

**MANAGING THE RESOURCE INTERMITTENCY TO  
MAXIMIZE THE SOLAR PHOTOVOLTAIC  
PENETRATION**

Madhurika Priyabhashini Palatuwa

(139576T)

Thesis submitted in partial fulfillment of the requirements for the degree Master of  
Science

Department of Electrical Engineering

University of Moratuwa

Sri Lanka

April 2018

## **DECLARATION OF THE CANDIDATE AND SUPERVISORS**

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and person except where the acknowledgement is made in the text.

Also, I hereby grant to University of Moratuwa the non-exclusive right to reproduce and distribute my thesis, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books).

Signature:

Date: 19<sup>th</sup> April, 2018

The above candidate has carried out research for the Masters thesis under my supervision.

Signature of the supervisor:

Date: 19<sup>th</sup> April, 2018

(Dr. Asanka S. Rodrigo)

## ABSTRACT

Sri Lanka as a developing country is in its way for a green environment with energy security. Sri Lanka has already agreed to reduce 20% of the greenhouse gases through the signed agreement COP21 of the United Nations Environmental Framework Convention on Climate Changes (UNFCCC).

The solar resource is the most commonly available renewable energy source in Sri Lanka. Therefore Sri Lankan government set its target to install 1000MW solar photovoltaic rooftop systems by 2020 from launching the programme called “Battle for Solar Energy”. The number of solar rooftop installations increased rapidly with the launch of this programme and at present the total rooftop installation capacity is more than 100 MW.

The intermittency behavior is the main obstacle associated with solar photovoltaic energy generation. The utility (Ceylon Electricity Board (CEB)) has to maintain thermal power plants running as spinning reserves to overcome the effect of intermittent nature of solar photovoltaic power plants. This research titled as “MANAGING THE RESOURCE INTERMITTENCY TO MAXIMIZE THE SOLAR PHOTOVOLTAIC PENETRATION” was carried out to find out a way for maximizing solar photovoltaic penetration. Two models were developed using Matlab Simulink to study the behavior of solar power plants integrated to the power distribution system. One is a centralized PV system and the other is a system of small PV plants geographically scattered and connected over a low voltage distribution feeder. The cumulative capacity of the scattered system is similar to the capacity of the centralized system.

The measurements of the simulations reveal that, more solar photovoltaic capacity can be connected to the distribution system while meeting the grid code requirements when the solar PV systems are geographically scattered.

## ACKNOWLEDGEMENTS

First and foremost I offer my sincerest gratitude to my supervisor, Dr. Asanka Rodrigo, who has supported me throughout my thesis with his patience and knowledge whilst allowing me to work in my own way. His remarkable guidance helped me throughout the research.

Special thanks goes to all the lecturers engaged in the MSc course sessions and research sessions for making our vision broader, providing us with the opportunity to improve our knowledge in various fields.

It is a great pleasure to remember the kind cooperation of all my superiors at my work place, my colleagues and my friends who have helped me throughout this Post Graduate programme.

Finally, I would like to thank my parents for supporting me throughout my life. Last but not least I would like to thank my husband for always motivating and supporting me throughout this research work.

# CONTENTS

DECLARATION OF THE CANDIDATE AND SUPERVISORS .....	i
ABSTRACT .....	ii
ACKNOWLEDGEMENTS .....	iii
TABLE OF FIGURES .....	vi
LIST OF TABLES .....	viii
ABBREVIATIONS .....	viii
1. INTRODUCTION .....	1
1.1 Background .....	1
1.2 Objective .....	4
1.3 Problem Statement .....	5
1.4 Motivation .....	5
1.5 Scope of Work .....	6
2. SOLAR PHOTOVOLTAIC .....	7
2.1 Solar Resource Variation due to Geographical Situation .....	7
2.2 Solar Resource Map of Sri Lanka .....	8
2.3 Solar Photovoltaic Technology .....	9
2.4 Conversion of DC power into AC power (Inverter) .....	11
2.5 Maximum Power Point Tracking .....	12
2.6 World Statistic of Solar PV .....	13
2.7 Solar PV growth in Sri Lanka .....	16
2.8 Irradiance Curve .....	17
2.9 Applicable standards for connecting solar PV to the grid .....	17
2.9.1 Voltage Fluctuations .....	19
2.9.2 Power factor variation capability .....	19
2.9.3 Voltage variation capability .....	19
2.9.4 Harmonic .....	20
2.9.5 Islanding Protections .....	20
3. DATA ANALYSIS .....	21
3.1 Analysis – 1 .....	21

3.2	Data Analysis Results - 1 .....	25
3.3	Analysis – 2.....	25
3.4	Data Analysis Results -2.....	26
4.	MATLAB MODEL.....	28
4.1	Utility Grid .....	28
4.2	Distribution Transformer Model .....	29
4.3	Distribution Line Model.....	30
4.4	Load model.....	30
4.5	Inverter model .....	31
4.6	Solar PV model.....	33
4.7	Irradiance curve model .....	34
4.8	Centralized solar PV system model.....	35
4.9	Scattered solar PV system model .....	37
4.10	Compensation with battery bank .....	39
5.	RESULTS.....	40
5.1	Centralized Solar PV System .....	40
5.2	Scattered Solar PV System.....	44
5.3	Centralized Solar PV System Compensated with Battery .....	49
5.4	Sensitivity Analysis .....	49
6.	DISCUSSION AND CONCLUSION.....	51
5.1	Discussion .....	51
5.2	Conclusion.....	52
5.3	Recommendation .....	52
	REFERENCES .....	53

## TABLE OF FIGURES

Figure 1: Growth of Solar Rooftop Systems .....	2
Figure 2 : Irradiance Variation throughout a Day .....	5
Figure 3 : Solar Resource Map of Sri Lanka (GHI) .....	8
Figure 4: Photovoltaic Effect .....	9
Figure 5: Solar PV System.....	9
Figure 6: Mono Crystalline Cells .....	10
Figure 7: Poly Crystalline Cell.....	10
Figure 8 : Thin Film Cells .....	11
Figure 9: Circuit Diagram of a Grid-tie Solar Inverter.....	12
Figure 10 : MPPT of I-V Curve.....	13
Figure 11: Global PV Market.....	13
Figure 12: Cumulative PV Installation Forecast .....	14
Figure 13: Power Generation Costs and Forecast .....	15
Figure 14: Cost Forecast for Solar PV Systems and Wind Turbines .....	15
Figure 15: PV System Price Forecast .....	16
Figure 16: Growth of the Installed Capacity of Solar PV in Sri Lanka.....	16
Figure 17 : Irradiance Curve of a Day .....	17
Figure 18: Data Collected Locations .....	21
Figure 19: Irradiance Curve in Hambantota.....	22
Figure 20: Irradiance Curve in Kilinochchi .....	22
Figure 21: Irradiance Curve in Balangoda .....	23
Figure 22: Irradiance Curve in Kalamatiya.....	23
Figure 23: Irradiance Curve in Seetha Eliya .....	24
Figure 24: Irradiance Curve in Sooriyakanda .....	24
Figure 25: Average Irradiance Curve .....	25
Figure 26: Power Curves of 10 Locations.....	26
Figure 27: Aggregated Power Curve .....	27
Figure 28: 50.08 kWp Solar System at location no 10 .....	27
Figure 29: Utility Grid Model .....	29

Figure 30: Distribution transformer model .....	29
Figure 31: Model of low voltage line .....	30
Figure 32: Load model.....	31
Figure 33: Load curve of the solar PV system owner.....	31
Figure 34: Inverter model and arrangement .....	32
Figure 35: Boost converter model .....	32
Figure 36: P-V and I-V curves .....	33
Figure 37: MPPT Simulink block.....	34
Figure 38: Signal builder block .....	34
Figure 39: Irradiance and Temperature Curves.....	34
Figure 40: Block diagram of the centralized solar PV system.....	35
Figure 41: Centralized PV system model.....	36
Figure 42: Scattered solar PV system .....	37
Figure 43: Scattered PV System Model.....	38
Figure 44: Battery system .....	39
Figure 45: Centralized System .....	40
Figure 46: Irradiance Curve on 01_10_2017 .....	41
Figure 47: Irradiance Curve on 01_08_2017 .....	41
Figure 48: Irradiance Curve on 01_06_2017 .....	42
Figure 49: Irradiance curve on 01_03_2017 .....	43
Figure 50 : Irradiance Curves .....	44
Figure 51: Scattered System.....	45
Figure 52: Irradiance curves on 01_10_2017.....	46
Figure 53: Vrms Variation with location .....	47



## LIST OF TABLES

Table 1: Parameter values according to the CEB guidelines .....	18
Table 2 : Maximum allowable grid utility parameters.....	18
Table 3 : Allowable limits of the system voltages.....	19
Table 4 : Harmonic limits.....	20
Table 5 : Utility grid modelling details .....	29
Table 6: Measurements of Centralized System on 01_10_2017 .....	41
Table 7: Measurements of Scattered system on 01_08_2017 .....	42
Table 8: Measurements of Centralized System on 01_06_2017 .....	43
Table 9: Measurements of Centralized System on 01_03_2017 .....	43
Table 10: Measurements of Scattered System .....	46
Table 11: Measurements of Scattered System .....	47
Table 12: Measurements of Scattered System .....	48
Table 13: Measurements of Scattered System .....	48
Table 14: Measurements of the centralized system with battery .....	49
Table 15: Measurements of Centralized System on 01_10_2017 .....	50
Table 16: Measurements of Scattered System on 01_10_2017 .....	50

## ABBREVIATIONS

PV	: Photovoltaic
DC	: Direct Current
AC	: Alternating Current
CEB	: Ceylon Electricity Board

### INTRODUCTION

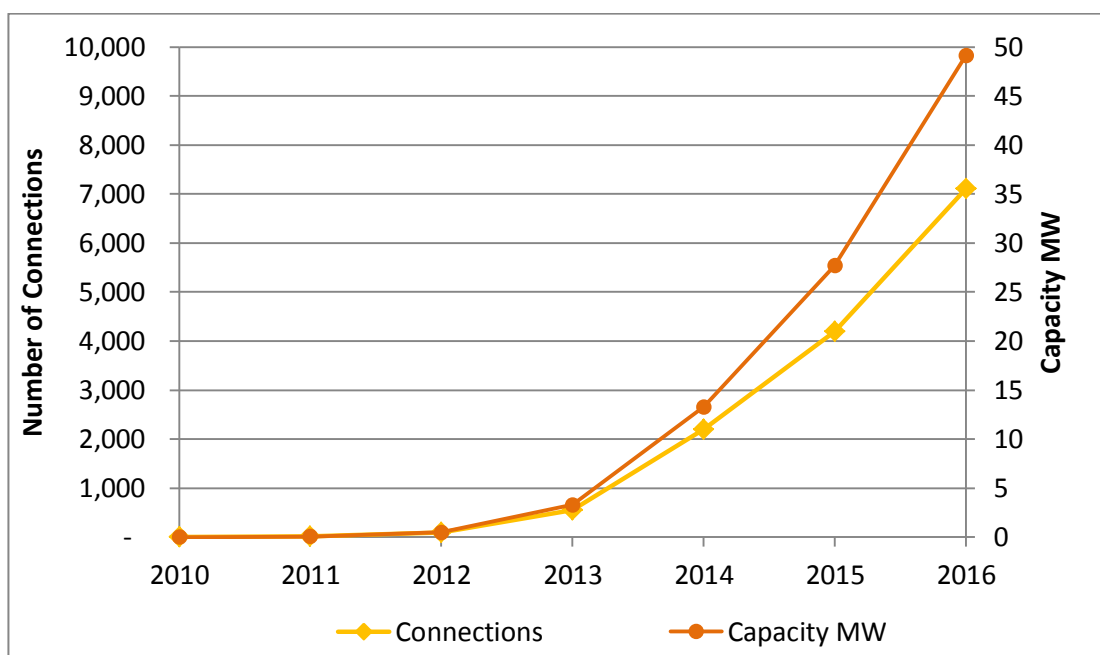
#### 1.1 Background

Sri Lanka is a country which blessed with plenty of sun light throughout the year due to its geographical location. With the world trend to convert the concrete world to a green world, most of the countries have stepped a way forward on renewable energy. Solar, wind, mini hydro and bio mass are the key renewable energy resources available in Sri Lanka. Mini hydro is in its edge of plant implementations. Solar is the most commonly usable energy resource in Sri Lanka.

Harnessing of solar energy in Sri Lanka mainly for converting to electricity have been practiced in last two three decades with the degradation of fossil fuel and heavy burden on the national economy due to importing fossil fuel. During early 1980's there had been some attempts to introduce solar PV technology to Sri Lanka, for water pumping applications and rural lighting applications. Some of these installations were able to introduce the solar PV technology to Sri Lanka's knowledge base. A leading example of this effort is the Prashakthi Pahan lighting solution offered by the National Engineering Research & Development (NERD) Centre. It managed to provide the basic lighting needs of rural communities by employing a small PV panel, a charge controller, lead acid battery and a DC fluorescent lamp.

Then the World Bank had launched a project in mid 1990's aiming at promoting renewable energy with the title Energy Serviced Delivery (ESD) Project, which played a major role in providing the basic energy needs of thousands of rural homes, which were away from the national grid at the time. At the time of conceptualization of ESD project, the level of grid electrification stood below 50%.

Based on the success of the ESD Project, a follow up project titled Renewable Energy for Rural Economic Development (RERED) had been launched. At the conclusion of this project, there were approximately 130,000 homes using solar PV for their basic electricity needs. The role for off-grid electrification quickly diminished with the advent of the national grid under the rapid grid expansion projects undertaken by the Government. Many off-grid systems went abandon in this period. The Government responded this situation by introducing net metering concept for solar roof top installations in 2010. The concept moved slowly but reached 50 MW in capacity at the end of year 2016.



**Figure 1: Growth of Solar Rooftop Systems**

Parallel to the introduction of rooftop net-metering concept, a pilot project which granted by Korean International Corporation Agency (KOICA) had been deployed in Hambantota with a capacity of 500 kW since 2011. Another plant was also built under a Japanese grant, adding 737kW to the national grid in 2012 nearby the first plant. The first commercial scale plant with 10MW capacity had been implemented and commissioned in December 2016.

Sri Lankan government has introduced “Battle for Solar Energy” Programme for upgrading the net metering interconnection of solar photovoltaic rooftop systems to another two new schemes in September 2016. Then there are three schemes for solar PV interconnecting to the national grid. They are,

- Net Metering Scheme

Excess energy of the generation is forwarded to the national grid which consuming from grid while the solar PV generation is not enough. The energy credit is forwarded up to 10 years.

- Net Accounting Scheme

A payment is done for the excess energy which forwarded to the grid.

- Net Plus Scheme

This scheme is similar to a micro scale power plant on the rooftop. Normal utility supply remains as it is and separate meter is there for exporting to the generated energy to the grid.

People thought of developing solar PV system on his rooftop in order to obtain an additional income from the solar PV generation with the introduction of above two schemes. A rapid spreading of solar PV industry was shown in year 2017 and almost 300 solar PV suppliers have been initiated installing solar PV systems. This development is not totally because of the implementation of above additional two schemes, but it is due to reduction of solar PV price throughout past three years.

The total capacity of the installed solar rooftop systems under those three schemes is more than 100 MW in the end of year 2017. Ground mounted solar PV capacity addition is 51.36 MW from 8 installations. According to the target level of adding the solar PV to the national grid through mega scale projects such as 100 MW solar parks are also in proposal stage at this moment (end of year 2017). The target level of interconnecting rooftop solar PV to the national grid is 1000MW by year 2020. Although a plenty of resource available in Sri Lanka with its location near equator, the fluctuations in sun light can severely cause on the generation of solar PV.

The cloud coverage, diffuse effect can severely effect on the irradiance level. A cloud movement can reduce the irradiance level rapidly to its minimum. The cloud passing out of the location can increase the irradiance level again to its maximum within few seconds. Therefore the total capacity installed would not be able to generate its 50% of capable energy generation at specific time. But in next minute the generation can be increased up to 100% of its capable energy generation.

Therefore it seems that the solar PV is the most emerging energy resource in Sri Lanka which can significantly effect on our national grid due to its intermittency behavior [1][7].

## **1.2 Objective**

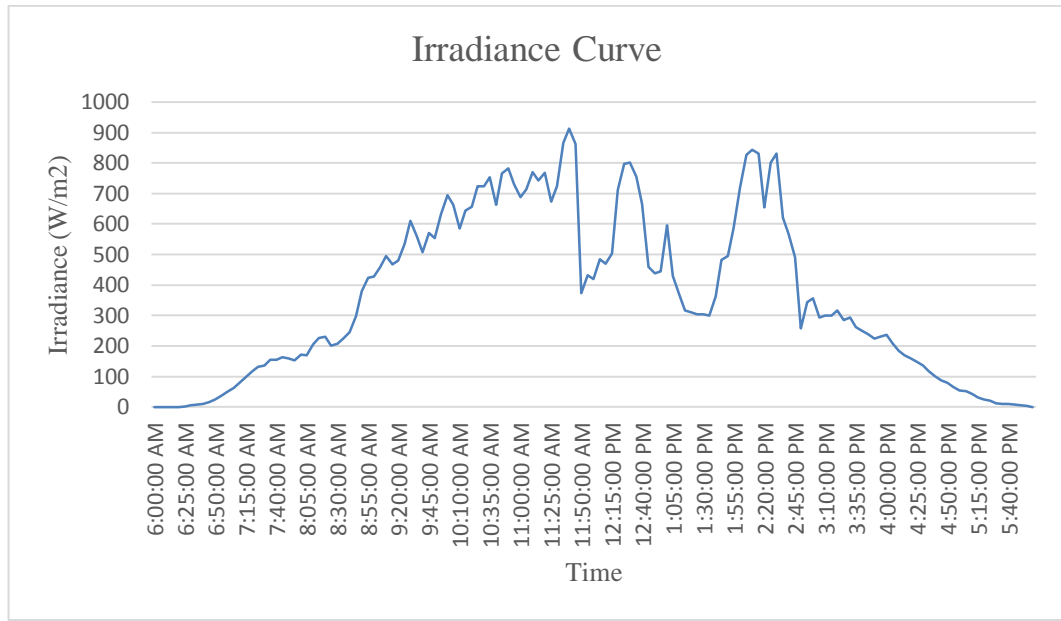
In Sri Lanka there are approximately nine thousand solar rooftop PV connections in households and industries. Total capacity is 100MW. Mega scale systems which is below 10 MW as ground mounted systems are only eight connections. Total capacity is 51.36MW. Solar rooftop systems are small in capacity compared to ground mounted solar PV systems. Therefore set of rooftop systems can be called as scattered solar PV system and the ground mounted large capacity solar PV system can be called as centralized PV system.

The main objective of this research is to study the effect of different PV systems which are, centralized PV plant and geographically scattered PV plants on the distribution network. Under this study;

- Aggregate effect of solar intermittency is studies,
- Effect of different solar PV systems to the system RMS voltage and the power factor will be studied using the MATLAB Simulink models,
- Effect of different capacity of PV systems such as 160kWp, 80kWp and 40kWp to the distribution network is studied.

### 1.3 Problem Statement

It is difficult to convert the full amount of irradiance to electrical energy because of the intermittency behavior of solar resource. The following graph shows the variation of the irradiance level from 6.00 am to 6.00 pm on January 01, 2017 at Dehiwala-Mount Lavinia area.



**Figure 2 : Irradiance Variation throughout a Day**

The energy conversion into electrical energy varies proportionally to the irradiance level. This behavior with fluctuations of energy generation effects on the power system stability [8]. At present it is a small amount compared to the total demand of the country, but with the commissioning of new solar photovoltaic farms, it will severely effect on the power system stability.

### 1.4 Motivation

The target level of the programme “Battle for Solar Energy” is connecting 1000MW solar rooftop systems in the year 2025. At present it is only 100MW from solar rooftop systems. The government has proposed to install mega scale solar PV parks (four 100MW solar PV plants) at present. The interconnection of 900MW of solar

rooftop PV in coming eight years and 400MW solar PV parks will create significant issues on the stability of the power system of Sri Lanka. This situation highly motivated me to initiate this research, “Managing the Resource Intermittency to Maximize the Solar Photovoltaic Penetration”.

### **1.5 Scope of Work**

Scope of work is as follows.

- Studying the literatures on the same research area.
- Collecting irradiance data on solar measuring stations of Sri Lanka.
- Analyzing the data separately and aggregated value.
- Collecting generation data of solar rooftop systems situated in close proximity to each other.
- Analyzing the above data separately and the aggregated value.
- Modeling the centralized solar PV system in Matlab Simulink.
- Modeling the scattered solar PV system in Matlab Simulink.
- Changing the solar PV capacities similar to 100%, 50% and 25% of maximum contract demand.
- Taking measurements of two solar PV system types for three solar PV capacities.
- Analyzing the effect of the use of a battery bank.
- Compare and analyze the measurements

**2.1 Solar Resource Variation due to Geographical Situation**

Solar energy undergoes rapid changes when the solar rays travel through the atmosphere. This is mainly due to the reflection, absorption and scattering of solar radiation by particulate and gaseous elements in the atmosphere. Depending on the presence or the absence of such atmospheric substances, the uniform spectrum of solar energy incident at the outer edge of the atmosphere can show a wide variation of intensity at ground level. Due to these interceptions, the solar radiation, incident purely as direct radiation at the outer atmosphere become a two component radiation direct radiation and diffuse radiation. On a rainy day, a major component of the solar radiation is reflected back by the clouds and another significant component is absorbed and a further component is retransmitted to earth as diffuse radiation.

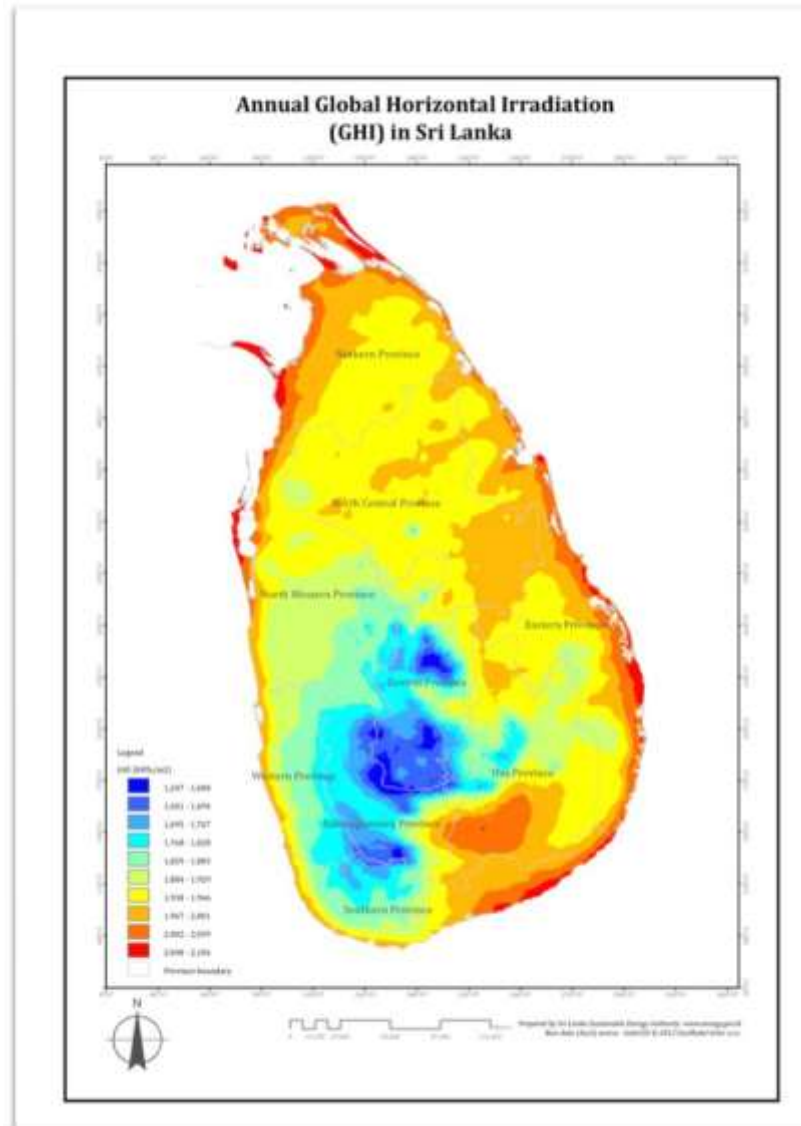
Apart from the particles in the atmosphere, the distances through which the solar rays have to travel plays an important role in determining the amount of radiation incident at the surface of the earth. Accordingly on a sunny day, the radiation incident at near sun rise and sunset is remarkably lower than the radiation incident at solar noon. This is due to the depth of atmosphere through which the radiation propagated differs considerably.

Sri Lanka, being a country which experience two monsoonal wind regimes is subjected to four distinct periods (two pre-monsoon and two post-monsoon) of fast moving cloud formations, which causes a lot of variability to the solar radiation incident at the earth's surface. This could be a concern for solar energy practitioners who are struggling to develop direct solar to electrical energy conversion systems concentrated in a certain geographical location.



## 2.2 Solar Resource Map of Sri Lanka

Sri Lanka receives significant amount of solar radiation across all geographical regions. Following figure depicts the spatial distribution of Global Horizontal Irradiation (GHI) in Sri Lanka. The intensity of solar irradiation in low land areas is high compared to mountainous regions. This is largely due to the continuous presence of clouds in mountainous areas and shadowing effect of mountains.



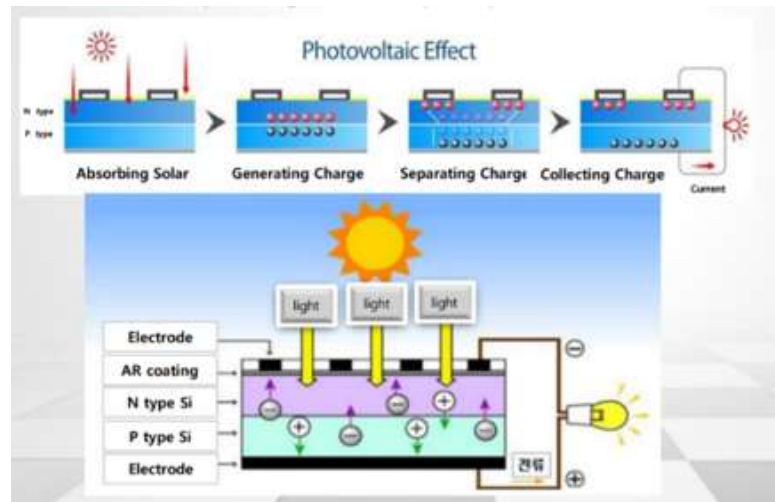
**Figure 3 : Solar Resource Map of Sri Lanka (GHI)**

[4] Solar Atlas of Sri Lanka

Sri Lanka Sustainable Energy Authority

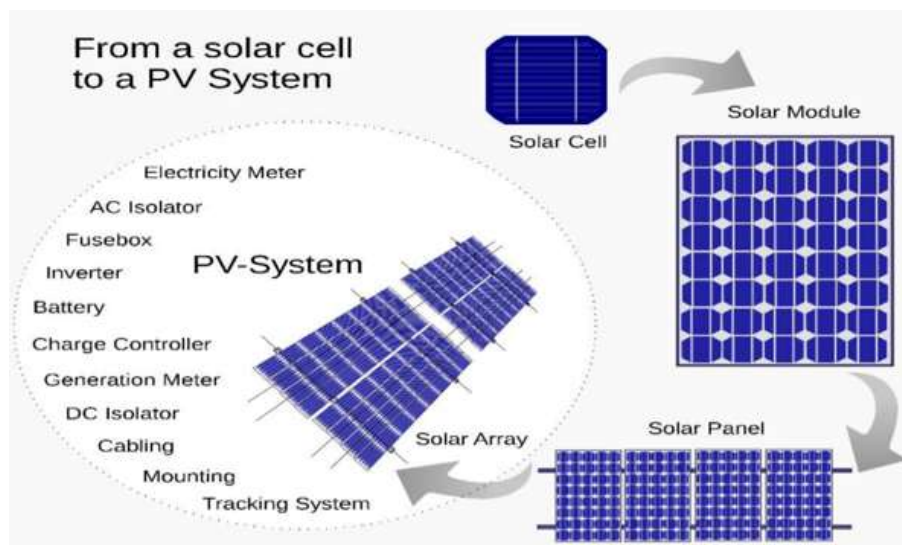
### 2.3 Solar Photovoltaic Technology

Solar photovoltaic cells absorb light energy from the sun and convert it into electrical energy.



**Figure 4: Photovoltaic Effect**

Photovoltaic module is generated by set of photovoltaic cells. Solar PV array is developed through set of PV modules. Following figure shows how a solar PV system is created.



**Figure 5: Solar PV System**

## Available cell technologies

- Mono-Crystalline Cells

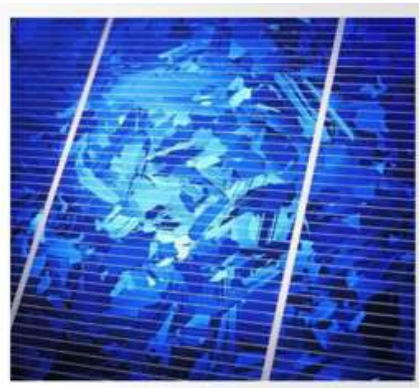
This is the most efficient PV cell in commercial market and also most expensive cell. In this module circular (square-round) cells are used to utilize the wasted space on the module optimally.



**Figure 6: Mono Crystalline Cells**

- Poly-Crystalline Cells

This is less expensive compared to mono-crystalline modules. Poly-Crystalline cells are slightly less efficient than a mono-crystalline. Square shape cells are used to fit into module efficiently using the entire surface of the module.



**Figure 7: Poly Crystalline Cell**

- **Thin Film Cells**

This is the most inexpensive technology to produce PV cells, which the metal grid replaced with transparent oxides. Efficiency of the Thin Film Cells is between 6 – 8 %. This can be deposited on flexible substrates and this is less susceptible to shading problems. It shows better performance in low light conditions compared to the crystalline modules.

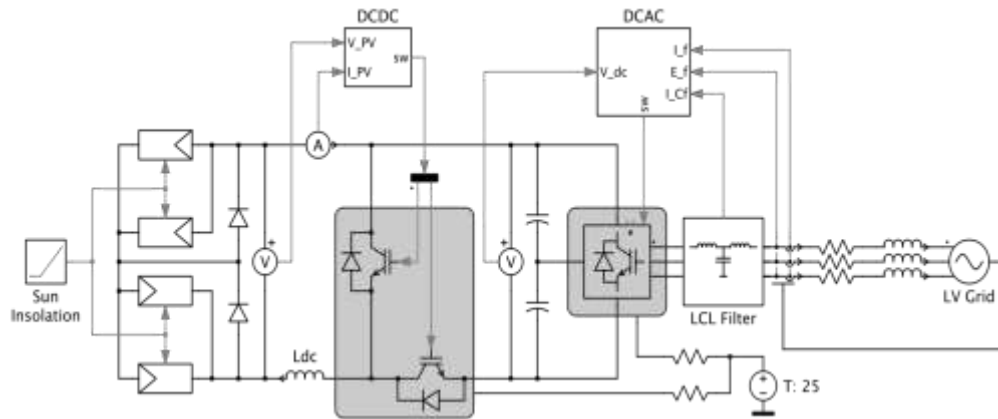


**Figure 8 : Thin Film Cells**

#### **2.4 Conversion of DC power into AC power (Inverter)**

The output of the PV array is in the form of direct current. The inverters are used to convert the generated DC power into AC power and synchronization with the electric utility grid. The power processing circuits of an inverter have similar working principle as that of a conventional standalone DC to AC inverter. The main differences are the control algorithm and safety features. An inverter basically takes a variable voltage from a DC source and inverts it to AC synchronized with the utility supply. It should automatically and instantaneously stop feeding power to the utility lines when the power from the utility grid has been cut off. This is a safety feature which prevents shock hazards to the workers who attempt to work on the feeder. This feature is known as Anti-islanding protection, which sense power outages and shuts off the inverter itself. The anti-islanding feature must be incorporated in any grid-tie solar inverter. The solar inverters are equipped with another main feature which is

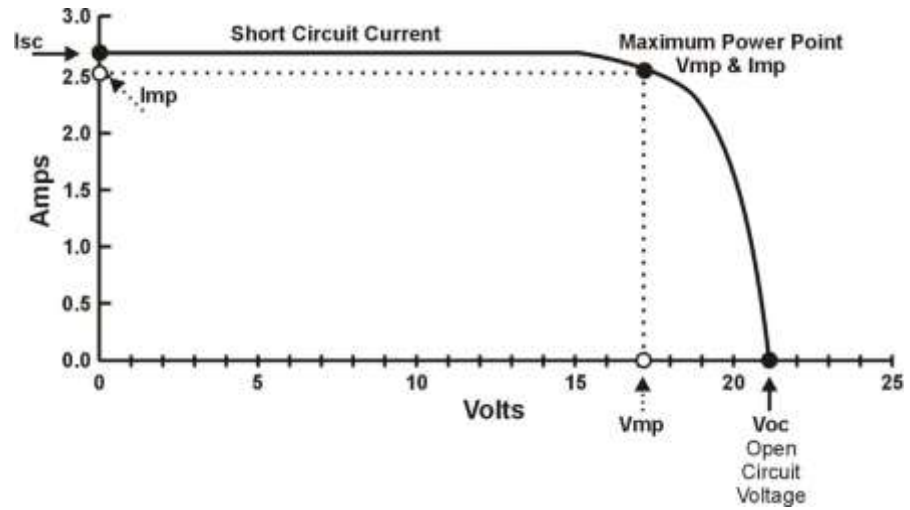
known as “Maximum Power Point Tracking (MPPT)” which enables the solar inverter to extract the maximum power from the available insolation level. A circuit diagram of a typical grid-tie three phase inverter is shown below.



**Figure 9: Circuit Diagram of a Grid-tie Solar Inverter**

## 2.5 Maximum Power Point Tracking

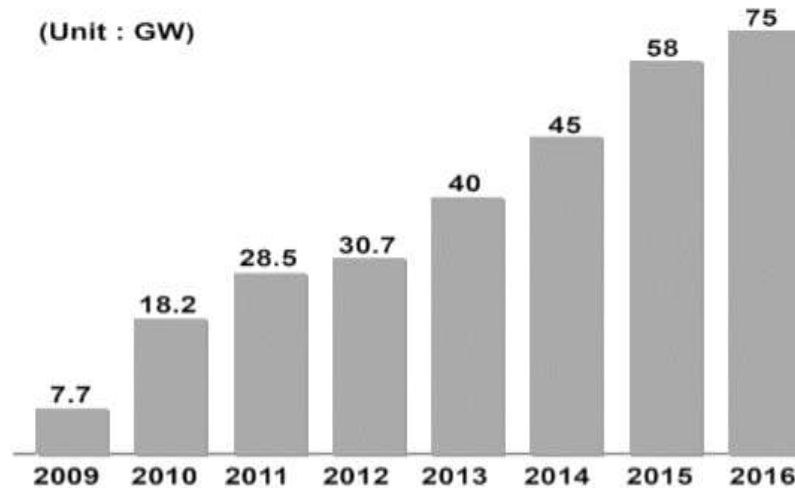
Maximum Power Point Tracking is a fully electronic system that varies the electrical operating point of the PV modules so that the modules are capable of delivering maximum power from the available insolation. The MPPT feature is embedded in the solar PV inverters and the inverter computes the voltage at which the solar PV array is capable of extracting maximum power. PV modules have a characteristic I-V curve that includes a short circuit current value ( $I_{sc}$ ) at 0 Vdc, an open circuit voltage ( $V_{oc}$ ) value at 0A and a “knee” at the point the maximum power point is found. It is the location on the I-V curve where the multiplication value of voltage by the current becomes highest value (maximum power). Below graph shows the MPPT on I-V curve. The  $V_{mp}$  and  $I_{mp}$  are the voltage and current at which the maximum power delivers.



**Figure 10 : MPPT of I-V Curve**

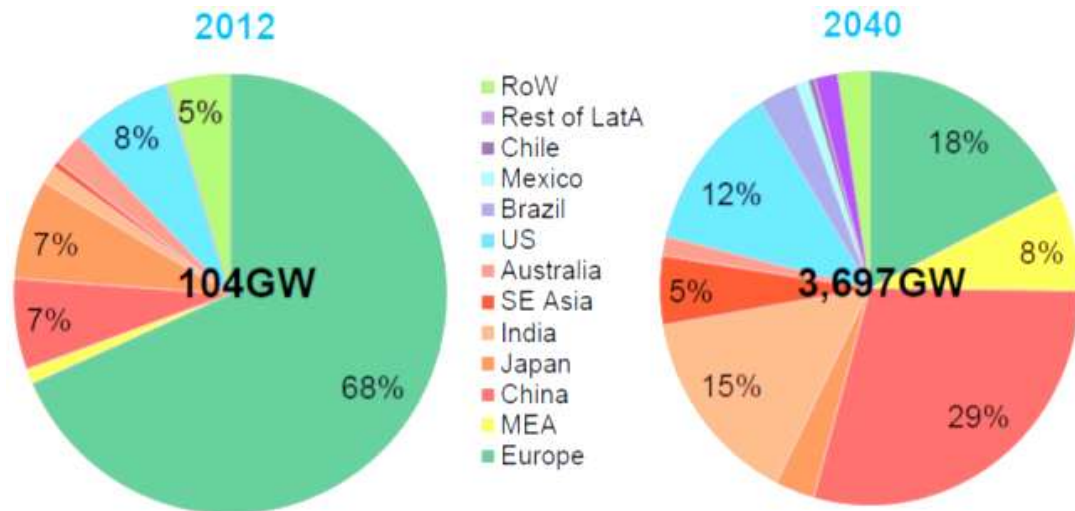
### 2.6 World Statistic of Solar PV

The following graph shows the global demand on solar photovoltaic in Giga Watts. The PV demand of three countries (China 17.5GW, Japan 11GW & USA 8.7GW) accounts for 64% of the total. The global PV market hit the recorded demand of 75GW in 2016.



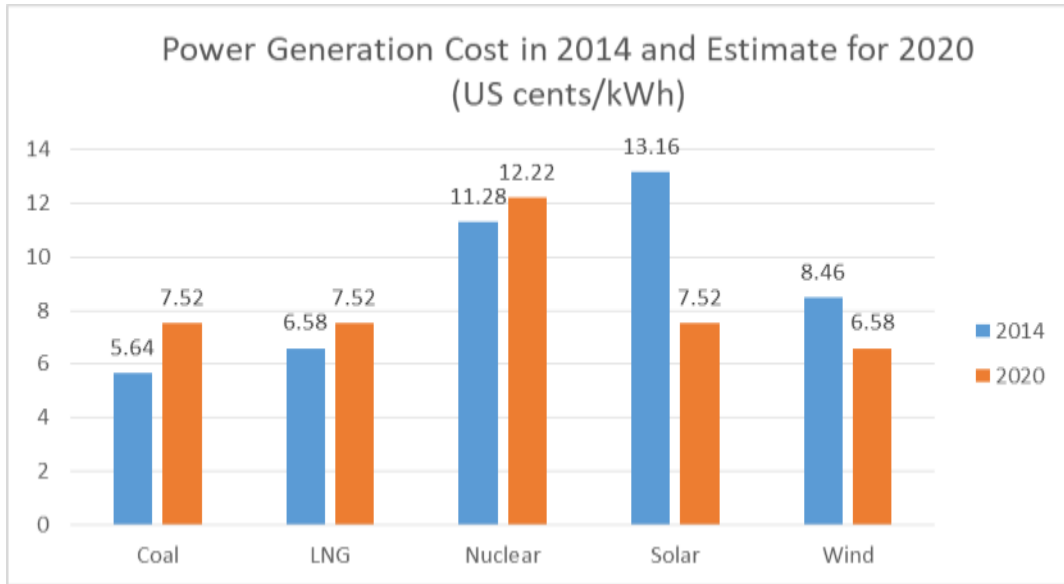
**Figure 11: Global PV Market**

The cumulative capacity of PV installation in 2040 is expected to reach about 3700 GW and the investment is estimated to be US\$ 3.6 trillion. The annual PV demand of 120GW is expected by the year 2040 and investment will be over \$150 billion. The improvement of economic efficiency of solar systems and reduction of greenhouse gas emissions cause the long-term growth of the solar power industry.

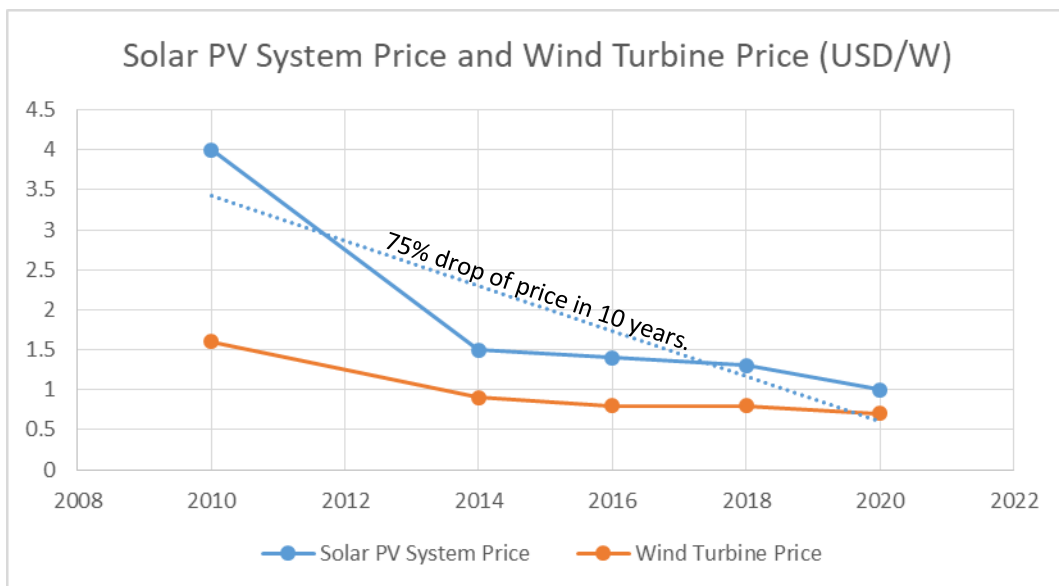


**Figure 12: Cumulative PV Installation Forecast**

The technological advancements and huge competition on the solar PV field the system prices are falling rapidly and solar system price is expected to fall to the level of coal and gas power generation by 2020.



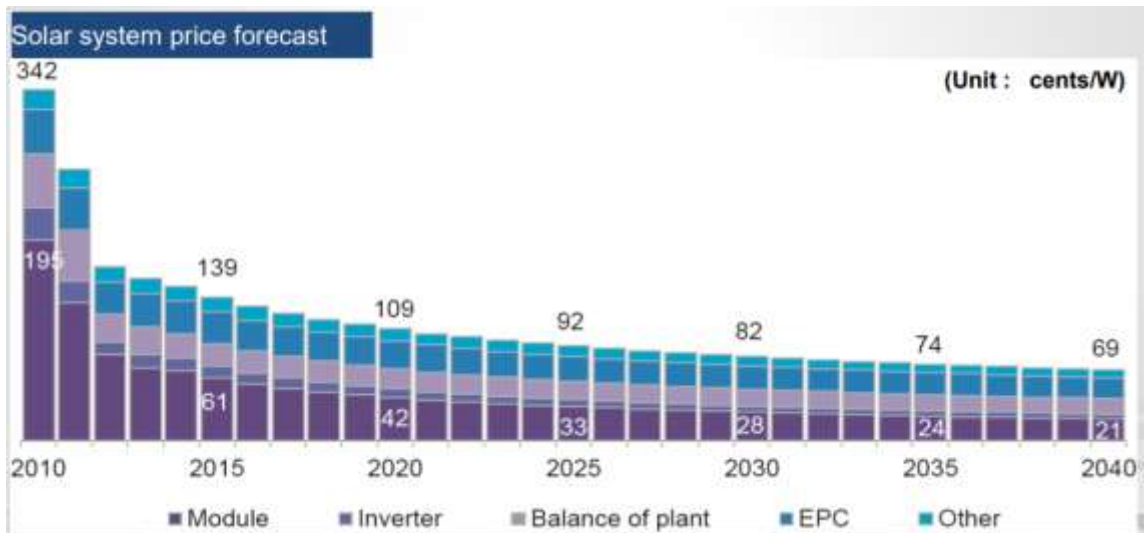
**Figure 13: Power Generation Costs and Forecast**



**Figure 14: Cost Forecast for Solar PV Systems and Wind Turbines**

In 2020, PV system prices are expected to reach US\$1/W with module prices dropping to US\$ 0.42/W. The PV system prices in 2040 will drop by more than 30%. As a result of mass production and technological development, module production cost of leading module companies in the first quarter of 2015 is US\$ 0.47/W.

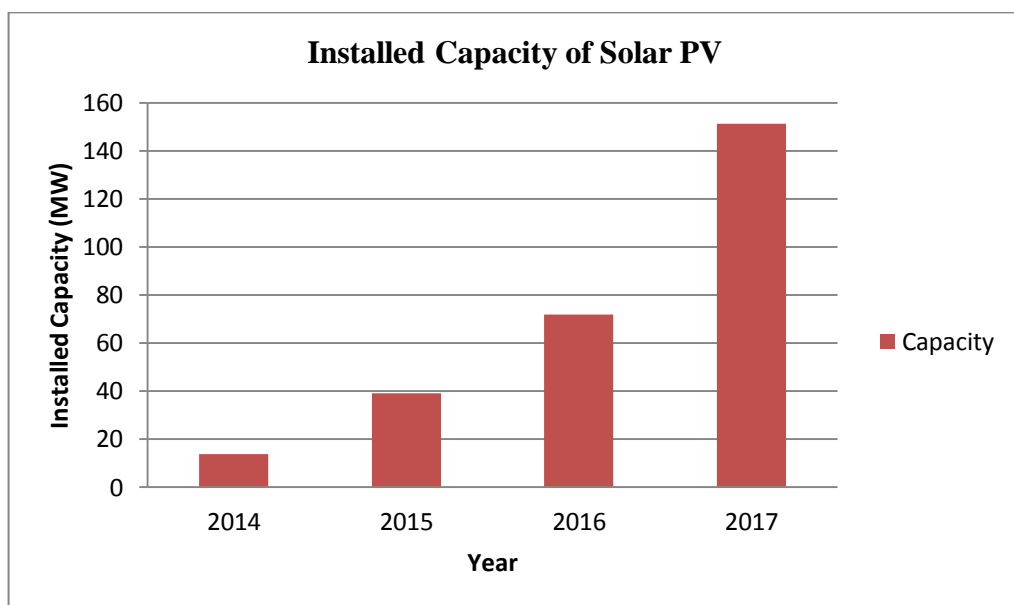




**Figure 15: PV System Price Forecast**

### 2.7 Solar PV growth in Sri Lanka

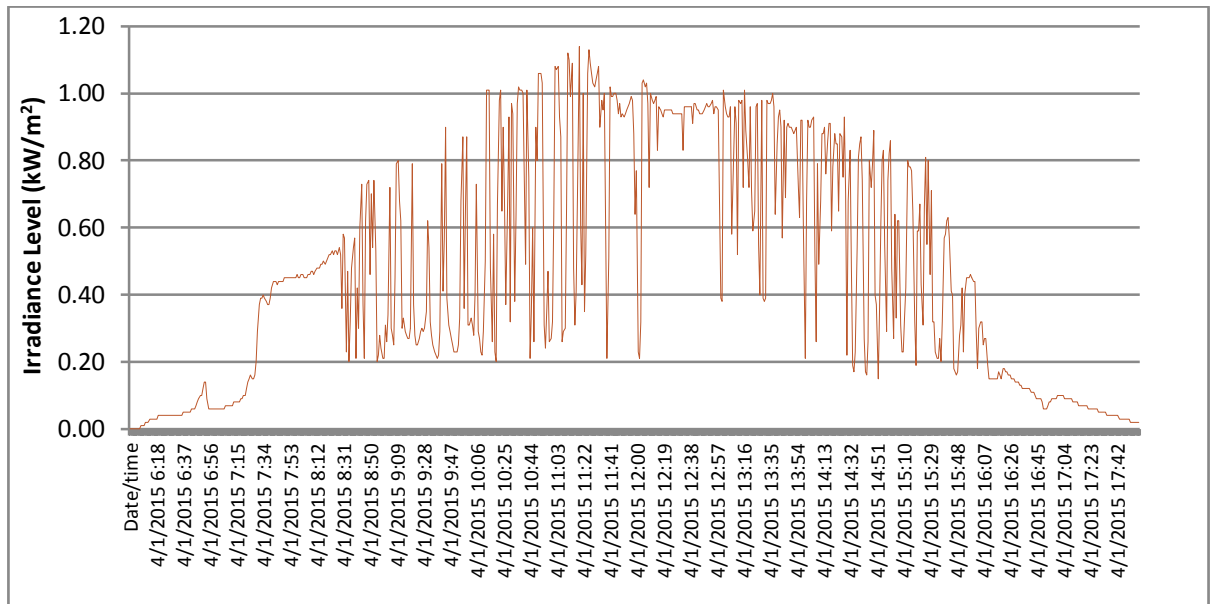
The growth of solar PV rooftop installation rapidly increased with the implementation of “Battle for Solar Energy” programme. The graph below shows how the PV installations have been developed during last few years.



**Figure 16: Growth of the Installed Capacity of Solar PV in Sri Lanka**

## 2.8 Irradiance Curve

The irradiance curve is a plot of the solar irradiance level (measured in  $\text{W}/\text{m}^2$ ) of a particular location for a given time span which includes sun rise and sunset. The irradiance curve of a particular location shows severe fluctuations. The reason for these fluctuations are its geographical location and the cloud movements. This is called as the intermittency behavior of the solar resource. A typical irradiance curve is shown in Figure 17. These fluctuations in the solar irradiance level directly affects the power output of the solar PV systems. This has become a major problem to the utility in interconnecting solar PV plants to the national grid.



**Figure 17 : Irradiance Curve of a Day**

## 2.9 Applicable standards for connecting solar PV to the grid

The guidelines and procedures for solar PV installations have been published by the Sri Lanka Standard Institution (SLSI) with the collaboration with Sri Lanka Sustainable Energy Authority (SLSEA). All grid tie inverters shall comply with SLS 1547:2016 (IEC 61727:2004). The allowable maximum or minimum values of

respective parameters are specified in the table below according to the utility (CEB) guidelines.

**Table 1: Parameter values according to the CEB guidelines**

<b>Voltage (at point of utility connection)</b>	<b>Maximum trip time*</b>
$V < 0.5 \times V_{\text{nominal}}$	0.1 s
$50 \% \leq V < 85 \%$	2.0 s
$85 \% \leq V \leq 110 \%$	Continuous operation
$110 \% < V < 135 \%$	2.0 s
$135 \% \leq V$	0.05 s

Trip time refers to the time between the abnormal condition occurring and the inverter ceasing to energize the utility line. The PV system control circuits shall actually remain connected to the utility to allow sensing of utility electrical conditions for use by the “reconnect” feature.

**Table 2 : Maximum allowable grid utility parameters**

<b>Ref. no</b>	<b>Parameter</b>	<b>Value</b>
1	Maximum output voltage of the inverter	$230V_{\text{rms}}$ ( $\pm 6\%$ of the nominal grid voltage)
2	Flicker	IEC61000-3-3 (less than 16A per phase), IEC61000-3-5 (greater than 75A)
3	DC injection	1% of the rated inverter output current (IEC 61727)
4	Frequency range	$50 \pm 1\%$ Hz

5	Total harmonic distortion	< 5%
6	Power factor	Lagging power factor greater than 0.90 at the 50% of rated inverter output power
7	Islanding protection	De-energized within 2 s

### 2.9.1 Voltage Fluctuations

During synchronization of a single generator, the induced voltage fluctuation on the grid should not normally exceed 6% at the Point of Common Coupling and should also meet the requirements of voltage step and flicker given in above table.

### 2.9.2 Power factor variation capability

Generating units shall be capable of continuously delivering the declared outputs. The minimum capability of intermittent resources based generating units shall not be lower than lagging 0.9.

### 2.9.3 Voltage variation capability

According to the Ceylon Electricity Board guideline following table shows the voltage variation capability for each nominal voltages.

**Table 3 : Allowable limits of the system voltages**

System Nominal Voltage	Variation
400 kV	±10%
220 kV	±10%
132 kV	±10%
33 kV	±6%
11 kV	±6%
400 V	±6%

#### 2.9.4 Harmonic

Acceptable harmonic limits are as below table.

**Table 4 : Harmonic limits**

<b>Individual harmonic order(h)</b>	<b>h&lt;11</b>	<b>11&lt;h&lt;17</b>	<b>17&lt;h&lt;23</b>	<b>23&lt;h&lt;35</b>	<b>35&lt;h</b>	<b>THD</b>
<b>Allowable Limit (%)</b>	4	2	1.5	0.6	0.3	5

#### 2.9.5 Islanding Protections

The solar PV systems should have the capability of disconnecting the entire plant when the grid supply is not available.

## DATA ANALYSIS

Number of researches have been carried out in some other countries to study the fluctuations in irradiance level. It was noted that the average of the irradiance level received to several parts of a country shows less fluctuations in irradiance curve. As the analysis – 1, the same analysis was done for Sri Lanka using the data collected from solar measuring stations in Killinochchi, Hambantota, Sooriyakanda, Balangoda, Seetha Eliya and Kalamatiya. Then as the analysis -2, an analysis was conducted on actual generation data from solar PV installations located in close proximity of Dehiwala-Mount Lavinia area. Ten solar PV rooftop systems in Dehiwala-Mount Lavinia area were selected for analyzing generation data.

### 3.1 Analysis – 1

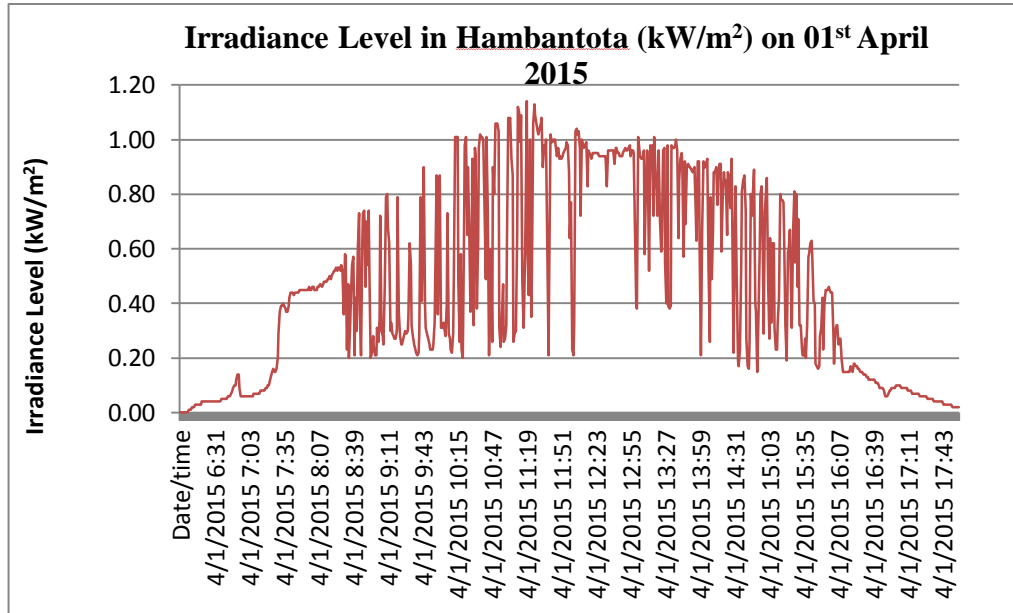
An analysis was conducted using the data collected from solar measuring stations in Killinochchi, Hambantota, Sooriyakanda, Balangoda, Seetha Eliya and Kalamatiya. Those locations are shown in following map.



**Figure 18: Data Collected Locations**

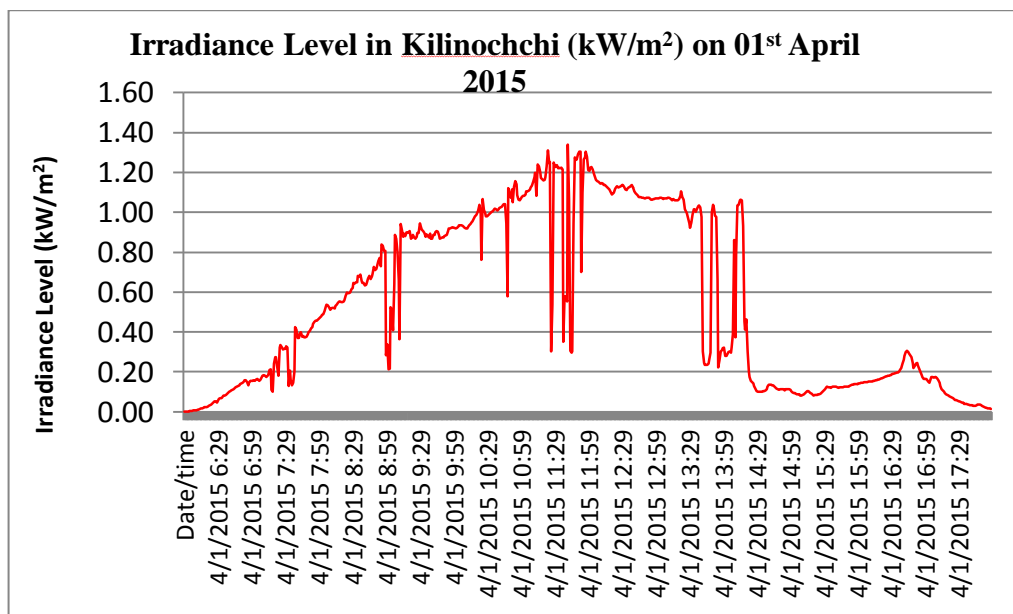
The gathered data for a specific date for all locations were plotted separately using Microsoft Excel.

The irradiance curve in Baruthakanda, Hambantota is shown in Figure 19.



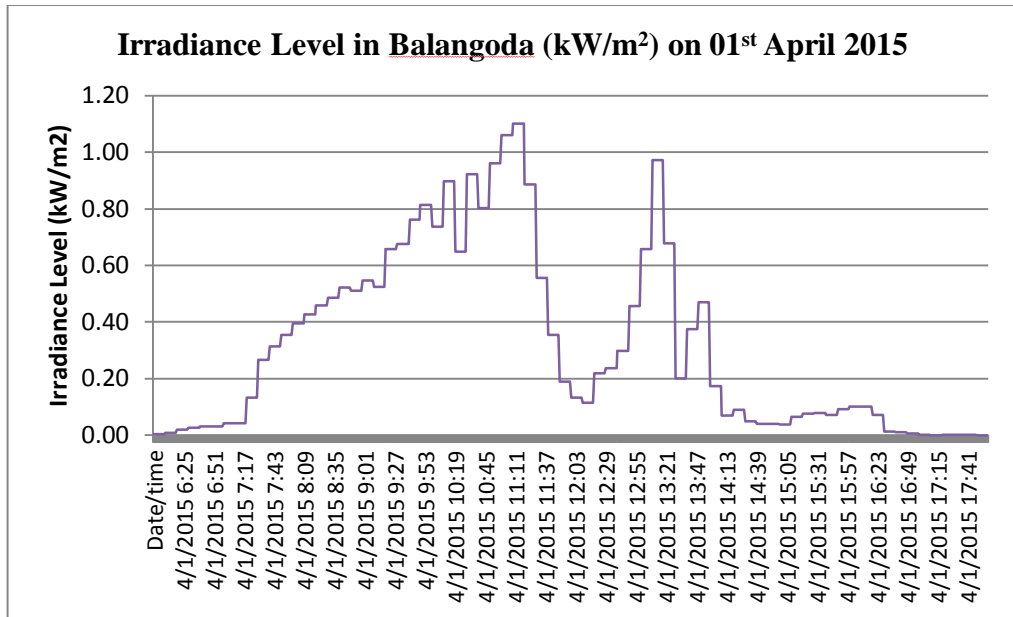
**Figure 19: Irradiance Curve in Hambantota**

The irradiance curve in Kilinochchi is shown in Figure 20.



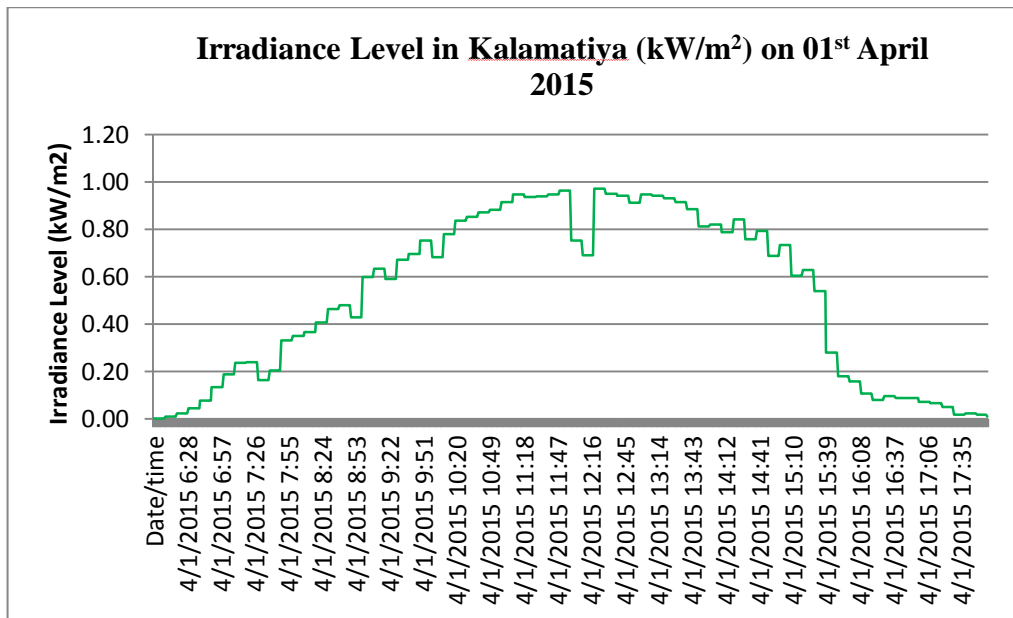
**Figure 20: Irradiance Curve in Kilinochchi**

Irradiance curve in Balangoda is shown in Figure 21.



**Figure 21: Irradiance Curve in Balangoda**

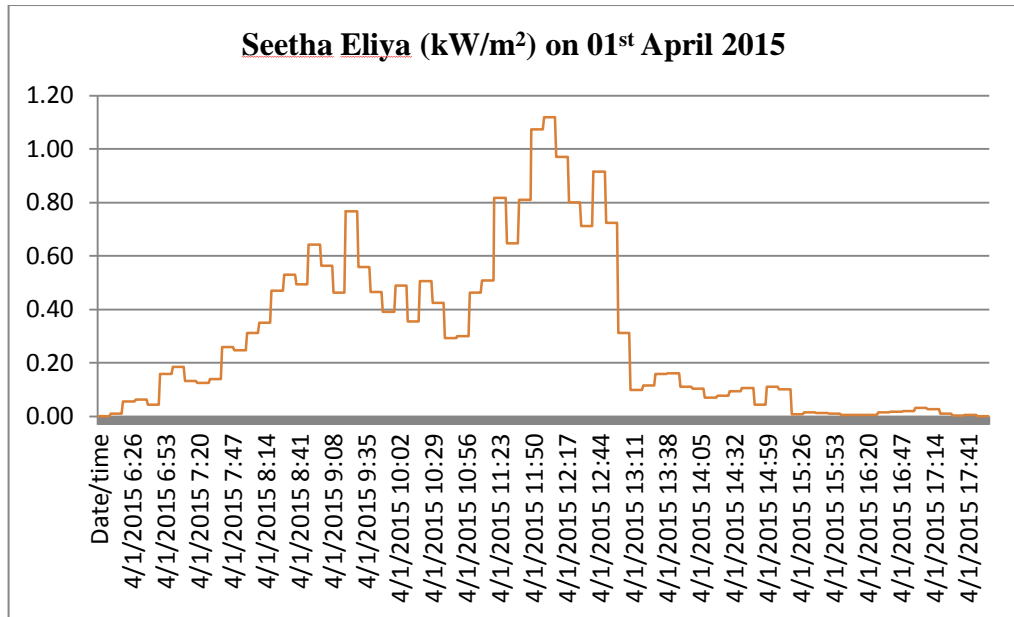
Irradiance curve in Kalamatiya is shown in Figure 22.



**Figure 22: Irradiance Curve in Kalamatiya**

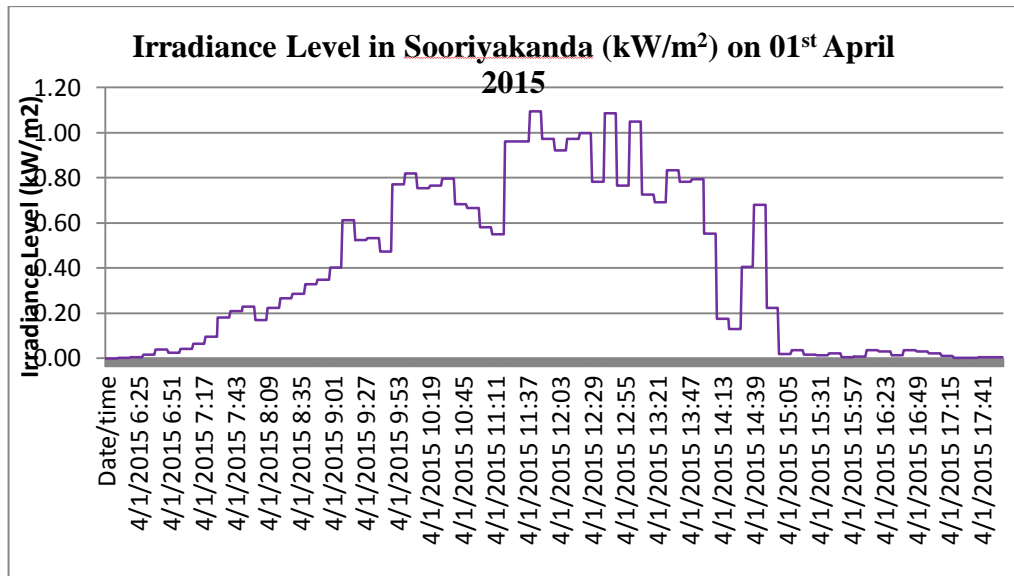


Irradiance curve in Seetha Eliya is shown in Figure 23.



**Figure 23: Irradiance Curve in Seetha Eliya**

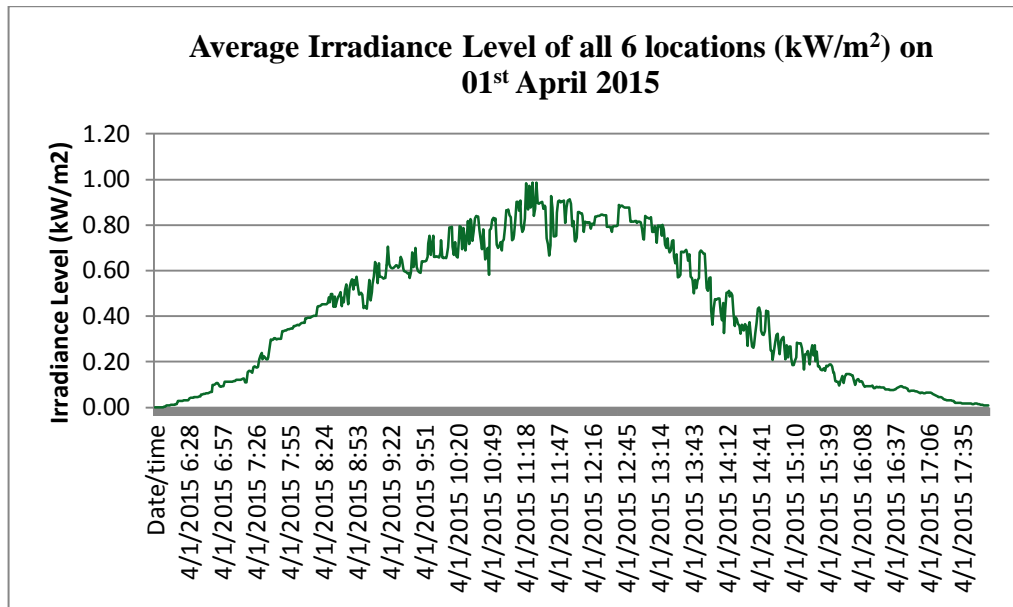
Irradiance curve in Sooriyakanda is shown in Figure 24.



**Figure 24: Irradiance Curve in Sooriyakanda**

### 3.2 Data Analysis Results - 1

The average value of irradiance at all the locations, Hambantota, Kilinochchi, Seetha Eliya, Kalamatiya, Sooriya kanda and balangoda was obtained and plotted. The average irradiance curve is shown in Figure 25.



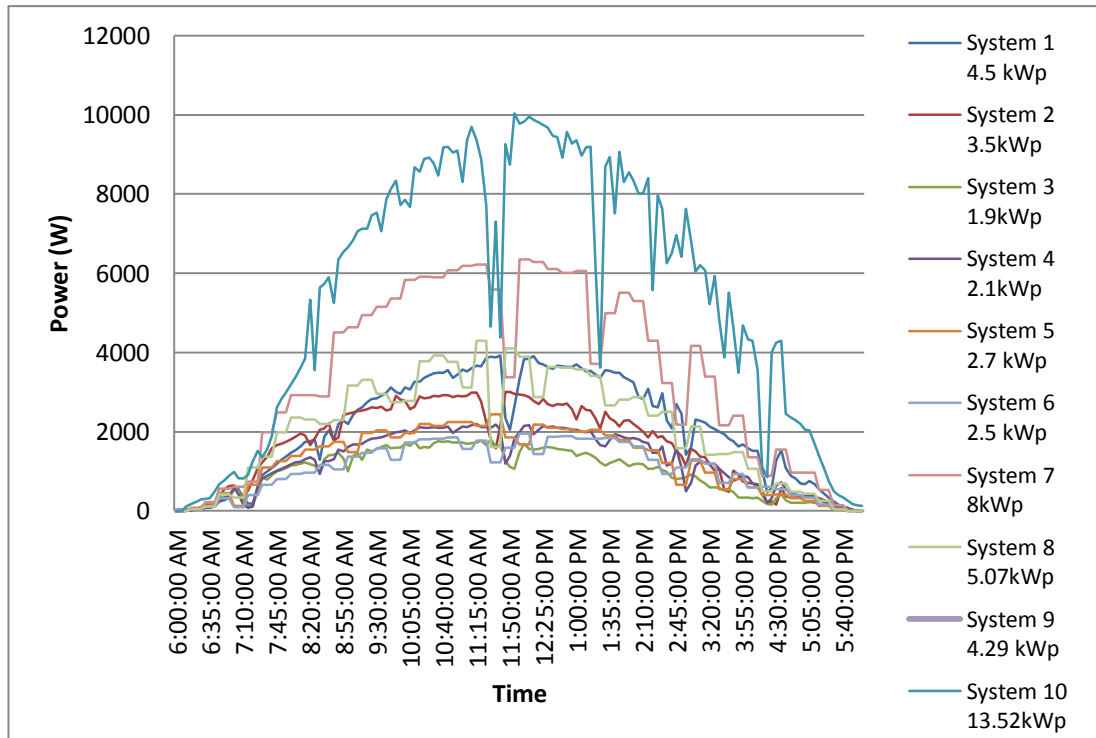
**Figure 25: Average Irradiance Curve**

The intermittent behavior of solar resource become less volatile with the average figure of irradiance level at distributed locations.

### 3.3 Analysis – 2

According to the analysis -1, it was resulted that the intermittent behavior of solar resource become less volatile with the average figure of irradiance level at distributed locations. The same analysis was conducted on actual generation data from solar PV installations located in close proximity of Dehiwala-Mount Lavinia area. Ten solar PV rooftop systems in Dehiwala-Mount Lavinia area were selected for analyzing generation data. The installed capacities of those ten solar rooftop systems are 4.5kWp, 3.5kWp, 1.9kWp, 2.1kWp, 2.7kWp, 2.5kWp, 8.0kWp, 5.07kWp, 4.29 kWp and 13.52kWp. Total installed solar PV capacity of those ten locations are 50.08kWp.

Power curves of ten solar PV rooftop systems in Dehiwala-Mount Lavinia area are plotted in same axis which is power to time.

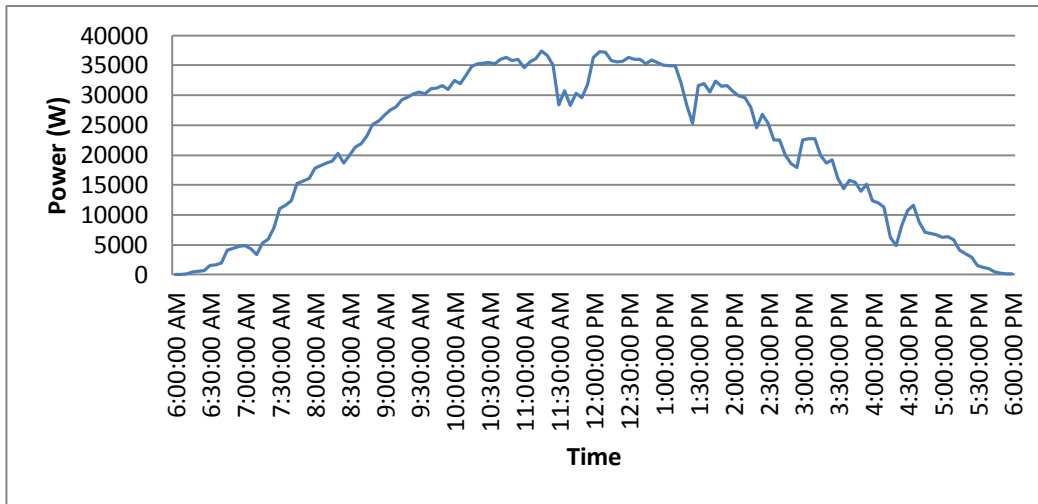


**Figure 26: Power Curves of 10 Locations**

### 3.4 Data Analysis Results -2

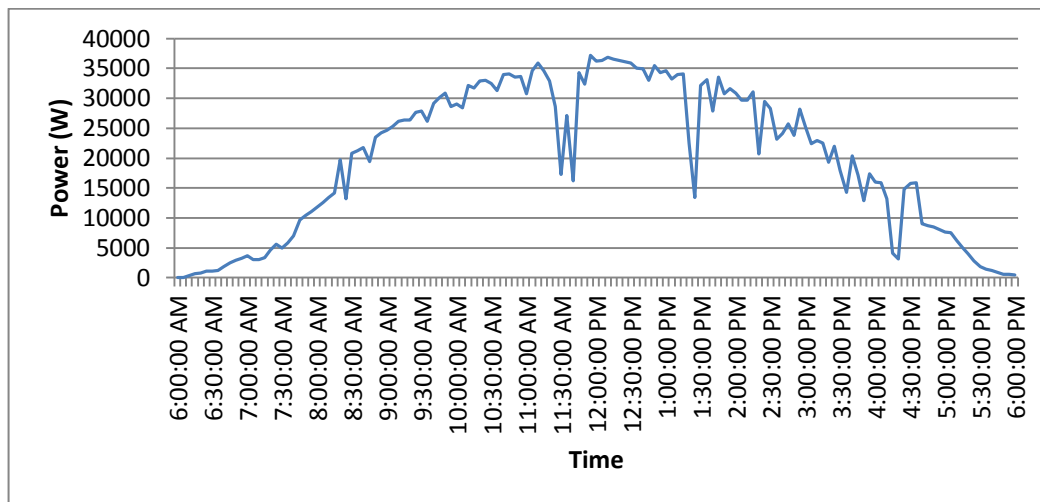
Aggregated power curve of ten solar PV rooftop systems (50.08kWp) in Dehiwala-Mount Lavinia area was calculated and plotted using the collected data at the same date. The aggregated power curve is shown in Figure 27.

Huge fluctuations were reduced with the average value of power as shown in above graph. Therefore the effect on the power system is low in scattered solar PV plants although they are in nearby areas.



**Figure 27: Aggregated Power Curve**

The power curve was plotted assuming the total capacity of those ten systems are installed in one location. Power Curve of 50.08kWp Solar PV rooftop system was generated, assuming that the 50.08kWp solar PV plant has been installed at the location of ‘System 10’ is shown in below Figure 28.



**Figure 28: 50.08 kWp Solar System at location no 10**

The variations of power output are significant in power curve in Figure 28, compared to power curve of the aggregated power values at ten locations. The intermittent behavior of solar resource become less volatile with the average figure of irradiance level at distributed locations although it is distributed vastly or nearby locations.

---

### MATLAB MODEL

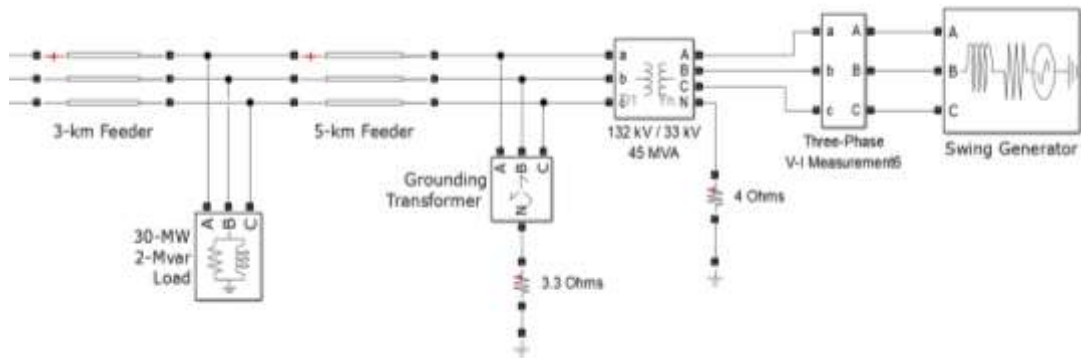
The results obtained from data analysis implies that the aggregated value of power or irradiance becomes less volatile on scattered small scale solar PV systems compared to a single centralized solar PV system. MATLAB Simulink was selected for the modeling of the required components and scenarios.

The domestic solar PV systems connect to the low voltage distribution system of the CEB and LECO parallel to the domestic load. Therefore the modelling of the two scenarios of solar PV systems requires the model of the distribution lines, distribution transformer and the utility grid. The following models were created using MATLAB Simulink to simulate and analyze the characteristics of two scenarios.

- a. Utility grid
- b. Distribution transformer model
- c. Distribution line model
- d. Load model
- e. Inverter model
- f. Solar PV model
- g. Irradiance curve model
- h. Centralized solar PV system
- i. Scattered solar PV system

#### 4.1 Utility Grid

The utility grid was modeled using a generator, 132kV/33kV transformer with grounding transformer, medium voltage feeders and loads in 33kV level. The main details of the utility grid modelling is shown in the Table 5.



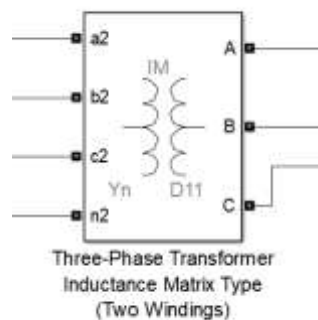
**Figure 29: Utility Grid Model**

**Table 5 : Utility grid modelling details**

Component	Description
Generator capacity/ Type	100MVA/ Swing
Transformer capacity/ Vector group	45MVA / YNd1
Feeders length/ Unit resistance	8km / 0.3913Ω/km
Loads	$(30+2j) * 10^6$

#### 4.2 Distribution Transformer Model

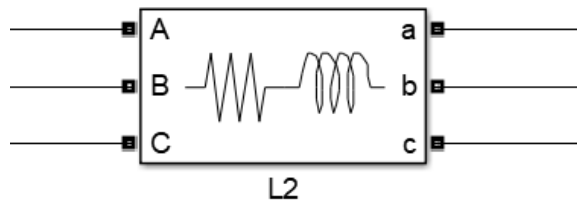
The three phase transformer block was used to model 33kV/400V distribution transformer. The capacity was set to 160kVA and the vector group was set to Dyn11.



**Figure 30: Distribution transformer model**

### 4.3 Distribution Line Model

The low voltage distribution lines are used as overhead bare lines, aerial bundled conductor and underground cables. The most commonly available type is the overhead bare conductors. The model was developed for the overhead bare conductor using MATLAB Simulink blocks. The parameters of a typical AAC Fly conductor was used to model the overhead line. The resistance of the Fly conductor is  $0.4505 \Omega/\text{km}$  at  $20^\circ\text{C}$ . The temperature was considered as  $40^\circ\text{C}$  and the corrected resistance of the conductor was set as  $0.4865\Omega/\text{km}$ . The inductance of the conductor was considered zero.

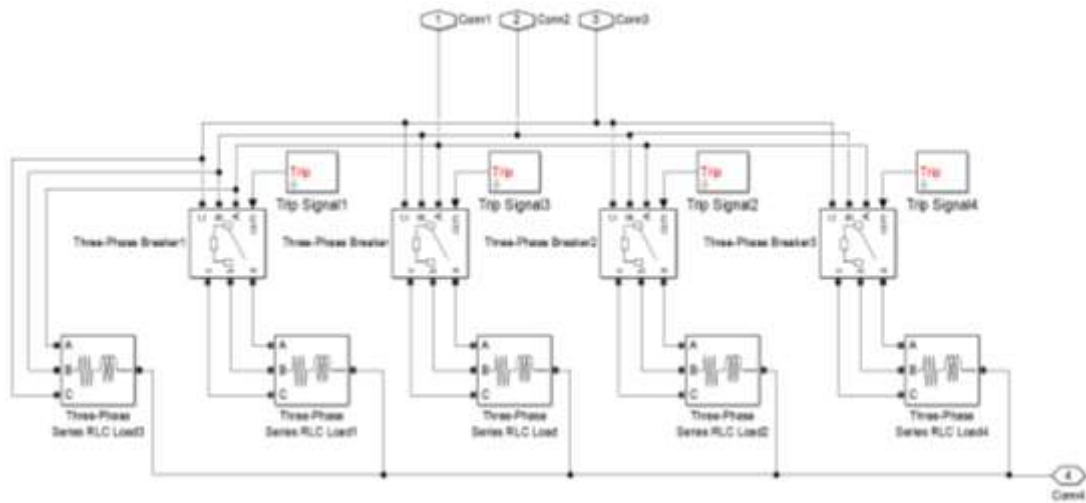


**Figure 31: Model of low voltage line**

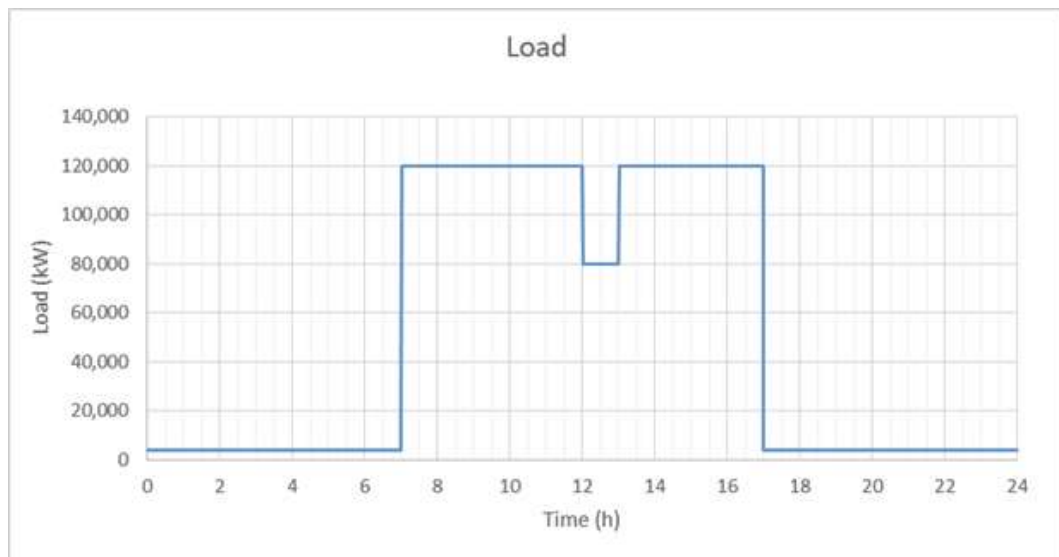
### 4.4 Load model

A varying load which has 120kVA peak was created according to the consumption pattern of the solar PV system's owner. The load model was developed by using series RLC loads. These loads were connected in parallel through circuit breakers as shown in Figure 32. The external trips signal was set to connect and disconnect the loads to obtain the required load curve.

The consumer was assumed as a small scale factory and developed the load curve. The load pattern of the consumer was kept unchanged for all the simulations. A continuous load with a demand of 3,000 kVA was considered there throughout the day. The machines start at 07.00 hours and the demand increases up to 120,000 kVA. The demand decreases during the lunch hour by 40,000kVA. The factory stops its operation at 17.00 hours. This pattern was used to develop the load curve as shown in Figure 33.



**Figure 32: Load model**

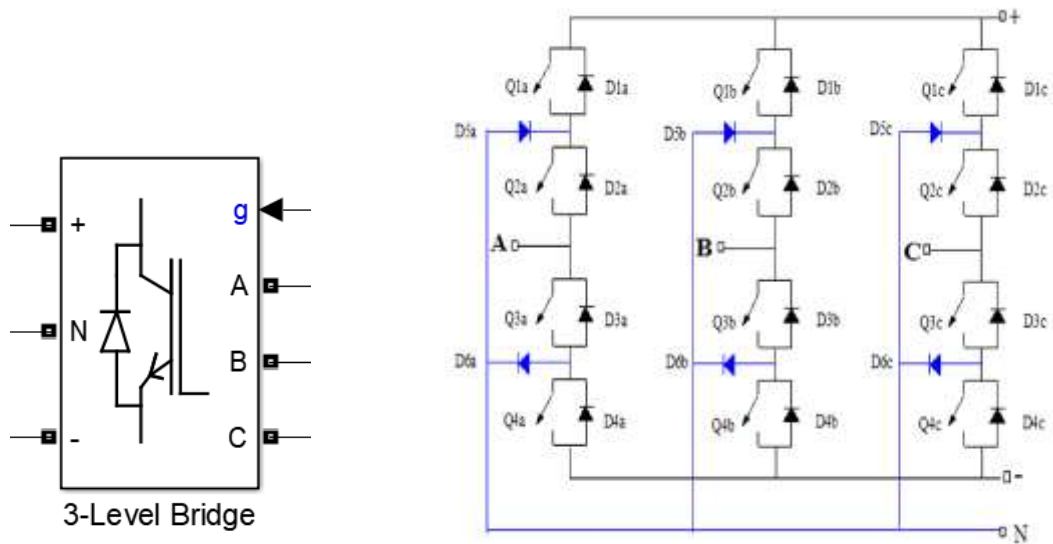


**Figure 33: Load curve of the solar PV system owner**

#### 4.5 Inverter model

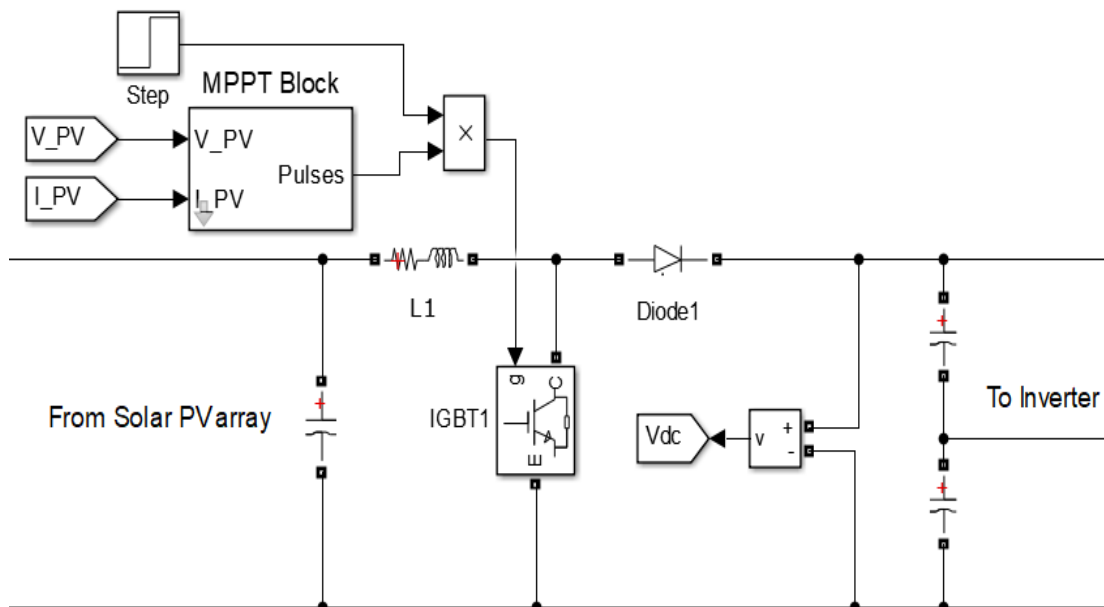
The inverter model was developed by using Three-Level Bridge of MATLAB Simulink. The power electronic device was set as IGBT/Diodes. This inverter has three legs each having four switching devices as shown in Figure 34.





**Figure 34: Inverter model and arrangement**

A boost converter was used to connect the inverter model to the solar PV model. The boost converter operates from the pulses generated according to the “Maximum Power Point Tracking” technique. The boost converter process the output of the solar PV model and feed to the inverter in order to obtain the maximum power from the available irradiance level.



**Figure 35: Boost converter model**

#### 4.6 Solar PV model

The solar PV model from MATLAB Simulink was used with following configurations.

The selected solar PV module is SolarWorld SW255 Polycrystalline. The parameters of the solar module are as follows.

- Maximum power : 255.02 W
- Open circuit voltage : 37.8 V
- Voltage at maximum power : 31.1 V
- Current at maximum power : 8.2 A
- Short circuit current : 8.73 A
- Cells per module : 60

The solar PV strings were configured to have 26 PV module per string. Therefore the maximum possible open circuit voltage is 982.8Vdc. The nominal DC bus voltage was set to 1000Vdc. The output voltage of the inverter is 400Vac. The MPPT method is used for obtaining maximum power output of the inverter. The P-V curve of a solar PV system is shown in Figure 36. The maximum power point obtains when the  $dP/dV=0$ .

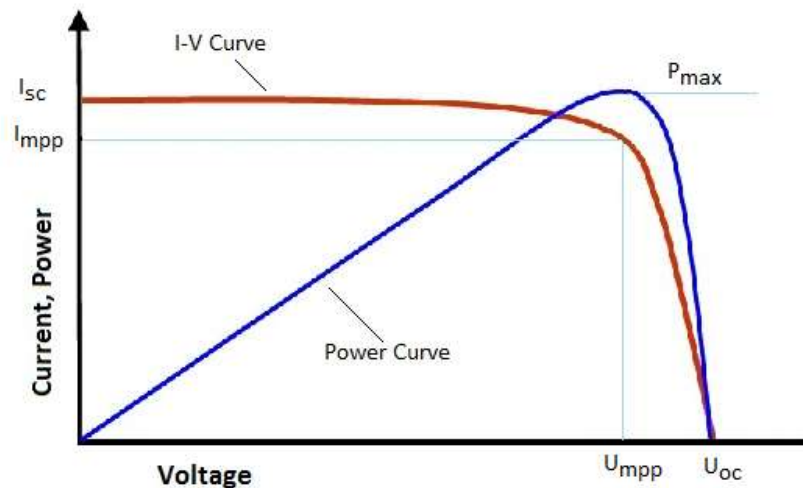
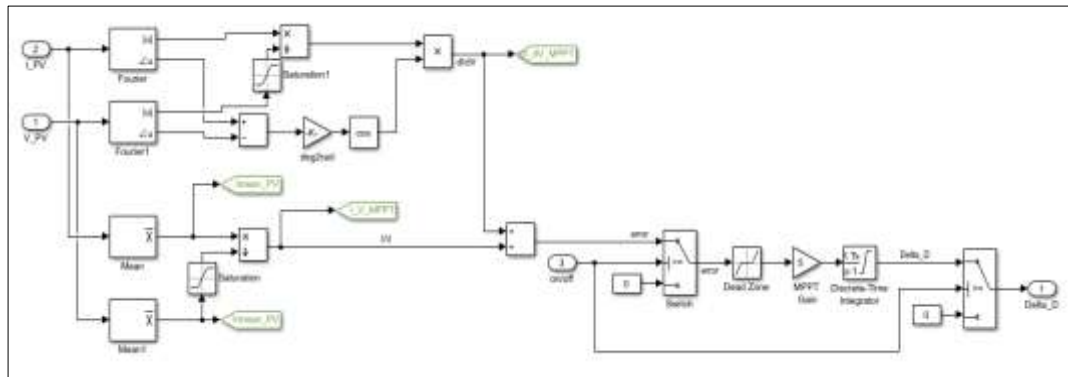


Figure 36: P-V and I-V curves

MPPT Simulink block which was used for the implementation of the solar PV system is shown in Figure 37.



**Figure 37: MPPT Simulink block**

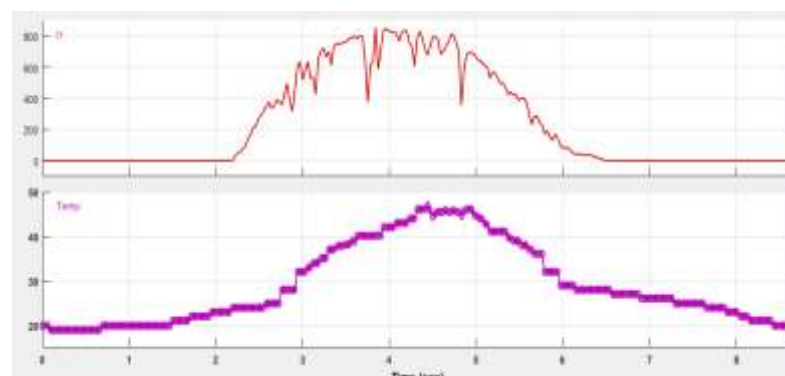
#### 4.7 Irradiance curve model

The Signal Builder model shown in the Figure 38 was used to feed the irradiance level and the temperature level to the solar PV model.



**Figure 38: Signal builder block**

The measured irradiance level and temperature data was used to develop the irradiance curve and temperature curve. These curves were fed to the solar PV model as input signals in the simulation.



**Figure 39: Irradiance and Temperature Curves**

The field data was processed in order to limit the simulation time of the Simulink model. The simulation time was considered as 8.64s so that 10,000s of actual duration was represented by one second in the simulation. The resolution of simulation was obtained as 0.09s by following calculation.

$$\begin{aligned} \text{Seconds per day} &= 24 \times 60 \times 60 \\ &= 86400\text{s} \end{aligned}$$

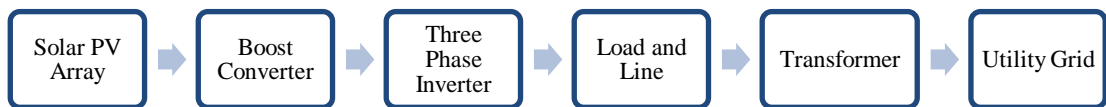
$$\text{The resolution of available data} = 900\text{s (15 mins)}$$

$$\begin{aligned} \text{Number of data points per day} &= \frac{86400\text{s}}{900\text{s}} \\ &= 96 \end{aligned}$$

$$\begin{aligned} \text{The resolution for simulation} &= \frac{8.64\text{s}}{96} \\ &= 0.09\text{s} \end{aligned}$$

#### 4.8 Centralized solar PV system model

The centralized PV system is a combination of the models mentioned above as shown in Figure 40. This Simulink model of the centralized solar PV system is shown in Figure 41. This model was used to analyze the characteristics of larger solar PV systems.



**Figure 40: Block diagram of the centralized solar PV system**

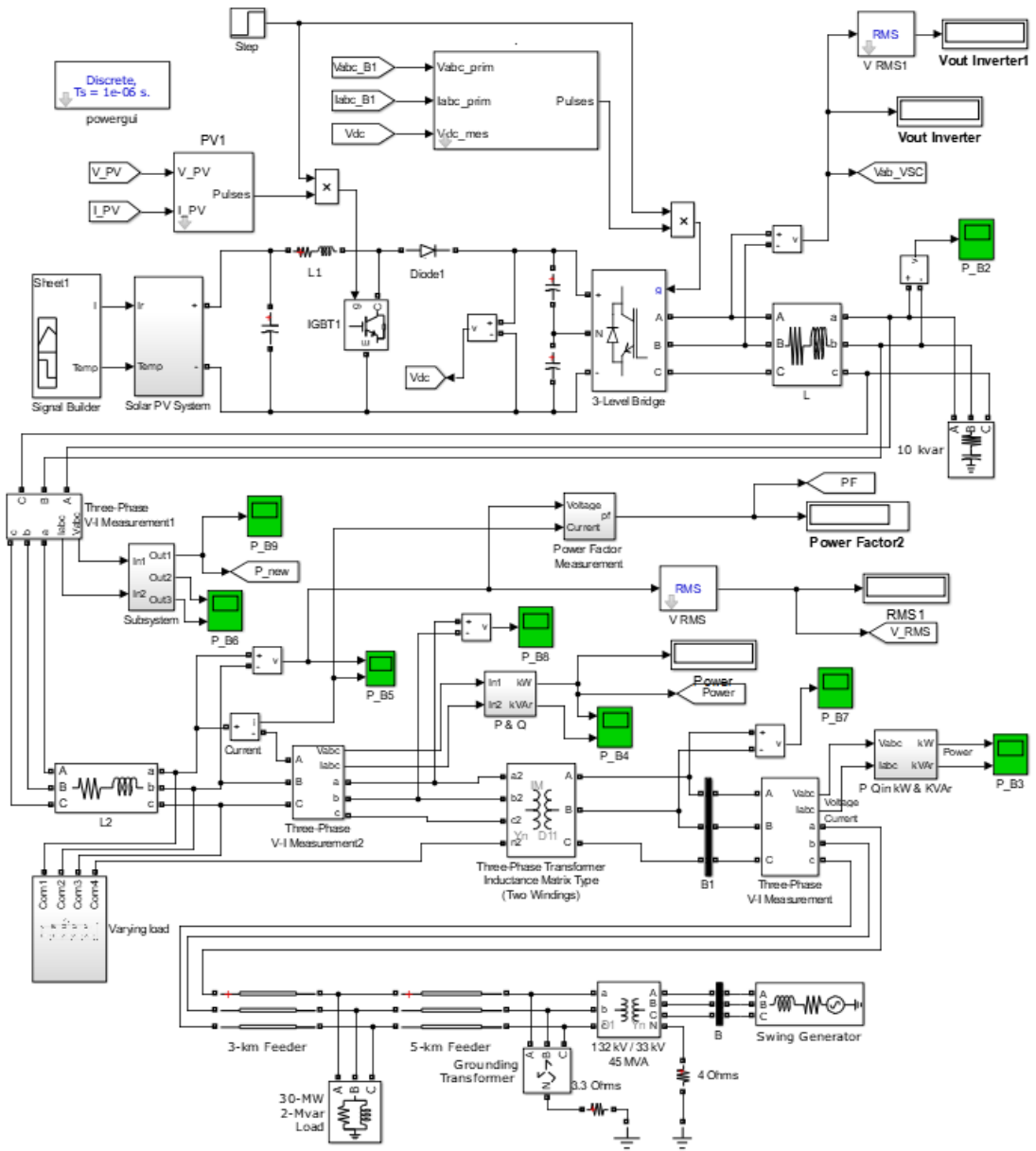
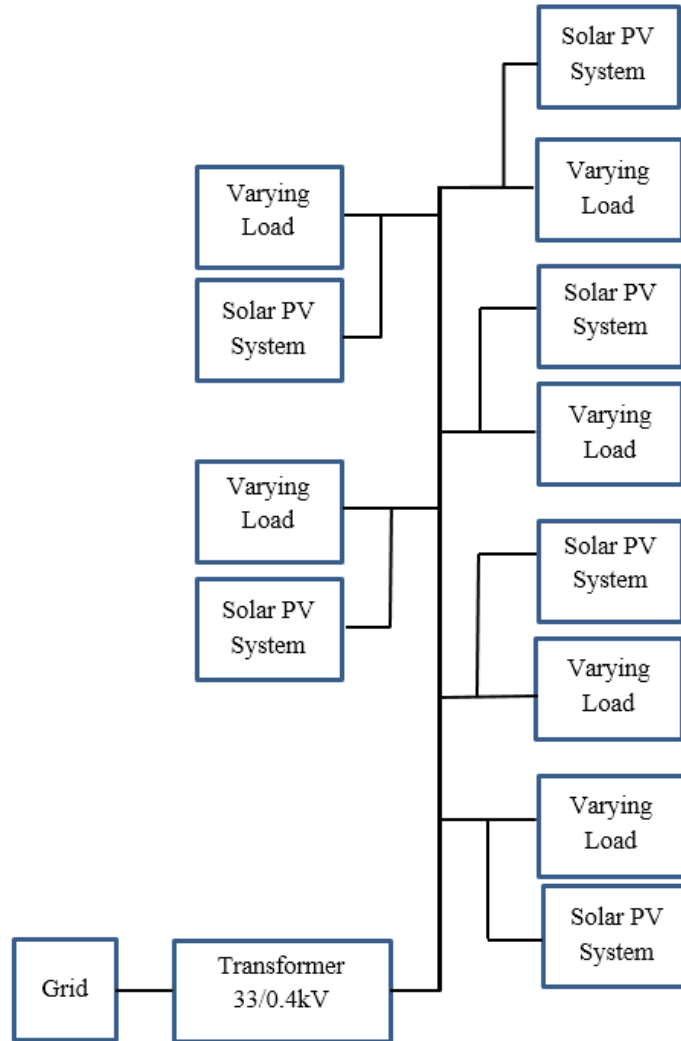


Figure 41: Centralized PV system model

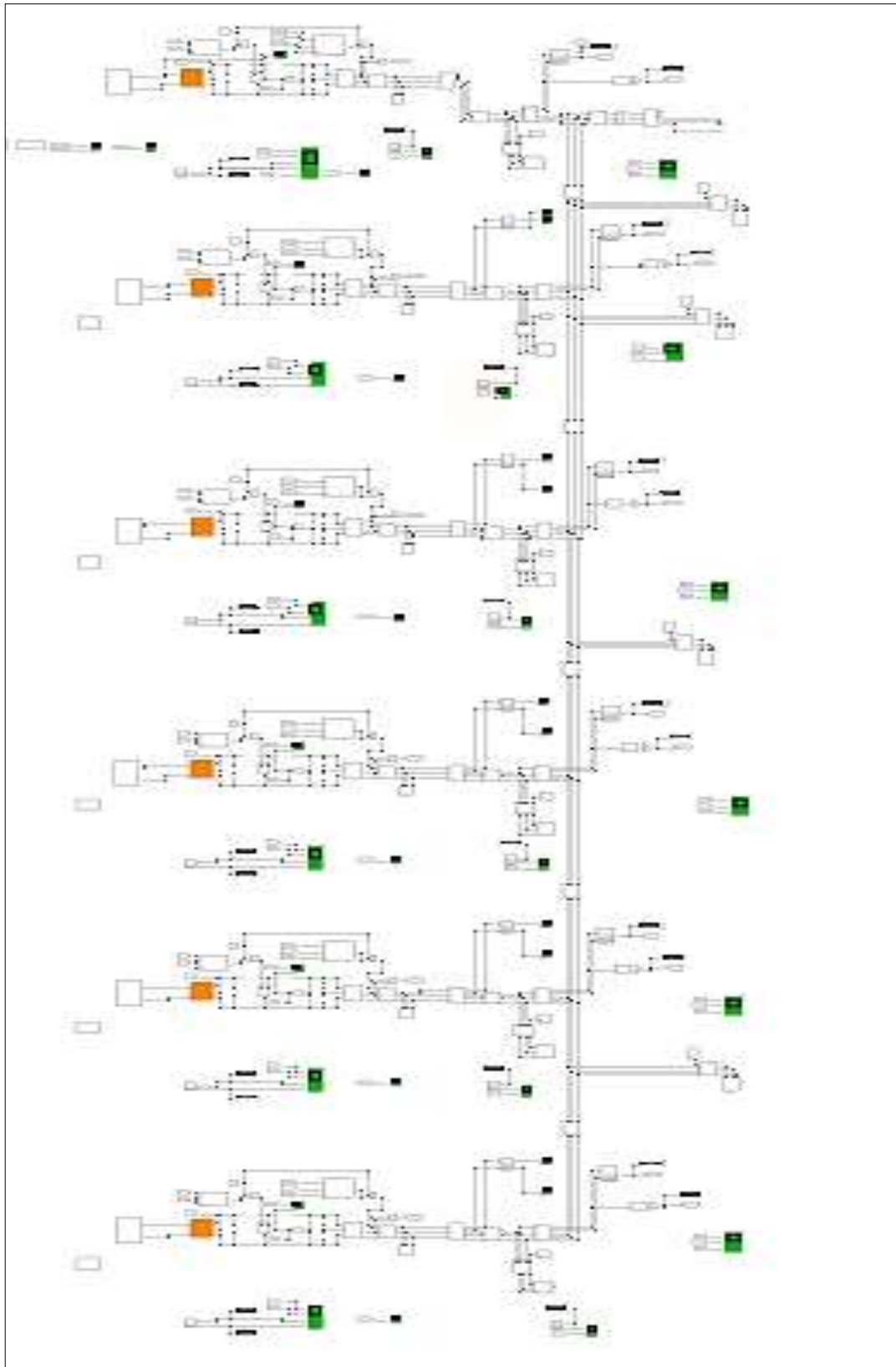
#### 4.9 Scattered solar PV system model

The scattered solar PV system is a set of loads and distributed solar PV systems along the low voltage distribution feeder as shown in the Figure 42.



**Figure 42: Scattered solar PV system**

These loads are served from a 160 kVA 33kV/400V distribution transformer. The scattered solar PV systems were created to connect to the feeder line with variable loads. The cumulative peak load of the model was set to 120 kVA. A load and a solar PV system combinations were used to represent an electricity consumer with grid connected solar PV system in their premises. In this model there are six load-solar PV combinations were considered to represent scattered units. The Simulink model of the scattered solar PV system is shown in the Figure 43.



**Figure 43: Scattered PV System Model**

#### 4.10 Compensation with battery bank

A battery bank was modeled using MATLAB Simulink in order to analyze the capability of compensating the effect on the power system due to the penetration of solar PV systems. This model is intended to use with the worst case of two solar PV systems mentioned above and analyze the capability of compensation. The battery was developed as a current source. The operation of battery bank starts with the startup of the solar PV system and battery shuts down when the solar PV system shuts down. The output current of the solar PV system is considered as the input to the battery controller. The battery initially at the state of charge of 50% of its maximum. The battery charges itself when the current output of the solar PV system shows hikes and discharges when the current output of the solar PV system shows sudden drops.

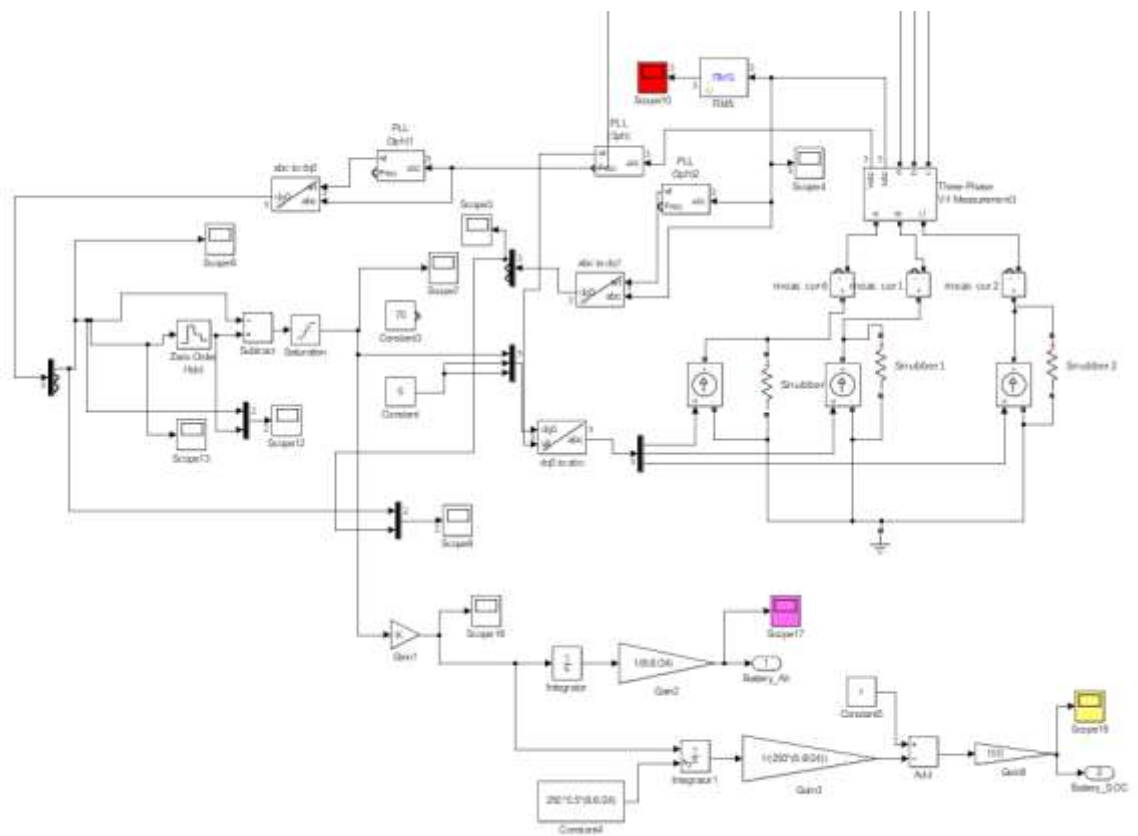


Figure 44: Battery system



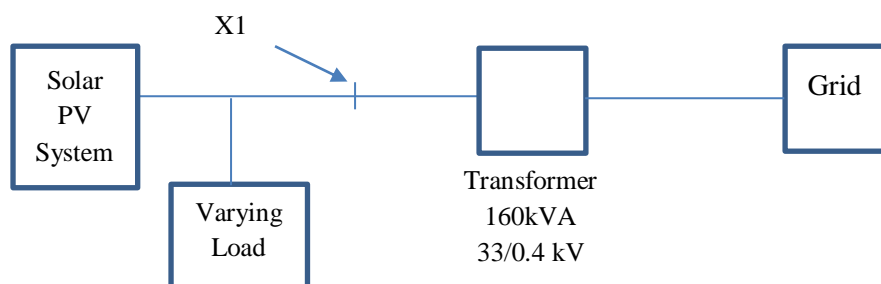
### 5.1 Centralized Solar PV System

The centralized system was developed in three solar PV capacities as 160kWp, 80kWp and 40kWp. The scattered solar PV plants were modelled so that the cumulative capacities of all scattered solar PV plants are 160kWp, 80kWp and 40kWp.

The capacity of the first solar PV model is 160kWp. Then the solar PV system capacity reduced to 50% and 25% respectively while keeping the capacity of the connected load unchanged. Irradiance data and the panel back temperature data were fed to the PV system. The module type, module capacity, number of modules per string, number of strings were configured to obtain the required solar PV system.

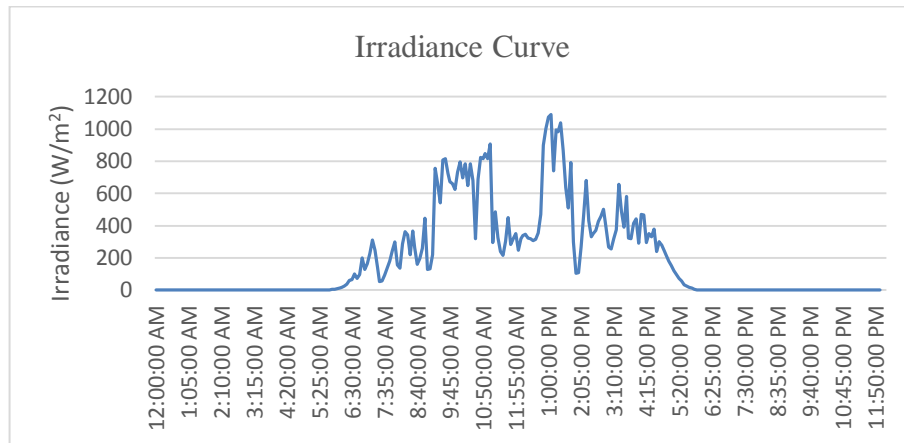
- 160kWp was created by 26 strings each having 24 modules
- 80kWp system was created by 16 strings each having 20 modules.
- 40kWp system was created by 8strings each having 20 modules.

Power factor and RMS voltage were measured in centralized solar PV system according to the following block diagram. The measurements were taken at X1 for different solar PV capacities as 160kWp, 80kWp and 40kWp.



**Figure 45: Centralized System**

Simulation was conducted for four different irradiance patterns. Irradiance curve on 01<sup>st</sup> October 2017 that was fed to the model is shown in Figure 46.



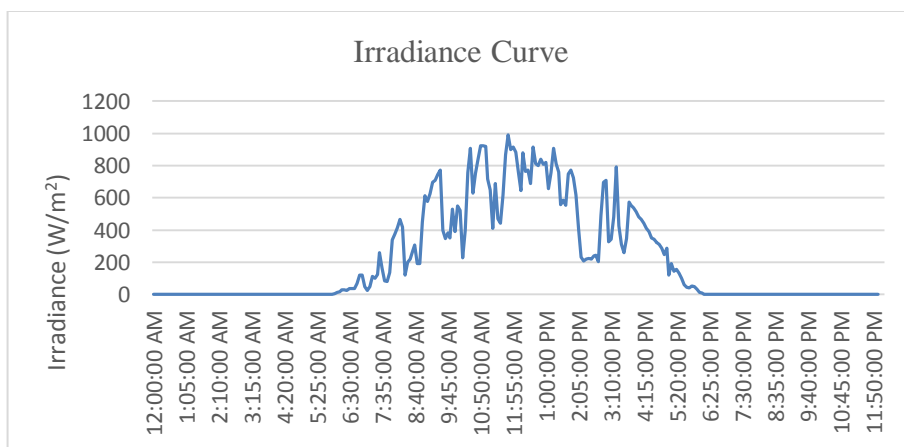
**Figure 46: Irradiance Curve on 01\_10\_2017**

The obtained measurements for 1<sup>st</sup> October 2017 are shown in following Table 6.

**Table 6: Measurements of Centralized System on 01\_10\_2017**

	Vrms (V)	Voltage Variation (%)	PF
160kWp Solar PV System	432 V	8.00 %	0.81-1.00
80kWp Solar PV System	419 V	4.75 %	0.81-1.00
40kWp Solar PV System	408 V	2.75 %	0.81-1.00

The voltage level has increased with the increment of solar PV capacity addition. The irradiance curve on 01<sup>st</sup> August 2017 which fed to the model as the second simulation is shown in Figure 47.



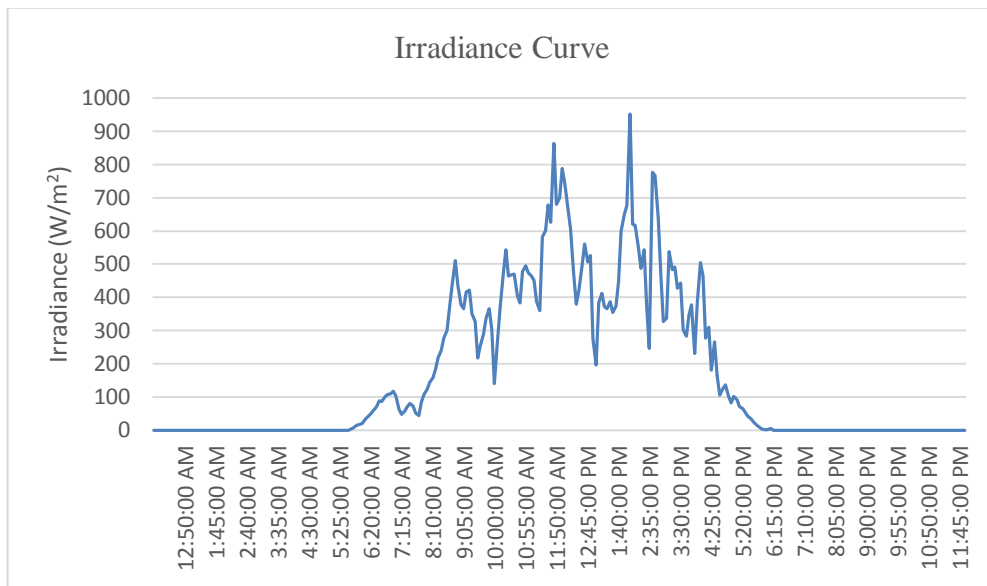
**Figure 47: Irradiance Curve on 01\_08\_2017**

The obtained measurements for 1<sup>st</sup> August 2017 are shown in following table.

**Table 7: Measurements of Scattered system on 01\_08\_2017**

	Vrms (V)	Voltage Variation (%)	PF
160kWp Solar PV System	434 V	8.50 %	0.81-1.00
80kWp Solar PV System	420 V	5.00 %	0.81-1.00
40kWp Solar PV System	408 V	2.75 %	0.81-1.00

The irradiance curve on 01<sup>st</sup> June 2017 which was fed to the model as the third simulation is shown in Figure 48.



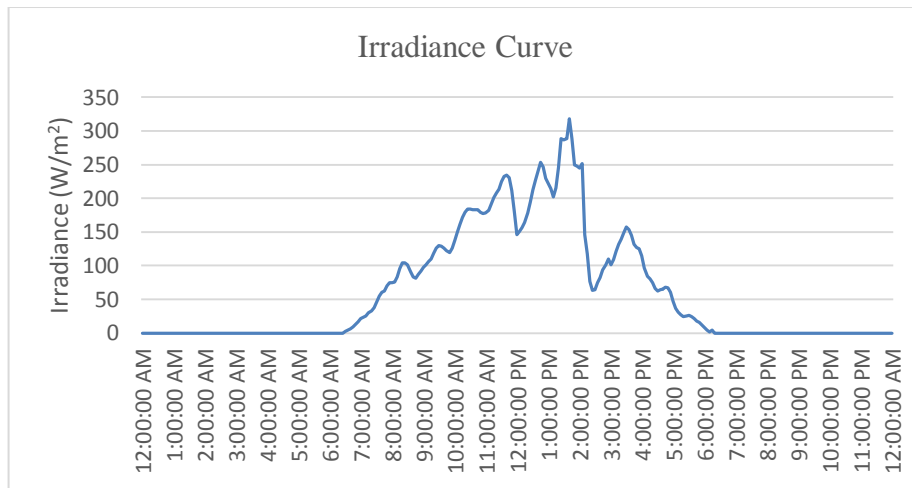
**Figure 48: Irradiance Curve on 01\_06\_2017**

The obtained measurements for 1<sup>st</sup> June 2017 are shown in following table.

**Table 8: Measurements of Centralized System on 01\_06\_2017**

	Vrms (V)	Voltage Variation (%)	PF
160kWp Solar PV System	428 V	7.00 %	0.81-1.00
80kWp Solar PV System	418 V	4.50 %	0.81-1.00
40kWp Solar PV System	407 V	1.75 %	0.81-1.00

The irradiance curve on 01<sup>st</sup> March 2017 which was fed to the model as the third simulation is shown in Figure 49.



**Figure 49: Irradiance curve on 01\_03\_2017**

The obtained measurements for 1<sup>st</sup> March 2017 are shown in following table.

**Table 9: Measurements of Centralized System on 01\_03\_2017**

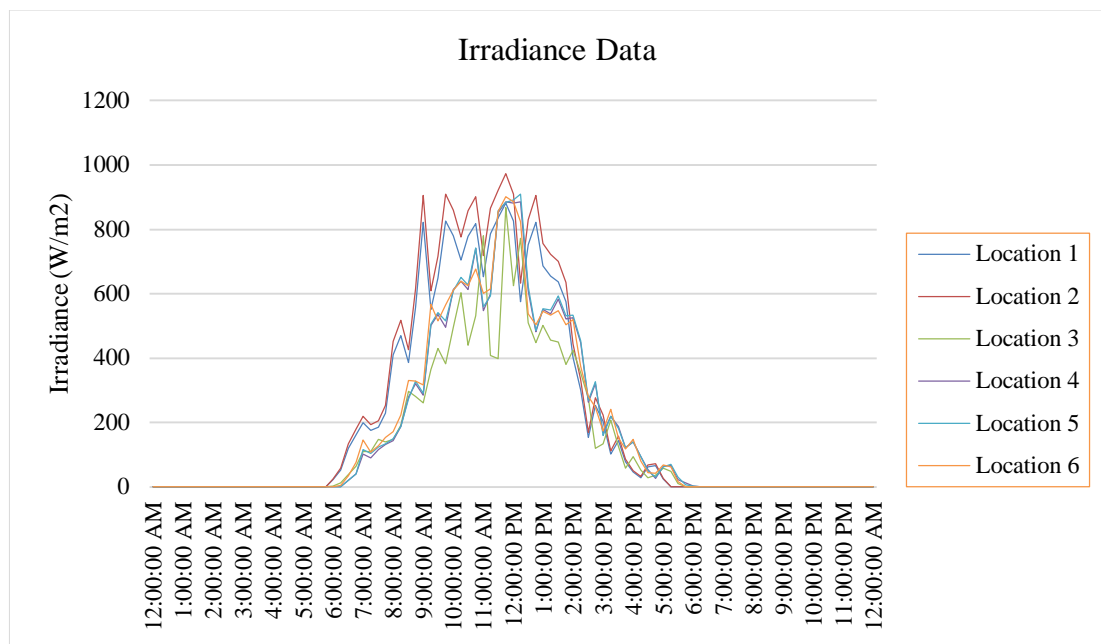
	Vrms (V)	Voltage Variation (%)	PF
160kWp Solar PV System	410 V	2.50 %	0.81-1.00
80kWp Solar PV System	408 V	2.00 %	0.81-1.00
40kWp Solar PV System	405 V	1.25 %	0.81-1.00

According to the results obtained the voltage variation is high in the maximum solar PV capacity which can be connected to this transformer which is 160kWp. On 01<sup>st</sup> March 2017, the irradiance level is very low. Therefore the voltage variation with maximum solar PV capacity has not exceeded the acceptable voltage level.

## 5.2 Scattered Solar PV System

Three separate models of scattered systems were created each having total solar PV capacity of 160kWp, 80kWp and 40kWp. Different solar irradiance patterns which were obtained from Dehiwala area was used to develop different irradiance curves for the solar PV systems of this model.

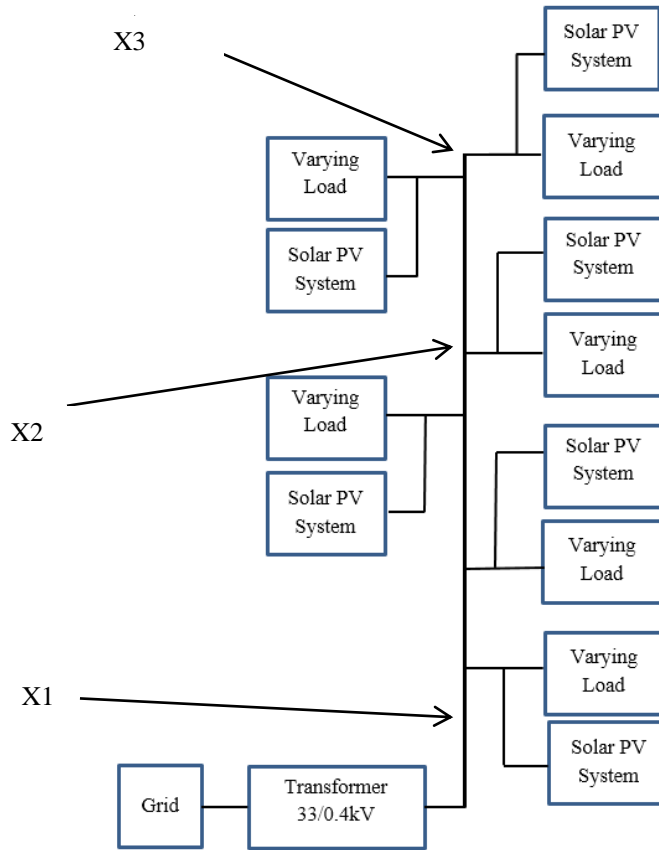
The irradiance curves at six locations in Dehiwala-Mount Lavinia Area which were input to the MATLAB model are as follows.



**Figure 50 : Irradiance Curves**

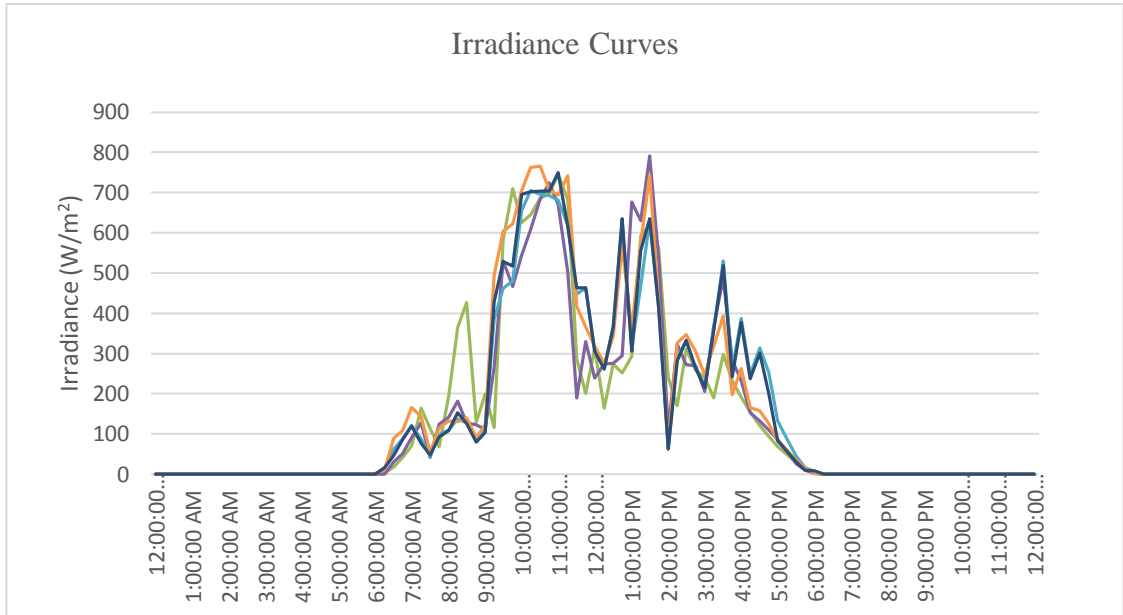
It was observed that there are differences between the irradiance curves although the geographical dispersion of those locations is less. Power factor and RMS voltage were measured in scattered solar PV system according to the following block diagram.

The measurements were taken at X1, X2 and X3. The measurements were taken for different solar PV capacities as 160kWp, 80kWp and 40kWp.



**Figure 51: Scattered System**

The obtained measurements for irradiance curves in Figure 50, on 01<sup>st</sup> October 2017 are shown in following table.

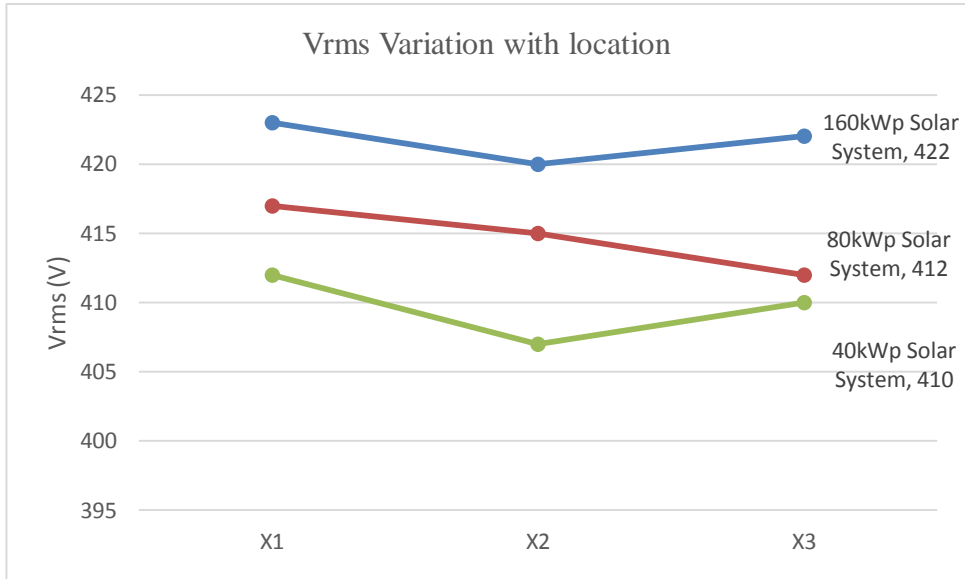


**Figure 52: Irradiance curves on 01\_10\_2017**

**Table 10: Measurements of Scattered System**

	Vrms (V)	Voltage Variation (%)	PF
160kWp Solar System X1	423V	5.75 %	0.9-0.98
160kWp Solar System X2	420V	5.00 %	0.9-0.98
160kWp Solar System X3	422V	5.50 %	0.9-0.98
80kWp Solar System X1	417V	4.25 %	0.9-0.98
80kWp Solar System X2	415V	3.75 %	0.9-0.98
80kWp Solar System X3	412V	3.00 %	0.9-0.98
40kWp Solar System X1	412V	3.00 %	0.9-0.98
40kWp Solar System X2	407V	1.75 %	0.9-0.98
40kWp Solar System X3	410V	2.50 %	0.9-0.98

The obtained measurements are shown in Figure 53.



**Figure 53: Vrms Variation with location**

The obtained measurements for 01<sup>st</sup> August 2017 are shown in following table.

**Table 11: Measurements of Scattered System**

	Vrms (V)	Voltage Variation (%)	PF
160kWp Solar System X1	422V	5.50 %	0.9-0.98
160kWp Solar System X2	421V	5.25 %	0.9-0.98
160kWp Solar System X3	422V	5.50 %	0.9-0.98
80kWp Solar System X1	419V	4.75 %	0.9-0.98
80kWp Solar System X2	417V	4.25 %	0.9-0.98
80kWp Solar System X3	412V	3.00 %	0.9-0.98
40kWp Solar System X1	410V	2.50 %	0.9-0.98
40kWp Solar System X2	408V	2.00 %	0.9-0.98
40kWp Solar System X3	410V	2.50 %	0.9-0.98



The obtained measurements for 01<sup>st</sup> June 2017 are shown in following table.

**Table 12: Measurements of Scattered System**

	Vrms (V)	Voltage Variation (%)	PF
160kWp Solar System X1	424V	6.00 %	0.9-0.98
160kWp Solar System X2	421V	5.25 %	0.9-0.98
160kWp Solar System X3	423V	5.75 %	0.9-0.98
80kWp Solar System X1	416V	4.00 %	0.9-0.98
80kWp Solar System X2	414V	3.50 %	0.9-0.98
80kWp Solar System X3	412V	3.00 %	0.9-0.98
40kWp Solar System X1	407V	1.75 %	0.9-0.98
40kWp Solar System X2	408V	2.00 %	0.9-0.98
40kWp Solar System X3	410V	2.50 %	0.9-0.98

The obtained measurements for 01<sup>st</sup> March 2017 are shown in following table.

**Table 13: Measurements of Scattered System**

	Vrms (V)	Voltage Variation (%)	PF
160kWp Solar System X1	406V	1.50 %	0.9-0.98
160kWp Solar System X2	406V	1.50 %	0.9-0.98
160kWp Solar System X3	405V	1.25 %	0.9-0.98
80kWp Solar System X1	405V	1.25 %	0.9-0.98
80kWp Solar System X2	405V	1.25 %	0.9-0.98

80kWp Solar System X3	406V	3.00 %	0.9-0.98
40kWp Solar System X1	404V	1.00 %	0.9-0.98
40kWp Solar System X2	405V	1.25 %	0.9-0.98
40kWp Solar System X3	404V	1.00 %	0.9-0.98

The above results shows that the effect on the power system is significant when large centralized solar PV plants connected to the power distribution system. The effect is less significant when small scale plants connected to the power distribution system from different geographical locations in close proximity.

### 5.3 Centralized Solar PV System Compensated with Battery

The battery model was integrated to the centralized solar PV system in order to mitigate the effect on the power system. The capacity of the battery was selected as 1300Ah (64kWh) which can store the 10% of the daily energy generated by the 160kWp centralized solar PV system. The battery charger was configured to charge the battery when the power output of the solar PV plant is presenting hikes and discharge the battery when the power output presenting sudden drops. The simulation was carried out to check the improvement of the total system with the battery bank.

**Table 14: Measurements of the centralized system with battery**

	Vrms (V)	Voltage Variation (%)	PF
160kWp Solar PV System with 64kWh battery	421 V	5.25 %	0.81-1.00

### 5.4 Sensitivity Analysis

The feeder impedance was considered as  $0.4865\Omega/\text{km}$  using the typical AAC Fly conductor for the above simulations. The AC current of the solar PV output is high.

Therefore it was decided to use a conductor having higher current carrying capacity. This conductor was implemented in the model assuming that the impedance of the conductor as 0.1218  $\Omega$ /km.

The simulations results obtained for above parameters using the data collected on 01th October 2017 are as follows.

Table 15: Measurements of Centralized System on 01\_10\_2017

	Vrms (V)	Voltage Variation (%)	PF
160kWp Solar PV System	430 V	7.50 %	0.81-1.00
80kWp Solar PV System	416 V	4.00 %	0.81-1.00
40kWp Solar PV System	407 V	1.75 %	0.81-1.00

Table 16: Measurements of Scattered System on 01\_10\_2017

	Vrms (V)	Voltage Variation (%)	PF
160kWp Solar System X1	423V	5.75 %	0.9-0.98
160kWp Solar System X2	421V	5.25 %	0.9-0.98
160kWp Solar System X3	422V	5.50 %	0.9-0.98
80kWp Solar System X1	416V	4.00 %	0.9-0.98
80kWp Solar System X2	415V	3.75 %	0.9-0.98
80kWp Solar System X3	413V	3.25 %	0.9-0.98
40kWp Solar System X1	411V	2.75 %	0.9-0.98
40kWp Solar System X2	407V	1.75 %	0.9-0.98
40kWp Solar System X3	409V	2.25 %	0.9-0.98

---

**DISCUSSION AND CONCLUSION****5.1 Discussion**

Sri Lanka as a developing country depends on the imported fossil fuels for energy generation at present. Sri Lankan government agreed to reduce 20% of the greenhouse gases through the signed agreement COP21 of the United Nations Environmental Framework Convention on Climate Changes (UNFCCC). Therefore Sri Lankan government launched a programme to install 1000MW solar photovoltaic rooftop systems by 2025 and 400MW will be added to the national grid as solar PV parks. The number of solar rooftop installations increased rapidly with the launch of this programme and at present the total rooftop installation capacity is more than 100 MW.

The installed capacity of Sri Lanka through solar PV rooftop systems have been reached to 100 MW in end of year 2017 and ground mounted solar PV capacity has reached to 51.36MW. Most of the rooftop systems are small in capacity. Therefore they can be considered as scattered system. The highest capacity of the total installation under, ground mounted systems is 10 MW. They can be considered as centralized system which includes large capacity in one place.

The intermittency behavior is the main obstacle associated with solar photovoltaic energy generation. The effect of the intermittency behavior on the power system with the interconnection of solar PV rooftop systems was checked during this thesis by modeling two different solar PV systems which are scattered solar PV system and capacity aggregation at one location as a centralized system. The actual irradiance data gather from Dehiwala-Mount Lavinia area was used for the model and it was observed that although the geographical dispersion is less there are differences in irradiance curves.

The tested solar PV capacities were 160kWp, 80kWp and 40kWp. As an example it was checked the characteristic variation of a 160kWp centralized PV system with six

27kWp solar PV systems located nearby. The voltage and power factor were checked at identified locations of two different systems.

The simulation results shows that there is a slight increase in voltage with the addition of more solar PV in scattered network without any domestic or industrial loads. The results obtained after adding loads to the scattered network.

When comparing scattered solar PV systems with centralized PV system, according to the measurements obtained, it reveals that voltage variation and power factor variation is less in scattered systems with smaller capacities compared to centralized systems with higher capacities although the dispersion is small.

## **5.2 Conclusion**

According to the measurements taken, the result can be summarized as the scattered solar PV implementation causes less effect on the power system than the centralized PV system although the system dispersion is small. The effect on the power system due to the intermittent behavior of the solar resource can be mitigated by installing smaller scattered solar PV systems.

The battery storage system is a valuable solution for the centralized system to overcome the negative effect on the power system. A battery which can store 10% of the daily energy of the installed solar PV system can improve the voltage variation of a centralized PV system which 100% utilized the transformer capacity.

## **5.3 Recommendation**

It is recommended to harness the solar PV through small scale scattered systems in order to minimize the effect on the power distribution system. But in concern of centralized solar PV system, it is recommended to implement it with a 10% battery storage facility.

## REFERENCES

- [1] G.J. Shirek and B.A. Lassiter, “Solar plant modeling impacts on distribution systems PV case study” in Rural Electric Power Conference (REPC), 2012 IEEE. doi: 10.1109/REPCon,2012.6194569
- [2] M. J. E. Alam, et al, “An Approach for Online Assessment of Rooftop Solar PV Impacts on Low-Voltage Distribution Networks” in Sustainable Energy. IEEE Transactions on (Volume:5 , No: 2), April 2014
- [3] Fares, R , “Renewable Energy Intermittency Explained: Challenges, Solutions, and Opportunities”. Retrieved March, 2015 Available: <http://blogs.scientificamerican.com/plugged-in/renewable-energy-intermittency-explained-challenges-solutions-and-opportunities/>
- [4] Sri Lanka Sustainable Energy Authority, “Solar resource maps & interpretation” in Solar Resource Atlas of Sri Lanka, 2013
- [5] Moaveni, H., et al, “Quantifying solar power variability for a large central PV plant and small distributed PV plant” in Photovoltaic Specialists Conference (PVSC) IEEE 39th, 2013
- [6] B. Tamimi, et al, “System Stability Impact of Large-Scale and Distributed Solar Photovoltaic Generation: The Case of Ontario, Canada” in Sustainable Energy. IEEE Transactions on (Volume:4 , Issue: 3), 2013. Doi: 10.1109/TSTE.2012.2235151
- [7] M.J. Hossain, et al, “Impacts of wind and solar integrations on the dynamic operations of distribution systems” in Universities Power Engineering Conference (AUPEC), 2011 IEEE.
- [8] S. Kabir, et al, “Impact of large-scale photovoltaic system on short and long term voltage stability in sub-transmission network” in Power Engineering Conference (AUPEC), 2013 Australasian Universities IEEE.