Assessment of Roof-Top Photovoltaic Installations on the Total Harmonic Distortion of Low Voltage Distribution Networks

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Abstract—**The connections of roof-top photovoltaic (PV) systems with low voltage distribution networks have been raised dramatically in the last years due to decreasing in the capital cost and investing in the operating cost. However, the power generation of this source is variable owing to the solar irradiance dependency. This variation in the PV generation can cause a Total Harmonic Distortion (THD) into the low voltage distribution network. In this paper, the effect of roof-top PV system installations on the total harmonic distortion is assessed under different weather conditions. Regarding this, the voltage and current of an on-grid PV system composited at the roof-top of Brunel university London campus are measured and analysed for sunny and cloudy days. Furthermore, this installed PV system is developed based on MATLAB/Simulink. The results prove that the solar irradiance of the surround PV system has a significant impact on the THD-current when compared with the THD-voltage.**

Keywords— **Roof-top Photovoltaic (PV), Total Harmonic Distortion (THD), Low voltage Distribution Networks and Input Solar Irradiance.**

I. Introduction

Recently, the global installations of photovoltaic (PV) sources have been increased dramatically. This is because that several countries have connected large PV plants with a grid such as China and India. Moreover, other countries have encouraged their citizens to install PV systems on the roof-top of their houses such as USA and UK. By the end of 2019, the global installations of PV systems exceeded 600 GW of which 72% in last five years [1]. However, the variable and light power production of the PV system is considered one of the biggest impact on the performance of a power distribution network when it is connected with utilize grid, because its electrical generation totally depends on the weather conditions [2]. This causes distortion in the output generation of PV system which knowns as a Harmonic Distortion. Although there are several measurements for this issue, the Total Harmonic Distortion (THD) is common considered, which is clarified as the percentage-ratio of the root sum-square of the order harmonic value to its primary value [3].

Many studies have been investigated in this challenge to assess it on the output-power feature of PV generation, among them, the authors in [4] have designed a model of PV inverter using Simulink/MATLAB to analyse the effect of high current THD on PV system operation under different solar irradiances. In same idea, the authors in [5] have proposed an accurate and fast Simulink model of grid-connected PV system to conduct the order harmonic distortion in property way. In contrast, the authors in [6] presented experimental results about the benefits of PV system when is connected with utilize grid by improving the total harmonic distortion of a voltage grid. The results of experimental PV system which is installed in the urban environment in Barisal are compared with the simulation results of a hypothetical PV system connected in the same area by using the ANAREDE-software.

In the same way, the authors of [7] have introduced an experimental study about the impacts of an On-grid PV system on the THD of low-voltage distribution network, which is determined by the EN50160 standard. The study was based on real data of THD on four PV systems with two transformer stations installed at the civilized electric distribution networks in Slovenia. While the authors in [8] have discussed the effect of types of an input solar irradiance on the THD of low power destitution network when the PV system connect with it. In this work, The MATLAB/Simulink model is developed using the data of an input real solar irradiance conducted from UTEM laboratory in Malaysia. In [9], the authors the effect of roof-top PV system installations on a Low voltage distribution network based on the THD issue. Different types of PV inverters are assessed in various operating days which are tested at the University of Queensland PV site in Australia.

In this paper, experimental data for grid-connected PV system installed at Brunel university London (as displayed in Fig.1) are analysed to assess the influence of the input solar irradiance on the THD of a low power distribution network. The voltage and current of the grid are conducted under sunny and cloudy days and then they are compared based on the THD issue. The Simulink/MATLAB model for the grid-connected PV system is developed to discuss the simulation results with experimental results. The study reveals that the THD-current is much effect by the variation of weather conditions when compared with THD-voltage. The rest of this research is marshalled as follows: Sections II covers the principal work of a PV system. While Section III introduces the issue of a total harmonic distortion. Section IV presents the procedure of the conducted data. In Section V, the results are provided and discussed. Finally, Section VI contains the conclusion.

FIG. 1. THE ROOF-TOP PV SYSTEM BUILT-UP AT THE LABORATORIES OF BRUNEL UNIVERSITY LONDON, UK.

II. ON-GRID PV SYSTEM

The essentially part in PV system to generate an electrical energy from irradiance is a solar cell. The solar cell is diode (semiconductor) which is connected in parallel and series resistances to design the PV cell. The general equation of a PV generation is given by Eq.(1) [10][11]:

$$I = I_{ph} - i_D \left[\exp\left(\frac{V + I.R_S}{V_T} \right) - 1 \right] - \left[\frac{V + I.R_S}{R_p} \right] \dots\dots (1)$$

where Iph is the generated current based on irradiance, I_D is the reverse saturation current of the PV diode, V is the cell voltage, VT is the thermic voltage (kT/q), K is the constant of Boltzmann, T is the temperature operation in Kelvin, q is the charge of electron, Rs is the series resistance of actual PV cell and Rsh is the parallel resistance of the actual PV cell. The PV array consists of many PV cells connect in series and parallel to give different PV configurations.

Next, A power conversion device is connected with PV array to enhance the quality of the output of PV system generation [12]. In general, there are two types of a power converting system which are divided into a single and double stage. Usually, the double stage is used to achieve the high-quality output-power from PV array; the first stage is employed to boost the input voltage and track the output maximum power of a PV array, while the second stage converts the DC power of a PV array into high-quality AC power. Due to the dependency of the PV generation on the variation of the input solar irradiance, several technical impacts appear in the operation system such as an overvoltage, voltage Fluctuation, power factor and harmonic distortion[13][14]. However, the harmonic distortion is considered one of the biggest challenges which happens because of the high variation in the output generation of PV system.

III. HARMONIC DISTORTION

An On-Grid PV system can cause several technical issues for power distribution network due to the light and various generation of a PV system during one-day. Although several technical issues are faced the performance of a national grid when the PV generation is connected such as Overvoltage, voltage Fluctuation and power factor, harmonic distortion is considered one of the major impacts on the operation of grid-connected PV systems. Harmonic distortions are known the variation in voltage and current electrical distribution network due to changes in operation conditions. It is defined mathematically as the parentage-ratio of the root sum-square of the order harmonic value to its primary value, as explained in Eqs. (2) and (3) [15]:

$$THD(I) = \frac{\sqrt{\sum_{n=2}^{\infty} I_{n=2}^2}}{I_1} \times 100\% \dots\dots\dots\dots\dots (2)$$

$$THD(V) = \frac{\sqrt{\sum_{n=2}^{\infty} V_{n=2}^2}}{V_1} \times 100\% \dots\dots\dots\dots\dots (3)$$

where I_1 and V_1 are the value of the primary frequency (50 Hz) component of the current and voltage, respectively, while I_n and V_n are the nth order harmonic for the current and voltage, respectively. The integration of PV systems generation to power distribution network must comply with the relevant standard form of the utility-grid designer. In general, many standard forms have been tested and recorded such as IEC 61727, ENC 61000-3-2, IEEE 1547 and IEEE 519-1992.

In this research, the standard IEEE 519-1992 is considered which refers that the percentage value of the THD for the grid-voltage should not exceed 5% for different types and sizes of PV systems, as presented in Table I [16]. While the THD of the grid-current should not exceed 5% when the maximum generation form the source under 20A which is the range of this research test, as explained in Table II. The maximum power voltage of the PV module which is tested in this work is 24 V, while, it open circuit voltage is 30.2 V. The short circuit current of the PV module test is 8.54 A, while its maximum current is 7.71 A. five PV modules are connected in series to generate about 250V and 3A in the side of a low voltage distribution network.

TABLE I. THE STANDARD IEEE 519-1992 FOR VOLTAGE HARMONIC DISTORTION

Grid-Voltage	2.3 ~ 69 kV	69 ~ 161 kV	> 161 kV
Individual Harmonic	3%	1.5%	1%
THD	5%	2.5%	1.5%

TABLE II. THE STANDARD IEEE 519-1992 FOR CURRENT HARMONIC DISTORTION FOR THE VOLTAGE VALUE OF 0.12~69 KV

Grid-Current (A)	Odd Harmonic Order					THD %
	<11	11<h<17	17<h<23	23<h<35	35<h	
< 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

IV. REAL DATA OF ON-GRID PV SYSTEM

An on-grid PV system has been installed at the lab of Brunel University London, Uxbridge, UK, to conduct the voltage and current of a grid-side comparison of input irradiance, as show in Fig. 2. The PV array, which is used in this test, consists of five PV-modules conducted in series. The type of the PV module is Sharp NU-S5E3E 185-Monocrystalline with actual efficiency about 14.1%. Each PV module consists of 48 PV cells. The actual power of this PV module is 185W under a standard operating test.

The temperature-coefficient of a maximum power PV module is -0.485%/^{0}C and the temperature-coefficient of its short circuit current is +0.053%/^{0}C, while the temperature-coefficient of its voltage open circuit is +0.053%/^{0}C. This PV array is connected with the electrical distribution network of Brunel university lab in side of a low voltage by using a Sunny Boy Inverter which has inbuilt communication system. To measure the essential parameters of the PV system, Sunny Controller Pulse is linked to this inverter by RS485 cable. Then, a weather station is installed and connected to the Sunny Controller Pulse by using RS232 cable.

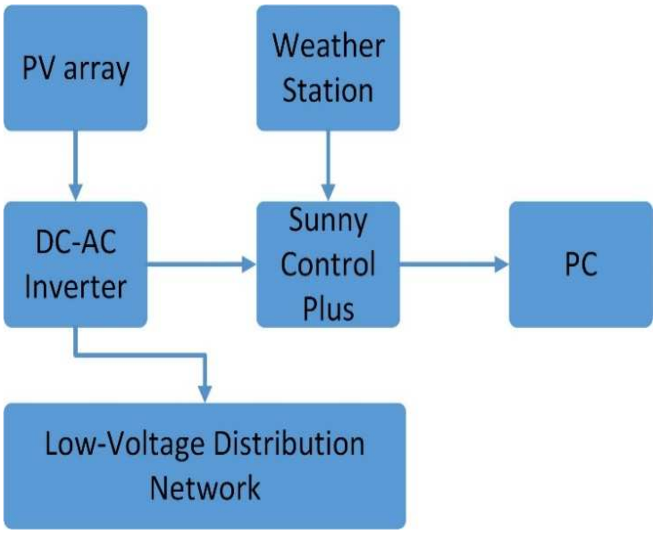


FIG. 2. SCHEMATIC DIAGRAM OF AN EXPERIMENTAL DATA COLLECTION.

To monitor and control the on-grid PV system, a SCADA system is used. Then, the SCADA system is connected to the local area network (LAN) of the Brunel university using TCP/IP-SBC Net Port system. The time sequence of reading data is designed to read and collect data every 5-minutes during the day and it switched off at night time, and then turns on every 15 minutes to exam the climatic conditions automatically. The weather parameters that surround PV system as well as the main parameters of the on-grid PV system are recorded on PC and stored as an Excel-Sheet. In this work, the grid-voltage and the gid-current comparison with the input solar irradiance are collected to study the effect of PV generation on the low voltage distribution network performance based on a harmonic distortion issue.

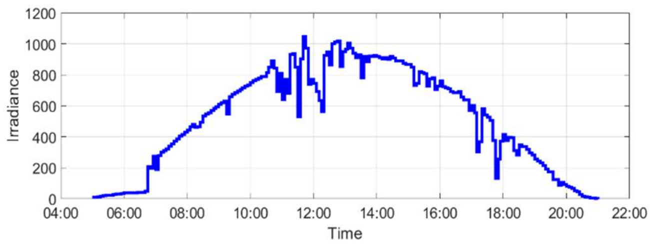
V. RESULTS AND DISCUSSION

In this work, real data are collected form experimental PV system connected with micro-grid installed at the roof-top of Brunel university London campus. The grid voltage (V-grid) and current (I-grid) are measured comparison of input solar irradiance to hold various data as explained in Section IV. The V-grid and I-grid Vs irradiance for sunny and cloudy days are collected to assess the effect of grid-connected PV system on harmonic distortion under different weather conditions. The input solar irradiance of a sunny and cloudy day has been used, as shown in Fig. 3. They are collected by using a weather station installed surrounded PV array, as mentioned in Section IV. A simulation model based on MATLAB/Simulink for this system is developed to calculate the THD by using a tool called 'FFT analysis' which is found in the Power GUI block. The simulation of the grid-connected PV system consists of a PV array, DC–DC boost converter with controller used maximum power point tracking (MPPT) technique, DC-AC inverter, step-up transformer and utility grid.

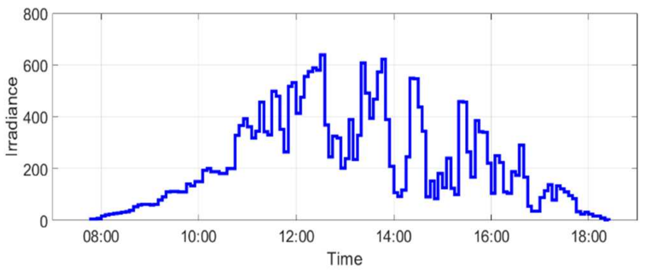
As shown in Fig.4, the THD-voltage was recorded 2.28% at the sunny day time and 2.48% at the cloudy time. This is because that the value of THD-voltage is not extremely influenced by the different levels of the input irradiance, as shown in Fig. 5. In contrast, the THD-current was measured about 3.17% and 14.10% at the sunny and cloudy day time, respectively, as presented in Fig. 6. This indicates that the value of the THD-current is extremely influenced by the different levels and types of the input irradiance due to a variable generation in the I-grid, as shown in Fig. 7. Those results show that The THD -current at cloudy days is exceed the promoted value which is 5%. Hence, the optimised system should be added to the roof-top PV system when it is connected with low power distribution network such as a filter. The comparative study between the THD of V-grid and the THD of I-grid is summarised in Table III.

TABLE III. COMPARATIVE STUDY BASED ON THE THD OF INSTALLED PV SYSTEM FOR SUNNY AND CLOUDY DAY.

Days	**THD %**	
	Grid-Voltage	**Grid-Current**
Sunny	2.28	3.17
Cloudy	2.48	14.10

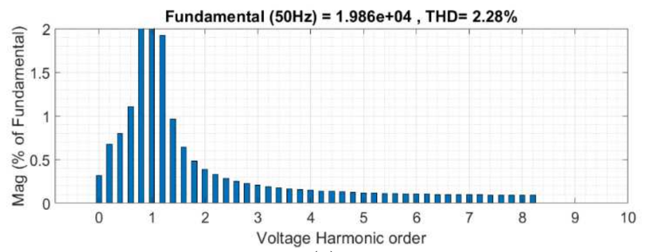


(A)



(B)

FIG. 3. THE INPUT SOLAR IRRADIANCE (A) SUNNY-DAY, (B) CLOUDY-DAY.



(A)

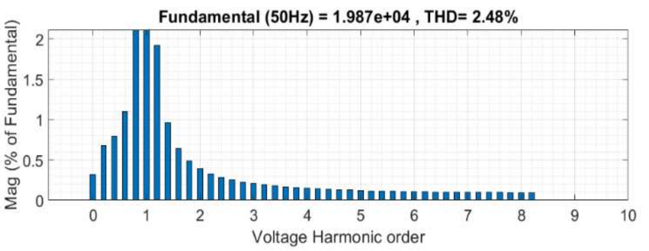


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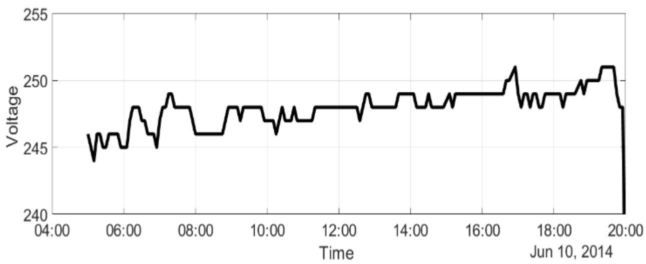
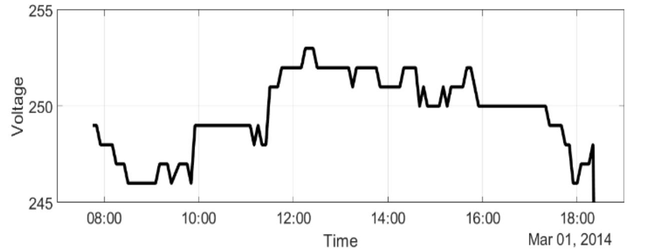
FIG. 4. THD-VOLTAGE AT (A) SUNNY-DAY TIME, (B) CLOUDY-DAY TIME.

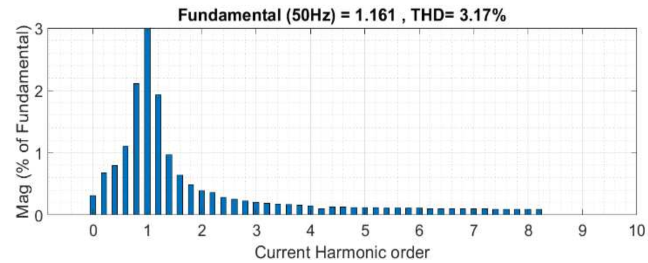


(A)

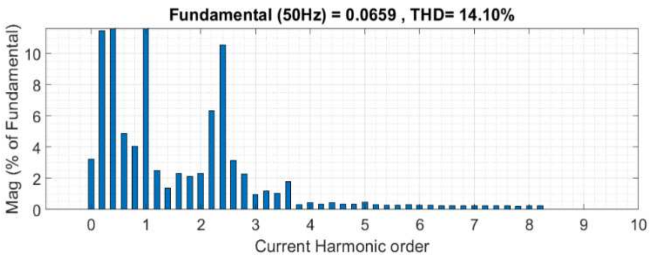


(B)

FIG. 5. V-GRID AT (A) SUNNY-DAY TIME, (B) CLOUDY-DAY TIME.

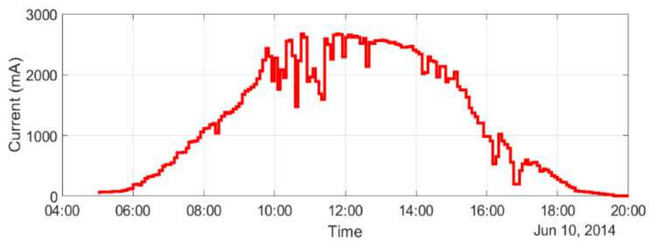


(A)

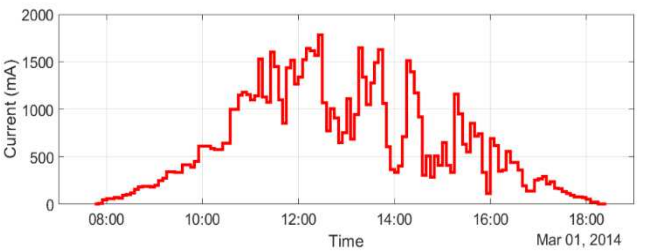


(B)

FIG. 6. THD-CURRENT AT (A) SUNNY-DAY TIME, (B) CLOUDY-DAY TIME.



(A)



(B)

FIG. 7. I-GRID AT (A) SUNNY-DAY TIME, (B) CLOUDY-DAY TIME.

VI. CONCLUSION

Experimental data and simulation results for an on-grid PV system which is built up at the roof-top of Brunel university London lab are analysed to assess the impact of PV system generations on the total harmonic distortion of low voltage distribution networks. The study has been shown that the input solar irradiance of a surround PV array has a significant effect on the THD-current when compared with the THD-voltage due to the high variation and low diffusion. To sum up, the grid-voltage and gid-current of the installed PV system comparison with the input solar irradiance have been measured under a sunny and cloudy days. A model based on MATLAB/Simulink has been proposed for the on-grid PV system. The THD-Voltage and the THD-current are calculated and analysed. The study proves that the optimised system should be added to the roof-top PV system when it is connected with low voltage distribution network such as a filter to avoid the hight total harmonic distortion in the grid-current. In future work, it is recommended to study the impact of PV system parameters on the order harmonic distortion individually.

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REFERENCES

[1] G. Masson et al., "IEA PVPS report - Trends in Photovoltaic Applications 2020". 2020.

[2] S. D. Al-Majidi, M. F. Abbod, and H. S. Al-Raweshidy, “Design of an intelligent MPPT based on ANN using a real photovoltaic system data,” in 54th International Universities Power Engineering Conference (UPEC), pp. 1–6, Sep. 2019.

[3] B. Yang, W. Li, Y. Zhao, and X. He, “Design and analysis of a grid-connected photovoltaic power system,” IEEE Trans. Power Electron., vol. 25, no. 4, pp. 992–1000, 2010.

[4] Y. Du, D. D. C. Lu, G. James, and D. J. Cornforth, “Modeling and analysis of current harmonic distortion from grid connected PV inverters under different operating conditions,” Sol. Energy, vol. 94, pp. 182–194, 2013.

[5] A. Menti, T. Zacharias, and J. Milias-Argitis, “Harmonic distortion assessment for a single-phase grid-connected photovoltaic system,” Renew. Energy, vol. 36, no. 1, pp. 360–368, 2011.

[6] J. Urbanetz, P. Braun, and R. Rüther, “Power quality analysis of grid-connected solar photovoltaic generators in Brazil,” Energy Convers. Manag., vol. 64, pp. 8–14, 2012.

[7] S. Seme, N. Lukač, B. Štumberger, and M. Hadžiselimović, “Power quality experimental analysis of grid-connected photovoltaic systems in urban distribution networks,” Energy, vol. 139, pp. 1261–1266, 2017.

[8] M. Ayub, C. K. Gan, and A. F. A. Kadir, “The impact of grid-connected PV systems on Harmonic Distortion,” 2014 IEEE Innov. Smart Grid Technol. - Asia, ISGT ASIA 2014, pp. 669–674, 2014.

[9] A. Chidurala, T. Saha, and N. Mithulananthan, “Harmonic characterization of grid connected PV systems & validation with field measurements,” IEEE Power Energy Soc. Gen. Meet., vol. 2015-Septe, 2015.

[10] S. D. Al-Majidi, M. F. Abbod, and H. S. Al-Raweshidy, “Design of an Efficient Maximum Power Point Tracker Based on ANFIS Using an Experimental Photovoltaic System Data,” Electronics, vol. 8, no. 8, p. 858, Aug. 2019.

[11] S. D. Al-Majidi, M. F. Abbod, and H. S. Al-Raweshidy, “A Particle Swarm Optimisation-trained Feedforward Neural Network for Predicting the Maximum Power Point of a Photovoltaic Array” Engineering Applications of Artificial Intelligence, vol. 92, no. June, pp. 103688, 2020

[12] F. Obeidat, “A comprehensive review of future photovoltaic systems,” Sol. Energy, vol. 163, no. March, pp. 545–551, 2018.

[13] F. H. M. Rafi, M. J. Hossain, and J. Lu, “Hierarchical controls selection based on PV penetrations for voltage rise mitigation in a LV distribution network,” Int. J. Electr. Power Energy Syst., vol. 81, pp. 123–139, 2016.

[14] Y. Yoldaş, A. Önen, S. M. Muyeen, A. V. Vasilakos, and İ. Alan, “Enhancing smart grid with microgrids: Challenges and opportunities,” Renew. Sustain. Energy Rev., vol. 72, no. January, pp. 205–214, 2017.

[15] X. M. Huang, W. B. Lu, and J. Li, “Photovoltaic grid simulation and harmonic analysis,” QR2MSE 2013 - Proc. 2013 Int. Conf. Qual. Reliab. Risk, Maintenance, Saf. Eng., no. 101, pp. 2014–2017, 2013.

[16] L. H. and M. S. Ketut Dartawan, Ricardo Austria, “Harmonic Issues That Limit Solar Photovoltaic,” in World Renewable Energy Forum2012, 2013, pp. 1–7.