} = 0$$

$$\frac{dU_{pv}}{dU_{pv}} \cdot I_{pv} + \frac{dI_{pv}}{dU_{pv}} \cdot U_{pv} = 0$$

$$I_{pv} + \frac{dI_{pv}}{dU_{pv}} \cdot U_{pv} = 0$$

$$\frac{dI_{pv}}{dU_{pv}} = -\frac{I_{pv}}{U_{pv}}$$

$$\frac{\Delta I_{pv}}{\Delta U_{pv}} = -\frac{I_{pv}}{U_{pv}}$$

Figure 2.12: Relationship between incremental & instantaneous conductance

3.1 Overview

As described in the methodology of the research, power quality measurements were to be obtained to check whether there is any impact to the power quality. Hence, the two existing plants which are located in Baruthankanda, Hambantota, nearby the proposed plants were selected for the measurements. Both these plants are owned & operated by Sri Lanka Sustainable Energy Authority. Installed capacities of these plants are 737 kW & 500 kW, built with the aids of Japanese & Korean grants respectively, in year 2011.

3.1.1 Geographical location & Grid interconnection

Figure 3.1 shows the geographical location of the existing plant & grid interconnection arrangement respectively. There is no any argument with the fact that these plants are nicely located where enough solar radiation is available most of the days throughout the year. This is proved by the average plant factor of 0.18 which is an attractive figure.

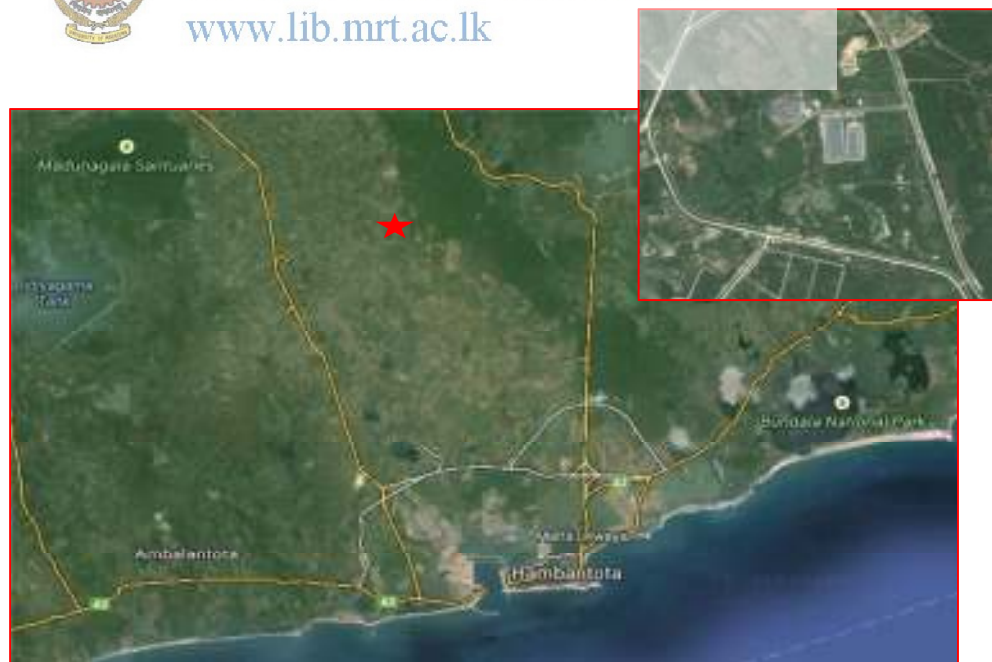


Figure 3.1: Geographical Map indicating the location of existing plants

3.1.2 Grid interconnection arrangement

Both these plants are physically located around 50m apart from each other and connected to the Feeder 6 (Nonagama Feeder) of Hambantota grid substation. The 737 kW plant is metered at low voltage level whereas 500 kW plant is metered at high voltage level. However, the interconnection point (Point of Common Coupling) is around 14 km away from the grid substation. Figure 3.2 & Figure 3.3 show the interconnection arrangement.

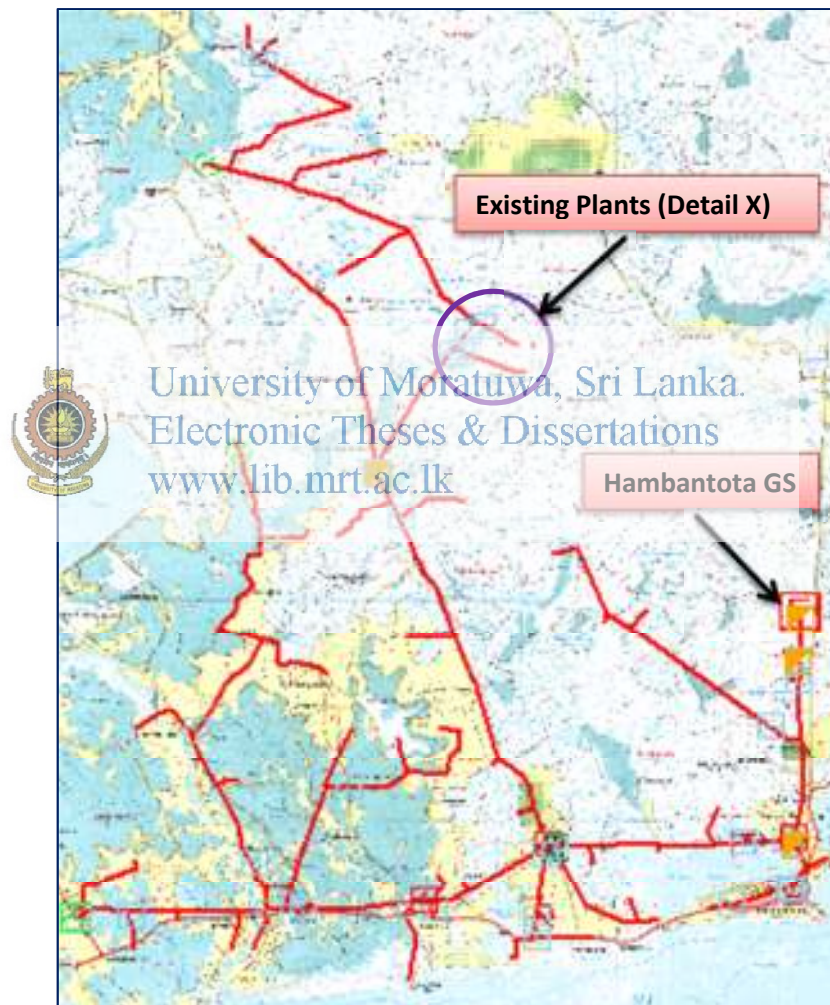


Figure 3.2: Network Map indicating the grid interconnection of existing plants

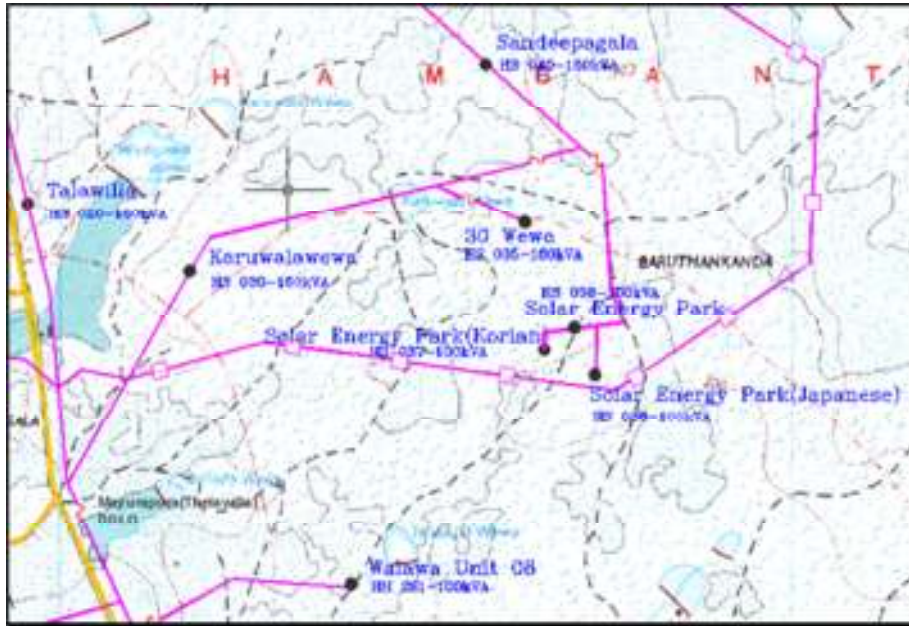


Figure 3.3: Detail X referred to Figure 3.2

3.2 Measurements

3.2.1. Parameters to be measured & data to be collected

Technical parameters were selected for the measurements in order to analyze the power quality aspects of existing plants are given below. However, only 737 kW plant was selected for some of the measurements, since the as built drawings, design details, data logging facility are not available in 500 kW plant. Therefore, Fluke 1735 power logger was fixed at the Point of Common Coupling of 737 kW plant for the period of 14 days from 24/08/2013 to 06/09/2013.

- Voltage (V)
- Current (A)
- Current Harmonics (Individual & THD)
- Voltage Harmonics (Individual & THD)

In addition to above measurements, following data were also obtained from the data logger installed within the plant for the same duration.

- Solar irradiance (kW/m^2)
- Module temperature ($^{\circ}\text{C}$)
- Open air temperature ($^{\circ}\text{C}$)
- Power generation (kW)

3.2.2 Point of Common Coupling

Impact to the power system by the solar plant or any other distributed resource has to be analyzed at the point of common coupling. Simply, point of common coupling is the first point where distributed resource serves another customer already connected to the power system. Figure 3.4 clearly demonstrates the definition of point of common coupling using a typical power system & distributed resource [9].

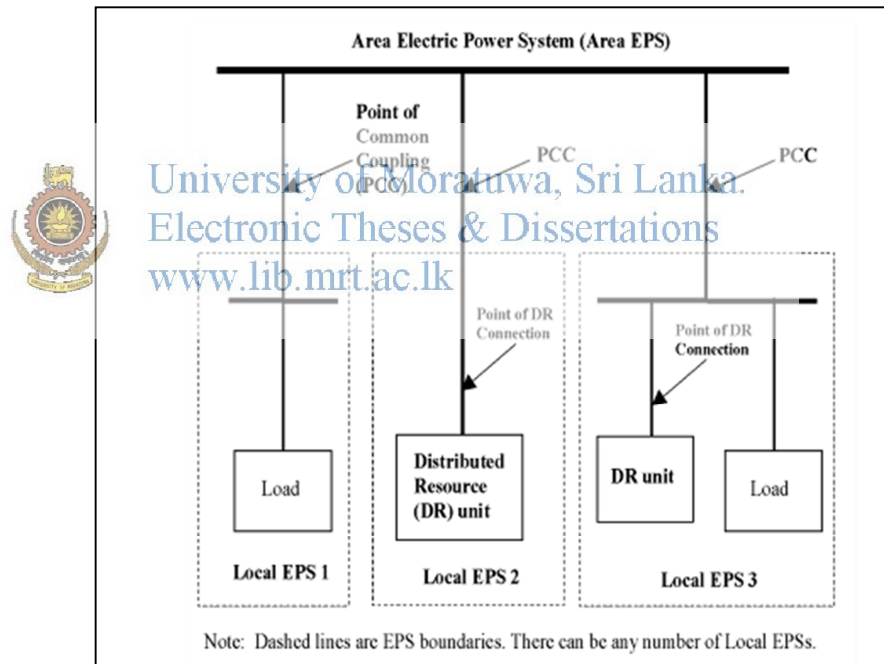


Figure 3.4: Point of Common Coupling of a typical power system

As far as the existing power plants at Hambantota are concerned, the point of common coupling is indicated by Figure 3.5. In addition to the point of common coupling, another three important nodes at the feeder were selected for the analysis as Node A,

Node B, Node C indicated in Figure 3.5. Figure 3.6 shows a few photographs taken during the measurements.

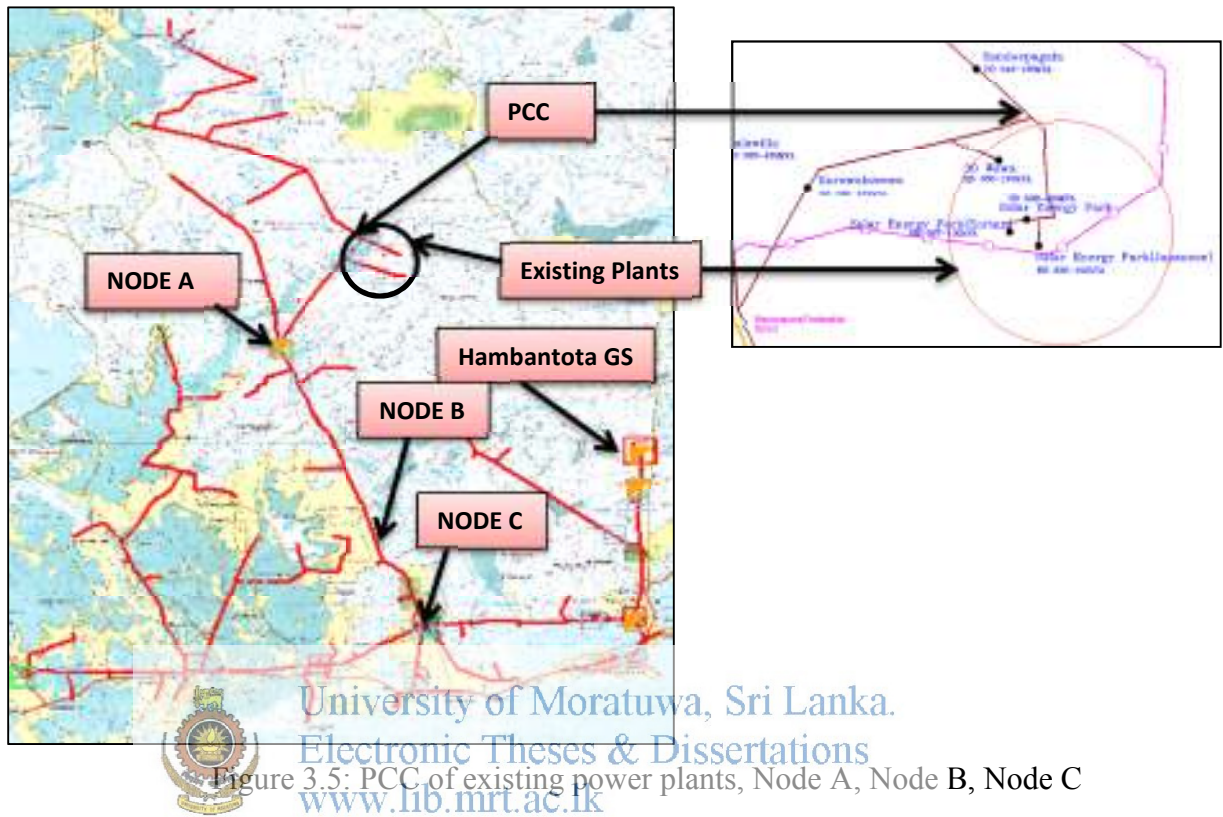


Figure 3.6: Photographs taken during the measurements

3.3 International Standards for Power Quality

In this research, two international standards were referred to identify the restrictions or limits for each power quality parameter. Those standards are IEEE 1547-2003, “IEEE standard for interconnecting Distributed Resources with Electric Power Systems” and IEEE 519-1992, “IEEE Recommended Practices and Requirements for Harmonic Control of Electrical Power Systems”

3.3.1 IEEE 1547-2003

IEEE 1547-2003, “IEEE standard for interconnecting Distributed Resources with Electric Power Systems” provides requirements relevant to the performance, operation, testing, safety considerations and maintenance of the interconnection.

This standard was originally created in 2003 and since then many subsequent versions have been released. The main drawback of the standard is that when created, it was just beginning of the rapid growth in photovoltaic and other distributed resources. Certain provisions that were outlawed are now required due to increasing PV penetration.

3.3.1.1 Limitations of the standard

The criteria and the requirements in this document are applicable to all distributed resource technologies, with aggregate capacity of 10 MVA or less at the point of common coupling. This limitation is the main drawback of this standard, so revision is very much required. Further, the frequency of the Distributed Resource (DR) has been considered as 60 Hz. Also, this standard does not define the maximum DR capacity for a particular installation that may be interconnected to a single PCC or connected to a given feeder.

3.3.1.2 Allowable limits for voltage & frequency

The distributed resource interconnection standard has outlined specific allowable limits for voltage and frequency of the power system the distributed resources are connected to. If the specific limits are exceeded the distributed resource must disconnect from the grid within the maximum clearing times if disturbance is still present. The voltage limits and clearing times are shown in Table 3.1.

Table 3.1: Interconnection system response to abnormal voltages [9]

Voltage Range (% of base voltage)	Clearing Time (S)
$V < 50$	0.16
$50 \leq V < 88$	2
$110 < V < 120$	1
$V \geq 120$	0.16

The clearing times for the respective DR size and frequency range is given in Table 3.2. It is important to note that these figures are applicable only for the distributed resources operating at 60 Hz.

Table 3.2: Interconnection system response to abnormal frequencies [9]

DR Size	Frequency Range (Hz)	Clearing Time (S)
 $\leq 30 \text{ kW}$	> 60.5	0.16
	< 59.3	0.16
$\geq 30 \text{ kW}$	> 60.5	0.16
	$< \{59.8 \text{ to } 57\}$ Adjustable set point	Adjustable 0.16 to 300
	< 57.0	0.16

3.3.1.3 Allowable limits for voltage & current harmonics

In addition to the voltage & frequency requirements specified by IEEE 1547, the standard also defines necessary power quality requirements for PV inverters based on the harmonic content. Actually, harmonic content standards are actually taken from another standard known as IEEE 519-1992 which is described under 3.3.2.

But, the requirement of the harmonic content of the system to be met before connecting the DR is given in IEEE1547 standard. In power quality point of view, it states that

voltage harmonic distortion should be less than 2.5 % before connecting the distributed resource.

3.3.2 IEEE 519-1992

This standard was originally issued in 1981 & revised in 1992.

Use of non-linear loads like static power converters, arc discharge devices, saturated magnetic devices...etc can change the sinusoidal nature of the ac power current (and consequently the ac voltage drop & distortion), thereby resulting in the flow of harmonic current in the ac power system. This standard is very important for this research since it states the limits for the power quality parameters to be maintained at the point of common coupling.

IEEE 519-1992, “IEEE Recommended Practices and Requirements for Harmonic Control of Electrical Power Systems” states that total harmonic distortion level should be less than 5% at the point of common coupling for the systems with rated voltage less than 69 kV [10]. Individual harmonics distortion level is limited to 3% of rated voltage [10].

The table 3.3 states the individual & total current harmonic limits based on the size of the load with respect to the size of the power system. However, in this research, everything is dealt with power distribution, the figures given in the first row of the below table are only applicable. Accordingly, the total current harmonic demand distortion should be limited to 5% whereas the individual harmonics should be limited to the given values with respect to the range of harmonic order.

Table 3.3: Harmonic distortion limits specified by IEEE 519 [10]

Max. Current Harmonic Distortion in % of I_L For voltages 0.12 kV- 69 kV						
I_{sc}/I_L	Harmonic order (Odd harmonics)					TDD
	$h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$h \geq 35$	
$< 20^*$	4	2	1.5	0.6	0.3	5

20<50	7	3.5	2.5	1	0.5	8
50<100	10	4.5	4	1.5	0.7	12
100<1000	12	5.5	5	2	1	15
>1000	15	7	6	2.5	1.4	20
• All generating equipment is limited to these values regardless of I_{sc}/I_L. (I_{sc}, I_L Max. Short CCT. and Load current at PCC) - Even harmonics limits are limited to 25% of odd harmonics						

3.3.3 Effects of Harmonics

It is very essential to be learnt why these harmonics are restricted or limited in a power system. Hence, the effects of harmonics to the power system or to the equipment connected are briefly illustrated in this section.

- Harmonic voltage & current causes additional heating in rotating machinery like motors & generators (Induction, Synchronous) due to increased iron loss & copper loss. This results in less efficiency of the machinery. It also affects the torque developed and increased audible noise emission compared with sinusoidal excitation. The other important fact is that some of the harmonic pairs like 5th, 7th can produce mechanical oscillations due to its forward & backward rotation (positive sequence & negative sequence).
- Power transformers are undergone in increased noise emission and heating due to the increased copper losses, core losses and eddy current losses.
- Voltage harmonics causes power cables to be subjected voltage stresses and corona, resulting in insulation degradation and cable failure. Also, it affects in additional heating due to increased losses caused by two phenomenon called “skin effect” & “proximity effect”.

- Electronic equipment can undergo misoperation due to harmonic distortion. This is basically happened as most of the electronic equipment operation depends upon the zero crossing of the voltage wave form. Harmonics distortion can shift the zero crossing point & point at which one phase-phase voltage is greater than other phase-phase voltage.
- Metering & instrumentation is also affected by the harmonics resulting in erroneous operation.
- As described above, almost all the power equipment is subjected to additional heating that reduces the life time of the equipment.
- Telephone interference is another issue created by voltage & current harmonics due to the voltage and magnetic field.

3.4 Analysis of measured data

The data measured and gathered as explained in 3.2 were plotted in different aspects and conditions to investigate what parameters affects power quality and how it varies with the different conditions. Results of the analysis carried out are presented here under with the observations, comments.

3.4.1 General Results

The results obtained in the process of data analysis which are not directly related to power quality, are presented in this section for the sake of completion.

3.4.1.1 Relationship between power generation & solar irradiance

Figure 3.7 & Figure 3.8 given below show the impact of solar irradiance over power generation in two different days having completely different radiation pattern. Both these graphs clearly indicate that power generation is directly dependent (directly proportional) on solar irradiance since both generation & radiation curves are similar in pattern.

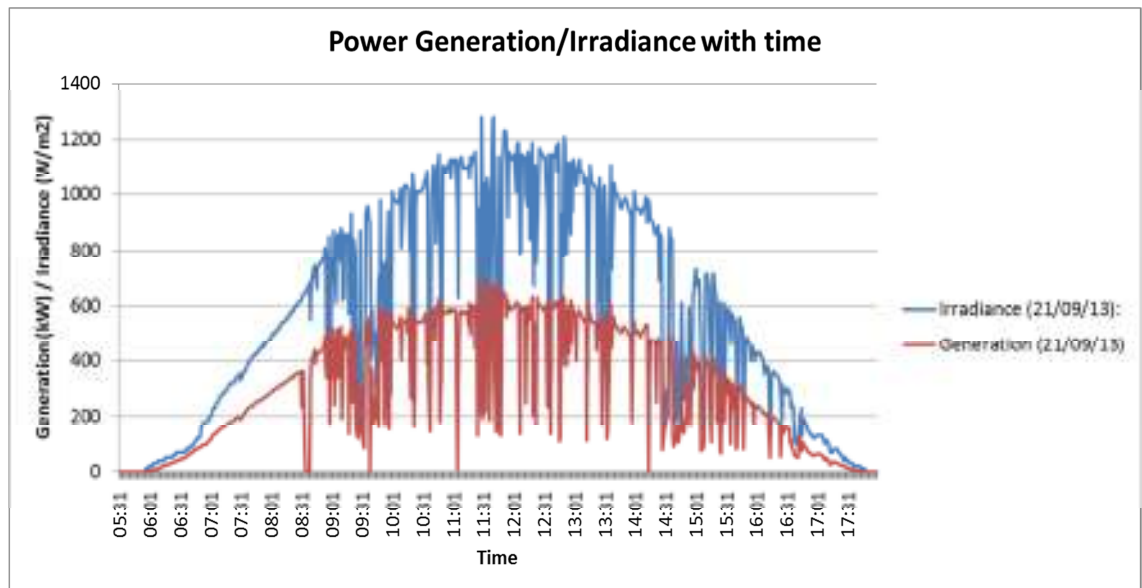


Figure 3.7: Relationship between Generation & radiation on 21/09/2013

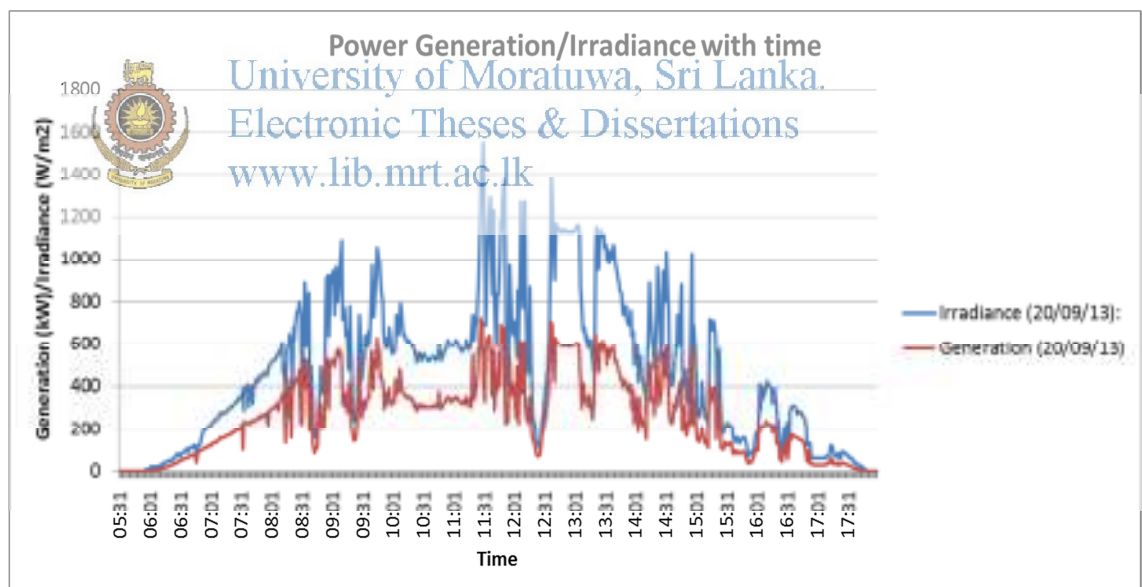


Figure 3.8: Relationship between Generation & radiation on 20/09/2013

3.4.1.2 Variation of module temperature with solar irradiance

Figure 3.9 & Figure 3.10 show how the module temperature varies with the solar radiation. Solar radiation directly affect to the module temperature as these graphs point out clearly.

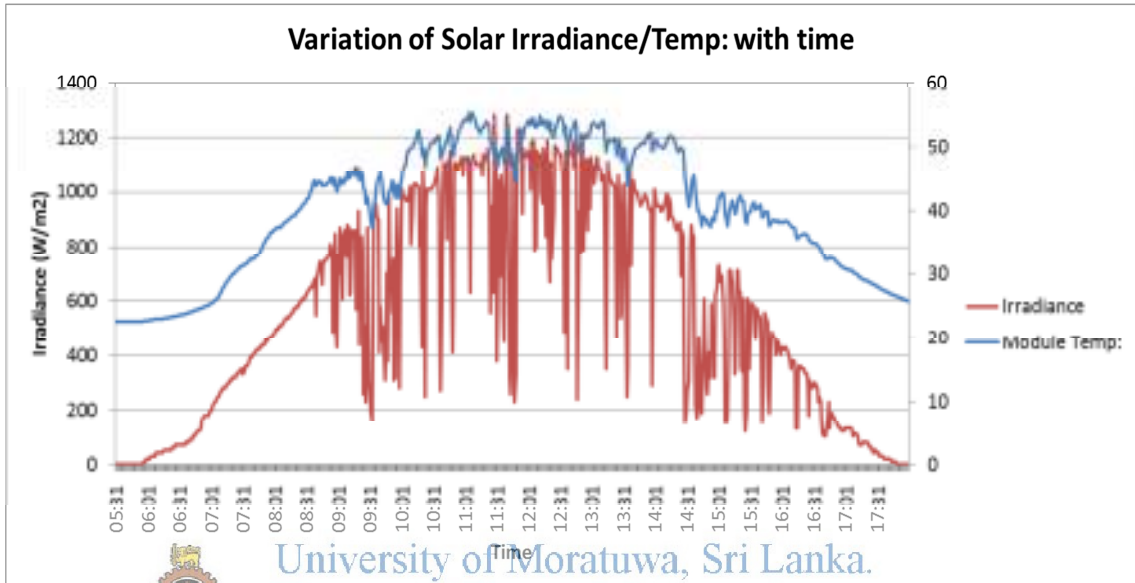


Figure 3.9: Relationship between Mod. Temp. & radiation on 21/09/2013

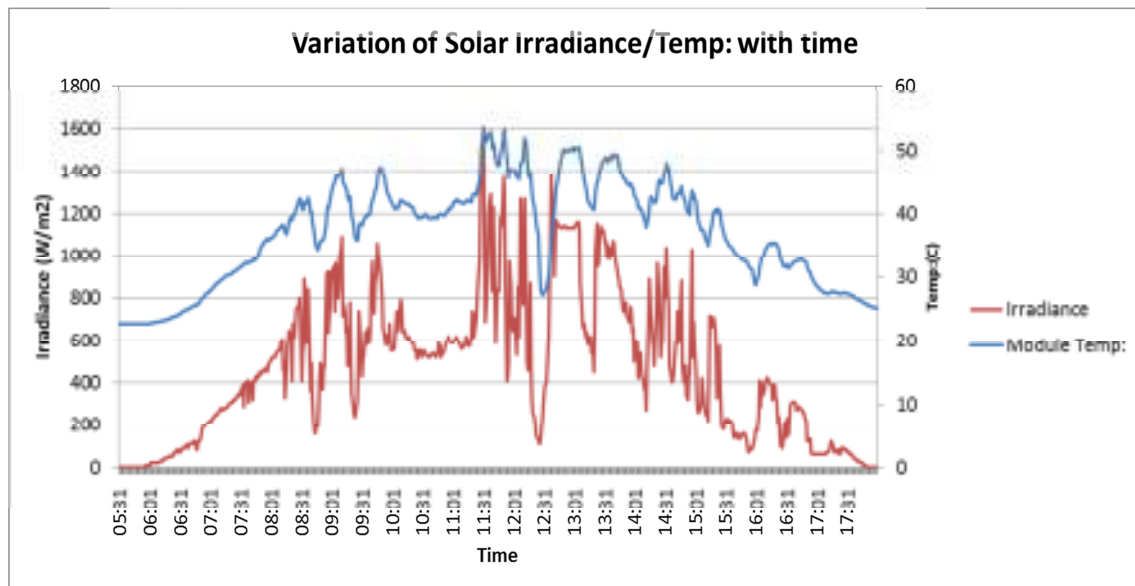


Figure 3.10: Relationship between Mod. Temp. & radiation on 20/09/2013

3.4.2 Results in respect of power quality

The base of this research was the results obtained through the analysis of measured data in respect of power quality since it demarcates the two important steps. One of them was to get an impression on the behavior of existing plants, how it impact to the power quality and degree of impact that creates the path to proceed with next steps. The other demarcation point was that these results were used for validation of PSCAD model. Analyzed results under each power quality parameter are laid down here.

3.4.2.1 Voltage fluctuations

Voltage at the point of common coupling of the 737 kW plant was measured under two different conditions, when the plant is totally and partly in operation. However, through the results given below, it was ascertained that this much of solar penetration cannot make significant affect to the system voltage.

Figure 3.11 & Figure 3.12 indicate the time varying voltage & averaged curve throughout the daytime on 01/09/2013 while all three inverters are in operation.

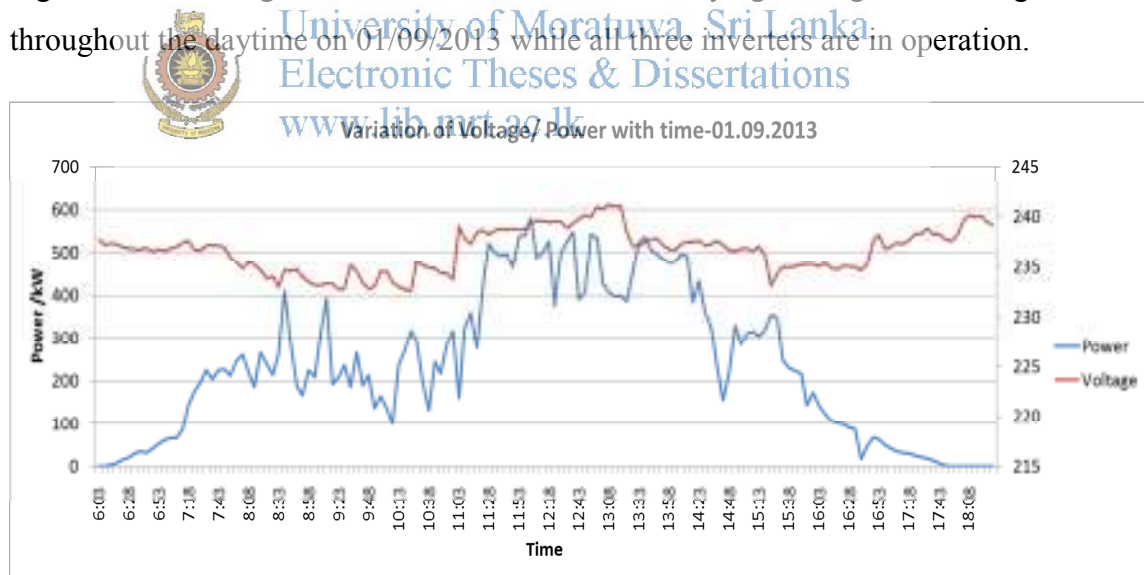


Figure 3.11: Variation of RMS voltage & radiation on 01/09/2013

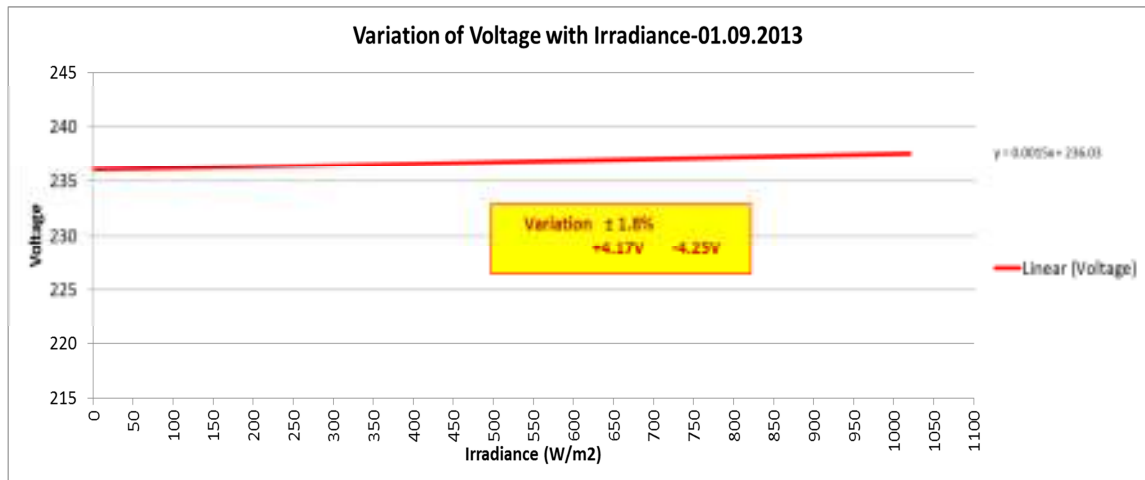


Figure 3.12: Average curve of variation of RMS voltage & radiation on 01/09/2013

Figure 3.13 & Figure 3.14 indicate the time varying voltage & averaged curve throughout the daytime on 02/09/2013 while all three inverters are in operation.

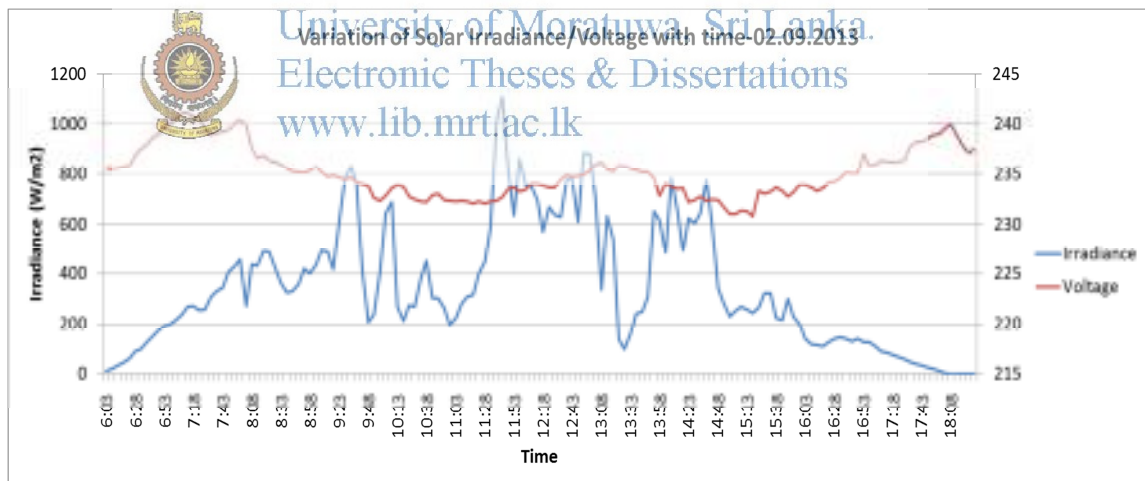


Figure 3.13: Variation of RMS voltage & radiation on 02/09/2013

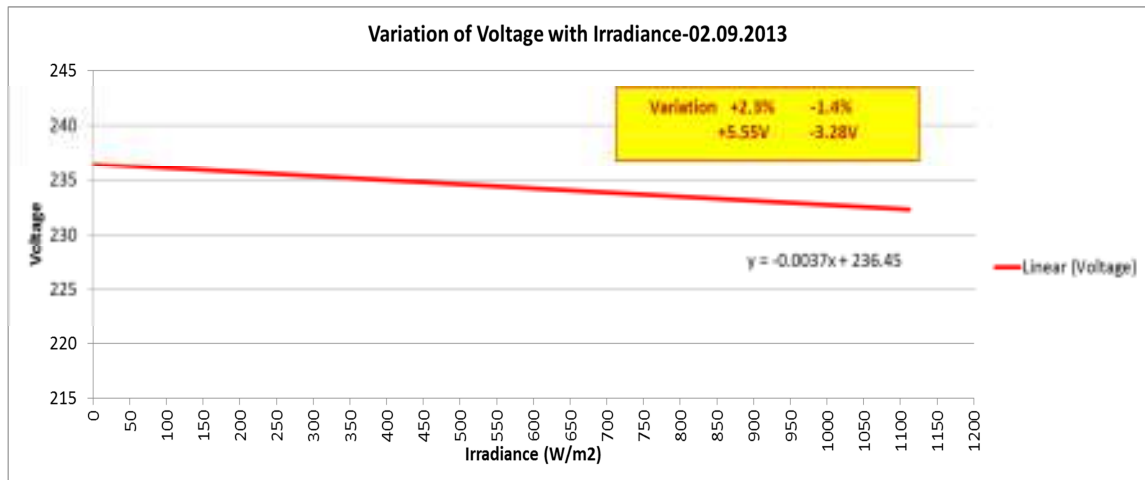


Figure 3.14: Averaged curve of variation of RMS voltage & radiation on 02/09/2013

Figure 3.15 indicates the time varying voltage & averaged curve throughout the daytime on 30/11/2013 while only one inverter is in operation.

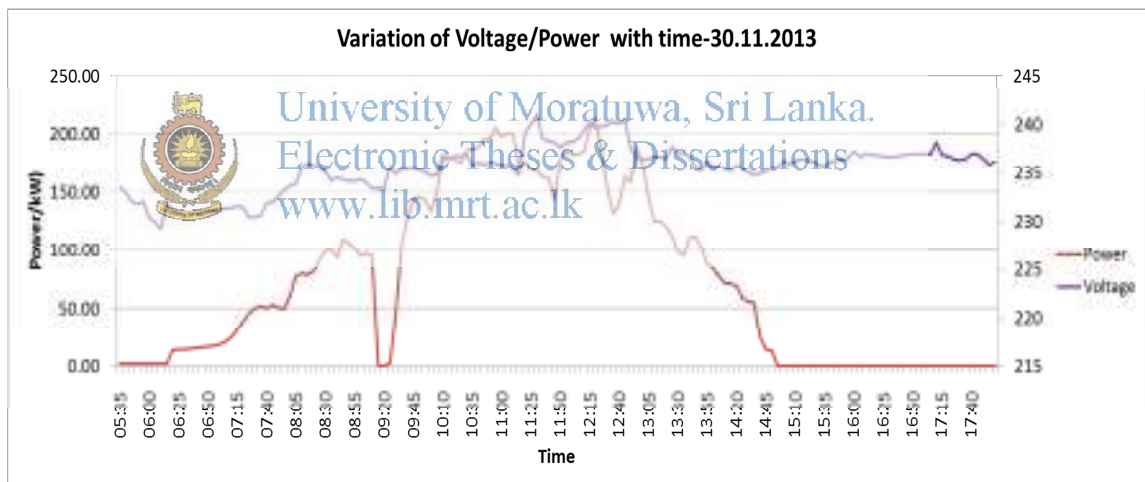


Figure 3.15: Variation of RMS voltage & radiation on 30/11/2013 at partly generation

The ultimate conclusion or observation is that RMS line voltage lies in the range of statutory limits ($\pm 6\%$ of rated voltage) given in CEB standards throughout the measured period & existing plants are not capable of resulting in a big impact to the voltage. Variation of the voltage with the time would be mainly due to the variation of feeder loading (active power flow), line impedance with the temperature, reactive power flow...etc.

3.4.2.2 Current Harmonic distortion

Current harmonics is the source of power quality problems as far as solar power plants are concerned. Because more & more harmonic current injection to the system distorts the system voltage waveform more & more, causing all other consumer loads, equipment to be subjected to the bad impacts pointed out under 3.3.3.

The Figure 3.16 shows the current harmonics variation over two consecutive days recorded in the power logger. By simply looking at it, one can easily understand that the pattern of harmonic variation is almost identical. As far as day time is concerned, current harmonics figure goes to a very high value (greater than 100%) in the morning and evening.

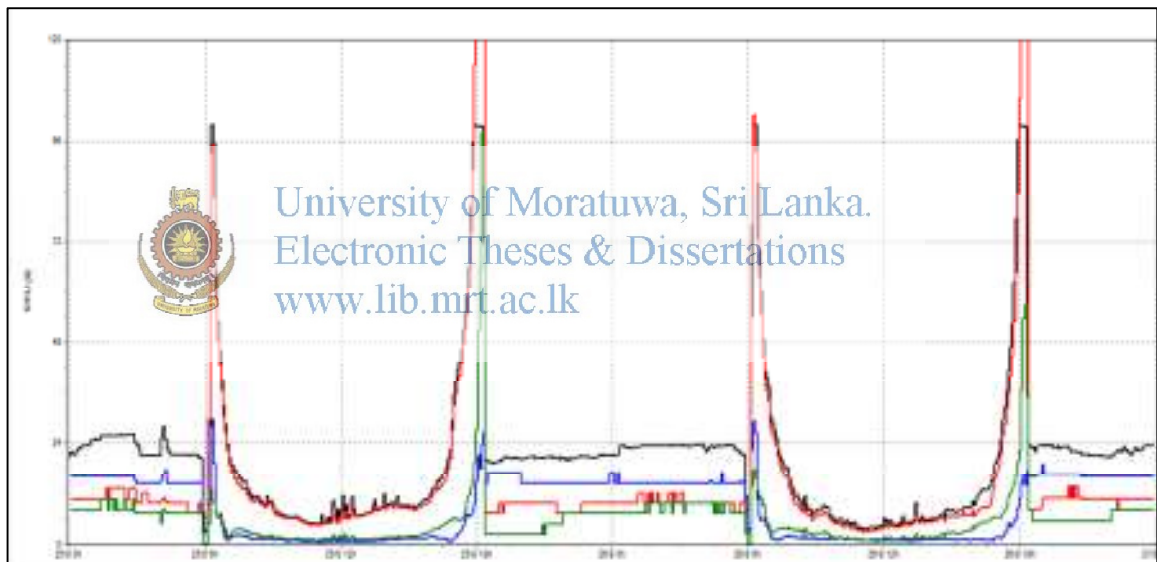


Figure 3.16: Variation of current harmonics over two consecutive days

In order to analyze in depth, current harmonics data logged in power logger were plotted in different forms. Among those graphs, Figure 3.17 is how THD-A varying over five consecutive days within same time domain. Figure 3.18 is given for one particular day (27/09/2013) in order to present more clear impression.

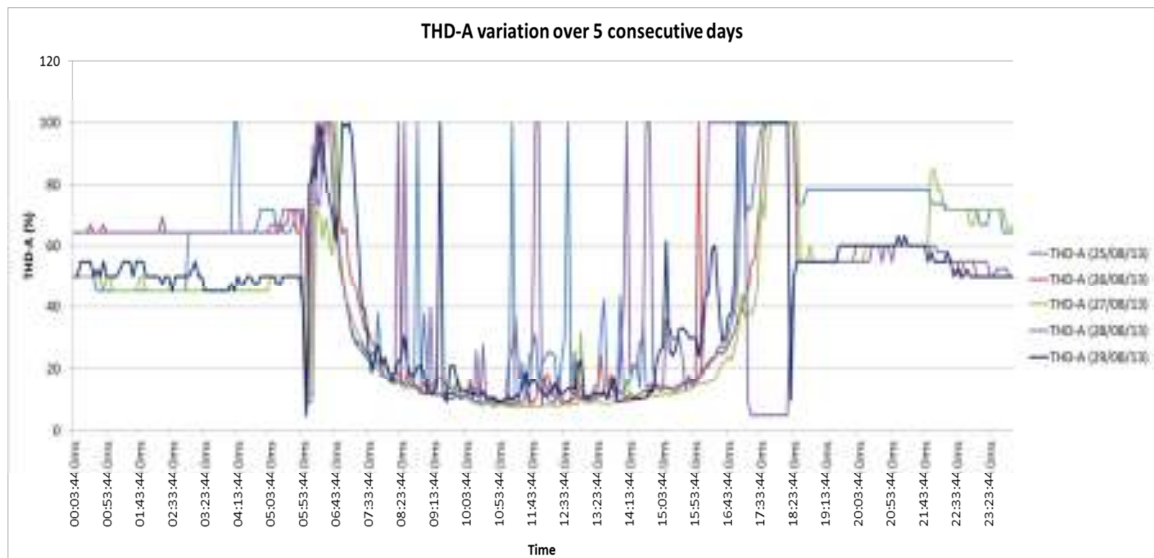


Figure 3.17: Variation of THD-A over five consecutive days

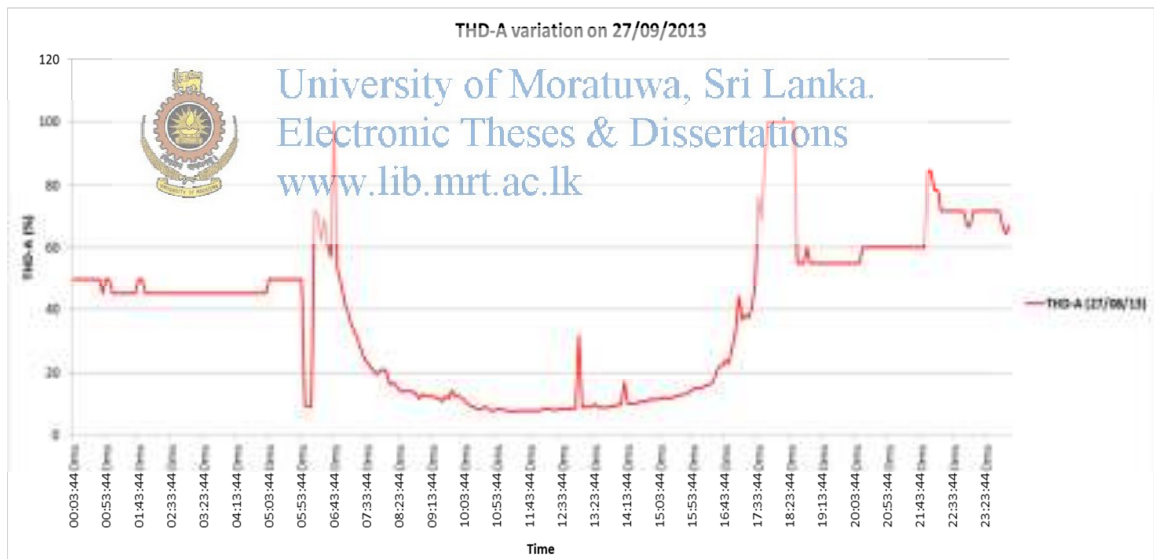


Figure 3.18: Variation of THD-A on 27/09/2013

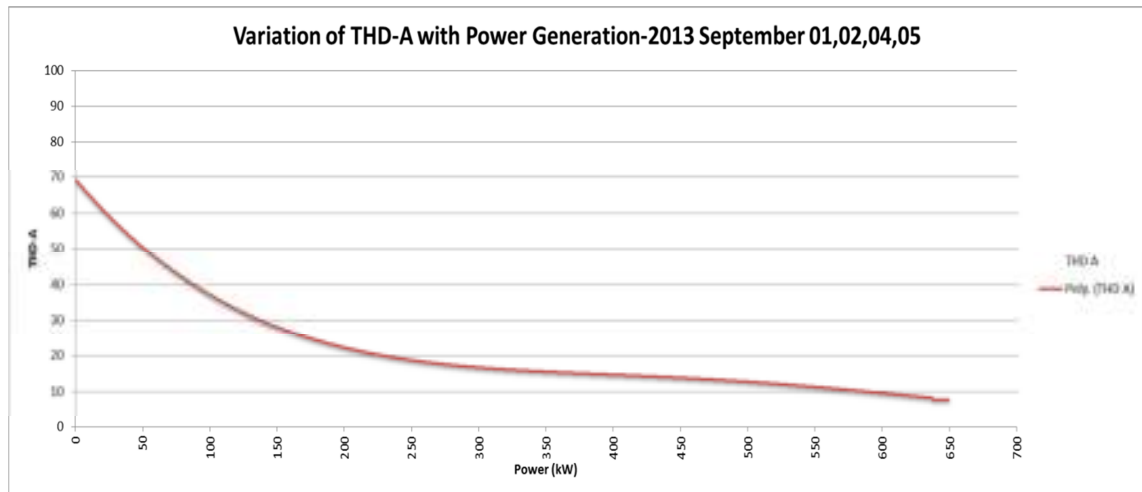


Figure 3.19: Averaged curve of THD-A variation

Through the observation at above graphs, it can come to conclusion that total current harmonic distortion varies in the range of 8% -10% during peak solar penetration & 20%-100% during low power generation.

Analysis of current harmonics distortion is not limited to THD-A. Individual current harmonics distortion was also considered in the analysis as it is required to check whether the given limits are violated.

Accordingly, Figure 3.20 was extracted from the power logger software which nicely indicates significant individual harmonics. It is proved that 5th, 2nd, 3rd, 7th, 4th order individual harmonics are dominated in descending order.

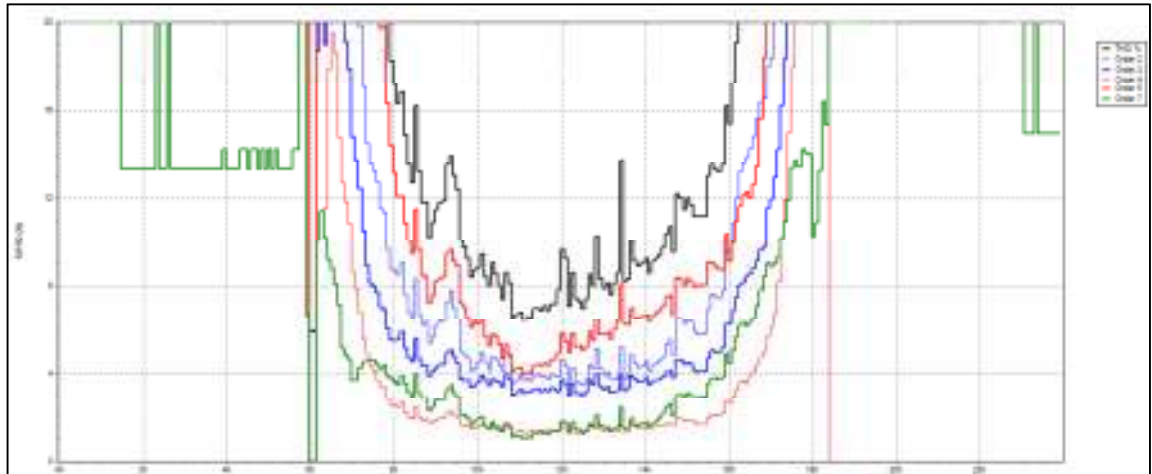


Figure 3.20: Individual harmonics variation

Individual current harmonic content was figured out by careful reference of above graph as given in Table 3.4.

Table 3.4: Individual harmonic content variation over the critical time slots

Harmonics	University of Moratuwa, Sri Lanka. Electronic Theses & Dissertations www.lib.mrt.ac.lk	
	10:00hrs-14:00hrs	Rest of the day time
2 nd	~ 1%	2%-90%
3 rd	~ 2.0 %	3.5%-50%
4 th	~ 1.0 %	1.5%-30%
5 th	4%-8%	8%-100%
7 th	2%-2.5%	2.5%-25%

3.4.2.3 Current Harmonic Demand Distortion

Current harmonic demand distortion is the parameter that assesses the impact of current harmonics at the point of common coupling. Total Demand Distortion (TDD-A) differs from Total Current Harmonic Distortion (THD-A) as shown in following equations where, I_1 , I_2 , I_3 , I_4 , I_5 , I_L are RMS currents of fundamental frequency, 1st harmonic, 2nd harmonic, 3rd harmonic, 4th harmonic, 5th harmonic and maximum demand at the point of common coupling respectively.

$$I_{THD} = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + I_5^2 + \dots}}{I_1} \times 100\% \quad \dots\dots\dots (A)$$

$$I_{TDD} = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + I_5^2 + \dots}}{I_L} \times 100\% \quad \dots\dots\dots (B)$$

Variation of TDD-A and individual harmonic demand distortion were plotted against the time with respect to the point of common coupling, Node A, Node B, Node C respectively. Results of the analysis are given below.

Calculation data sheet of the maximum day peak demand current (I_L) at above nodes is given in Table 3.5. Maximum demand current at the Node C was directly measured at that point and given in Table 3.6.

Table 3.5: Calculation data sheet of maximum demand

Node	Calculation of loading at the considered nodes				
	 Ser. No	TF Name	TF Capacity (kVA)	Load Current (A) Day (A)	Cumulative Phase Current (A)
	HS 037	Solar Park	100	8	3
	HS 040	Sandeepagala	160	30	13
	HS 050	Walsapugala-1	160	22	20
	HS 060	Walsapugala-2 (Ruhunupura)	160	41	33
	HS 070	Usgala	100	17	39
	HS 080	Andarawewa	100	104	73
	HS 090	Mahawelikada ara	160	79	100
	HS 096	Wewegama	100	20	106
PCC	HS 093	Weliara	100	58	126
	HS 035	30 -wewa	160	0	126
	HS 030	Karuwalawewa	160	59	145
	HS 020	Talawilla	160	132	189
Node A	HS 010	Baruthankanda	100	93	220
	HH 282	Walawe Unit 7	100	23	228
	HH 280	Mahaweli Office	100	92	259
	HH 281	Walawe Unit 8	100	32	269

	HH 277	Bellagaswewa Water	100	60	289
	HH 275	Bo Ara	160	53	307
	HH 270	Maha Ara	100	168	363
	HH 265	Army Camp	160	63	384
	HH 260	Rangiri Uyana	160	70	407
Node B	HH 255	Katuwewa Junction	100	9	410

Table 3.6: Maximum demand current at the PCC, Node A, B, C

Node	LV Side (A)	HV side (A)
Load at point of Common Coupling (per phase) (Sandeepagala DDLO)	126	1.58
Load at Customer Node A (per phase) (Mayurapura DDLO)	220	2.77
Load at Customer Node B (per phase) (Katuwewa Junction)	410	5.16
Load at Customer Node C (per phase) (Kajuwatta ABS)	-	58.00

- Current harmonic demand distortion at PCC

The graphs presented below show how the TDD and individual harmonic distortion varies with the time at the point of common coupling.

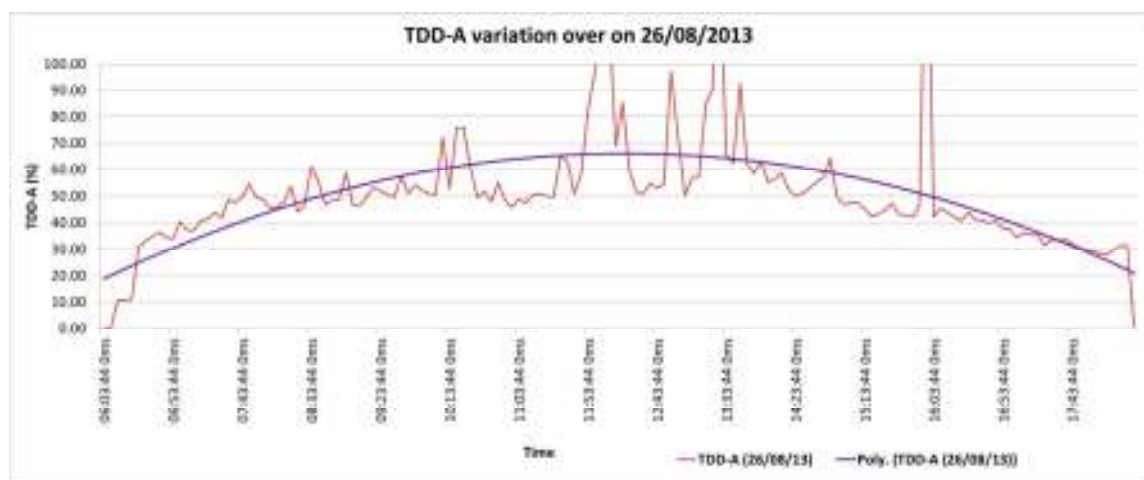


Figure 3.21: TDD-A variation

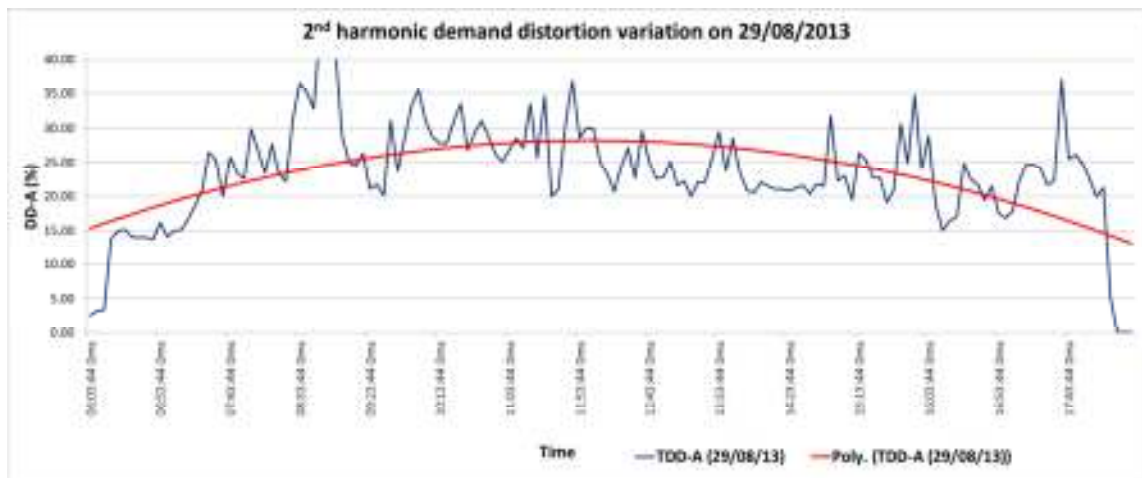


Figure 3.22: 2nd harmonic demand distortion variation

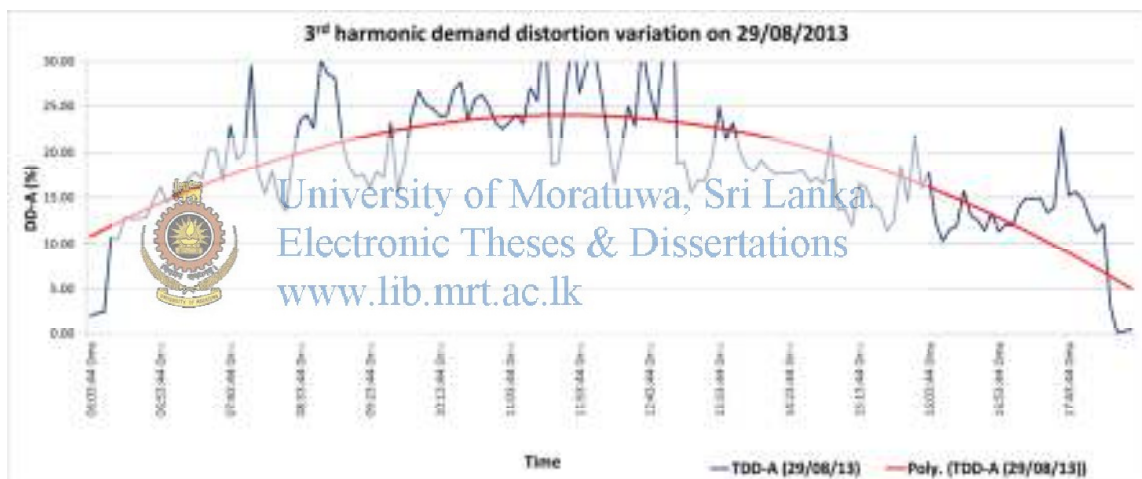


Figure 3.23: 3rd harmonic demand distortion variation

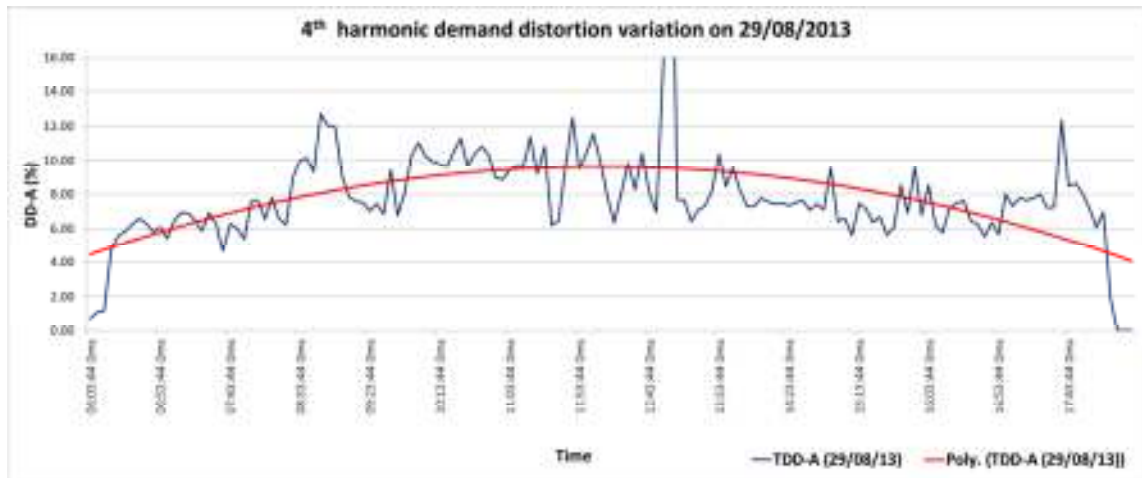


Figure 3.24: 4th harmonic demand distortion variation

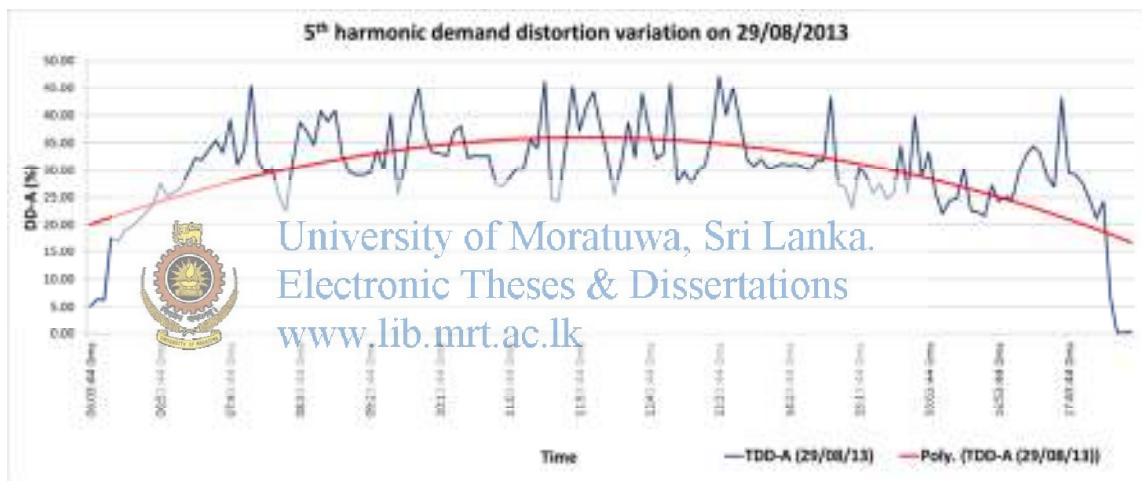


Figure 3.25: 5th harmonic demand distortion variation

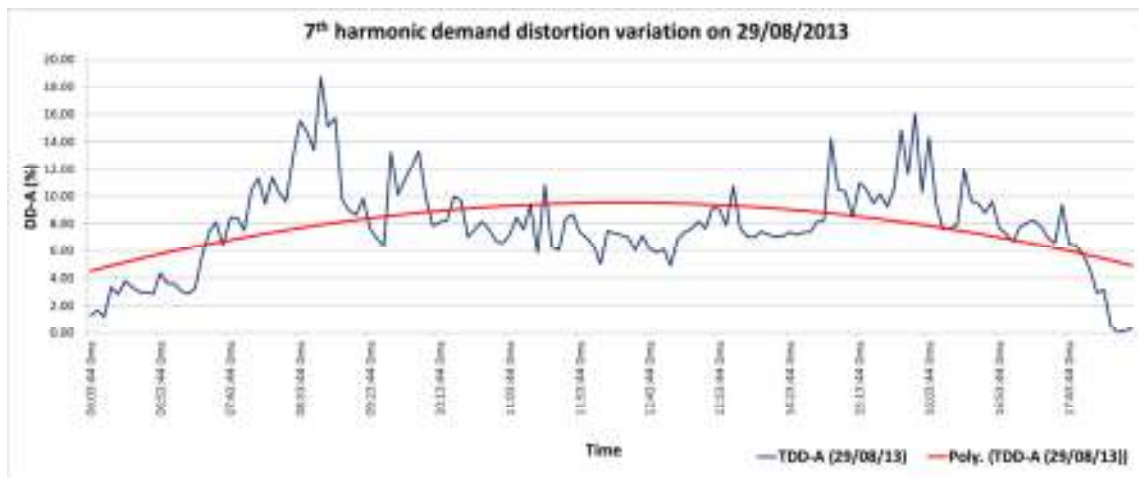


Figure 3.26: 7th harmonic demand distortion variation

From all above graphs, the extracted data and analyzed results are appended in Table 3.7.

Table 3.7: Summary of the current harmonic distortion at PCC

Harmonic order	Min. Value	Max. Value	Allowable Limit	Duration exceeding the limits
TDD-A	20%	65%	5%	Through out the day
2	7 %	28%	1 %	Through out the day
3	8 %	20 %	4 %	Through out the day
4	3 %	8 %	1 %	Through out the day
5	18 %	35 %	4 %	Through out the day
7	3 %	9 %	4 %	07.30-17.30

According to above results, it is ascertained that TDD-A and all the individual harmonics given above violate the stipulated limits at the PCC.

- Current harmonic demand distortion at Node A

Similar analysis was done for Node A and the summarized results are given in Table 3.8.

Table 3.8: Summary of the current harmonic distortion at Node A

Harmonic order	Min. Value	Max. Value	Allowable Limit	Duration exceeding the limits
TDD-A	20 %	40 %	5 %	Through out the day
2	7 %	15%	1 %	Through out the day
3	6 %	10 %	4 %	Through out the day
4	2 %	5 %	1 %	Through out the day
5	10 %	20 %	4 %	Through out the day
7	2 %	6 %	4 %	07.30-17.30

According to above results, it is ascertained that TDD-A and all the individual harmonics given above violate the stipulated limits if the existing plant would have been connected to Node A.



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- Current harmonic demand distortion at Node B

Analyzed results for Node B is given in below table.

Table 3.9: Summary of the current harmonic distortion at Node B

Harmonic order	Min. Value	Max. Value	Allowable Limit	Duration exceeding the limits
TDD-A	10 %	20 %	5 %	Through out the day
2	4 %	7%	1 %	07.20-17.50
3	2.5 %	5.5 %	4 %	09.30-15.30
4	1 %	2.5 %	1 %	Through out the day
5	5 %	10 %	4 %	Through out the day
7	1 %	3 %	4 %	Not exceed

According to above results, it is ascertained that TDD-A and 4th, 5th individual harmonics violate the stipulated limits if the existing plant would have been connected to Node B. 2nd, 3rd individual harmonics exceeds the limits during a particular period only. 7th harmonic does not exceed the limit.

- Current harmonic demand distortion at Node C

Through the analysis, it was observed that Node C would have been the technically most suitable node for choosing as the point of common coupling to connect existing plants to the national grid. Table 3.10 shows the results.

Table 3.10: Summary of the current harmonic distortion at Node B

Harmonic order	Min. Value	Max. Value	Allowable Limit	Duration exceeding the limits
TDD-A	1 %	2 %	5 %	Not exceed
2	0.4 %	0.6 %	1 %	Not exceed
3	0.1 %	0.5 %	1 %	Not exceed
4	0.1 %	0.2 %	1 %	Not exceed
5	0.5 %	1.0 %	4 %	Not exceed
7	0.1 %	0.3 %	4 %	Not exceed

3.4.2.4 Voltage harmonics

Voltage harmonics is the most vital power quality parameter that other consumers are affected. Therefore, it is important to carefully analyze the impact of solar power plants to the voltage harmonics & level of background voltage harmonics in order to verify whether they are within the specified range. Both THD-V & individual voltage harmonics were considered in this analysis too.

Figure 3.27 shows the total voltage harmonic distortion (in black color) and dominant individual harmonics (5th, 3rd, 7th order) at the point of common coupling of 737 kW plant for one particular day when whole the plant is in operation. Figure 3.28 is a similar

graph obtained during the part of the plant (only one inverter) is in operation. So, it is understood through this graph that THD-V is very much below (below 2%) the maximum allowable limit of 5%. Similarly, among the dominant individual harmonics, 5th order harmonic is significant which reaches maximum value of nearly 2%. It is also below the specified limit, 3%.

In addition, it is proved that this much of solar penetration does not do big impact to the voltage harmonics since no any significant difference is observed when only one inverter is running.

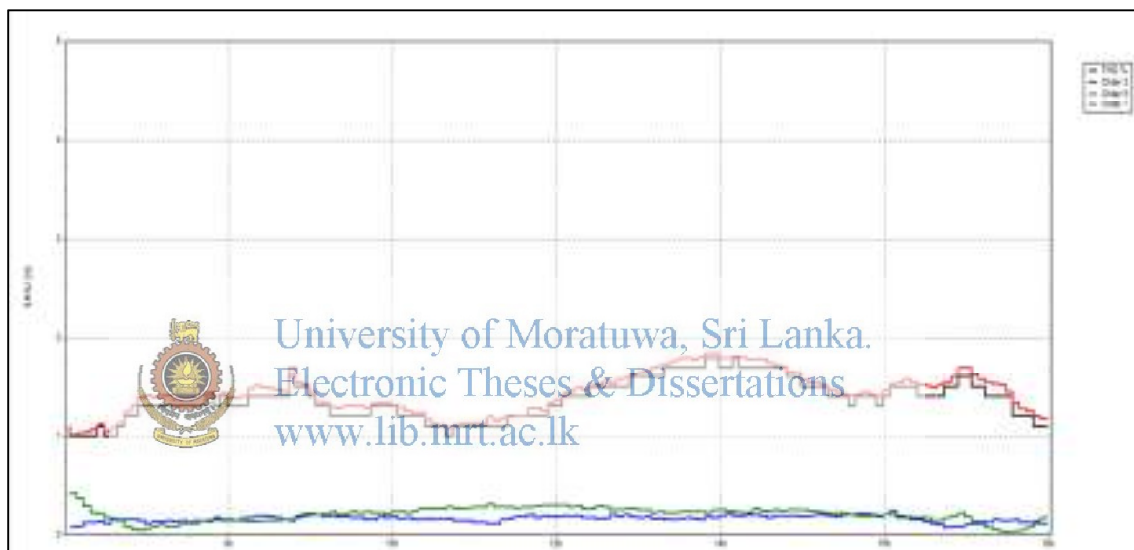


Figure 3.27: Individual voltage harmonics & THD-V variation at full generation

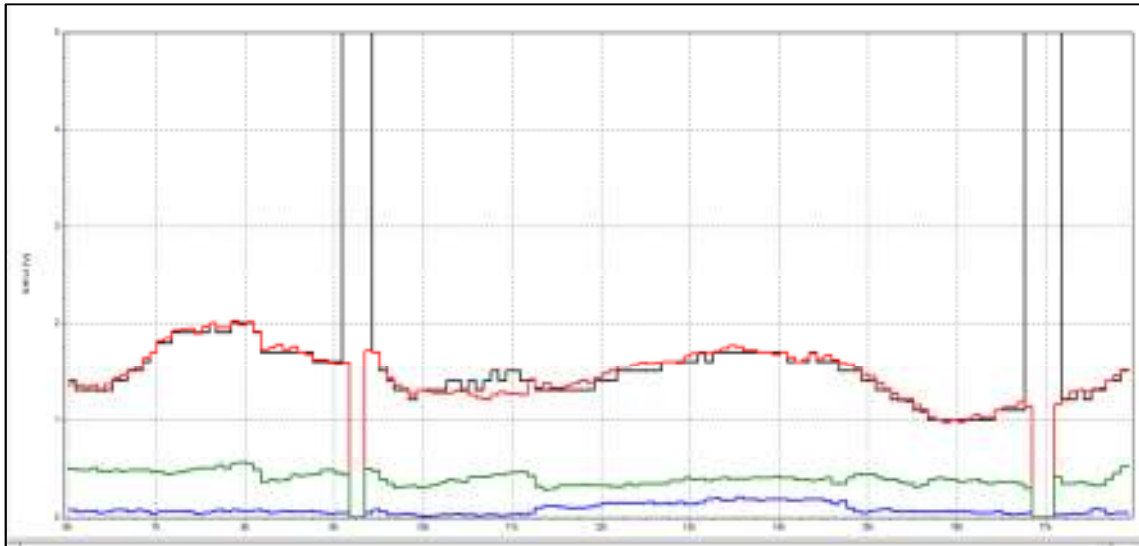


Figure 3.28: Individual Voltage harmonics & THD-V variation at partly generation

3.4.3 Oscilloscope results

To verify all above results, some of the screenshots taken from the power logger in oscilloscope mode are given here.

3.4.3.1 Voltage waveform & current waveform

The series of figures (screenshots) given below nicely demonstrates the gradual change of shape of waveform, especially current waveform with the increasing solar power penetration. The voltage waveform is almost pure sinusoidal whereas the current waveform is highly distorted. With the time, solar penetration increases and current waveform distortion is gradually reducing.

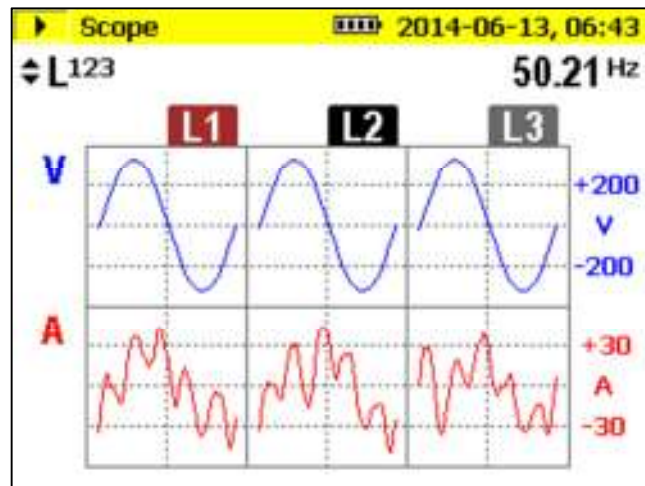


Figure 3.29: Voltage & current waveforms at 06.43 hrs. On 13/06/2014

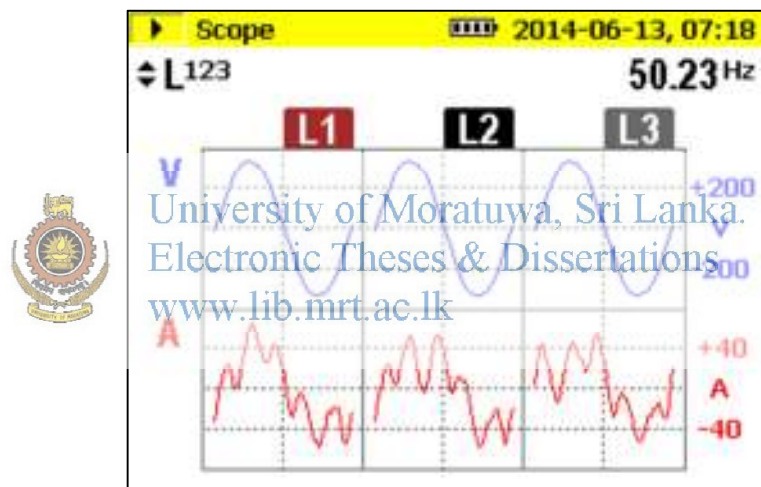


Figure 3.30: Voltage & current waveforms at 07.18 hrs. On 13/06/2014

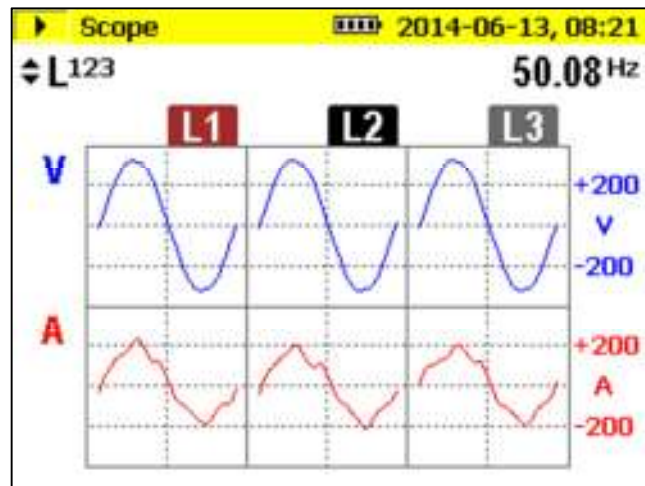


Figure 3.31: Voltage & current waveforms at 08.21 hrs. On 13/06/2014

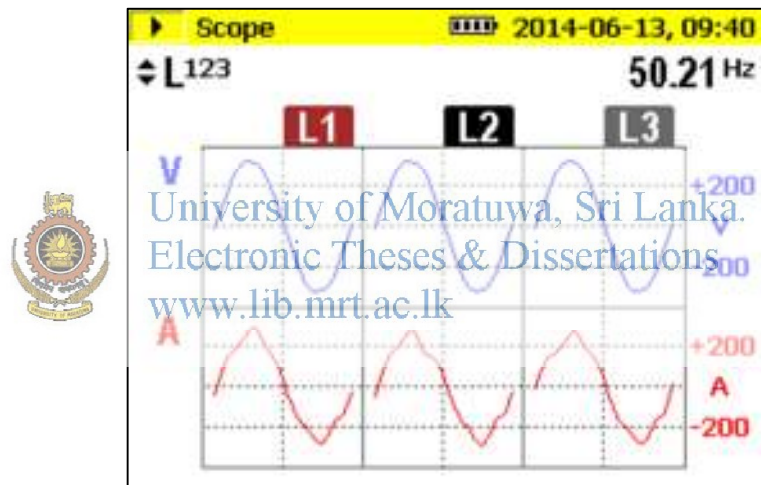


Figure 3.32: Voltage & current waveforms at 09.40 hrs. On 13/06/2014

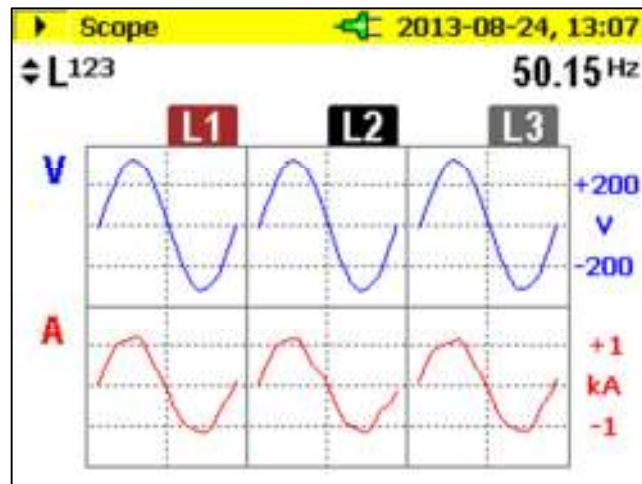


Figure 3.33: Voltage & current waveforms at 13.07 hrs. On 24/08/2013

3.4.3.2 Current Harmonics distortion

Current harmonic spectrums with the instantaneous figures given in Figure 3.34 validate the results presented under 3.4.2.2.

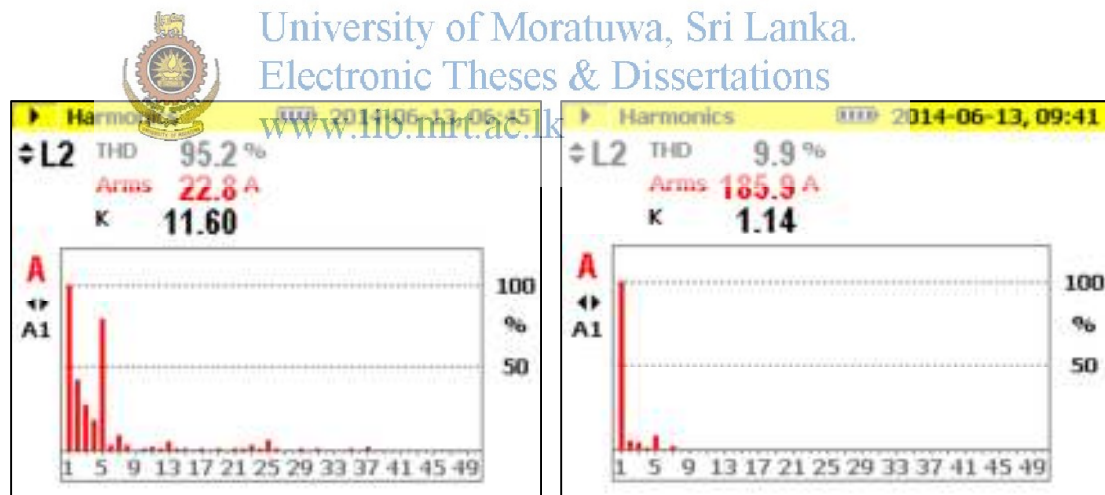


Figure 3.34: Spectrum of current harmonics at 16.45, 09.41 hrs. On 13/06/2014

4.1 PSCAD Software

Power System Computer Aided Design (PSCAD) is a very comprehensive user friendly software package developed by the Manitoba HVDC research center in Canada. It is a powerful and flexible graphical user interface to the world-renowned, EMTDC electromagnetic transient simulation engine. PSCAD enables the user to schematically construct a circuit, run a simulation, analyze the results and manage the data in a completely integrated graphical environment. Online plotting functions, controls and meters are also included, enabling the user to alter system parameters during a simulation run and thereby view the effects while the simulation is in progress.

Compared to earlier versions of PSCAD software, version 4.5 has very much significant feature of having building blocks for “PV array” and “Maximum Power Point Tracking” that played vital role in this research.

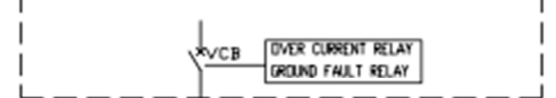
4.2 PV generation system of existing solar power plant at Hambantota (737 kW)

4.2.1 Single line diagram of the solar power system

Figure 4.1 shows the single line diagram of the Japanese plant of 737 kW. It mainly consists of following subsystems.

- 3 nos. of connection boards to which junction boxes at the PV array field are connected
- 3 nos. of power conditioners to which connection boards are connected. Whatever the power injected through the connection boards is inverted to AC & does the conditioning of output power.
- Step-up panel to which the power output from power conditioners are connected.
- Step-up transformer of 1 MVA, 0.415/33kV owned to CEB & energy meter.

CEB 33kV NETWORK (CEYLON ELECTRICITY BOARD)
HAMBANTOTA SUB-STATION



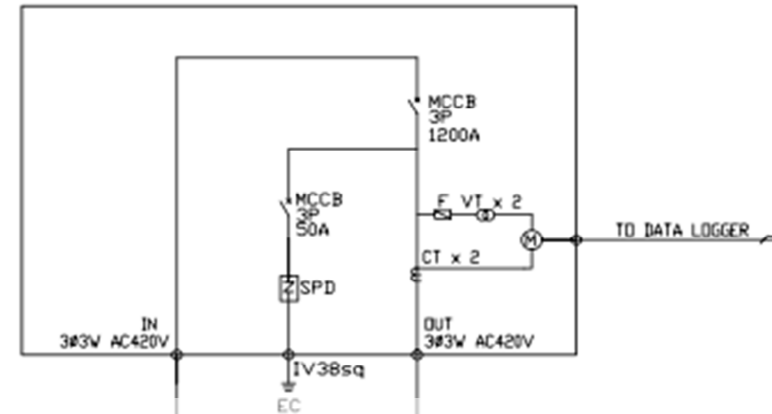
DS
(POWER FUSE)

NETWORK TRANSFORMER
301000kVA

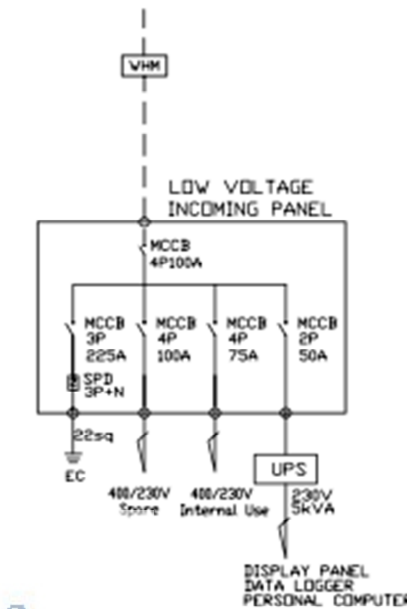
NETWORK TRANSFORMER PANEL
(SUB STATION)
MOLDED CASE CIRCUIT BREAKER
ENERGY METER (MULTI METER)
(V.A.F.F.K.V.A.K.W.H)

303W AC420V
CV250sq-3cx3

STEP-UP PANEL
(TRANSDUCER PANEL)

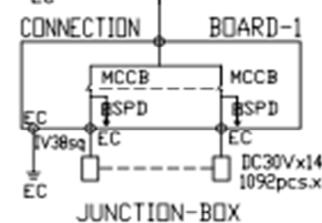
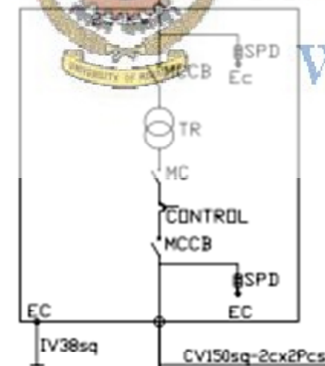


FROM CEB LV LINE
304W 400/230V 50Hz
30kVA



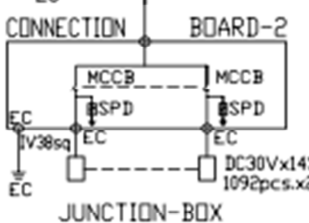
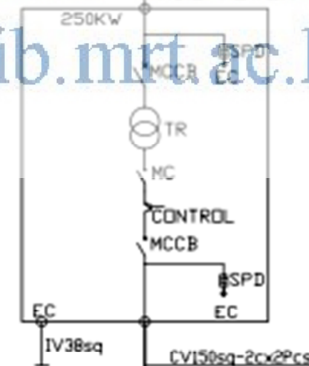
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No.1 POWER CONDITIONER



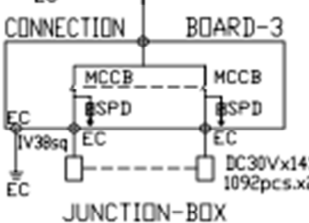
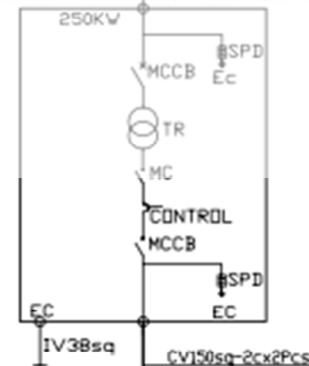
Note: Refer to detail of junction box
(Drawing No. E-01-2A)

No.2 POWER CONDITIONER



Note: Refer to detail of junction box
(Drawing No. E-01-2A)

No.3 POWER CONDITIONER



Note: Refer to detail of junction box
(Drawing No. E-01-2A)

LEGEND	
Symbol	Description
DS	Out out switch
CT	Current transformer
F	Fuse
TR	Transformer
VT	Voltage transformer
LA	Lightning Arrester
SPD	Surge Protection device
MCCB	Molded case circuit breaker
M	Multi Meter
PT	Power Transducer
UPS	Uninterruptible Power Supply
WHM	Watt hour Meter

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4.2.2 Connection board & Junction box

Figure 4.2 shows the arrangement of a connection board to which 17 nos. of type A, B, C, D junction boxes are connected. Each connection board is integrated with 1092 PV modules where type A, type B, type C, type D junction boxes have 84,70,56,42 modules connected respectively. Each circuit of a junction box is connected to 14 nos. of PV modules in series resulting 420V (i.e. 30×14) DC output. Power output of one connection board is 245.7 kW (i.e. $225W \times 1092$).

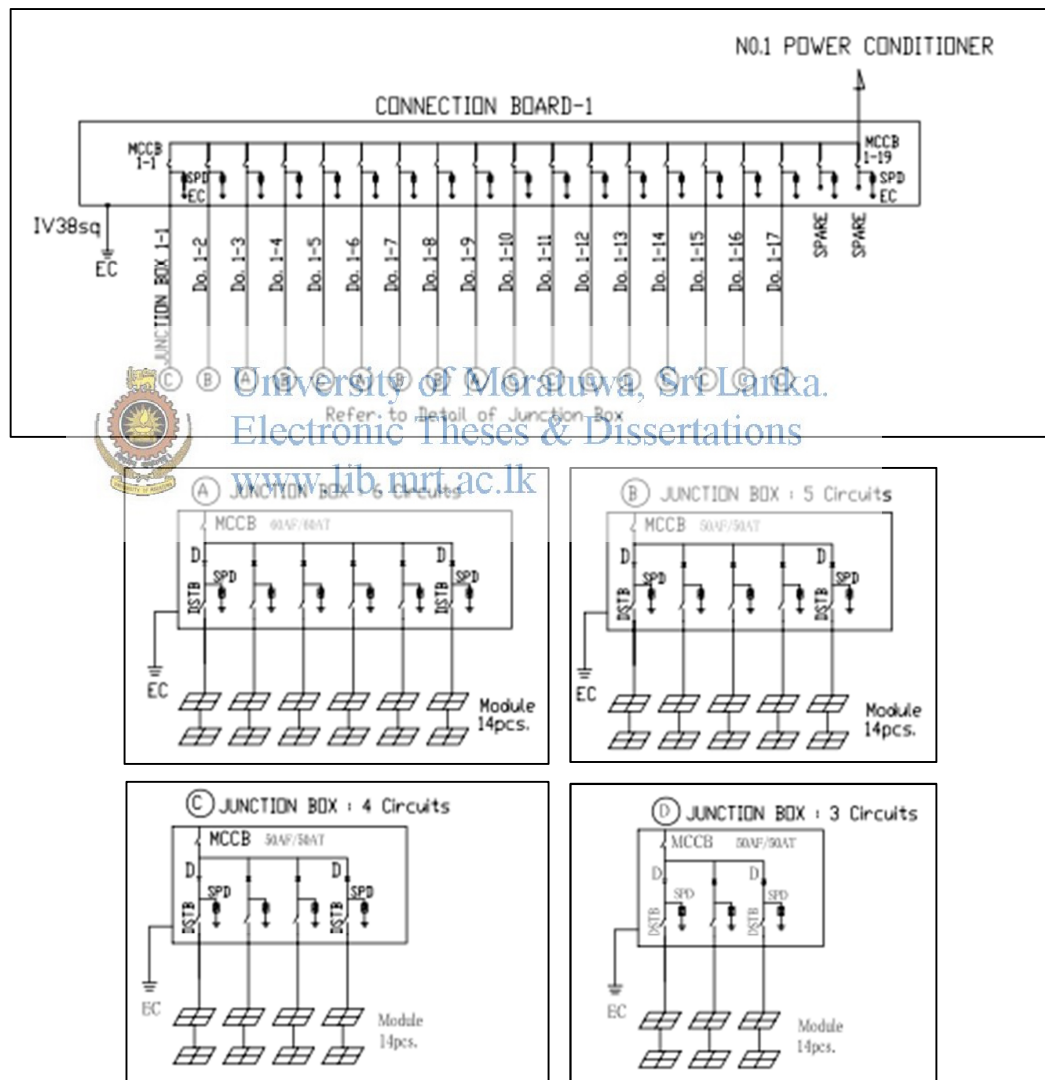


Figure 4.2: Arrangement of a connection board & junction boxes

4.2.3 Power Conditioner

Each power conditioner is connected to one connection board. Inside the conditioner, there are three main subsystems to play crucial role. Those are power inverter, LC filter & internal transformer of 190/420 V, 250 kVA. Figure 4.3 shows internal arrangement of a power conditioner.

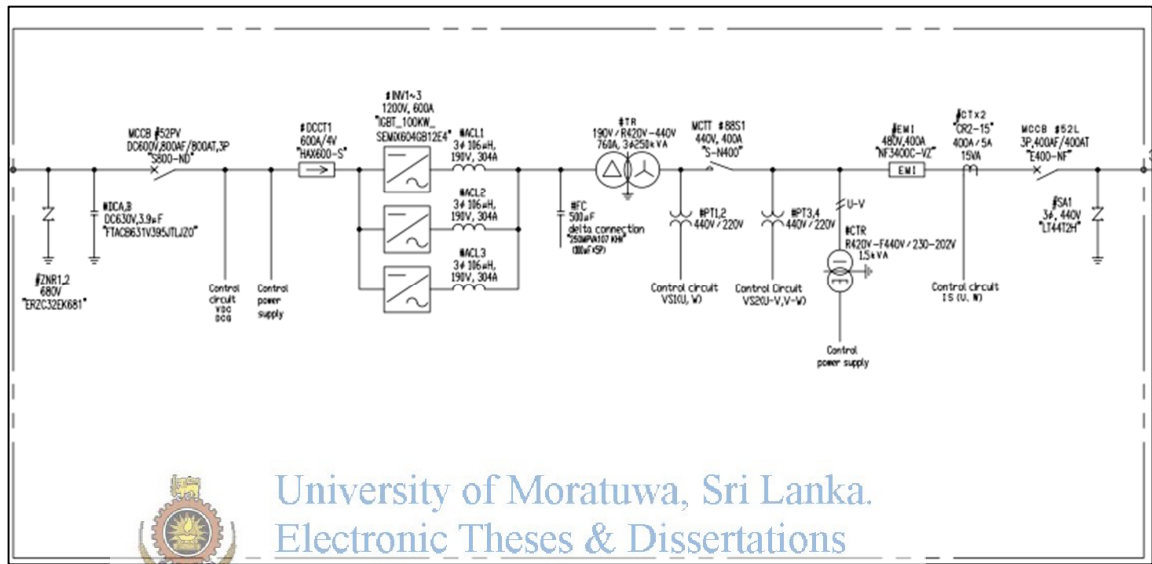


Figure 4.3: Internal arrangement of a power conditioner

- Power inverter

Power inverter consists of three leg IGBTs as indicated in Figure 4.4.

- LC filter

LC filter is equipped with serially connected 106 μ H inductor & delta connected 100*5 μ F capacitor as shown in Figure 4.5.

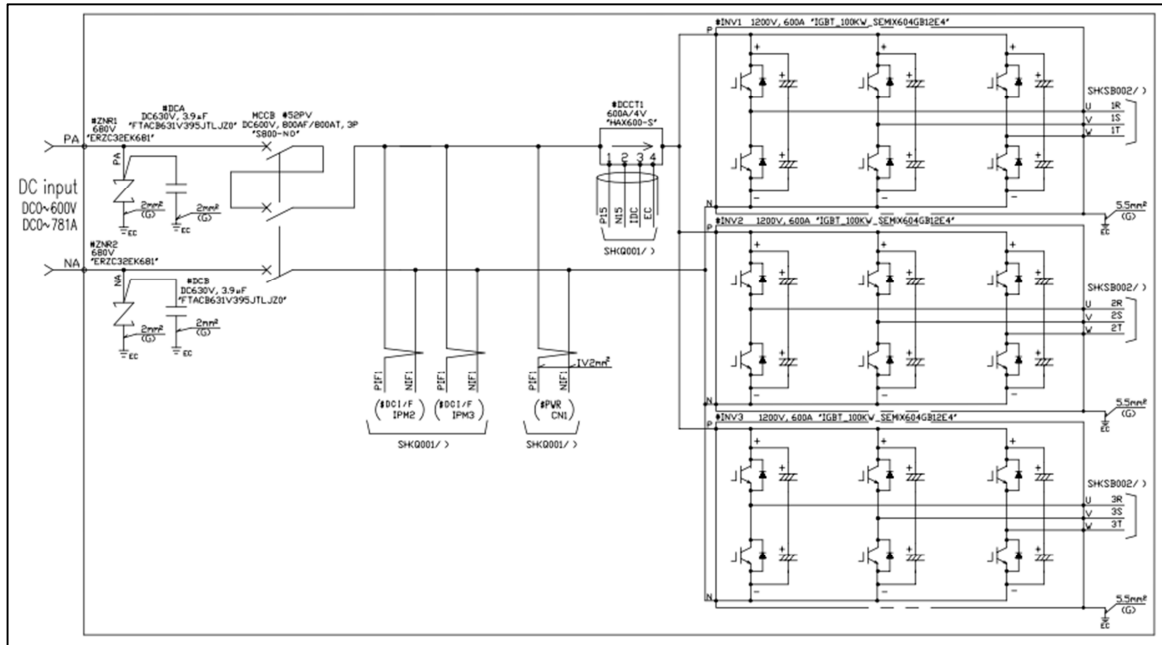


Figure 4.4: Arrangement of the inverter

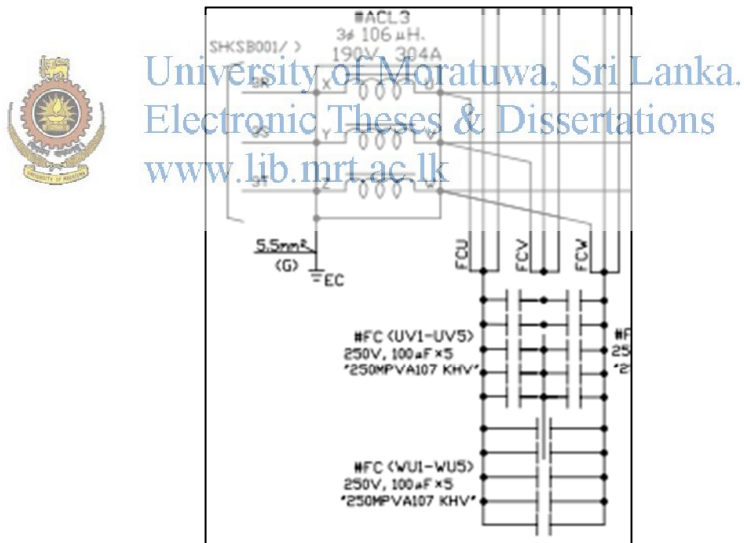


Figure 4.5: LC filter

4.3 Modeling of existing power system in PSCAD

Identification of suitable building blocks available in PSCAD that can represent the actual subsystems or components of the power system was very important for modeling and analyzing to have more accurate results. In addition, understanding of technical parameters of each component & their values was useful too. Modeling of the power system is described step by step below.

4.3.1 PV model

The PV model used in this modeling was developed by Dr. Athula Rajapakse of the University of Manitoba. This model makes use of two custom library components. The two custom components are the PV array and the Maximum Power Point Tracker (MPPT). Figure 4.6 shows the PSCAD model of the two custom library components.

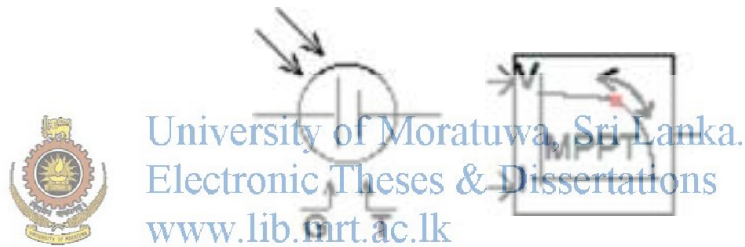


Figure 4.6: Custom library components of PV model

As far as existing solar plant is concerned, it basically consists of three solar PV arrays where each array is built up with 78 parallel strings of 14 serially connected PV modules. Figure 4.7 shows the setup of a PV array together with the inverter and array has two input signals such as solar irradiance, “G” and cell temperature, “T”. Two sliders have been used for those input signals so that values of them could be varied during the simulation.

Figure 4.8 shows the technical parameters of the array and respective configured values. Each module has 60 cells connected in series. Similarly the no. of module strings in series & parallel was configured. Effective cell area, short circuit current at the reference

conditions, temperature coefficient of photo current were set according to the values given product data sheet. All the other parameters were with default values.

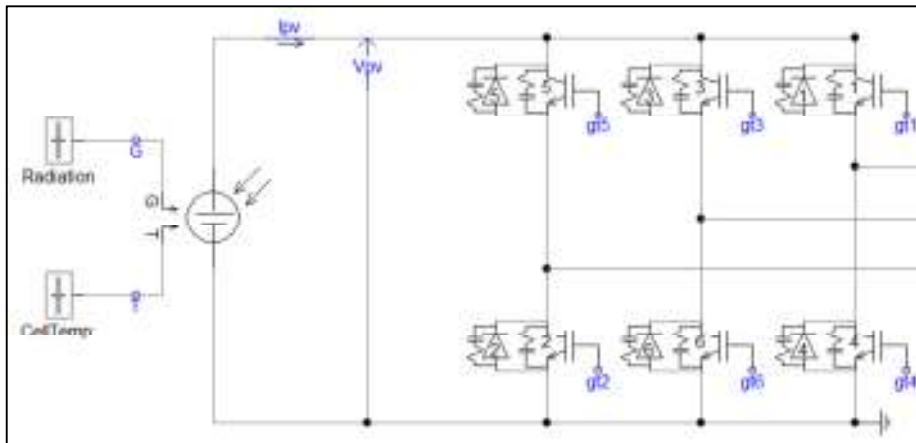


Figure 4.7: Custom library components of PV model

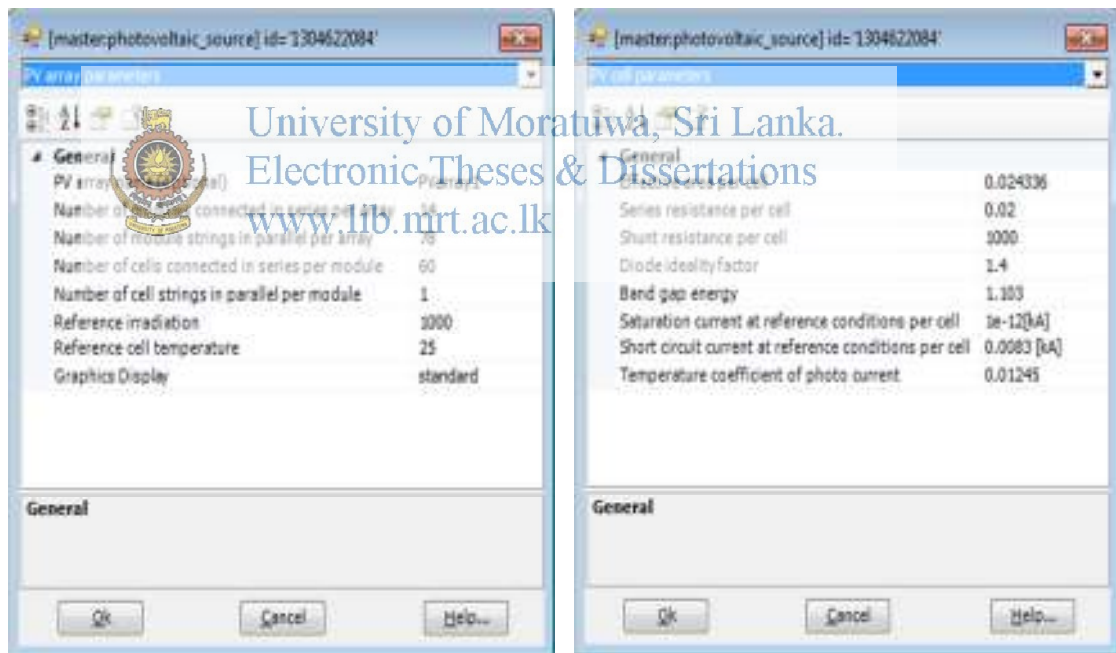
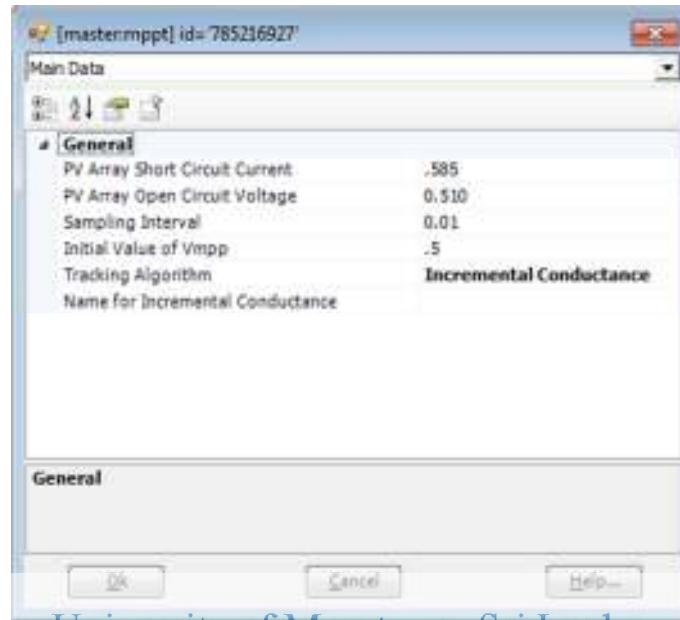


Figure 4.8: Technical parameters & respective values of the PV array

The Maximum Power Point Tracker (MPPT) is to track the knee point of P-V curve of the PV array so that it operates optimum operating point. Algorithm used was incremental conduction as shown below.



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Figure 4.9: Parameters of the MPPT library component

4.3.2 Inverter, LC filter & internal transformer

Figure 4.10 shows how three leg IGBT inverter, LC filter & internal transformer are modeled in PSCAD.

- **Inverter**

Inverter converts direct current (DC) power into alternating current (AC) power. The input to this inverter is DC power being generated by the solar panels and the output power is 50 Hz three phase AC power interfaced to the national grid.

The inverter topology selected for this design is a basic six switch three phase configuration. The Insulated-Gate Bipolar Transistors (IGBTs) switches are operated by a control signal generated through a Sinusoidal Pulse Width Modulation. This is quite similar to power transistors except for one major improvement. Power

transistors require a current to be applied at the gate in order to force the transistor to conduct while IGBTs require a voltage at the gate terminal. This advancement allows the IGBT to be controlled by an applied gate voltage, with minimal current flow, which gives them the ability to switch much faster than the current driven power transistors. IGBTs also have much higher voltage and current ratings than other switching devices. These characteristics make them optimal for high power high frequency applications such as a voltage sourced inverter.

- **LC filter**

The filter after the PWM inverter is a vital component to ensure the voltage and current waveforms being injected into the grid are high quality sinusoidal waveforms. One huge benefit of using high frequency PWM switching technique is the undesirable harmonic content of the unfiltered signal occurs around the switching frequency which is usually much higher than the fundamental. The benefit of this is that since the harmonic content is at a much higher frequency than the fundamental the filtering requirements are less drastic, smaller components can be used, and overall the filter will be less expensive. A simple first order low pass LC filter can be used to extract the fundamental component and attenuate the higher frequency content.

The filter used in this inverter has 106 μH series connected inductor & 100*5 μF delta connected capacitors.

4.3.3 Step-up transformer & 33kV equivalent system

Power output of three inverters is fed to the step-up transformer (0.42/33kV, 1MVA) as shown in Figure 4.11. A multi meter is also connected to LV side of the transformer to measure and monitor the power quality parameters.

Existing solar power plants are connected to Hambantota-Nanagama Feeder. Accordingly the 33 kV system was modeled with P, Q loading points at important nodes and conductor impedance of each section. In addition, the grid substation was modeled with infinite 33 kV bus since its voltage is maintained at that level most of the time by

transformer tap changing. Also upstream equivalent impedance was considered as zero (ideal source) since it does not affect to the analysis.

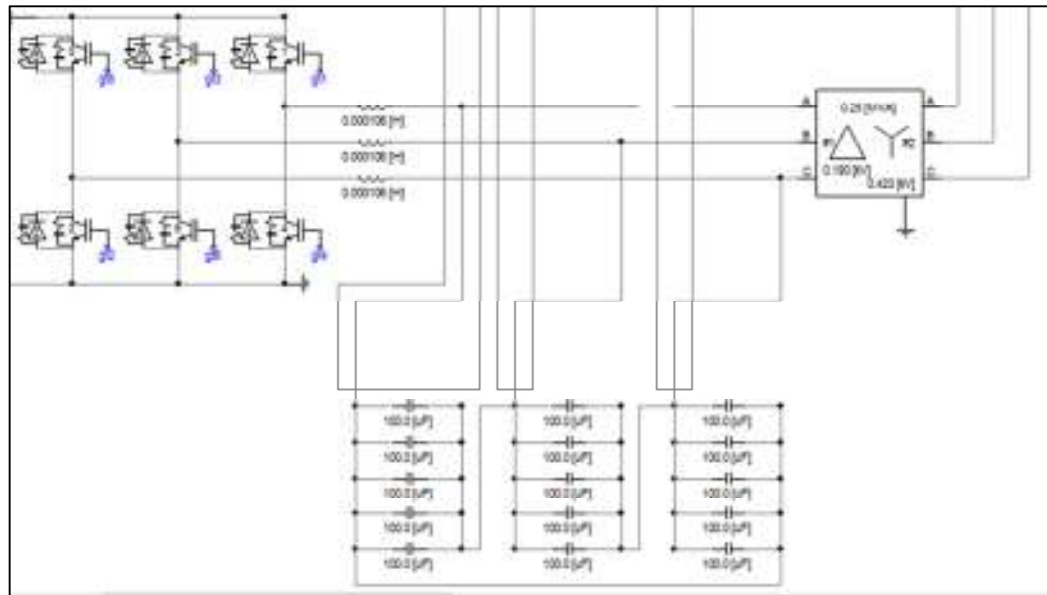


Figure 4.10: PSCAD model for inverter, filter & internal transformer

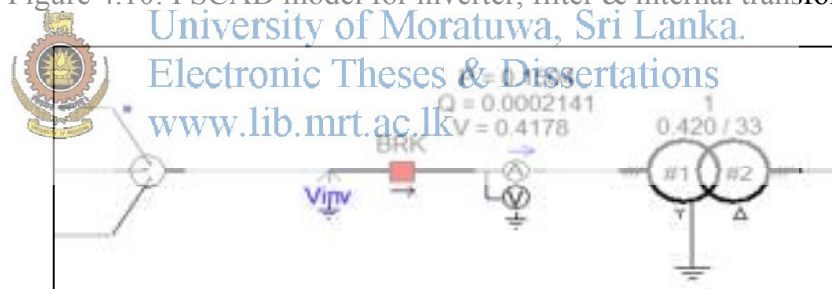


Figure 4.11: PSCAD model for multi meter & step-up transformer

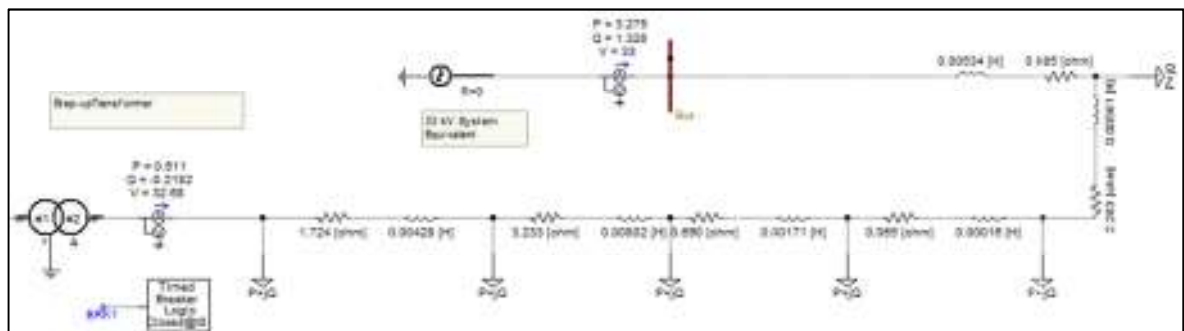


Figure 4.12: PSCAD model for 33kV equivalent system

4.3.4 Maximum Power Point Tracking (MPPT)

Since the optimum operating point of solar cells occurs at the knee of the I-V curve. In order to extract the maximum amount of power from PV array, it is desirable to operate at the optimum operating point at all times. The model shown in Figure 4.13 does the expected task.

In this model, V_{pv} , I_{pv} measured at the PV array is sent through a low pass filter whose gain is 1 and time constant is 0.01 to filter out unnecessary frequency components. The filtered signals are sent to MPPT block which gives the Maximum Power Point voltage (V_{mppt}) as the output signal at which PV array should operate to harness maximum power.

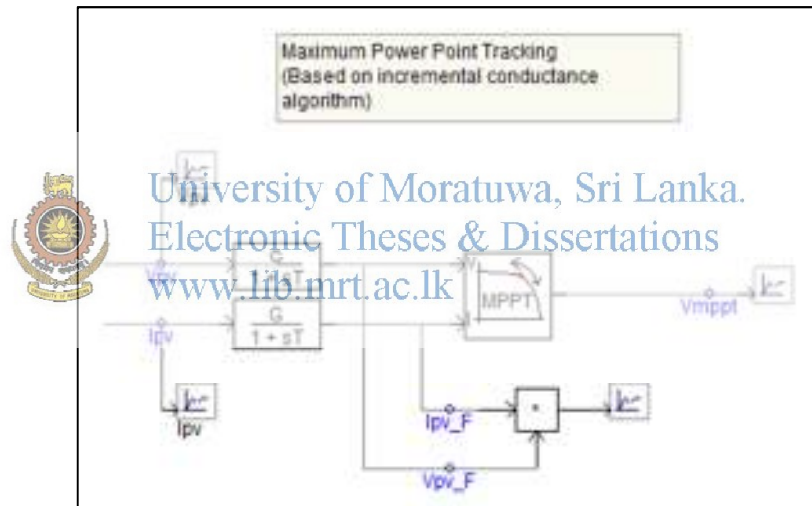


Figure 4.13: PSCAD model for MPPT

4.3.5 Active Power control

The power produced by the solar array is in a DC form before it is inverted and filtered into an AC grid injectable form. Controls need to be considered so that all of the power generated minus loss across the inverter is transformed through the system and into the power network. This control is modeled around the basic real power flow equation for a two-port network.

$$P_{12} = (V_1 V_2 \sin \delta) / X_{12} \dots\dots\dots (A)$$

Where, P_{12} is the power flowing from port one to port two shown in Figure 4.14. The voltages V_1 and V_2 are the magnitudes of the two port network.

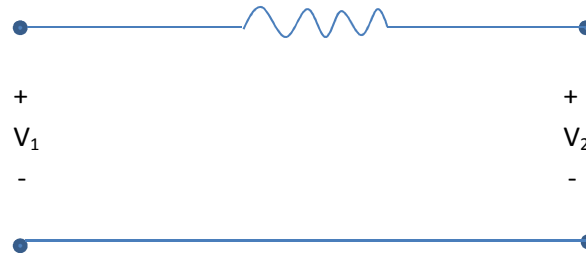


Figure 4.14: Two port network

The equation (A) assumes the equivalent system impedance has a high reactance to resistance ratio. Analyzing the variables in equation (A), the reactance X_{12} is a fixed parameter and does not change. V_2 is the grid voltage which is usually considered as “stiff” or not easily changed from its nominal value. V_1 is the inverter produced voltage which is controllable & does not vary far above or below its nominal value. This leaves last variable delta, also known as the power angle, the dominating variable in the equation. Delta is the phase difference between voltages. Since the power systems phaser is a stiff quantity controlling the power angle, and hence the power delivered to the grid is easily achieved by adjusting the phase input signal applied to the PWM reference waveforms.

Ideally, the power angle needs to adjust so the power delivered to the grid is equal to the PV generated power minus loss. If the power angle is too large the controller is trying to send more power than is available and DC bus voltage decreases because the required PV operating point is not on its operating curve. If the power angle is too small, the system is not making efficient use of the PV system because it is not operating at the MPP voltage. In order to realize the control action, the difference between the measured PV voltage is fed through a Proportional Integral (PI) controller and output is the phase

applied to the PWM reference sine waves. This control scheme is shown in Figure 4.15 forces the power angle to modulate until both the grid injected power is equal to the PV array and the array is operating at its MPP.

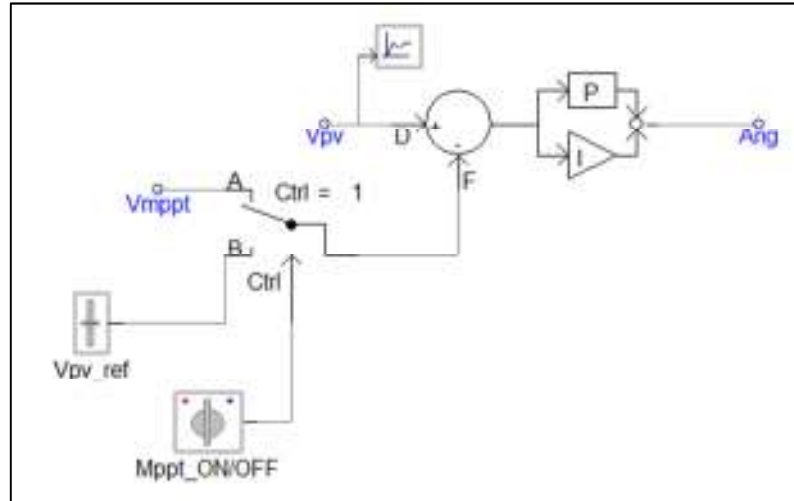


Figure 4.15: PSCAD model for active power control

4.3.6 Reactive power control

The control method of reactive power injected or absorbed is based on a simple reactive power flow equation just as in the real power control method. Referring back to the two port network shown in Figure 4.14, reactive power flowing from port 1 to port 2 can be described as;

$$Q_{12} = \{(V_1 V_2 \cos \delta) / X_{12}\} - (V_2^2 / X_{12}) \dots \dots \dots (B)$$

In this case, V_1 is the dominating factor that controls the reactive power flow since V_2 is fixed at the grid voltage. Therefore by controlling the inverter output voltage, reactive power can be controlled.

Most inverters are required to operate at unity power factor. Therefore adjusting the modulation index of the PWM reference sine wave can control the inverter voltage and consequently the reactive power output. The control is realized by subtracting the measured reactive power from a set point of zero and sending the difference through a PI

controller which outputs the “Mag” signal to be input to the PWM reference sine wave as shown in Figure 4.16.

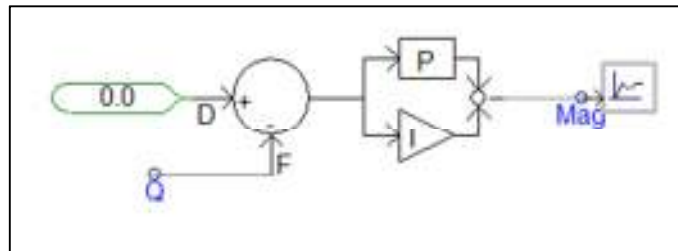


Figure 4.16: PSCAD model for reactive power control

4.3.7 Sinusoidal Pulse Width Modulation

The AC output waveforms shape and quality is directly related to how the conduction intervals of the switches are controlled. Methods for controlling the switches range from simple to complex. The method chosen for this application was unipolar sinusoidal pulse width modulation (SPWM). This control technique is very well known and was used because it allows the control of three very important output waveform variables. These three variables are the phase, magnitude and frequency of the generated AC waveform. SPWM is a control technique that requires three different sinusoidal waveforms (for three phase operation) of the same frequency as the desired output and one high frequency triangle waveform known as the carrier signal. The signal deciding when the appropriate switch should conduct or remain off is determined by comparing the magnitudes of the sinusoidal & triangle waveforms. Between the comparing logic and the gate terminal of the IGBT is a driving circuit providing the necessary voltage and power to operate the switch. The reference sinusoidal waveforms can be modeled as follows.

$$V_{Aref} = A \sin (2\pi f_r t + \phi) \dots \dots \dots (C)$$

$$V_{Bref} = A \sin (2\pi f_r t + \phi - 120^\circ) \dots \dots \dots (D)$$

$$V_{Bref} = A \sin (2\pi f_r t + \phi + 120^\circ) \dots \dots \dots (E)$$

Where A is the amplitude of the reference sine wave also known as the modulation index, f_r is the desired frequency of the output waveform and ϕ is the phase shift. Triangular waveform is varying from -1 to 1 with a duty cycle 50% at a frequency of 5 kHz which is much higher than that of f_r . The modulation index is technically the ratio of the amplitudes of the reference amplitudes of the reference sine waves to the triangular carrier signal, but since the triangle waveform typically has an amplitude of one, the amplitude of the reference sine waves can be considered the amplitude modulation factor. Figure 4.17 shows the control scheme of SPWM modeled in PSCAD. The input signal “Freq” is set to 50 Hz and how other two signals “Mag” & “Ang” generated is described under previous sections. The generated switching signals “gt1”, “gt3”, “gt5” are sent to upper three IGBTs of the inverter and “gt4”, “gt6”, “gt2” to lower IGBTs as shown in Figure 4.7.

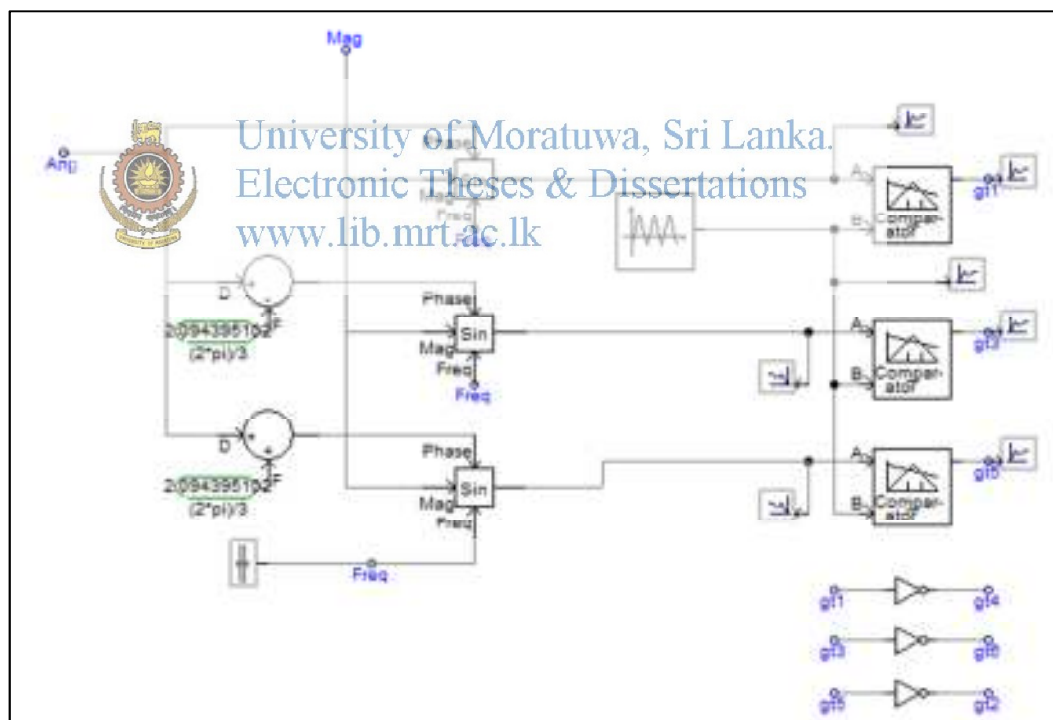


Figure 4.17: PSCAD model for Sinusoidal Pulse Width Modulation

4.3.8 Harmonics analysis

This is the most important part of the research and PSCAD modeling. The measured RMS voltage (E1) and current (I2) at the point of common coupling are sent to Fast Fourier Transformation block that extract the amount of harmonic content. The output is then sent to Harmonic Distortion block in order to separately output the individual harmonic & total harmonic distortion levels. In order to obtain the final output as a percentage, the measured value is divided by the rated value and multiplied by 100. The PSCAD model is shown in Figure 4.18.

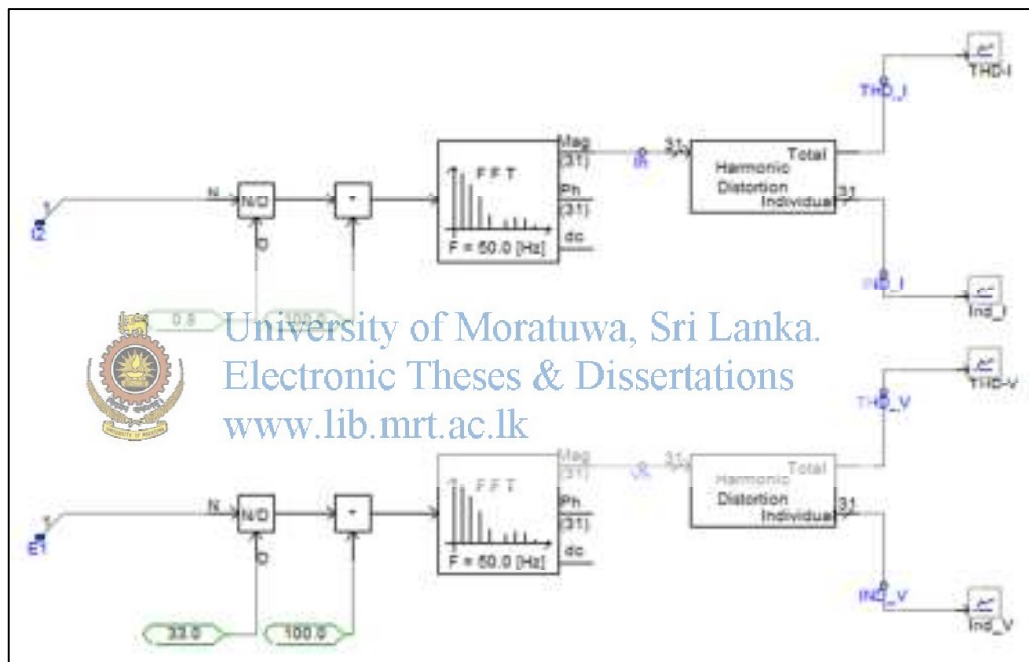


Figure 4.18: PSCAD model for Harmonic analysis

4.3.9 Control Panel

In this PSCAD model, there are few variables, value of which can be changed during the simulation as well. Those are, solar radiation, cell temperature, reference voltage of the active power control, MPPT On/Off, frequency of PWM control scheme as shown in Figure 4.19.

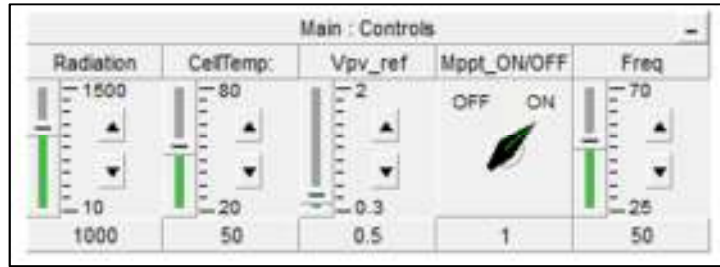


Figure 4.19: Control panel

4.4 Simulation Results & PSCAD model validation

Simulations were carried out under different conditions for the PSCAD model built as described previously. Then those simulation results were compared with actual measurements in order to validate the PSCAD model and modeling principle.

4.4.1 Power, Voltage & Current

Simulations were carried out for two different conditions of solar radiation & cell temperature. Figure 4.20 shows the variation of solar power generation with the irradiance over few consecutive days.

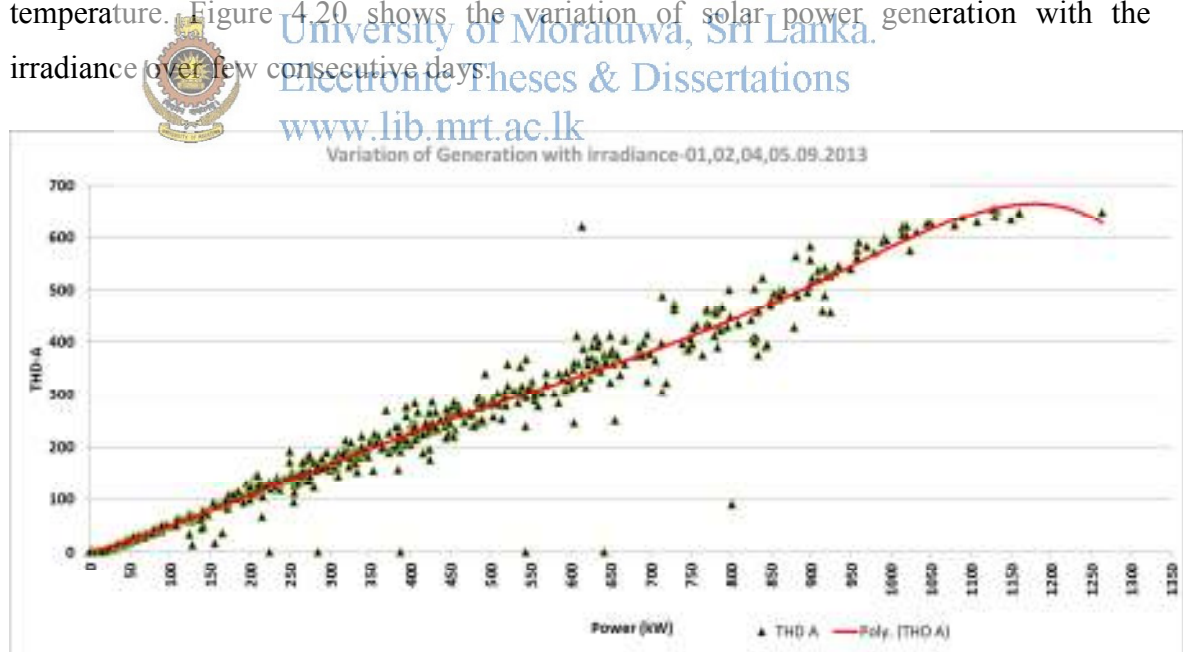


Figure 4.20: Variation of solar generation over the irradiance

4.4.1.1 Solar irradiance at 1000 W/m² & Module temperature at 50 °C

As per the Figure 4.21, it is observed that the solar power generation is around 600 kW which is in line with the actual measurement shown in Figure 4.20. The RMS line-line voltage & current wave forms given by simulation results are similar to the actual measurements.

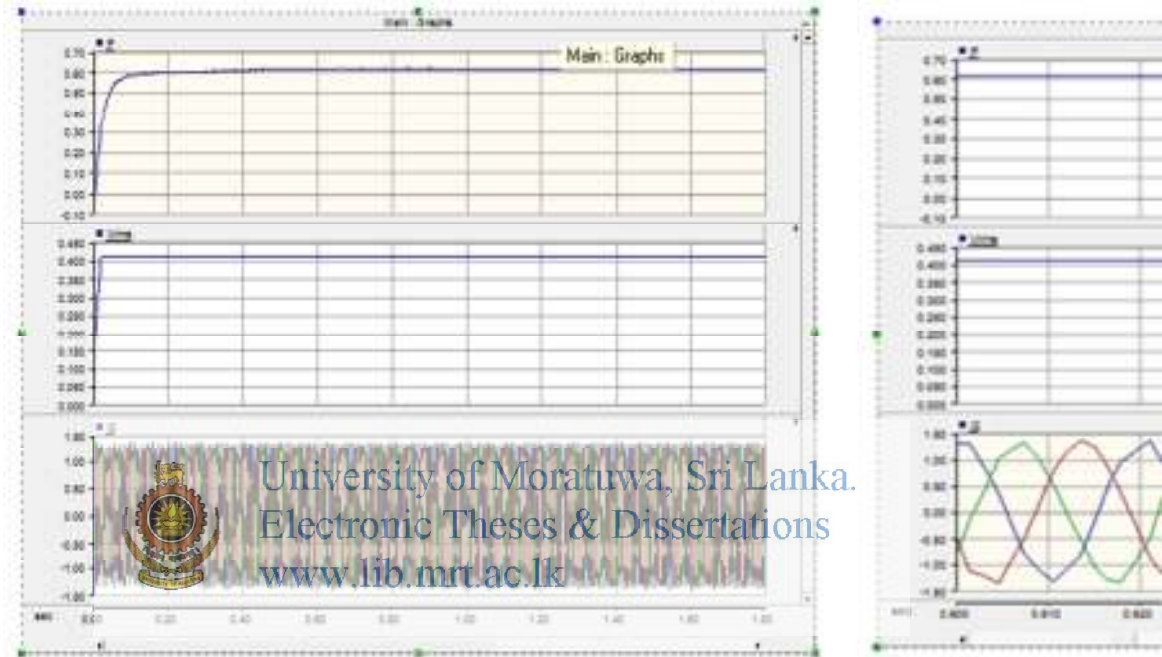


Figure 4.21: Simulation results at irradiance, 1000 W/m² & cell temperature 50 °C

4.4.1.2 Solar irradiance at 200 W/m² & Module temperature at 28 °C

Figure 4.22 indicates that the solar power generation is around 125 kW which is comparable with the actual measurement shown in Figure 4.20. The RMS line-line voltage & current wave forms given by simulation results are similar to the actual measurements.

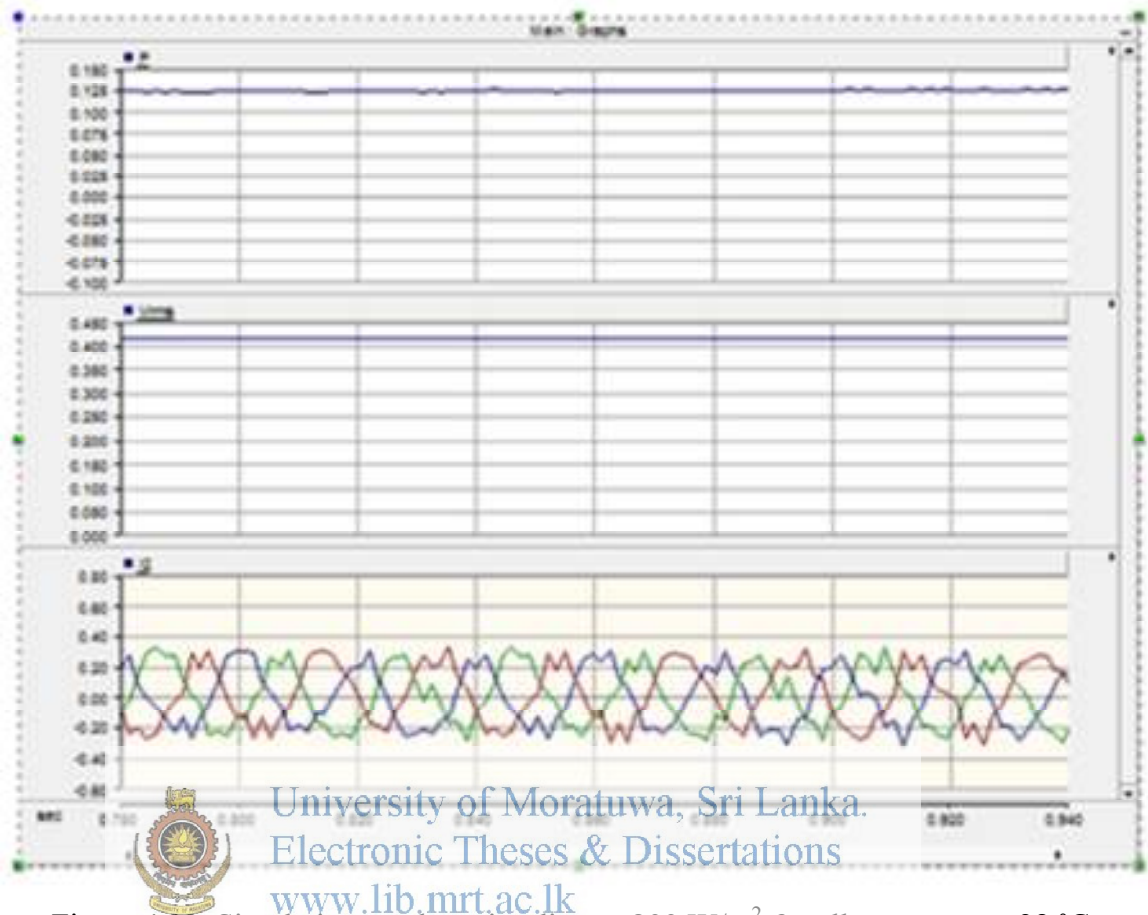


Figure 4.22: Simulation results at irradiance, 200 W/m² & cell temperature 28 °C

4.4.2 Current Harmonics

Figure 4.23, 4.24, 4.25, 4.26 shows the variation of THD-A, 5th, 7th, 3rd current harmonic content over the irradiance respectively. The trend line shown in red color shows the averaged curve which will demonstrate the averaged values with respect to irradiance that can be used for comparison of simulation results.

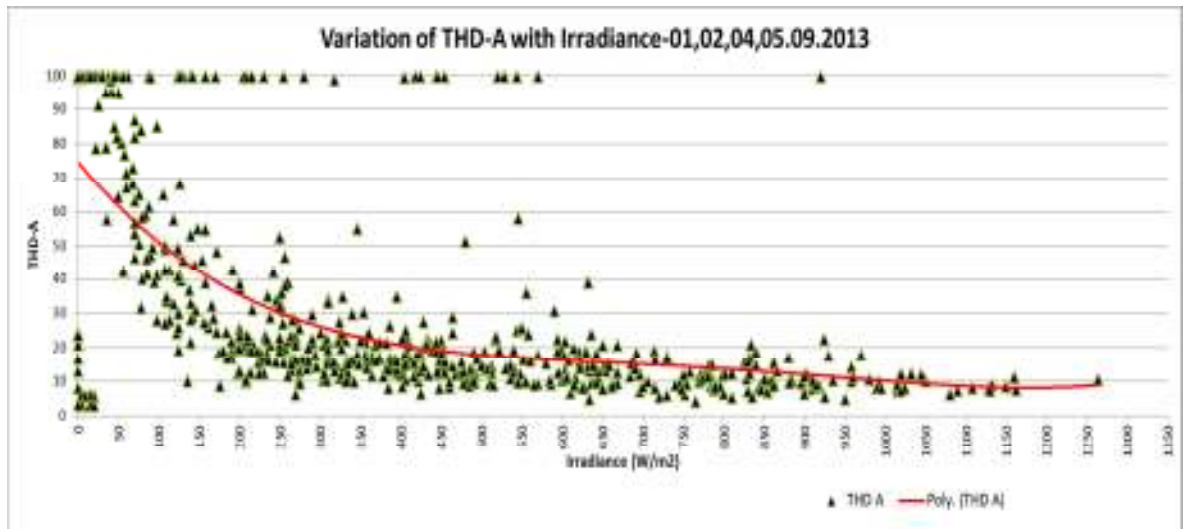


Figure 4.23: Variation of THD-A current harmonic content with irradiance

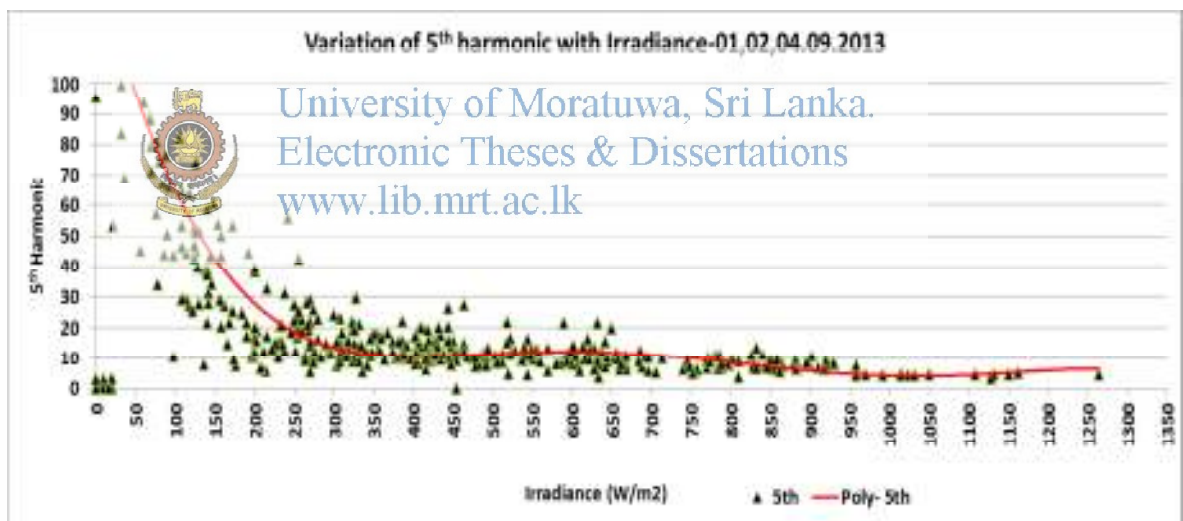


Figure 4.24: Variation of 5th current harmonic content with irradiance

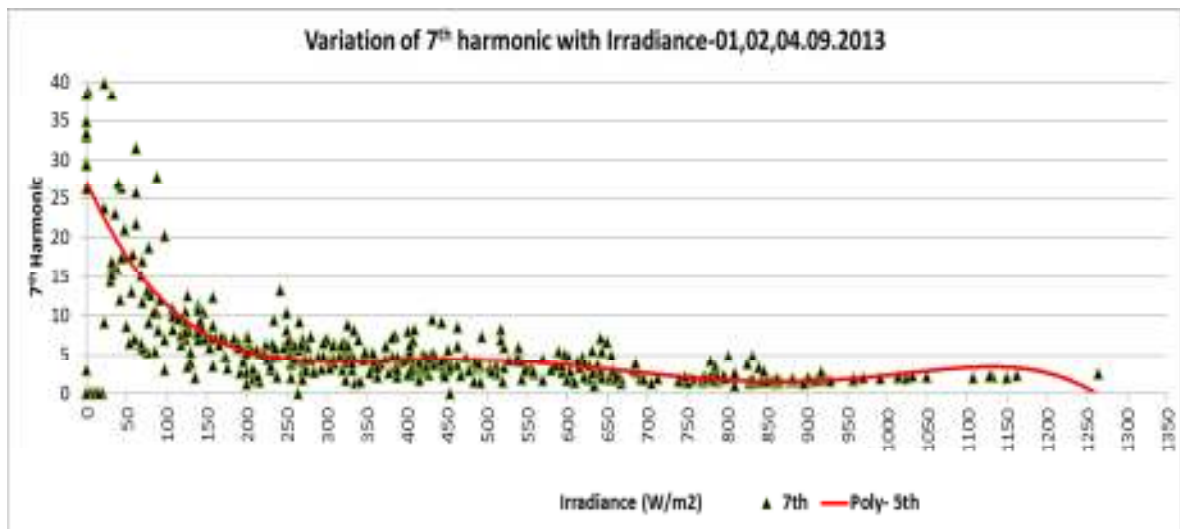


Figure 4.25: Variation of 7th current harmonic content with irradiance

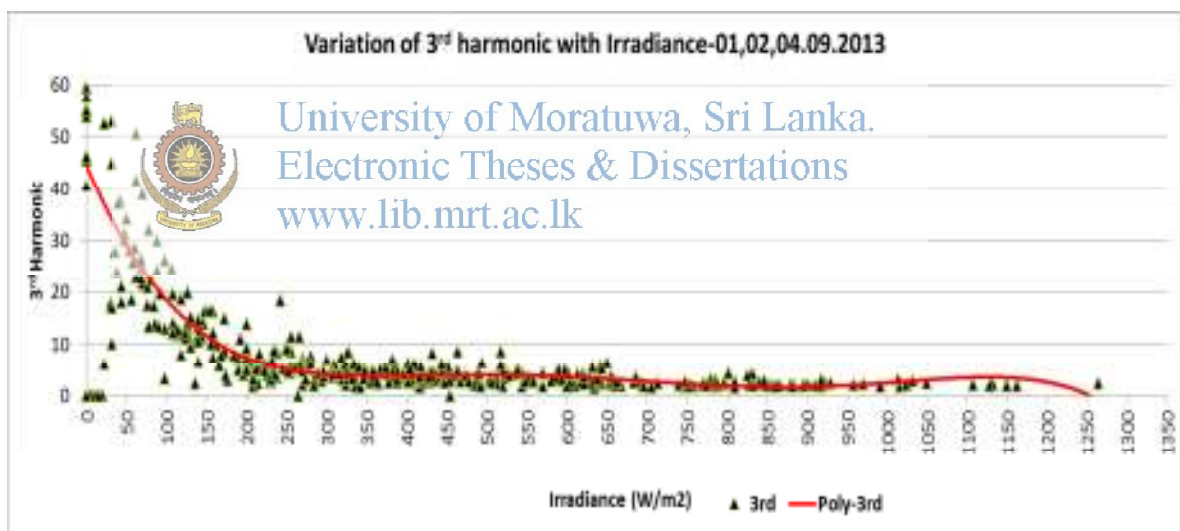


Figure 4.26: Variation of 3rd current harmonic content with irradiance

4.4.2.1 Current harmonics at solar radiation, 1000 W/m² & Module temperature at 50 °C

Simulation was carried out at solar radiation, 1000 W/m² & Module temperature at 50 °C, results of which are shown below. Figure 4.27 shows the content of individual current harmonic components where 5th, 7th, 2nd, 3rd harmonics dominate throughout the spectrum. When compared these results with the respective values shown in Figure 4.24, 4.25, 4.26, it is clear that both are almost same where 5th, 7th, 3rd harmonic values are 4%, 2%, 1.5% respectively.

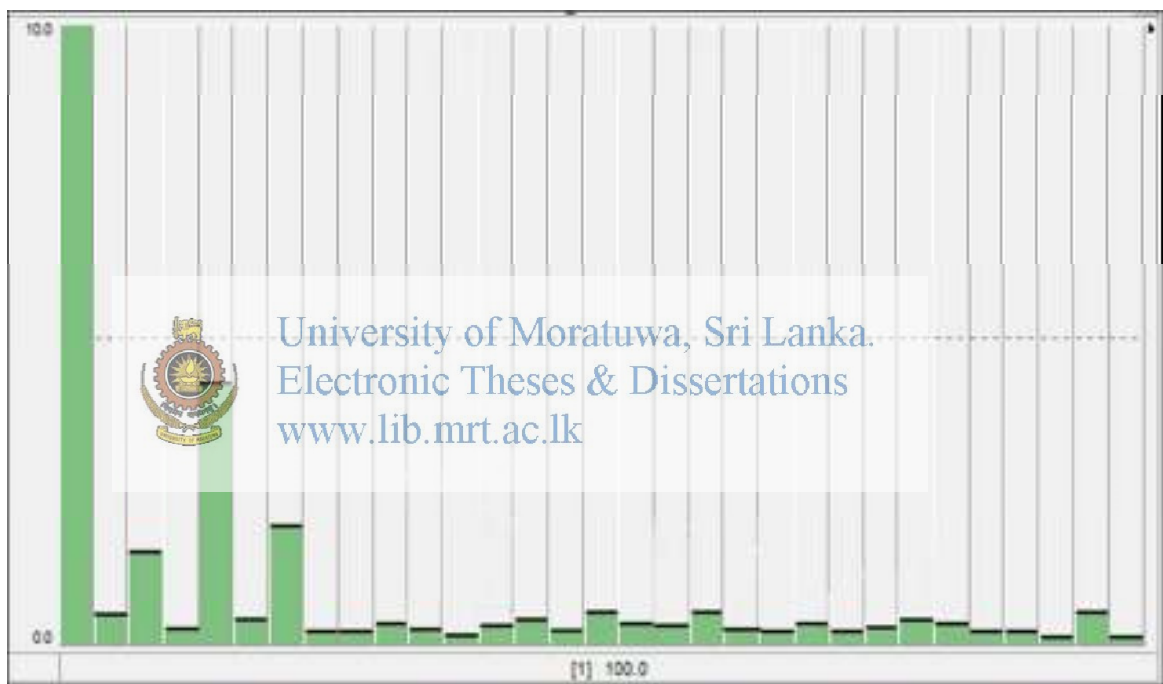


Figure 4.27: Individual harmonics at irradiance, 1000 W/m² & cell temperature 50 °C

Total current harmonic distortion at irradiance level, 1000 W/m² is around 8% as per the actual measurements shown in Figure 4.23 & same is verified by the simulation results shown in Figure 4.28 as well.



Figure 4.28: THD-A at irradiance, 1000 W/m^2 & cell temperature 50°C

4.4.2.2 Current harmonics at solar radiation, 200 W/m^2 & Module temperature at 28°C

Figure 4.29 shows the content of individual current harmonic components at low solar irradiance level. When compared these results with the respective values shown in Figure 4.24, 4.25, 4.26, it is clear that both are almost same where 5th, 7th, 3rd harmonic values are 25%, 7%, 8% respectively.

Similarly the THD-A under these conditions is around 38 % which is verified by the simulation results too since it lies in the range of measured data as shown in Figure 4.30.

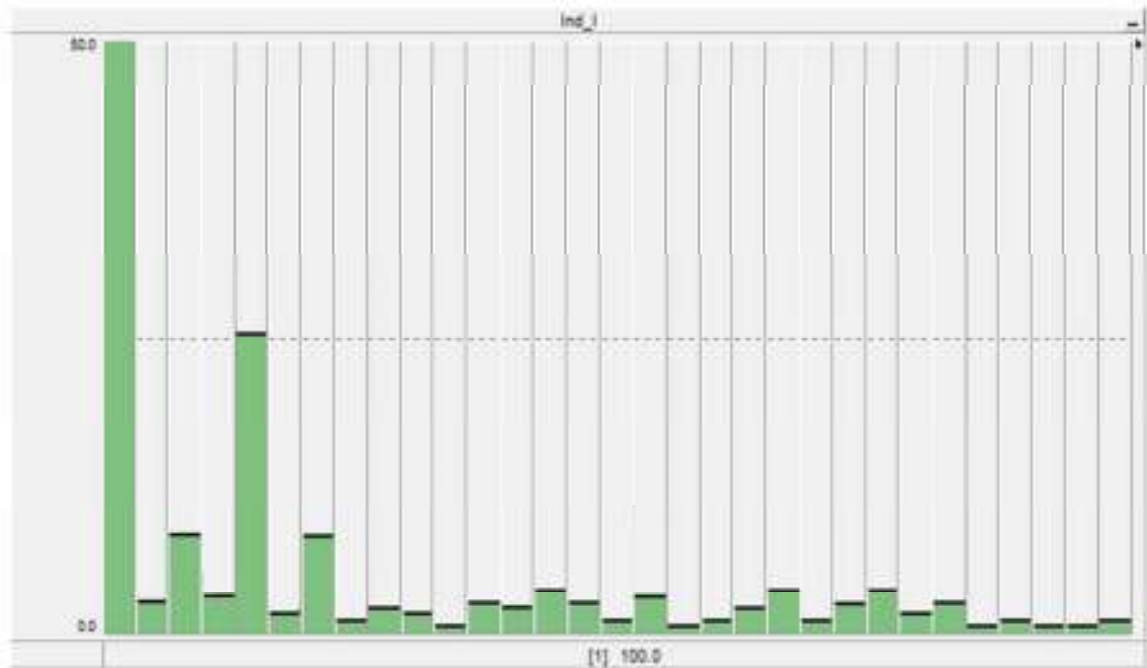


Figure 4.29: Individual harmonics at irradiance, 1000 W/m² & cell temperature 50 °C

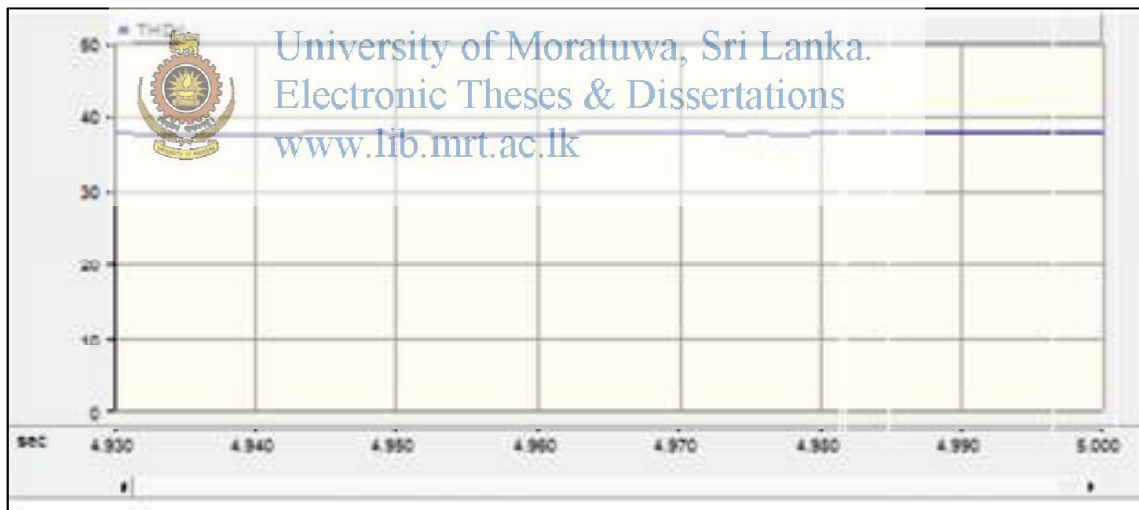


Figure 4.30: THD-A at irradiance, 1000 W/m² & cell temperature 50 °C

4.4.3 Voltage Harmonics

4.4.3.1 Voltage harmonics at solar radiation, 1000 W/m^2 & Module temperature at 50°C

Figure 4.31 & Figure 4.32 show the individual voltage harmonics content & THD-V when irradiance is 1000 W/m^2 . This is without the background harmonics.

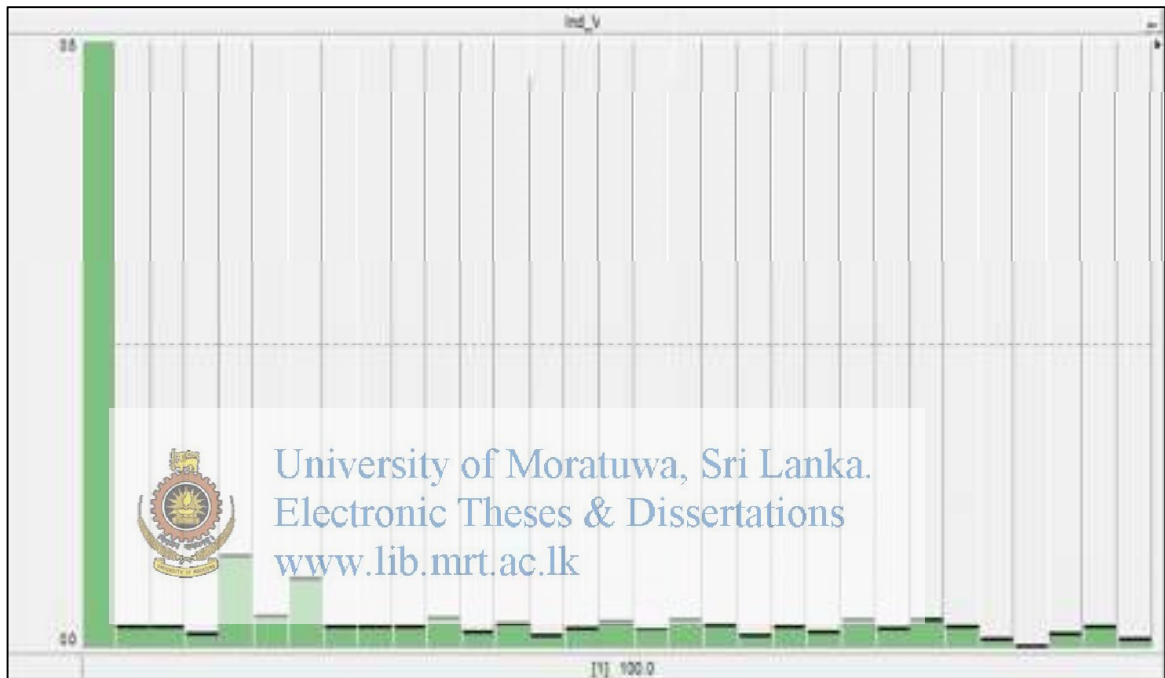


Figure 4.31: Voltage harmonics at irradiance, 1000 W/m^2 & cell temperature 50°C

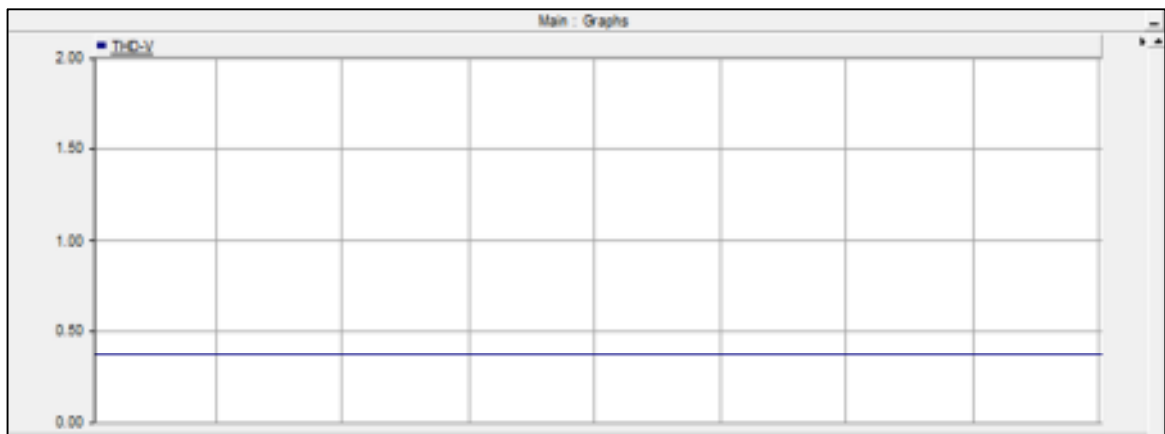


Figure 4.32: THD-V at irradiance, 1000 W/m^2 & cell temperature 50°C

4.4.3.2 Voltage harmonics at solar radiation, 200 W/m² & Module temperature at 28 °C

Figure 4.33 & Figure 4.34 show the individual voltage harmonics content & THD-V when irradiance is 200 W/m². This is without the background harmonics.

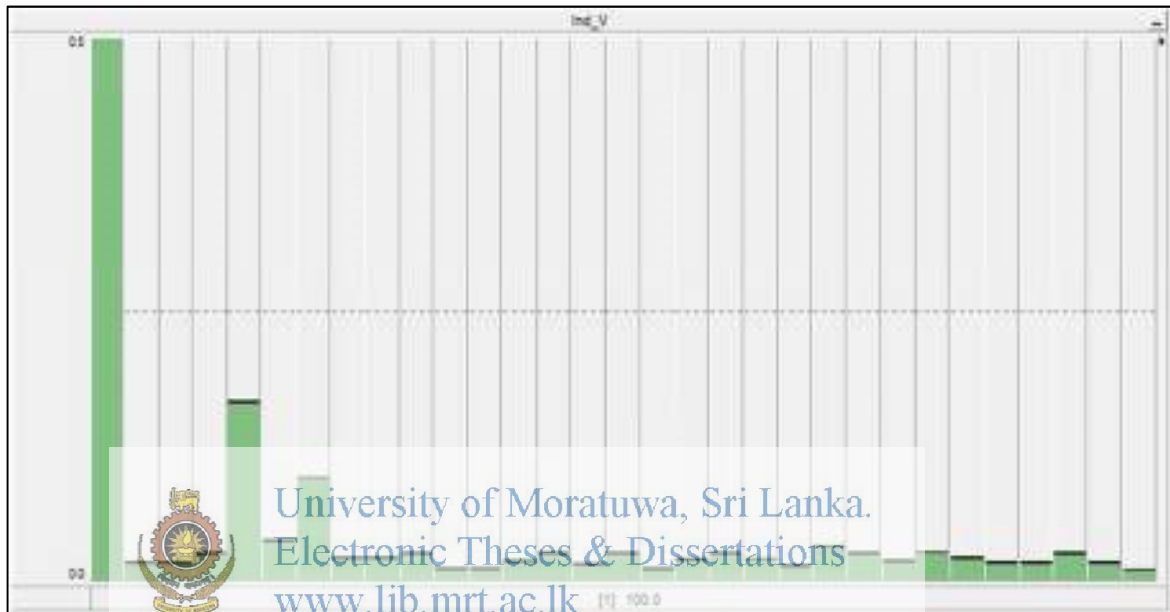


Figure 4.33: Voltage harmonics at irradiance, 200 W/m² & cell temperature 28 °C

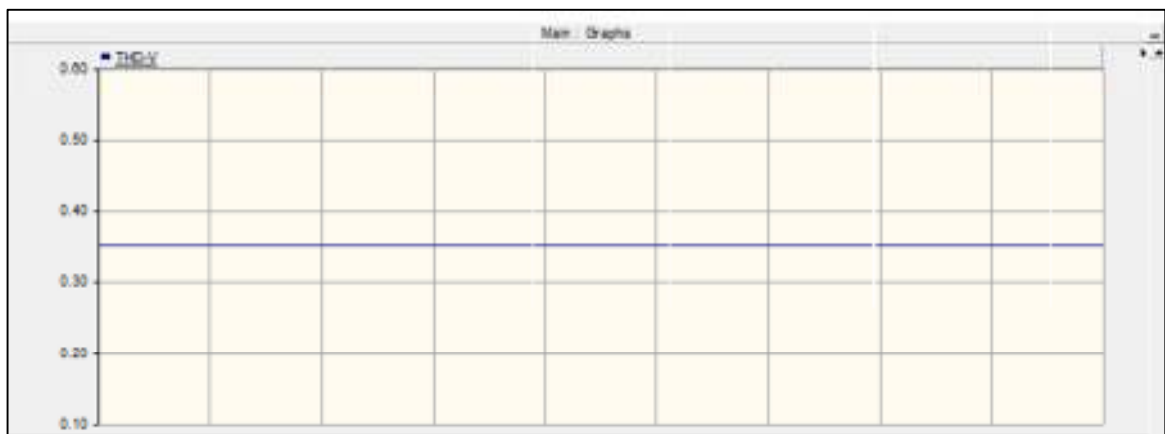


Figure 4.34: THD-V at irradiance, 200 W/m² & cell temperature 28 °C

4.4.4 Simulation results under varying conditions

Simulation was carried out to check the behavior of PSCAD model. Solar radiation was changed during the simulation as 1000-1500-350-1000 W/m². Figure 4.35 shows the simulation results as expected.

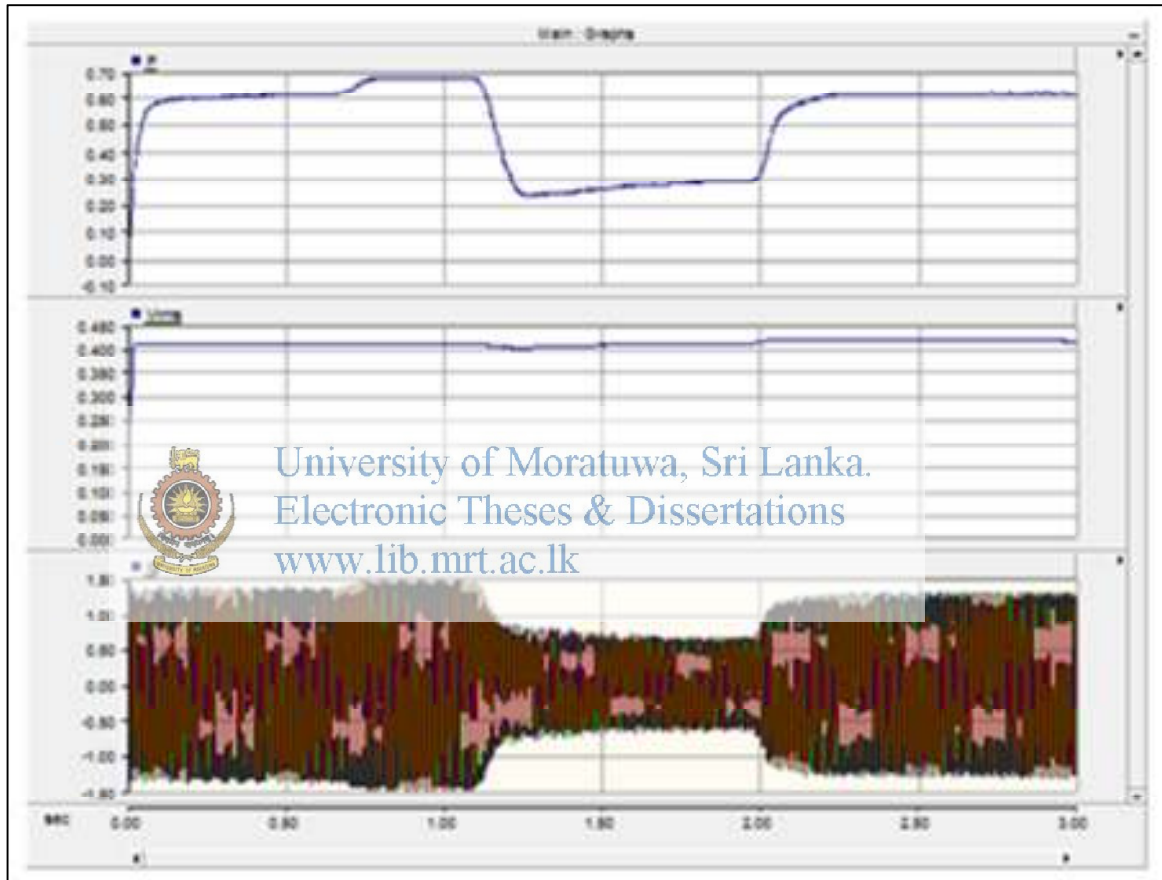


Figure 4.35: Simulation results under varying irradiance

POWER QUALITY ANALYSIS OF PROPOSED SOLAR PLANTS**5.1 Overview**

Three solar power plants, each of 10 MW are proposed to be put up by three private developers at Baruthankanda, near to the existing plants. They are proposed to be connected to the 33 kV bus through 8km Lynx double circuit pole line as shown in Figure



Figure 5.1: Geographical overview of proposed power plants & interconnection

5.2 PV generation system of one 10 MW plant**5.2.1 Single line diagram of the solar power system**

Appendix A shows the single line diagram of one of the proposed solar plant of 10 MW. It mainly consists of following subsystems.

- 11 nos. of PV arrays out of which 10 nos. have 151 module strings connected in parallel where each string has 24 modules connected in series. The other array has 157 module strings connected in parallel. Altogether, there are 1667 modules.
- 11 nos. of power inverters of 750 kW each to which PV arrays are connected.
- There are four LT panels. Three of them have been connected to nine inverters and the other is connected to remaining two.
- There are two three winding step-up transformers 33/0.36/0.36 Dyn11 where each primary winding is connected to one LT panel. Both transformer output will be connected to a 33 kV bus bar and then to grid connection line through a gantry.

5.2.2 PV Array & Inverter characteristics

Technical details (electrical, photovoltaic, and mechanical) of the PV array, PV module and inverters are given in Table 5.1. Some of these data was very important in PSCAD modeling.



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Table 5.1: Characteristics of PV array & inverters

Parameter	Description
PV Array	
Type	Si-mono
Model	ES-250-M60(250) Diamond
Manufacturer	EMMVEE Solar, India
No. of modules in series	24
No. of module strings in parallel	1667
Array global power (at STC)	10002 kWp
Array global power (at operating Cond :)	8979 kWp (50 °C)
Voltage, MPP (at operating Cond :/ 50 C)	653 V
Current, MPP (at operating Cond :/ 50 C)	13749 A

PV Module	
Rated power at STC (1000W/m ² , 25 °C, 1.5 AM)	250 Wp
Module efficiency at STC	15.2 %
Cell efficiency	17.7 %
Open circuit voltage, Voc	36.78 V
Short circuit current, Isc	8.75 A
Rated Voltage, Vmpp	30.06 V
Rated Current, Impp	8.32 A
Temp. coefficient open-circuit voltage	- 0.33% /K
Temp. coefficient short-circuit current	+0.04 %/K
Temp. coefficient rated power	- 0.43% /K
Normal operating cell temperature	48 °C± 2°C
Number of cells & cell type	60, mono crystalline (semi-square, 156*156 mm)
Cell manufacturer	Bosch, Germany
Dimensions	1660 mm * 990 mm
Inverter	
Model	Sunway TG 760 -1000 V MT
Manufacturer	Santerno
Operating voltage	550-820 V
Unit Nom. Power	749 kW AC
No. of inverters	11
Total Power	8239 kW AC

5.2.3 LC filter

The arrangement of harmonics filter connected to the inverter output is shown in Appendix B. It consist of 0.128 μ H series connected inductor & 100*5 μ F capacitor bank.

5.3 PSCAD Model

As far as PSCAD model is concerned, most of the things are similar to what described under Chapter 4 except the changes made due to the design changes of proposed plant. The most important parts of the PSCAD model will be described here under.

5.3.1. PV array

Arrangement of PV arrays was mentioned previously. Accordingly, the configured parameters of one PV array described above, having 151 module strings are shown in Figure 5.2.

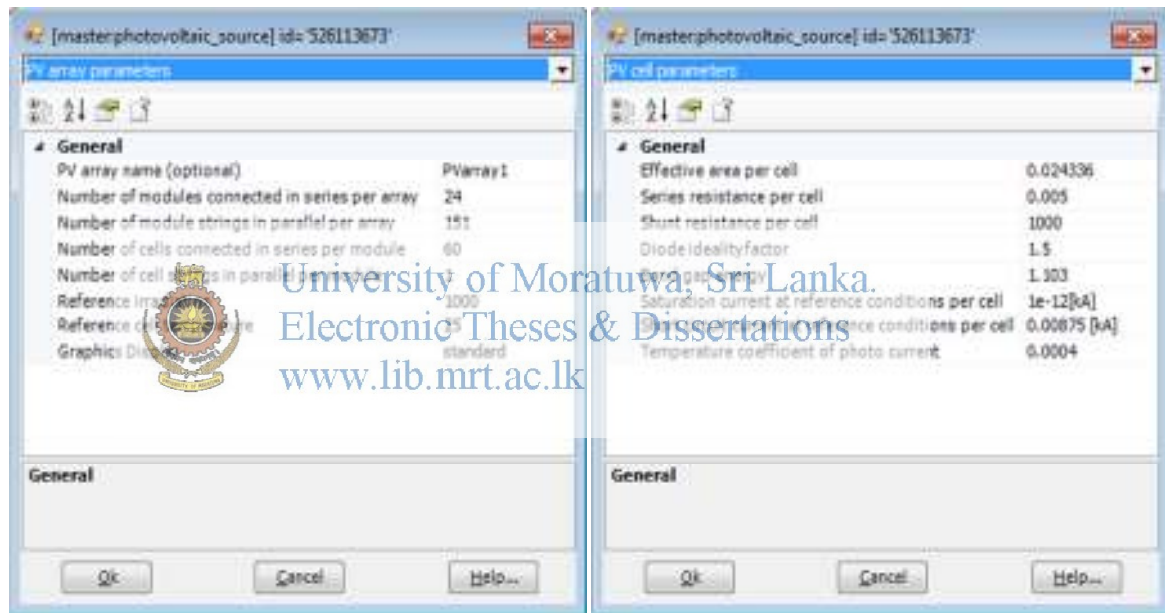


Figure 5.2: Parameters of a PV array configured in PSCAD

5.3.2. LC Filter

PSCAD model for harmonics filter as per the inverter design is shown in Figure 5.3.

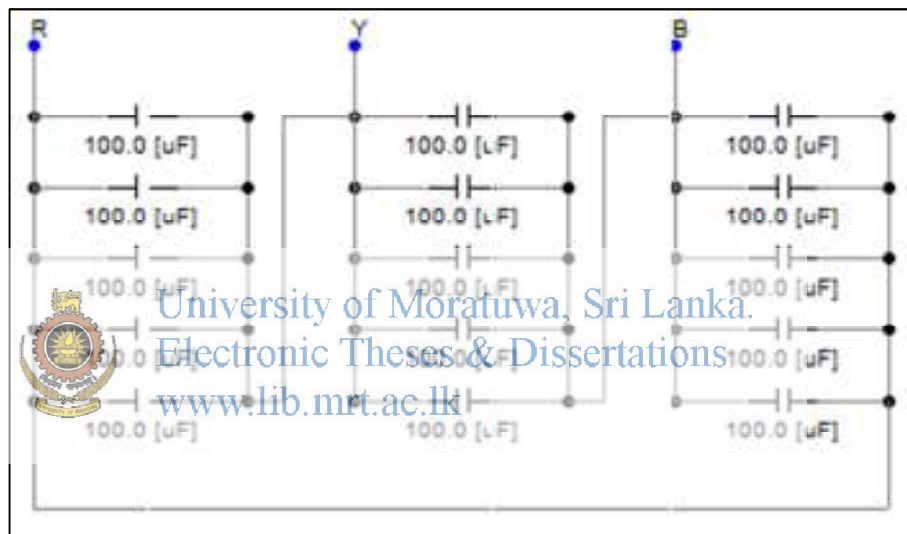
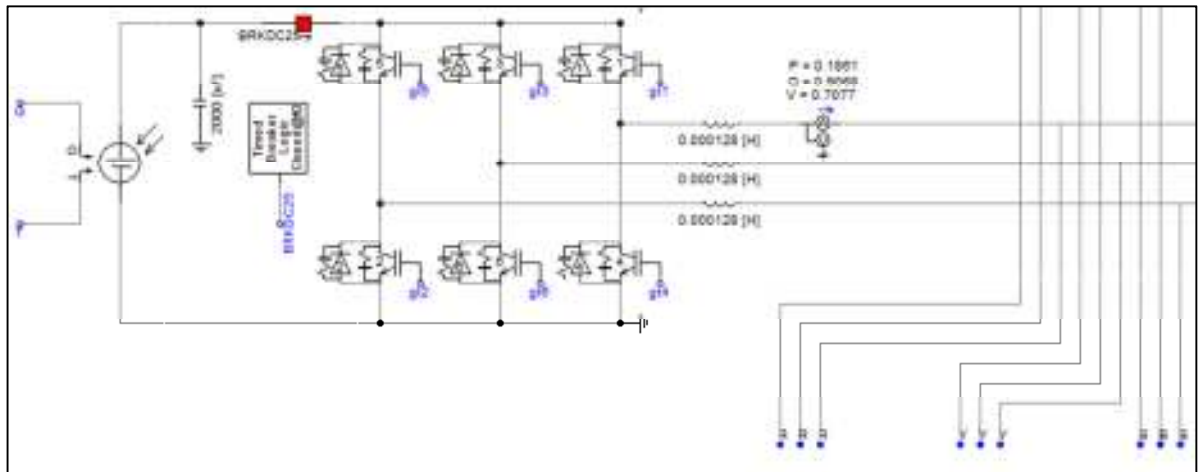


Figure 5.3: Harmonics filter modeled in PSCAD

5.3.3. Three winding step-up transformer

Three winding transformer modeled in PSCAD with the technical parameters is shown in Figure 5.4.

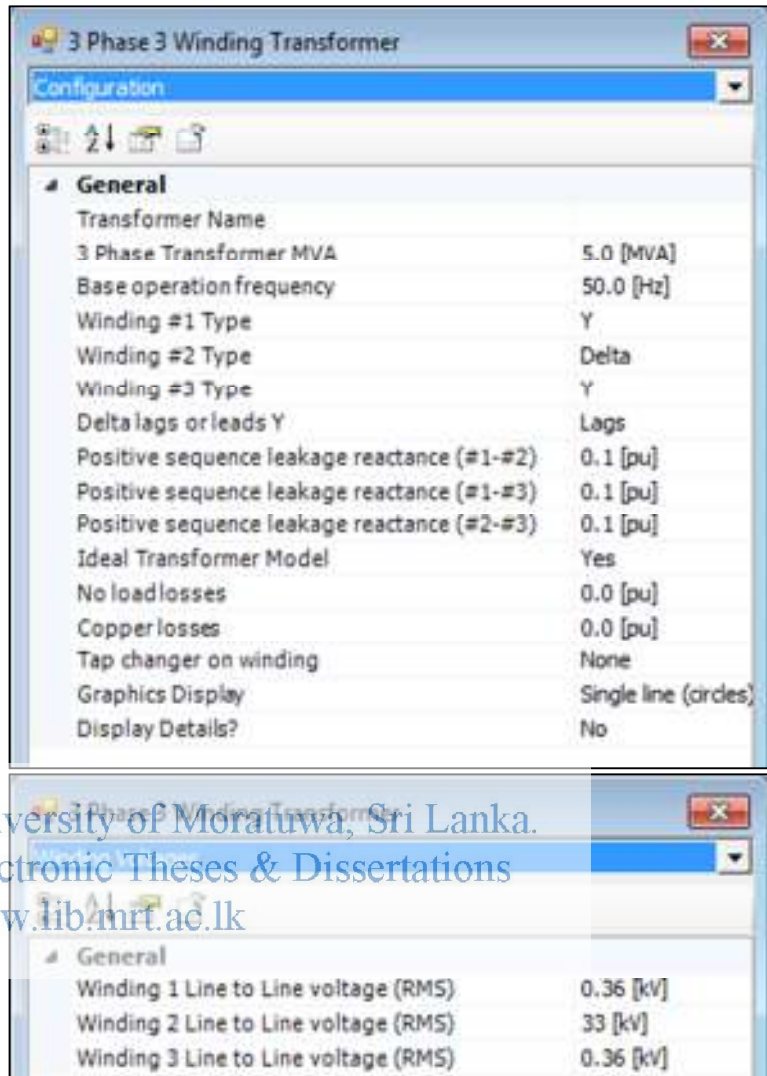
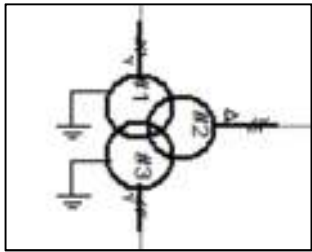


Figure 5.4: Three winding transformer modeled in PSCAD

5.3.4. The equivalent system

The equivalent power system has 33kV Lynx double circuit line, 33 kV bus (point of common coupling) of Hambantota grid substation, P-Q loading at 33 kV bus & upstream source with equivalent impedance as shown in Figure 5.5.

- Calculation of resistance of Lynx line-8km**

Per kilometer resistance of Lynx conductor = 0.177 Ω

Resistance of 8km line = 0.177*8 = 1.416 Ω

- **Calculation of inductance of Lynx line-8km**

Per kilometer reactance of Lynx conductor = 0.319

Reactance of 8km line = $0.319 \times 8 = 2.552$

Inductance = $2.552 / (2 \times 50 \times \pi) = 0.008123 \text{ H}$

- **Calculation of upstream equivalent impedance**

Fault level at 33 kV bus of Hambantota GS = 11 kA

Equivalent Impedance = $33000^2 / (\sqrt{3} \times 33000 \times 11000)$

= 1.732

Angle = 87.6°

Equivalent resistance = $1.732 \times \cos(87.6)$

= 0.072

Equivalent reactance = $1.732 \times \sin(87.6)$

= 1.73

Equivalent inductance = $1.73 \times \sin(87.6)$

= $1.73 / (2 \times 50 \times \pi)$

= 0.0055

- **Calculation of P,Q loading**

Maximum Day peak demand (Active) = 16.1 MW

Maximum Day peak demand (Reactive) = 7.8 MVar at P.F. 0.9

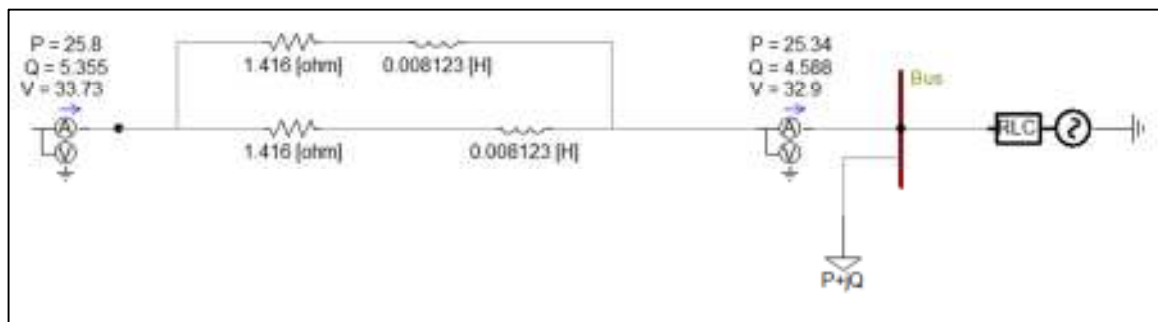


Figure 5.5: The equivalent system

5.4 Simulation Results

5.4.1 Power, Voltage & Current

5.4.1.1 At Solar irradiance, 1000 W/m^2 & Module temperature at 50°C

The RMS line-line voltage & current wave forms given by simulation results are shown in Figure 5.6 as expected. As per the results, power, voltage & current are equal to 24.9 MW, 33.04 kV, and 0.44 kA.

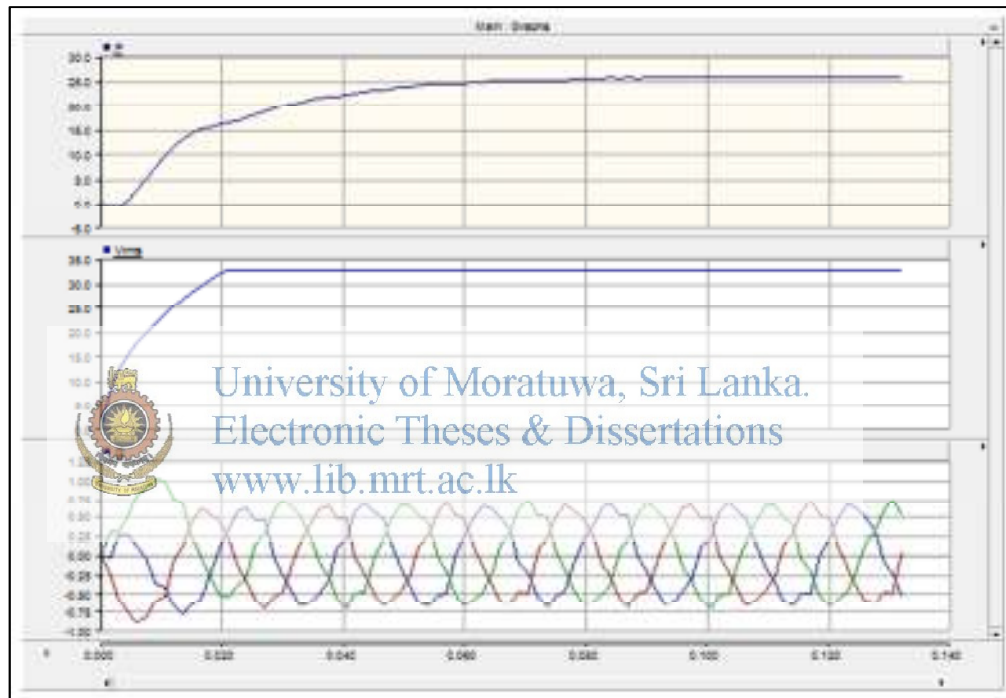


Figure 5.6: Simulation results at 1000 W/m^2

5.4.1.2 Solar irradiance at 200 W/m² & Module temperature at 28 °C

The RMS line-line voltage & current wave forms given by simulation results are shown in Figure 5.7. As per the results, power, voltage & current are equal to 5.6 MW, 32.5 kV, and 0.10 kA.

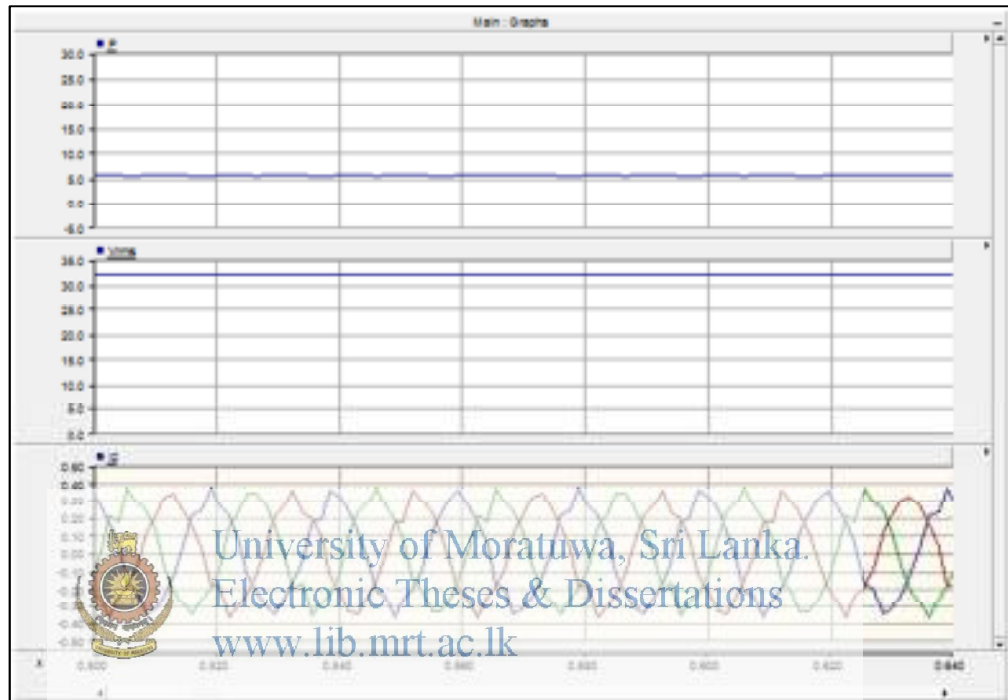


Figure 5.7: Simulation results at 200 W/m²

5.4.2 Current Harmonics

5.4.2.1 Current harmonics at solar radiation, 1000 W/m² & Module temperature at 50 °C

Simulation was carried out at solar radiation, 1000 W/m² & Module temperature at 50 °C, results of which are shown below. Figure 5.8 shows the content of individual current harmonic components where 5th, 7th, 9th, 11th, 3rd harmonics dominate throughout the spectrum. The respective values are 10.02%, 4.95%, 2.1%, 1.2%, and 0.9%. Analysis to check whether they exceed the stipulated limits is described in later section.

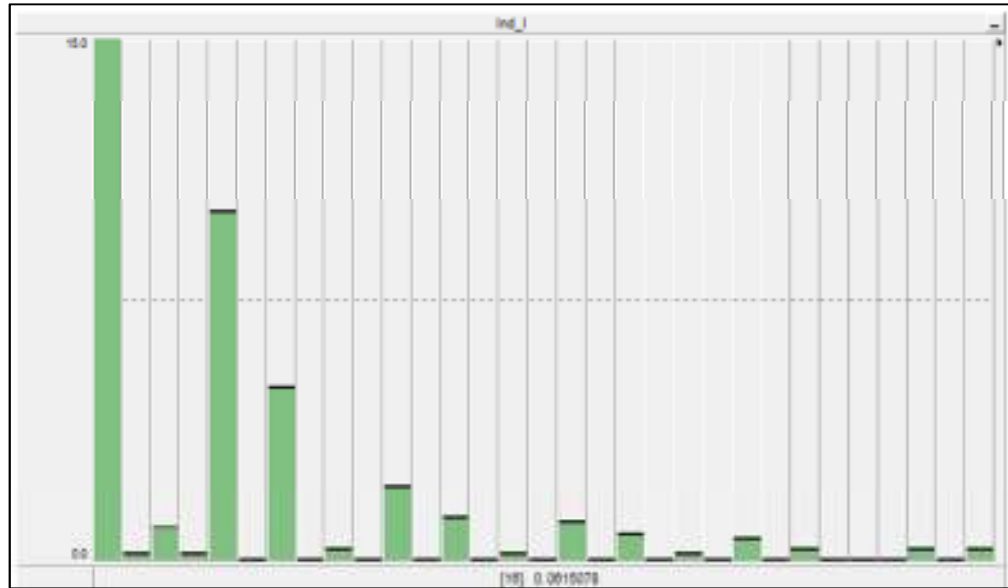


Figure 5.8: Individual harmonics at irradiance, 1000 W/m² & cell temperature 50 °C

Total current harmonic distortion at irradiance level, 1000 W/m² is around 11.6% as per the simulation results shown in Figure 5.9.

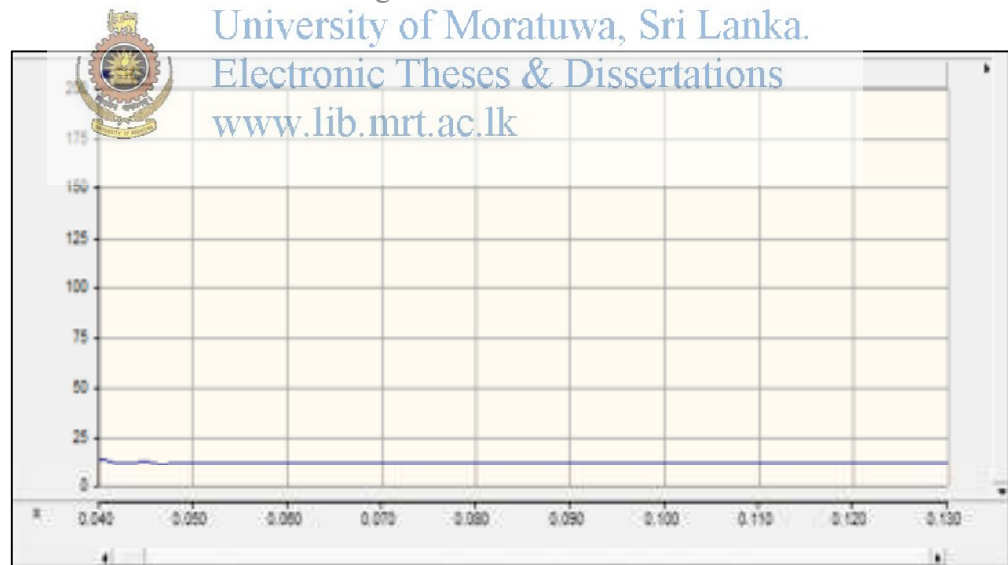


Figure 5.9: THD-A at irradiance, 1000 W/m² & cell temperature 50 °C

5.4.2.2 Current harmonics at solar radiation, 200 W/m² & Module temperature at 28 °C

Figure 5.10 shows the content of individual current harmonic components at low solar irradiance level. 5th, 7th, 11th, 2nd, 13th harmonics have comparatively higher values in descending order as 10.4 %, 6.8%, 2.6%, 1.9%, 1.8% respectively.

Similarly the THD-A under these conditions is around 12.8 % as shown in Figure 5.11.

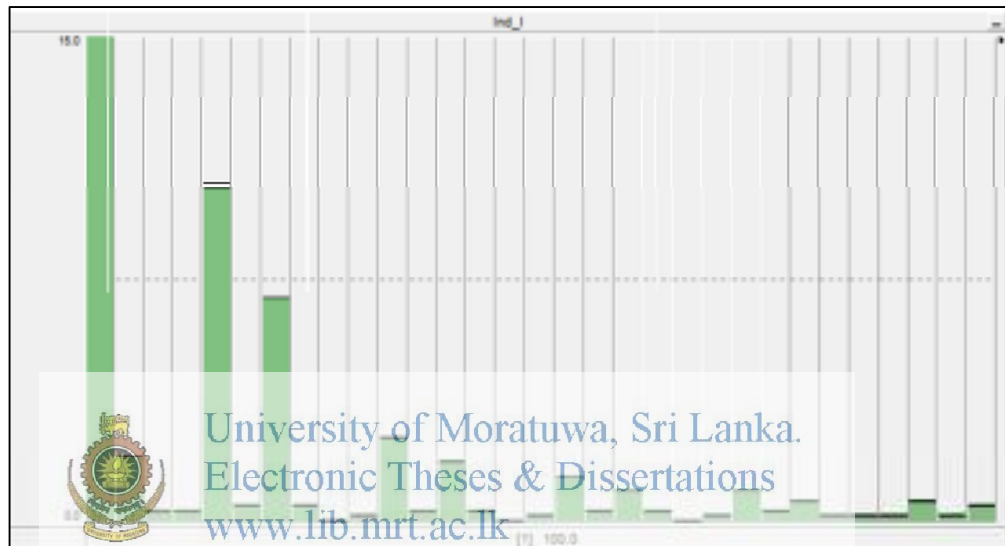


Figure 5.10: Individual harmonics at irradiance, 200 W/m² & cell temperature 28 °C

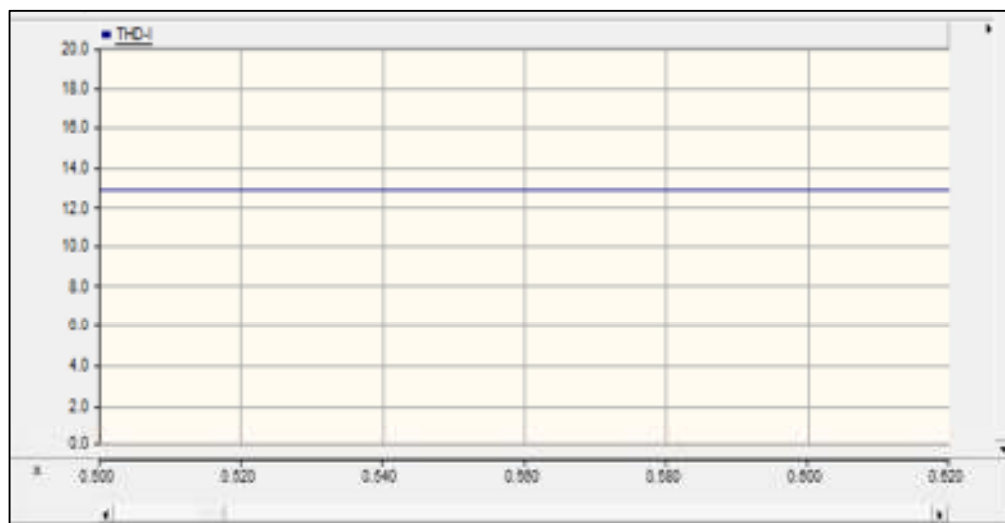


Figure 5.11: THD-A at irradiance, 200 W/m² & cell temperature 28 °C

5.4.3 Voltage Harmonics

5.4.3.1 Voltage harmonics at solar radiation, 1000 W/m^2 & Module temperature at 50°C

Figure 5.12 & Figure 5.13 show the individual voltage harmonics content & THD-V when irradiance is 1000 W/m^2 . This is without the background harmonics. Accordingly, 5th, 7th individual harmonics & THD-V are 2.05%, 1.41% and 2.95 % respectively.

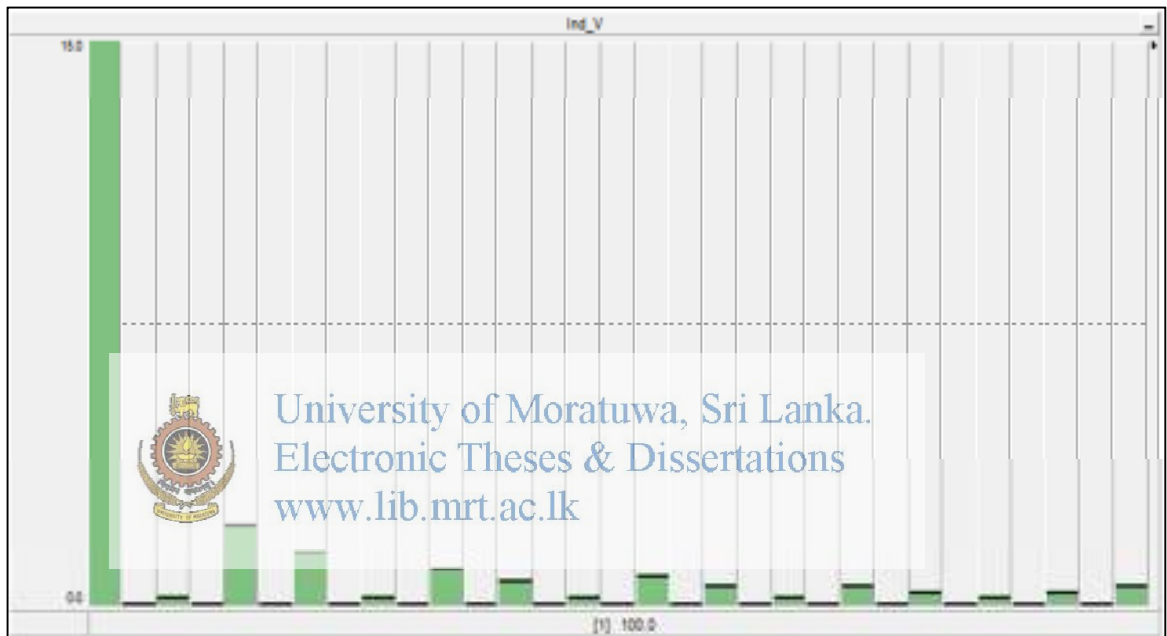


Figure 5.12: Voltage harmonics at irradiance, 1000 W/m^2 & cell temperature 50°C

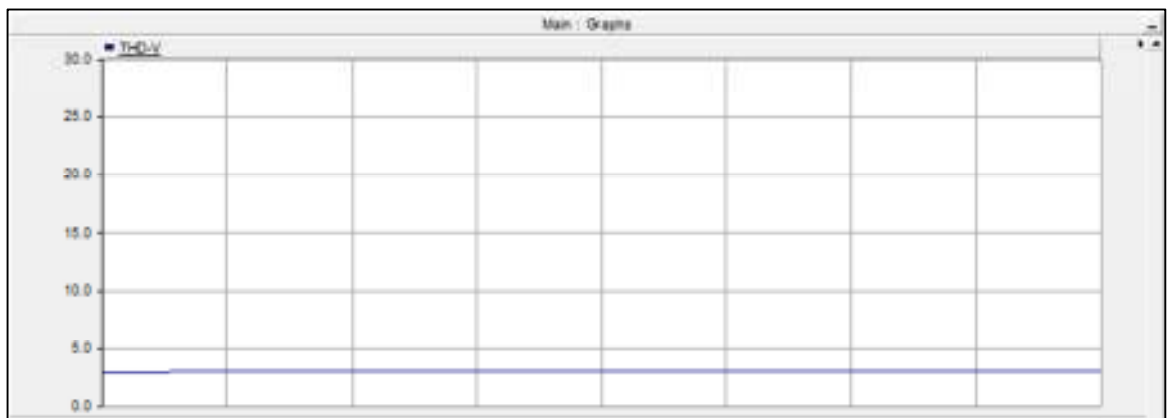


Figure 5.13: THD-V at irradiance, 1000 W/m^2 & cell temperature 50°C

5.4.3.2 Voltage harmonics at solar radiation, 200 W/m² & Module temperature at 28 °C

Figure 5.14 & Figure 5.15 show the individual voltage harmonics content & THD-V when irradiance is 200 W/m². This is without the background harmonics. Accordingly, 5th, 7th individual harmonics & THD-V are 1.0%, 0.9% and 1.7% respectively.

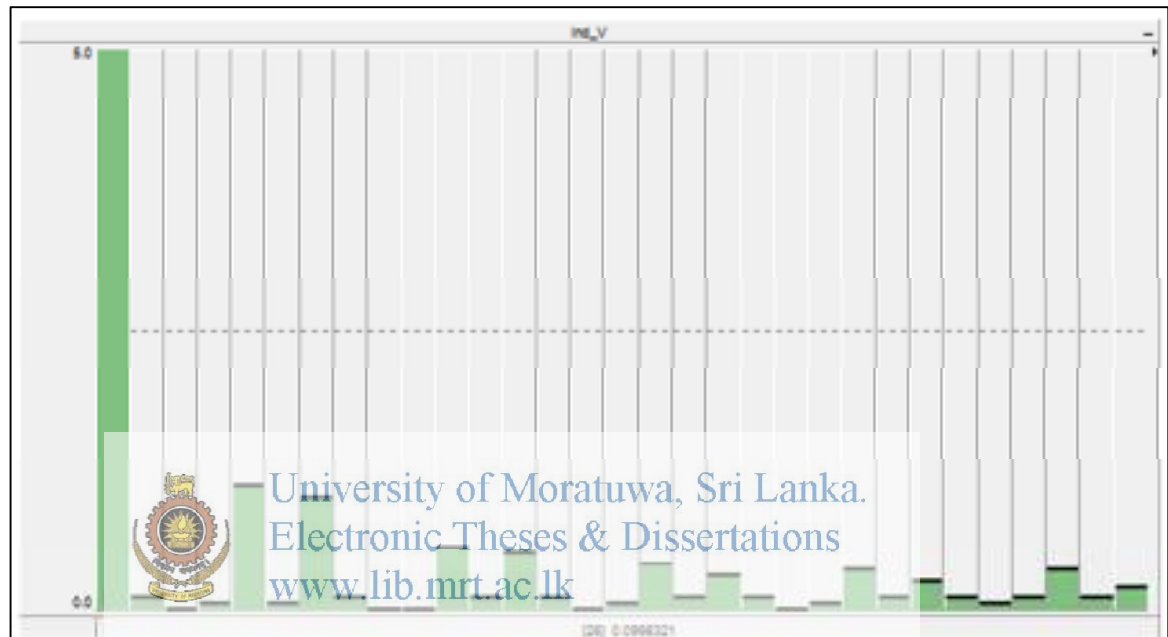


Figure 5.14: Voltage harmonics at irradiance, 200 W/m² & cell temperature 28 °C



Figure 5.15: THD-V at irradiance, 200 W/m² & cell temperature 28°C

5.4.4 Analysis of results on harmonics

5.4.4.1 Voltage Harmonics

As far as voltage harmonics are considered, it was revealed that the THD-V and individual voltage harmonics obtained through the simulations as described above are below the stipulated limits by IEEE 519 after background voltage harmonics of 1.4 % is taken into consideration too. As per the standard, the individual harmonics & THD-V level should be below 3 % and 5% respectively.

The THD-V at high radiation & low radiation is 2.95 % and 1.7 % without background harmonics. With background harmonics (1.4 %), it can be mathematically proved that THD-V is below the 5% limit.

5.4.4.2 Current Harmonics

The THD-A at high radiation & low radiation is 11.6 % and 12.8 %. However, the TDD-A is the parameter that determines the current harmonics impact at the point of common coupling. Hence, the TDD values can be calculated for above two conditions as follows.

- **At high irradiation**

Maximum day peak demand at the PCC	= 16.1 MW
Maximum demand, I_L	= 296 A
Fundamental Current, I_1	= 440 A
TDD-A (%)	= $(\text{THD-A} * I_1) / I_L$
TDD-A (%)	= $11.6 * 440 / 296$
	= 17.24 %

This TDD value exceeds the stipulated 5 % limit.

Similarly, as per the following calculations, 5th and 7th harmonics seems to be over the given limit 4%.

DD-A (%), 5 th order current harmonic	= $10.02 * 440 / 296$
	= 14.9 %

$$\begin{aligned}\text{DD-A (\%)}, 7^{\text{th}} \text{ order current harmonic} &= 4.95 * 440 / 296 \\ &= 7.36 \%\end{aligned}$$

- **At low irradiation**

$$\begin{aligned}\text{Maximum day peak demand at the PCC} &= 16.1 \text{ MW} \\ \text{Maximum demand, } I_L &= 296 \text{ A} \\ \text{Fundamental Current, } I_1 &= 100 \text{ A} \\ \text{TDD-A (\%)} &= (\text{THD-A} * I_1) / I_L \\ \text{TDD-A (\%)} &= 12.8 * 100 / 296 \\ &= 4.32 \%\end{aligned}$$

This TDD value does not exceed the stipulated 5 % limit.

As far as individual harmonics are concerned, it is not required to calculate the current demand distortion levels at low radiation levels because, even the TDD-A does not exceed the given limit.

5.4.5 Voltage Fluctuations at varying irradiation

Simulations were carried out to check whether the system voltage is drastically varying at the point of common coupling under sudden change of solar radiation level. Accordingly, simulation was started at the irradiation level of 1000 W/m^2 & it was suddenly reduced up to 400 W/m^2 . Simulation was kept for short duration until the parameters are stabilized & after that the irradiation was increased up to 1500 W/m^2 by using control bar while simulation is in progress. Simulation results are shown in Figure 5.16 & zoomed version of same is shown in Figure 5.17.

For easy comparison, the corresponding values are given with percentage variation as well.

As per the given results, it is clearly understood that the voltage fluctuation is not much significant (below 1.5% of nominal value of 33 kV) under varying solar radiation level & lies within the stipulated limits (31kV-35kV).

Table 5.2: Variation of voltage at PCC under varying irradiation

Irradiation Parameter	1000 W/m ²		400 W/m ²		1500 W/m ²	
	Value	Variation (%)	Value	Variation (%)	Value	Variation (%)
Voltage	33.043 kV	0.13	33.005kV	0.015	33.047kV	0.14
Power	24.9 MW	-	12.8 MW	-	26.0 MW	-

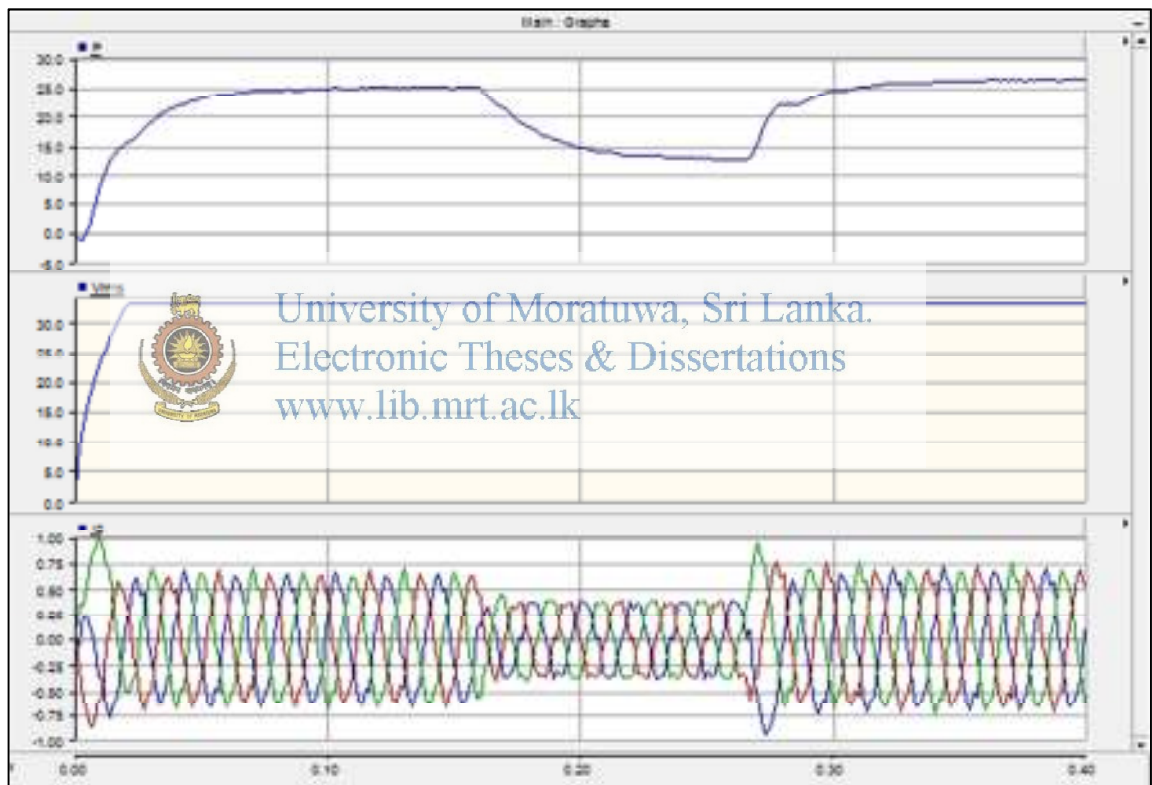
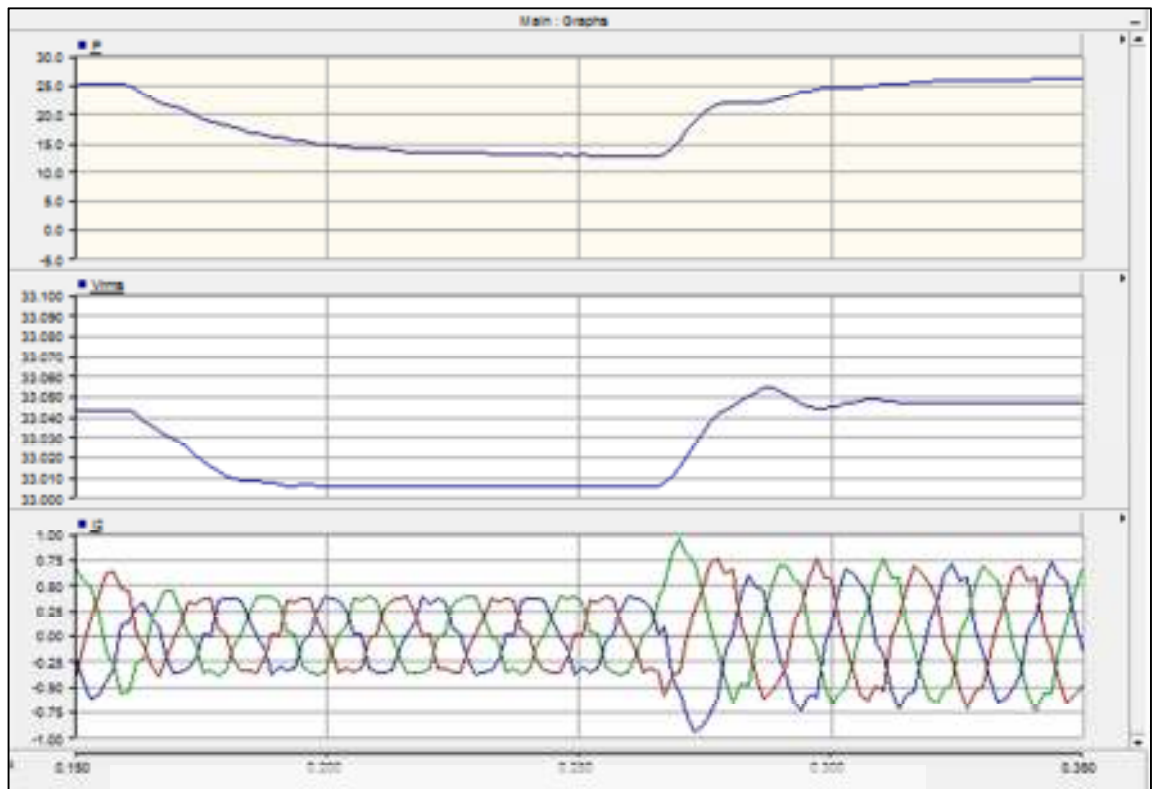


Figure 5.16: Voltage fluctuations under varying irradiation



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CONCLUSIONS AND RECOMMENDATIONS**6.1 Conclusions**

This study could set a platform for new area to be focused in renewable energy sources based grid interconnections, especially solar plants. In Sri Lanka, the experience of medium scale solar plants is less. But there is a positive trend. Therefore, this research is very much valuable for future applications like solar parks proposed in Sri Lanka. Since most of the areas are electrified, the quality of the power supply is one of the vital factors to be considered in future as a utility. So, this research would give kind of initiation in this particular area (embedded generator interconnections).

As far as the results obtained through this analysis are concerned, several important conclusions can be made.

- Solar power plants produce current and voltage harmonics.
- Current harmonics injected to the power system varies with the solar radiation level and system design like no. of inverters, filter design, switching frequency...etc.
- Current harmonics injected by existing plants and proposed plants at the point of common coupling violates the stipulated limits under high solar radiation.
- PSCAD is very user friendly software for modeling this kind of applications and simulating to have more precise results.
- It is required to take appropriate measures to mitigate the harmonics so that the other consumers are not affected.
- This can be considered as a routine practice when preparing future solar plant grid interconnections.
- This can also be used to determine the suitable point of common coupling for grid interconnections.

6.2 Recommendations

The study reveals that the proposed solar power plants will not create any significant effect on voltage distortions in steady operating conditions but the injection of current harmonics are beyond the stipulated limits. Voltage fluctuations at different locations in the system due to random variations in the irradiance level and its effect on the system stability need to be checked up with appropriate simulation runs.

Although the THD-V is not yet violated, the situation could drastically change if more solar plants come in to operation with the concept of “solar park” and this could also be checked with appropriate modifications to the present model. In such an eventuality it would be required to take suitable mitigation measures such as centrally operated filters or dedicated grid substation which could also be investigated using the model.



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