Electrical Engineering
https://doi.org/10.1007/s00202-020-01110-7

ORIGINAL PAPER

Developed analytical expression for current harmonic distortion of the PV system's inverter in relation to the solar irradiance and temperature

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Received: 15 July 2020 / Accepted: 17 September 2020

Abstract
This paper deals with modeling and simulation of the total harmonic distortion of the current (THD_I) dispatched from the inverter and connected to nonlinear load. The change of THD_I was examined in relation to the ambient temperature (T) and solar irradiance (G). The developed model is being used to extract parameters for a given THD_I as a function of temperature and solar radiation. This study outlines the working principle of photovoltaic (PV) panel as well as PV array. Off-grid PV system is modeled by using Matlab/Simulink program, and detailed analytical study has been carried out in this work. The design, modeling and simulation of this study are performed from 50 up to 988 W/m^2 for solar irradiance. Harmonic components have negative effects on the steady-voltage stability of the PV system. Therefore, analytical expression is needed for steady-state stability analysis in order to reduce negative effects. Hence, two analytical expressions of THD_I were obtained by two new different methods which are statistical package for the social sciences program and genetic expression programming. Eventually, two different methods have been verified by the Matlab/Simulink program in order to find out THD_I and demonstrated the effectiveness of the proposed strategy. As a result of this study, it is observed that input current THDI of nonlinear load is too high at low irradiance. It is suggested that active harmonic filters should be used at low irradiance in order to produce better quality energy and avoid damages in the PV system.

Keywords Solar irradiance · Photovoltaic panel temperature · Total harmonic distortion · Photovoltaic system · Nonlinear load

1 Introduction

Nowadays, the installations of PV have been growing dramatically because of the rapid dropping in the price of PV panels, and its many advantages such as abundant source of energy, having a very low operating cost and not causing environmental pollution [1–6]. These make PV solar energy more attractive among other renewable energy sources.

In this study, it is aimed to find the analytical expression of THD_I in terms of variables of temperature and irradiance in PV system. This analytical expression has many advantages in the analysis process of the PV system. Irradiance and ambient temperature are affecting PV solar systems severely.

High temperature may reduce the cells efficiency and the lifetime of the equipment [3, 4], whereas solar irradiance variation causes frequency disturbances and trip of the PV system. That's why the effect of irradiance and temperature on the PV solar system has been studied widely in the previous literatures. In this paper, the relation between irradiance

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Published online: 03 October 2020

and ambient temperature in one side and the THD_I in another side is investigated. Another parameter [7, 8] that plays an important role on PV system effectiveness is the THD_I.

Semiconductor elements in the power electronics devices generate the THD_I [6–9]. Any injected harmonics from nonlinear loads or power electronic devices can damage the equipment or cause protective relay failures if the harmonic come close or align with any one of the frequencies of the resonant modes [10]. The effects of THD_I on the PV systems have been studied widely in the literatures. In [9–11], the relation between THD and pulse width modulation (PWM) is studied, whereas in [12] the relation between the used controller and the generated THD is investigated. However, none of the previous works discussed the relation between THD_I and the irradiance and temperature and developed a mathematical expression to understand the relation. In [13], a unique modeling of harmonics in PV systems has been developed.

In [14], the THD in relation to T and G has been studied. The authors concluded that THD_I analysis is more important than voltage THD analysis in the case of PV systems under varying solar irradiation. They also found that the current harmonics are higher at low solar irradiation. However, the collected data and analysis in [14] are not deep and there is no any developed analytical expression. Having more THD_I during low solar irradiation might force PV system operators to either use bigger and more expensive filters or even disconnecting the PV system from the grid to avoid paying the high THD_I levels penalty specified by the utility operator. Investigating the THD_I in relation to T and G is essential for efficient PV system and off-grid PV power system; in addition, developing a mathematical expression is so much important for some reasons such as understanding the relation, steady-state stability analysis and reducing the negative effect. This paper deals with the modeling and simulation of THD_I in relation to the G and T. It is called the Maximum Power Point Tracker (MPPT). It follows the peak value of the power and ensures that it is sent to the load. It is generally used in PV system and wind turbines [14, 15].

The proposed solar system is a combination of a boost DC/DC converter, DC/AC single-phase solar inverter and nonlinear load as shown in Fig. 1. Thus, analytical expression of THD_I was found by new methods which are SPSS program and GEP. Finally, Matlab/Simulink study has been performed to verify the theoretical analysis and demonstrate the effectiveness of the proposed strategy.

Methodology of this study was implemented as follows: a prototype experiment was carried out in the province of Mardin which is located in Turkey's southeastern region, in the electrical laboratory of the Vocational School of Mardin Artuklu University. By connecting three 315 W panels to each other, a prototype experiment was carried out by mounting it on the roof of the building where the laboratory

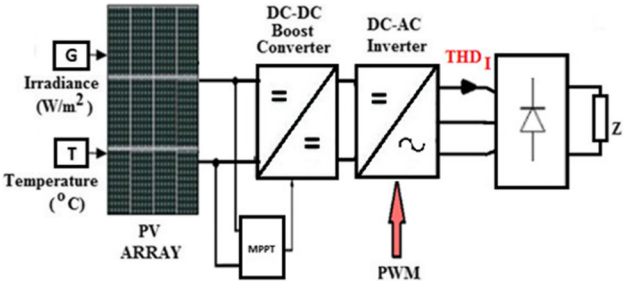

Fig. 1 Schematic diagram of the PV system

is located. In the experiment set, a three-phase half-wave uncontrolled rectifier, resistor and capacitor which are connected in parallel as a nonlinear load in order to make THD measurements related to temperature and radiation. The experiment was carried out in the spring season and on a sunny and partly cloudy day. Using a thermometer to measure the temperature and a solar meter to measure solar radiation, measurements were made between 06:00 a.m. and 17:25 p.m. hours and data were recorded every half hour. Depending on the temperature and radiation measured on the panels, the THD value was measured with an HT brand analyzer. The temperatures measured by the thermometer are recorded every half hour and are shown in Table 1. Likewise, the solar radiation is recorded every half hour and is shown in Table 1.

The rest of this paper is organized as follows: Sect. 2 describes harmonics distortion in solar energy system; Sect. 3 describes the relation between THD_I on one side and solar irradiance and temperature on the other side; Sect. 4 shows PV system configuration and simulation results; Sect. 5 presents the finding analytical equation of the THD_I in relation to solar G and T; then, Sect. 6 concludes the paper and suggests possible future work.

2 Harmonics distortion in solar energy system

Harmonic currents are generated by power electronics-based devices, and cause serious power quality problems in off-grid PV systems. Harmonics are being increased day by day in PV power systems. As a result, heat losses, power bills and reduction in the efficiency occur in the system. Inverters, DC/DC boost converter and battery chargers are the most significant harmonic sources in PV off-grid power systems. The current equation that includes harmonic components generated by solar irradiance (for $T = 20$ °C, $G = 940$ w/m^2) is given in Eq. (1).

$$i(\omega t) = 5.069\sin(\omega t + 0.251) + 2.33\sin(4\omega t - t + 133.6) + 2.297\sin(6\omega t + 48.251) + 1.617\sin(9\omega t - 48.48)$$

Table 1 Temperature and solar irradiance and THD_I measurements for the experimental study

Time (h)	Temperature (°C)	Solar irradiance (w/m^2)	THD_I %
6:00	6	50	268.5
6:30	7.4	60	265.9
7:00	8	120	209.9
8:00	14	155	202.2
8:30	14.3	280	186.8
8:45	15	390	175.3
9:00	16	560	161.4
9:15	16.5	620	157.5
9:30	17	725	152.2
9:45	17.6	770	150.5
10:00	19	820	149.8
10:15	19.7	860	148
10:30	20	880	147.6
10:45	20.2	920	147.1
11:00	20.7	940	146.9
11:15	21	952	146.8
11:30	21.7	955	146.8
11:45	22	979	146.7
12:00	22.4	981	146.7
12:15	23	985	146.6
12:30	23.2	988	146.6
12:45	22	975	146.7
13:00	22.5	960	146.7
13:15	21	950	146.8
13:30	21.6	940	146.9
13:45	20	910	147.8
14:00	19.1	860	148
14:15	19	855	148.1
14:30	18.3	850	148.2
14:45	18	825	148.8
15:00	17	770	150.5
15:15	15	710	152.9
15:30	14	675	154.5
15:45	13	640	156.4
16:00	11.5	550	162
16:15	11	405	173.9
16:30	10.4	290	185.7
16:45	10	150	202.9
16:50	9.8	110	253.4
17:00	9.6	90	255.5
17:25	7	40	271.1

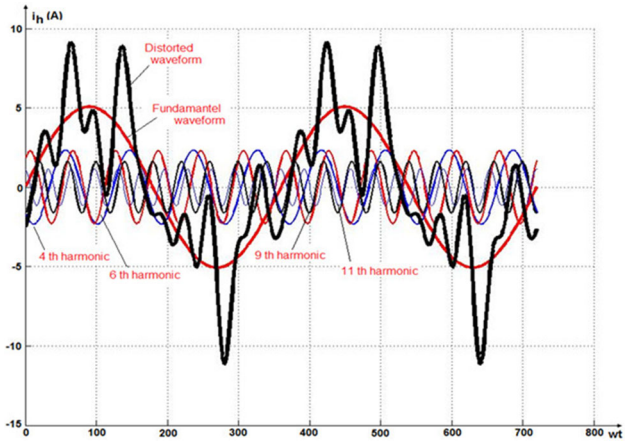

Fig. 2 Nonlinear current waveform and harmonic components

$$+ 1.155 \sin(11\omega t + 94.76). \quad (1)$$

The fundamental and harmonic components of the current given by Eq. (1) are shown in Fig. 2

The current THD is more effective on the fluctuation of solar irradiance than the respective voltage THD. Current THD greatly decreases with the increase in the solar irradiance, while voltage THD slightly increases with the increase in solar irradiance. Power factor varies linearly for values of solar irradiance lower than 200 w/m^2 and remains close to unity for higher solar irradiance values. In addition, reactive power injection increases at low irradiance and then causes increasing power losses, degrading the conductors, having negative effect on the distribution systems and other electrical segments. Harmonic distortion is generally caused by a nonlinear source or load in PV power systems. There are many benefits of low harmonic distortion in electrical installations such as noiseless operation less power loss and long life. Harmonics in the off-grid power PV system cause the following damages:

- Increased losses of elements in the off-grid energy system.
- Disruption of the dielectric insulation of elements in the off-grid energy system.
- Increase in voltage drop,
- Incorrect measurements on induction-type meters,
- Disorders in control circuits,
- Incorrect opening in protection relays,
- Incorrect operation of microprocessors and data loss.
- Noise in communication devices.
- Change of power factor.
- Overheating of solar PV equipment such as solar cables, DC/DC converters and DC/AC converters, battery and solar panels.
- Incorrect operation of MPPT algorithm.

- Shortened life span of PV devices such as DC/DC boost converters and DC/AC inverters, battery and solar panels.
- False triggering of switching elements such as IGBT and MOSFET.
- Erroneous measurements of voltage, current and power in off-grid PV system.

One of the biggest challenges of the off-grid operators is to keep the power quality at high level, by limiting the line voltage and currents' THD at the Point of Common Coupling (PCC). Harmonics must be continuously monitored for power quality. THD_I is a common measurement of the level of harmonic distortion present in electrical power networks. The THD_I term is expressed as an effective value of all harmonics, divided by the effective value of its fundamental current. The distortion as a percentage of $\mathrm{THD_I}$ is defined as follows:

$$\mathrm{THD}_I = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_h^2}}{I_1}, \tag{2}$$

where I_h is the effective current of the h_{th} harmonics and I_1 is the effective current of the fundamental frequency. THD_I is a common measurement of the level of harmonic distortion present in off-grid PV systems. If the harmonic components are equal to the "0", then THD will be equal to the "0". The presence of harmonic currents and voltages in the power system means the distortion of sinusoidal waves. Deteriorated waves are called as non-sinusoidal waves. Voltage and current waveform distortion due to harmonics can lead to the off-grid PV system and electrical consumer either damaged or stayed out of order [16].

The most important reason for the deterioration of the voltage waveform is that the correlation between the terminal voltage and current with nonlinear loads is non-sinusoidal sources. Even if nonlinear loads are low powering solar system, they distort sinusoidal current and voltage waveforms. Harmonics cause serious pollution problem for solar system and they also reduce the quality or the energy supplied to the consumer. Sunlight irradiance variation also affects the amplitude of the harmonic components. All harmonics decrease the quality of a power PV system and loads connected to it. The high THD has negative effects on off-grid PV power system such as equipment overheating motor vibration, neutral overloading and low power factor.

3 Changing THD_I according to solar irradiance and temperature

The produced DC voltage from PV panels completely depends on ambient temperature and solar radiation level.

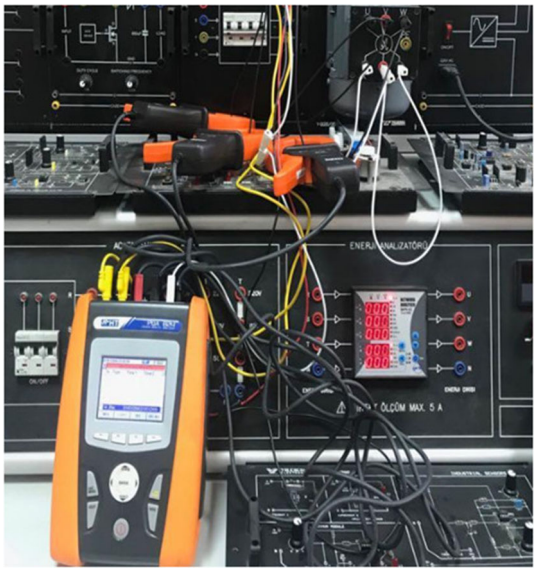

Fig. 3 Application: measurement of THD_I values of nonlinear load fed from PV panels for experimental purposes in the electrical department laboratory of Mardin Artuklu University with HT analyzer device

As a result of increase in temperature, PV panel's short circuit current increases, whereas open circuit voltage decreases severely. This leads to a reduction in the output power. So the efficiency of the cells decreases with the temperature increasing. Although ambient temperature throughout the day is significantly unchanged, solar irradiance may change more severely based on the weather situation. One of the values that play an important role in the establishment of the PV system is the regional solar irradiance values. Solar irradiance values are used to determine the number of panels to be used in the installation of the system. The solar irradiance from the solar energy needs to be stored when the supply is high, but energy storage has a lot of problems. Figure 3 shows the measurement scheme for THD_I values of nonlinear load fed from PV panels for experimental purposes in the electrical department laboratory of Mardin Artuklu University with HT analyzer device.

4 PV system configuration and simulation results

As a clean renewable energy, PV generation has attracted significant interests of researchers. To compute the THD generated by a single-phase nonlinear load is depending on the solar irradiance and temperature.

Thus, we can analyze the harmonic that will be generated by the off-grid PV systems, and thus design the circuit in Matlab/Simulink program. Many techniques were proposed to reduce the size of the DC link capacitor while maintaining a good inverter power quality so that a more reliable film

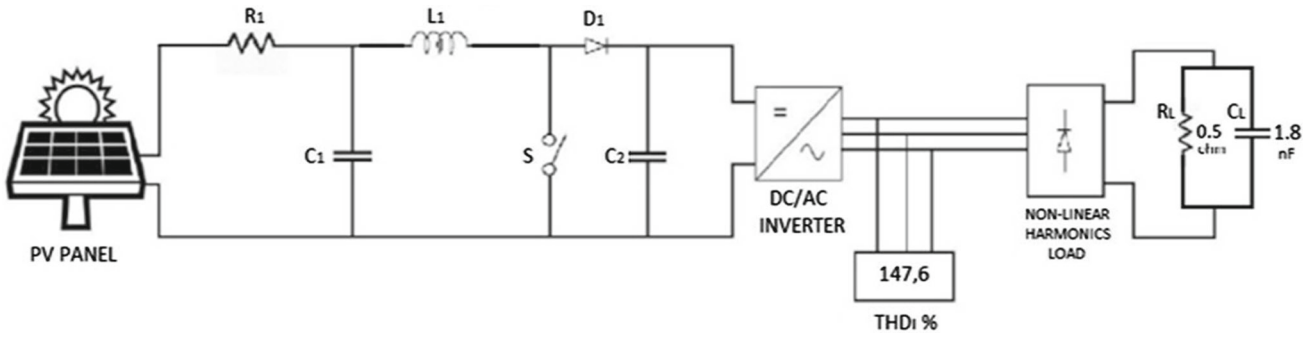

Fig. 4 The simulated block diagram model for off-grid PV

type capacitor can be used. The smallest unit of PV systems is photovoltaic cell.

A PV cell is solid-state semiconductor devices which generate electricity when it is exposed to the solar irradiance so that PV cell can generate around 2.5 watts at almost 0.48 V DC and also the cells have to be connected in series and parallel in order to produce high-efficiency in solar energy applications. Table 1 shows that measurements have been taken for a PV prototype system in Mardin Province which is located in the southeast of Turkey.

The distortion of input current of nonlinear load can be reduced by changes of the solar irradiance. The topology of off-grid PV system is given in Fig. 4, which consists of PV array, a boost DC chopper and three-phase inverter connects at single-phase nonlinear load. There are two operational modes in the system according to the different working statuses of PV panels, battery and mains supply.

The Matlab/Simulink program can be advantageously used to simulate solar PV system, and analysis of solar inverter [17]. DC link in solar system contains pulsation. Large electrolytic capacitors are connected to the DC link so as to absorb this pulsation so that the DC link voltage ripple can be kept small. The all PV system has been simulated by Matlab/Simulink program. Model off-grid PV system is as shown in Fig. 4. The Matlab/Simulink program has been done for different values solar irradiance. The aim is to find optimal input current distortion of nonlinear load. A DC to DC boost converters are used when the voltage is required by the inverter. Solar inverter transfers energy to nonlinear load. The purpose of this study is to analyze relationship between solar irradiance and input current distortion of nonlinear load. The principle scheme of proposed system model is as shown in Fig. 4.

PV array and DC/DC boost converter are connected to MOSFET transistor-based solar inverter, which is further connected to the nonlinear load. Here, in this circuit, an IGBT has been connected at DC/DC boost chopper. In practical, there should be a voltage drop across it. As here the ideal switch has been used, there is no voltage drop. The

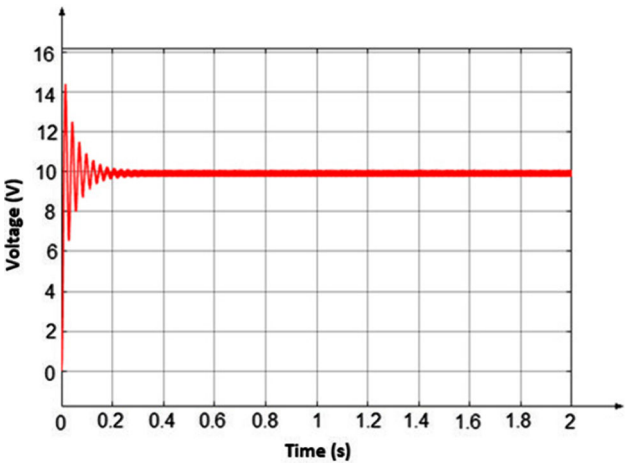

Fig. 5 The output voltage waveform of nonlinear load

purpose of article simulation and analysis of PV-based solar single-phase inverter output current distortion depends on solar irradiance with power factor correction. The nonlinear load consists of a three-phase half-wave uncontrolled rectifier, resistor and capacitor which are connected in parallel. The output waveform of the nonlinear load is given in Fig. 5.

Advantages of PWM techniques are: practically current does not flow when the switch is off, as little as negligible voltage drop on the key switch is turned on. The main advantage of PWM is that power loss in the switching devices is very low. When a switch is off there is practically no current, and when it is on and power is being transferred to the load, there is almost no voltage drop across the switch. The system changes the on–off switching can provide fit that is so much more comfortable. The simulation model of the solar PV system could be used in the future for extended study with a different boost DC/DC chopper, DC/AC inverter varied topology.

The purpose of this article, for values of temperatures and irradiance, is to find input current THD_I of nonlinear load. As a result of the study, one can benefit from this model as a PV power system in the framework of the Sim-Power-System toolbox in the field of solar PV power conversion systems.

In addition, such a model would provide a tool to predict the behavior of any solar PV cell, module and array under different climate parameters changes. Theoretical analysis and simulation results are provided to explain the principle and to validate the effectiveness of the improved topology.

4.1 Changing of output voltage of DC/DC boost converter

Switched-mode power supplies, which are used for many purposes, include DC/DC converters. A DC/DC boost converter is based on the principle of increasing the voltage and reducing the current. These converters are designed for obtaining the desired voltage values. Boost converter circuit consists of coil, diode, capacitor and switching element such as MOSFET and IGBT. The boost converter circuit can be operated into two modes.

The first switching element is for the transmission mode and the second is for the cut mode. Therefore, the inductor will reverse change or reduction in current. Thus, the polarity will be reversed. The effectiveness of the proposed controller is confirmed by numerical simulations. They are connected to the DC bus that could be connected to a different energy storage system, or inject the current directly with a DC/AC inverter. Performance of proposed inverter is verified with exhaustive simulation results on the Matlab/Simulink program. Functions of DC/DC converters have some functions. Capacitor is used to filter ripple currents on DC link. These ripples are caused by power semiconductor IGBT switching. Capacitors are also used to keep the DC voltage stable.

4.2 Electrical characteristics of PV inverter

The most important device is an inverter which influences the quality of photovoltaic power systems. The inverter is a device which converts the DC waveforms into AC waveforms by a set of solid-state switches. Therefore, it is essential to use MOSFETs for this purpose. The results for different THD values of input current of the nonlinear load are completely related to the different solar irradiance. MOSFET-based bridges are used in the PV inverter because their operating voltage is low and they are connected in parallel. PWM generator block is used to produce triggering pulses for MOSFET transistor which is used in the single-phase inverter.

Solar inverter does not generate excessive noise and harmonics. This study analyzes input current of nonlinear inductive load, and also finds the analytical equation between solar irradiance and THD_I. In this study, the Simulink model not only helps to predict the behavior of any PV cell under different environmental conditions, but also it can be considered a smart tool to extract the parameters of any solar PV cell the ideal factor, series and shunt resistance. Some of these parameters are not always provided by the manufactures. GEP mimics to biological evolution to evolve a computer program encoded in linear chromosomes of fixed-length. The main purpose of GEP is to find a mathematical function that fits a set of data presented to GEP model. In GEP, a mathematical function is defined as a chromosome with multi-genes and developed using the data presented to it.

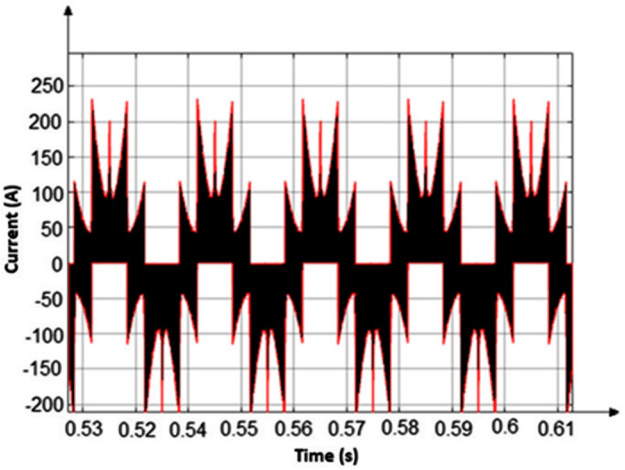

Fig. 6 The output current waveform of solar inverter

At the end of the analysis, the following GEP model is generated. According to the results of Table 1, total current harmonic distortion of a solar generation systems has parabolic characteristic from sunrise to sunset. First one hour from sunrise and before sunset, total current harmonic distortion increased hugely in low irradiation and temperature conditions. Changing of total current harmonic distortion is nonlinear during daylight times. As seen in Fig. 8, proposed mathematical model captured these nonlinearities successfully. The simulation is done by Matlab/Simulink software program. Output current of inverter is as shown in Fig. 6.

SPSS statistical program can be used to summarize the relationship among more than two variables. Photovoltaic-based inverter outputs current harmonic distortion belonging to solar irradiances are primarily discussed in this paper. System structure and working modes are analyzed in detail firstly, and then THD was measured depending on both solar irradiance and temperature practically and also theoretical analyses have been implemented by the simulation.

5 Finding analytical equation THD_I according to solar irradiance and temperature

The main subject of this paper is to find the relationship among the solar irradiance, temperature and THD for input current nonlinear load. There are two methods to generate

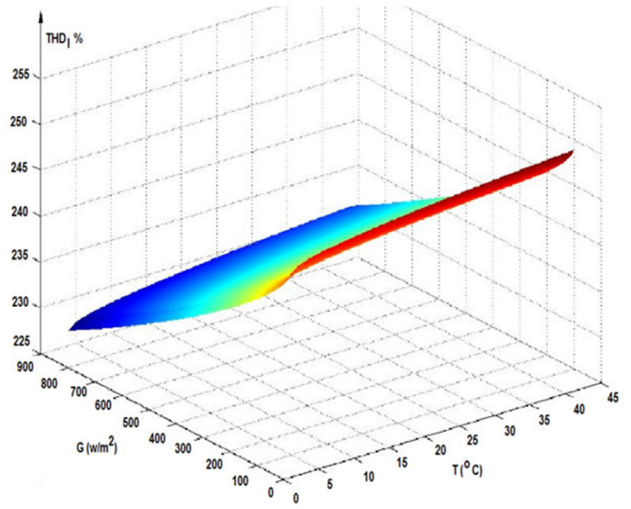

Fig. 7 Change of THD_I generated from the output of the inverter in relation to solar irradiance and temperature

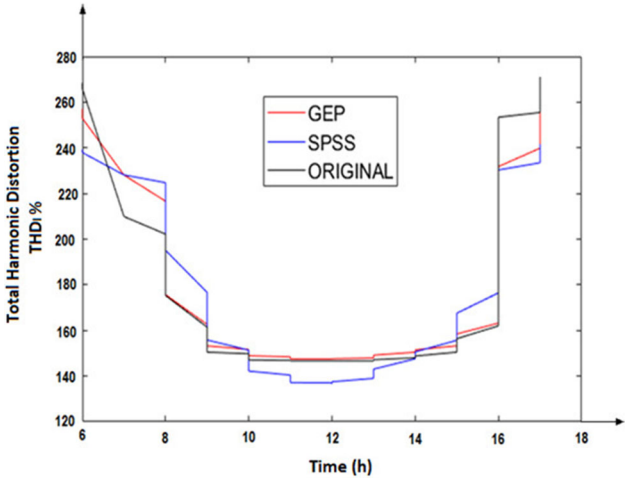

Fig. 8 Comparison between SPSS and GEP methods based on original data

analytical expression for THD in relation to solar irradiance and temperature. The first used method to find out the THD is SPSS. This method has many advantages in order to find analytical equations. In addition, analytical expression of SPSS statistical program has many algorithms explained in the literature.

The second method is GEP. The main purpose of GEP is to find a mathematical function that fits a set of data presented to GEP model. THD_I values change depending on T and G variables, and then it can be said there is a relationship between these variables. G and T values were taken from Table 1 as independent variables in the SPSS package program. Analytical Expression 3 was provided by clicking "Analyze/Regression/Nonlinear Equations" in SPSS program. When we plotted both equations, we observed that the graphics were in compliance with each other for both methods' equations. The SPSS statistic program is used to find the THD_I analytical expression. Depending on panel's temperature (T) and the solar irradiation (G), the equation of THD_I can be obtained from Table 1 as shown below;

$$\mathrm{THD}_I = 2.052 * T^{0.5} - 0.683 * G^{0.75} + 247.064. \tag{3}$$

This new Eq. (3) is obtained by SPSS statistical program, and program is used to achieve analytical expression. SPSS program has a lot of advantage for finding the best value of analytical expressions. Theoretical analysis and simulation are provided to explain the principle and to validate the effectiveness of the improved topology. The curve of new Eq. (3) is as shown in Figs. 7 and 8.

From the original data shown in Table 1, the change of THD_I generated from the output of the inverter in relation to solar irradiance and temperature is shown in Fig. 7. Two different methods have been used to generate the analytical expression (GEP and SPSS). GEP and SPSS have different analytical expressions however same results have been obtained from both methods. Equation (3) was obtained by SPSS method as well as different analytical expressions have been obtained by GEP method in Eq. (4). Depending on panel's temperature (T) and the solar irradiation (G), the equation of THD_I can be obtained from Table 1 as shown below:

$$\mathrm{THD}_I = (\mathrm{Arctan}T^{20} + 1)^5 + [\mathrm{Arctan}G^{20} + \sin(\log G)]^5 + \left[\mathrm{Arctan}G^{15} + \left(\frac{1}{\sqrt[5]{G}}\right)\right]^5. \tag{4}$$

The other new generated Eq. (4) is developed for the estimation of THD_I in PV system. Proposed function is obtained by using a genetic expression tool. The regression is $R2 = 0.979$. In developed model, input variables are the temperature of ambient and the solar irradiation. That model covers from sunrise to sunset time.

6 Conclusion

In this article, the change of THD_I has been investigated depending on the variation of temperature and irradiation values. Furthermore, two different analytical expressions were obtained for THD_I by two different methods which are SPSS and GEP, respectively, since analytical expression is needed for steady-state stability analysis. It also shows us how to reduce negative effects of harmonics by finding these analytical expressions. Harmonics have negative effects in the off-grid PV systems such as distortions of voltage waveform and decrease efficiency in the system. Harmonics are increased drastically too much at low irradiance. Therefore,

they cause damages in the off-grid PV systems in this case. Eventually, active harmonic filter should be used to avoid damaging the PV system.

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