Analysis of Power Quality Issues due to the Proposed Solar Power Plants in Hambantota

[1]JP Karunadasa, [2]MD Ratnasiri

[1]*Kotelewala Defence University, Kandawala Road, Ratmalana, Sri Lanka*
[2]*Ceylon Electricity Board, No.01, Fairline Road, Dehiwala, Sri Lanka*
karu@elect.mrt.ac.lk, engratnasiri@gmail.com

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 paper 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.

Keywords— Power Quality, Solar irradiance, harmonics, photovoltaic systems, PSCAD

I. INTRODUCTION

Solar photovoltaic technology is now expanding into the level of bulk power generation in electric power systems. This is a clean technology and a promising solution to the energy crisis faced by theworld on the fast depletion of conventional energy sources. However, a large scale solar penetration into a system can create power quality issues owing to the random fluctuation of the plant output and careful considerations should be given when designing such interconnections.

Proposed 30 MW solar plant in Hambantota is going to be the largest such plant in Sri Lanka. This will be in addition to the two existing solar plants of capacities 737 kW and 500 kW operating in the same area. Thisresearchinvestigates the power quality aspects of the system likely to be caused by the operation of all three plants.

In this study, first, the present system at Hambantota with the 737 kW and 500 kW plants was modelled using PSCAD (version 4.5) and the simulation results were compared with theactual measurements carried at the sites. This was done to assure the validity of the model. For this comparison, power quality measurements were taken for a period of two weeks by fixing a power logger at the point of common coupling of the 737 kW plant. For the same duration, irradiance, module temperature and power generation data too were gathered from the plant. Power quality parameters were analysed over varying radiation, power output, and module temperature through various graphs.

Then, the complete model incorporating the proposed 30 MW plant was developed. In this process 30 MW plant was modelled as a scaled up version of the existing plants.
The results of the simulation and the recommendations are presented in the paper.

II. STANDARDS FOR PV-GRID CONNECTED SYSTEMS

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. In power quality point of view, it states that voltage harmonic distortion should be less than 2.5 % before connecting the distributed resource. It doesn't describe the limits after a photovoltaic system is added to the system.
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. Individual harmonics level is limited to 3% of rated voltage.

The limits for current harmonics injection is indicated in Table 1 which is same as what is given in IEEE 1547 standard.

III. MEASURED RESULTS

Measured data were plotted in different forms to analyse the variation of power quality parameters. The most important graphs with the comments are given below.

Table 1: Current Harmonic limits given by IEEE 519

Max. Current Harmonic Distortion in % of I_L For voltages 0.12kV-69 kV						
I_{sc}/I_L	Harmonic order (Odd harmonics)					TDD
	h<11	11-17	17-23	23-35	h>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						

A. Voltage variation at PCC

Variation of voltage was plotted against the irradiance over few days and Figure 1 shows the averaged curve for one particular day. Through these results, it was found that the impact of solar penetration has negligible effect on the system voltage which is mainly varying with the loading conditions and other system parameters. The voltage lies within the statutory limits, ± 6% of rated voltage.

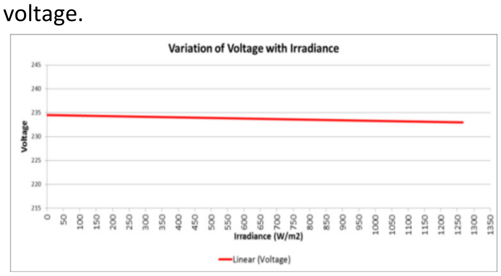


Figure 1: .Averaged voltage variation at PCC against irradiation

B. Current Harmonics

Variation of THD-A (%) over the day time had a unique pattern throughout the measured duration as shown in Figure 2.

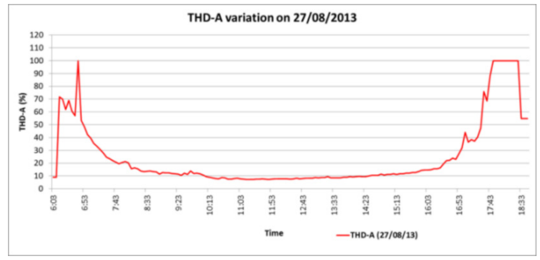


Figure2: THD-A (%) over the time on 27/08/2013

It is clearly seen that the current harmonic distortion is very high at low irradiance, especially in the morning and evening, in the range of 20 % to100% for period of 1.5 hrs. During rest of the time, it varies from8 to 20%.

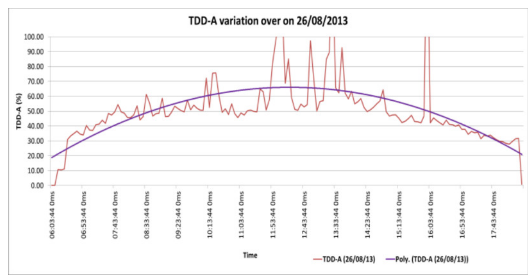


Figure3: Variation of TDD-A at PCC throughout the day

TDD-A value varies from 30% to 100% as shown in Figure 3.All these values violate the limits given in IEEE 519.

Figure 4 shows the averaged curve of THD-A (%) over the irradiance.

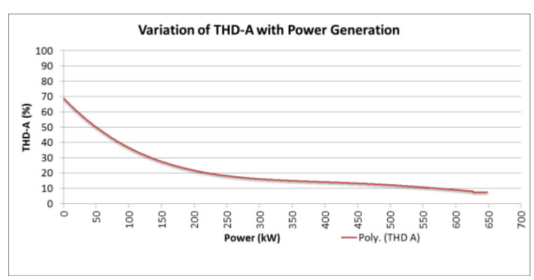


Figure4: Averaged THD-A variation at PCC against irradiation

Table 2: Individual Harmonics distortion in %

Harmonic order	Min. Value	Max. Value	Allowable Limit	Duration exceeding the limits
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

As far as individual harmonics are concerned, it was found that the limits given in IEEE 519 are violated by the order of harmonics given in Table 2.

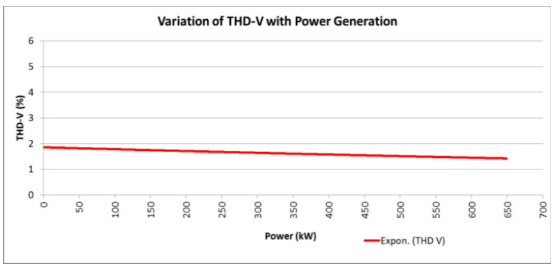


Figure5: Averaged THD-V variation at PCC over irradiation

C. *Voltage Harmonics*

Averaged curve for variation of THD-V (%) over the power generation is shown in Figure 5. It is very much below the limit (5%) given in IEEE 519 since the current harmonic injection of 737 kW plant does not make big impact to the system.This is same as the System THD-V even when power plant is partly in operation. However, the large solar penetration can change this situation.

IV. PSCAD MODELLING

PSCAD model of the power system was developed in terms of appropriate modelling blocks in PSCAD of its major components. The components of the existing solar PV plants were identified from their design details.The host power system beyond the 33 kV busbar of the Hambantota GSS (grid substation) was modelled in terms of its Theveninequivalent.

A. *Solar Array & Inverter*

737 kW plant has 3276 nos.of solar modules each of 225 W in capacity connected to 3 nos. of power electronic inverters.Figure 6 shows the PV array & inverter modelled in PSCAD. Sliding control is used for Irradiation & cell temperature which are to be input to the PV array. The three leg inverter was modelled with IGBTs to which control gate signals are fed. The following parameters were to be configured in PV array block.

- No.of modules connected in series per array
- No.of module stringsin parallel per array
- No.Ofcells connected in series per module
- No.Ofcell stringsin parallel per module
- Reference irradiation
- Reference cell temperature
- Effective area per cell
- Series resistance per cell
- Shunt resistance per cell
- Diode ideality factor
- Band gap energy
- Saturation current at reference conditions per cell
- Short circuit current at reference conditions per cell
- Temperature coefficient of photo current

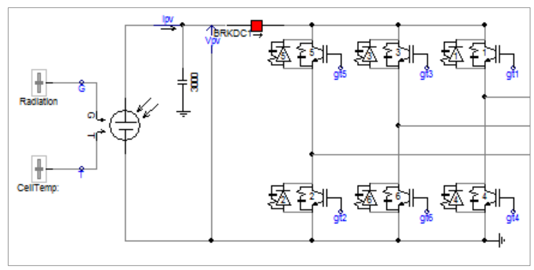


Figure6: PV array and three leg inverter in PSCAD

B. *Internal 250 kVA transformer & filter*

As per the design, the inverter output is connected to a 250 kVA, 190/420 V transformer through an LC filter consisting of 106 µH series connected inductor and 500µF delta connected capacitor bank as shown in Figure 7.

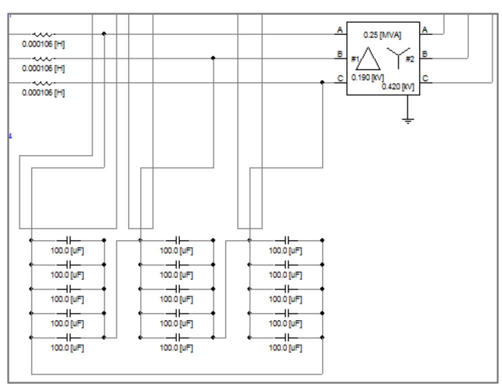


Figure7: LC filter & 250 kVA transformer in PSCAD

C. *33kV equivalent system*

Figure 8 shows the equivalent model of the 33 kV interconnection feeder of Hambantota Grid substation. There are few *P*, *Q* loading points at the critical points. All the three inverter outputsare fed to the 1MVA, 0.415/33 kV step-up transformer. The line impedances were also modelled.

D. *Maximum Power Point Tracking(MPPT)*

Figure 9 shows the modelfor generating reference voltage (V_{mppt}) based on the incremental conductionalgorithm. Photovoltaic array output voltage (V_{pv}) and current (I_{pv}) are fed to the MPPT block through a low pass filter in order to filter out high frequency components. The parameters of filter, gain (G) and time constant (T) were set to 1 and 0.01 respectively.

The incremental conduction algorithm is to track the voltage at which the slope of the PV array power curve shown in Figure 10 is zero where the slope is positive on the left side and negative on the right side. This is done by comparing the instantaneous conductance (I/V) with the incremental conductance (ΔI/ ΔV) as in (1).

$$\left.\begin{array}{ll} \Delta I/\Delta V = -I/V, & \text{at MPP} \\ \Delta I/\Delta V > -I/V, & \text{left of MPP} \\ \Delta I/\Delta V < -I/V, & \text{right of MPP} \end{array}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ (1)$$

E. *IGBT control gate signals*

Sinusoidal PWM technique has been used for generating gate signals which are created by comparing sinusoidal reference waveform with triangular carrier waveform as shown in Figure 11.There are three inputs to generate reference waveform such as angle, magnitude and frequency. Frequency is set to 50 Hz. “Angle” is the parameter that determines the power flow. However, the photovoltaic system should operate so that its maximum power is injected to the grid. In order to do that, the operation voltage of the PV array should always be at V_{mppt}. Therefore, the “angle” is determined by comparing the instantaneous PV array output voltage (V_{pv}) with V_{mppt} and sending it through a PI controller as shown in Figure 12.

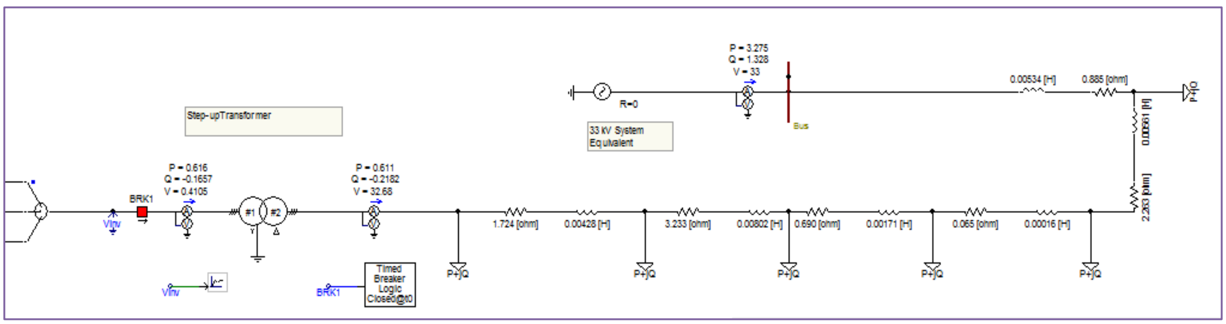


Figure 8: Equivalent model of the interconnection feeder

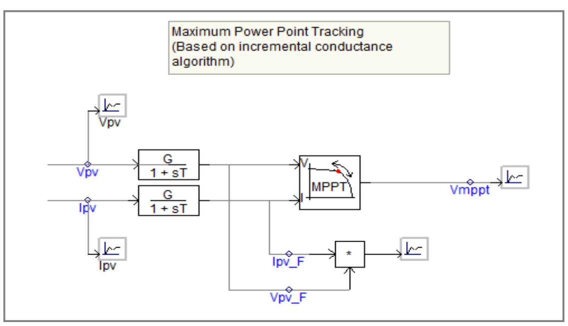


Figure 9: Maximum power point tracking model in PSCAD

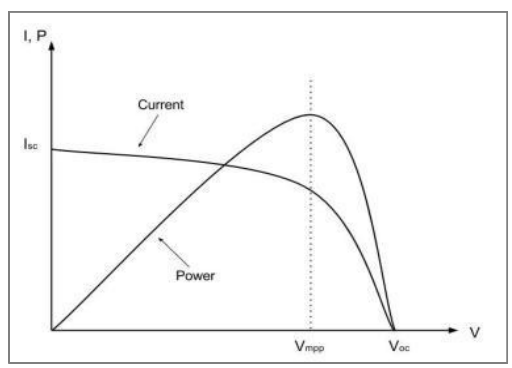


Figure10: Power& VI curves of a PV system

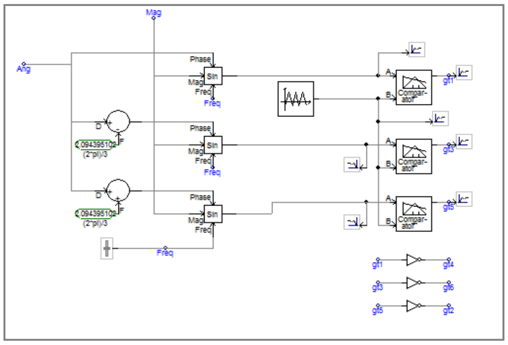


Figure 11: PSCAD model for generating gate signals

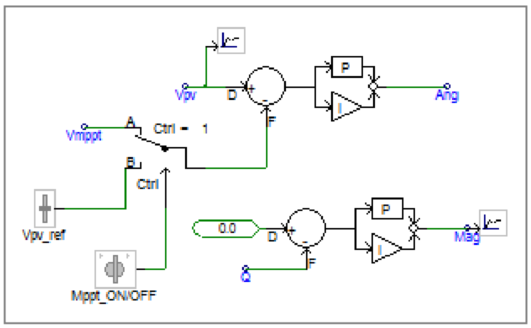
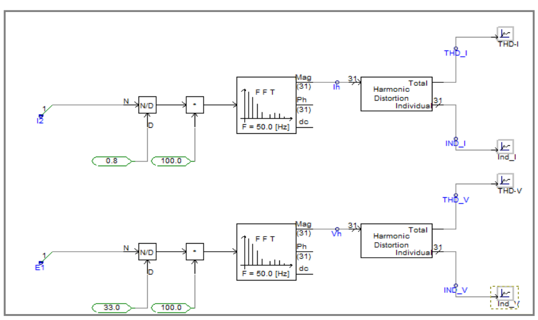


Figure 12 : PSCAD model for generating gate signals

Figure13: PSCAD model for harmonics analysis



The other parameter, "magnitude" determines the reactive power flow. Since the inverters are to be operated at unity power factor, reactive power flow should be zero. Therefore, the reactive power measured at the inverter output is compared with "zero "and sends through a PI controller to generate "magnitude".

F. *Harmonics analysis*

In order to calculate the voltage and current harmonic distortion, the model indicated in Figure 13 was made with the use of standard blocks in PSCAD. The instantaneous RMS voltage and current measured at the PCC are divided by the rated values and fed to the Fast Fourier Transformation block, after multiplying by 100 in order to get the output in percentages. Then the resulting harmonic magnitude is fed to the "Harmonic distortion" block to extract magnitudes of total and individual components.

V. SIMULATION RESULTS OF PSCAD MODEL FOR EXISTING PLANTS

In this section, the simulation results of the PSCAD model for existing plants are presented and compared with the measured values.

A. Power, Voltage and Current

Figure 14 shows simulation results for power, voltage and current at the plant output at the irradiance, 1000 w/m^2 and module temperature, 50 ˚C.

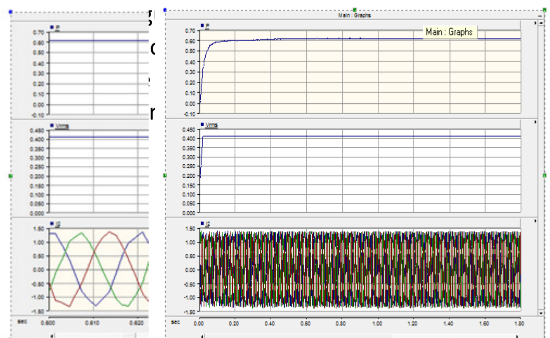


Figure14: Simulation results for P, V, I at high irradiance

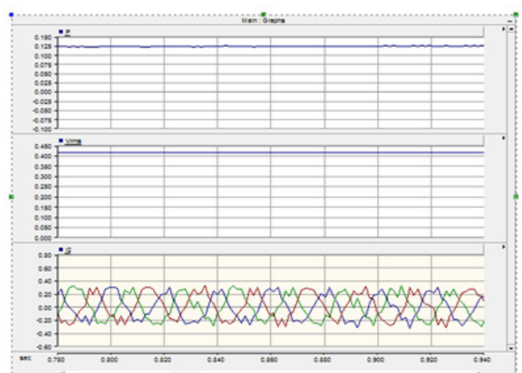


Figure15: Simulation results for P, V, I at low irradiance

B. Current harmonics

Figures 16 and 17 show the THD-A (8%) and individual current harmonics at high irradiance (1000 w/m^2) values, which are consistent with the measured values given in section III. Individual current harmonics at low irradiance (200w/m^2) is given in Figure 18.

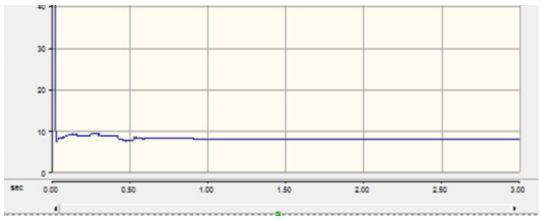


Figure16: THD-A at high irradiance

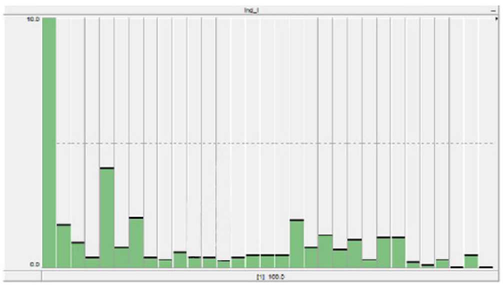


Figure 17: Individual current harmonics at high irradiance

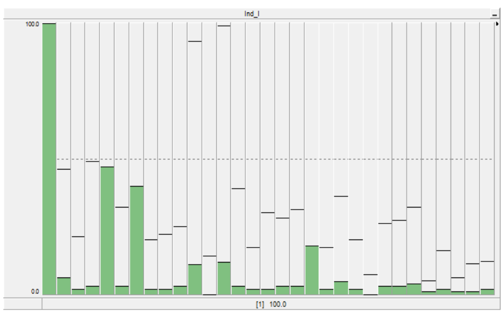


Figure18 : Individual current harmonics at low irradiance

C. Voltage harmonics

Figure 19 shows simulation result of the THD of voltage at high irradiance due to the operation of the existing plants. This is again consistent with the measured values given in section III and clearly shows that the effect on voltage harmonic is insignificant, less than 0.4 % when the background system harmonics are not present.

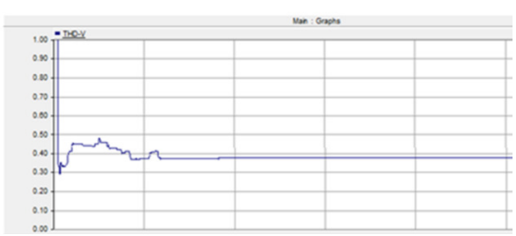


Figure19: Impact to the voltage harmonics at high irradiance

VI. SIMULATION RESULTS OF PSCAD MODEL W ITHTHE PROPOSED 30 MW SOLAR PVPLANT

The PSCAD model of 737 kW existing plant was scaled up to deduce a model for the proposed 30 MW plant (3 nos. of 10 MW plants) with appropriate modifications to account for the changes in the arrangement of PV arrays, internal transformers, LC filters and step-up transformers. It is important to note that the value of 10 MW_p is the global powerof a plant at Standard Test Conditions (STC) but the value at operating conditions (50 ˚C) is 8979 $MW_p$and the actual AC power is about 8240 MW. The equivalent system was modeled for Lynx D/C line directly connected to the 33 kV busbar of the GSS.

A. *Power, Voltage and Current*

Figure 20 shows simulation results of power, voltage and current at the GSS at operating conditions of 1000 w/m^2 and 50 ˚C. The corresponding values are nearly 25 MW, 33 kV and 0.45 kA which are consistent.

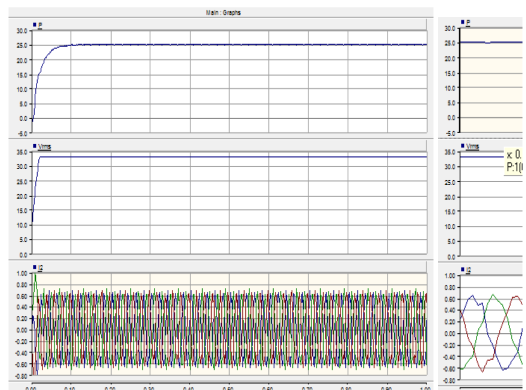


Figure20: Simulation results of P, V, I for 30 MW plant

B. *Current Harmonics*

Figures 21 and 22 show the simulation results for individual current harmonic and THD-A respectively. Accordingly, the 5^{th} (11.2%) and 7^{th} (5.7%) individual harmonics and THD-A (13%) leads current distortion values as 8%,4.07% and 9.33% respectively that appear to violate the standard limits.

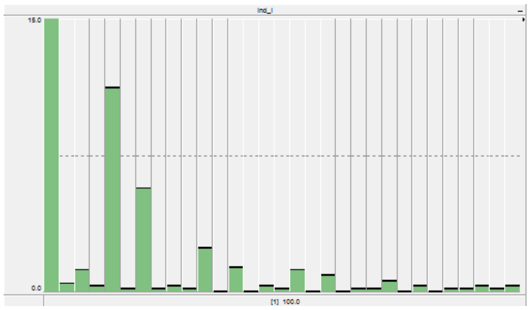


Figure21: Simulation results for individual current harmonics

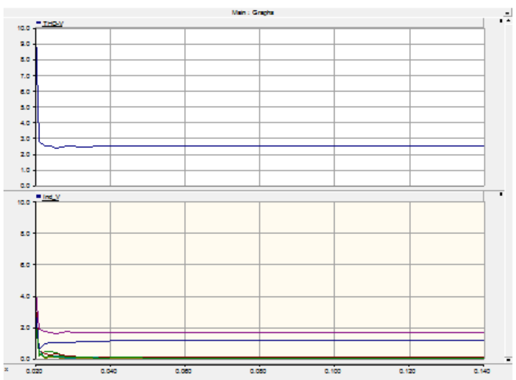


Figure22: Simulation results for THD-A (%)

C. *Voltage Harmonics*

Figure 23 shows THD-V and individual voltage harmonics distortion at the GSS. It is now observed that THD value has been increased up to 2.47% without background harmonics which is around 1.4 %. However, still it lies in the safe range of below 5% given in IEEE-519.

As far as individual voltage harmonics are concerned, the 5th and 7th harmonics values are higher compare to others but they too are below the 3% of individual limit.

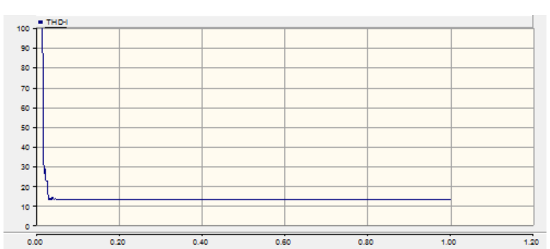


Figure23: Simulation results for THD-V (%) & individual voltage harmonics

VII. 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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BIOGRAPHY OF AUTHORS

Prof. JP Karunadasa is a lecturer of Electrical Engineering at the University of Moratuwa, Sri Lanka. His research interests include Power Electronics, Machines and Power Systems. He has produced more than 30 referred international and local publications to his credit. He is a chartered engineer and reviewer for several international and national journals in Power Electronics and Machines. Prof. JP Karunadasa has supervised over twenty research projects at MPhil and MSc levels and has examined more than 20 theses including 2 PhD theses. At present he is on sabbatical leave at the KotelawalaDefence University, Sri Lanka

M.D.Ratnasiri is an Electrical Engineer attached to Ceylon Electricity Board & currently working at Planning & Development division of Distribution Division 4. He is passed out from Faculty of Engineering, University of Ruhuna and currently pursuing Master's degree in Electrical Installation from University of Moratuwa. He directly involves in embedded generation interconnections in CEB-DD4.