Energy Nexus 9 (2023) 100172

Contents lists available at ScienceDirect

Energy Nexus

journal homepage: www.elsevier.com/locate/nexus

Full Length Article

Artificial neural networks based harmonics estimation for real university microgrids using hourly solar irradiation and temperature data

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ARTICLE INFO

Keywords:
Power quality
Harmonic estimation
Campus PV Systems
Microgrid

ABSTRACT

The need for renewable energy is increasing day by day due to different factors such as increasing energy demand, environmental considerations as well as the will to decrease the share of fossil fuel-based generation. Due to their relative low-cost and ease of installation, PV systems are leading the way for renewable energy deployments around the globe. However, there are meticulous studies that need to be undertaken for realization of such projects. Studying local weather and load patterns for proper panel sizing or considering grid components to determine cable and transformer sizing can be named as some examples for pre-installation studies. In addition to these, post-installation impact studies, e.g. accurate harmonic analysis contribution, is more important to ensure safe and secure operation of the overall system. These steps need to be taken for all PV installation projects. The aim of this study is to show a step-by-step analysis of the effect of a real PV system on the network and to improve the prediction and give a new perspective to the harmonic estimation by using the hourly temperature and radiation data together. At the first phase of the study, a detail real-time 250 kW PV system was modeled for real university campus, and then harmonic estimation based on hourly solar irradiation and hourly temperature was performed with artificial neural networks (ANN) and nonlinear autoregressive exogenous (NARX). The accuracy of the prediction made with ANN was 0.98, and the accuracy of the prediction made with NARX was 0.96.Researchers in PV sizing and control field as well as engineers in power quality area would find these findings beneficial and useful. Use of ANNs and NARX for such analysis indicates the trend in this field that can be targeted by new research projects.

1. Introduction

Energy has always been an important issue that affects all countries and shows the level of development. Energy resources for countries are divided into two categories as non-renewable and renewable [1]. Non-renewable energy sources such as coal, oil and natural gas are fossil-based and conventional technologies are used. Although fossil fuels are not sustainable and have serious environmental and health problems, they are still the sources that make the biggest contribution to the energy sector. The importance of renewable energy sources has increased all over the world due to the rapid depletion of fossil fuels such as coal, oil and gas, and greenhouse gas emissions [2]. In order to emphasize the importance of renewable energy sources, the Paris Agreement was signed by 195 countries to take action against global climate change and to be a roadmap for further actions. Turkey is a country where all four seasons are actively experienced. Investments in renewable energy sources in Turkey are increasing day by day [3]. Konya is one of the provinces where the daily/yearly sunshine duration is high and therefore it is an efficient region to obtain electricity from solar energy.

With the incentives provided by countries to increase renewable energy exponentially, the place of renewable energy in the energy market is increasing and continues to increase. However, some power quality problems caused by this increase is an undeniable fact. The concept of power quality plays a decisive role in the grid integration of renewable energy sources [4]. In the integration of renewable energy sources, it can be listed as voltage fluctuation, voltage flicker, harmonic distortion, increase in short circuit current level, behavior during/after fault, volt-

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https://doi.org/10.1016/j.nexus.2023.100172
Received 6 April 2022; Received in revised form 29 December 2022; Accepted 8 January 2023
Available online 10 January 2023

Nomenclature

V_g	Input voltage of converter
I_g	Input current of converter
V_o	Output voltage of converter
I_o	Output current of converter
R	Output load of converter
Fs	Switching frequency of converter
P_0	Output power of converter
ΔI_L	Peak-to-peak fluctuation of inductance of converter current
ΔVc	Peak-to-peak fluctuation of capacitor of converter voltage
Pnom	Power of Inverter
Fnom	Frequency of Inverter
Vnom	Voltage of Inverter
Vdc	DC Voltage of Inverter
D	Duty Cycle of Swicth
R_x	Load of LCL Filter
L_x	Endüktans of LCL Filter
Q_C	Reaktif Power of LCL Filter
P_C	Active Power of LCL Filter
Pk	Short-Circuit Power of Transformer
Uk	Short-Circuit Voltage of Transformer
In	Nominal Current of Transformer
P0	Open-Circuit Power of Trasnformer
Un	Nominal Voltage of Transformer
I0	Open-Circuit Current of Transformer
Rc	Iron resistance of transformer
Xm	Magnetization reactance of transformer
L1	Primary inductance of transformer
L2	Secondary inductance of transformer
X1	Primary reactance of transformer
X2	Secondary reactance of transformer

age/frequency changes [5]. The main source of these problems is the power electronic devices used in the integration of renewable energy sources [6]. Renewable energy sources contain layers of power electronics and these are the main cause of power quality problem. Power electronics have two main roles in PV systems; Maximum power is obtained from PV and PV is synchronized to the grid .Renewable energy sources, such as solar energy, do not function as conventional energy production sources; the energy produced by the PV panel varies according to exposure to the sun. Despite the imbalance in production, the manufacturers make their designs according to working conditions at full load.

2. Literature review

A grid-connected hybrid power system consisting of wind turbine sources based on photovoltaic panel and permanent magnet synchronous generator is modeled in [7]. In the hybrid energy system, the design of the inverter which increases the direct current (DC) bus voltage to which solar and wind energy are jointly connected is fixed and modeled the system in Matlab / Simulink environment with grid connection. Total harmonic distortion (THD), which is one of the power quality problems and causes detrimental effects on the entire connected power system and connected loads, is examined in [8]. In Egypt, Benha Engineering Faculty is working on a network with an installed power of 5.5 kW. The introduction and simulation of the installed Pv system, THD measurements taken from the PCC point are presented in the study. Some techniques are suggested for harmonic reduction.

Studies on the relationship between power quality and weather data [9–13] are also examined. Power quality problems in a power system connected to a photovoltaic grid are studied in [9]. A real-life power distribution system was first modeled in PSCAD and then combined with a photovoltaic (PV) system to form a grid-connected power system. In order to determine possible power quality problems with the grid-connected power system, they produced different radiation and temperature scenarios and analyzed them. Simulation results showed that the grid connected power system experienced various power quality problems such as sudden current, power fluctuation, frequency fluctuation, harmonic distortion and low power factor. Harmonic distortion from PV inverters is studied in [10]. They have stated that high total harmonic distortion (THD) occurs when PV inverters are operated under low radiation conditions. In order to analyze the harmonic formation process, they mentioned a model in the traditional control structure. They summarized the causes of current harmonics and analyzed the power value generated by current harmonics. They obtained the measurement results in the real PV system, particular for two-stage inverters, they proposed a new model that changes periodically by incorporating DC-link voltage fluctuation into the conventional current control loop model.

The relationship between power quality and different electrical power in a PV system was investigated in an experimental study in [11]. Evaluation of power quality and power quality components is the main topic of the article because of the frequent fluctuations of solar radiation, cloud movements and shadows. They analyzed for three different situations as low, medium and high solar radiation situations and based on these results, they showed the effect of radiation on degradation. Likewise, the effects of PV generation on the distribution network were investigated in [12]. Harmonic distortion is the main factor studied in this study and they created a typical distribution network in Matlab/Simulink to understand the harmonic problem. To estimate the maximum level of PV penetration at the common coupling point (PCC), they evaluated the distortion of the current to total demand. Instead of evaluating under standard test conditions, the effect of radiation changes was investigated and observed that harmonic distortion increased under low radiation conditions. A simple and low-cost solution is proposed to dynamically change the settings of the inverter filter elements against radiation, and harmonic distortion is successfully reduced at low radiation of the inverter. Studies have also been carried out for rooftop Pv systems. In [13], the authors measured the voltage and current of a rooftop grid-connected PV system of Brunel University London campus for sunny and cloudy days and analyzed the analyzes in a Matlab/Simulink environment. he results proved that the solar radiation of the PV system has a significant effect on the THD current compared to the THD voltage. The authors conducted a power quality analysis of the PV roof system in [14]. They made analyzes on parameters such as power harmonics, unbalanced current, vibration and also mentioned the effects of generation value on these parameters.In [15], the authors performed harmonic analysis for the PV system under different generation conditions such as high generation (summer) and low generation (winter). As a result of the studies, it has been observed that there is a big difference between these two production scenarios and the THD value increases at low temperatures.

The grid-connected PV system with incremental conductance algorithm under different radiation conditions is studied in [16]. They investigated the power quality effects of non-linear PV inverters and uncertainty of atmospheric conditions. They have developed different control algorithms to improve power quality for PV inverters and maximum power point monitoring systems. 20 MW of the 80 MW PV system of the largest installed power in Canada is examined in [17]. Under different operating conditions, they have analyzed the harmonics of the PV system, the worst scenarios were obtained on cloudy days. They suggested that harmonic analysis should be performed carefully for PV systems to be installed at large power. In [18], long term performance of PV panels under different weather conditions have been studies and documented for benchmarking purposes.

Analyzing the features of inverter impedance models when used in harmonic integration studies is studied in [19]. They were aimed to estimate the harmonic current contribution as a function of the background harmonic voltages components. They take the measurements in a 1.4 MW PV plant connected in a distributed grid are used to validate the simulation based on impedance models during different power injections and harmonic voltage profiles. The impact of solar irradiance to current and voltage THD is studied using the simulation model developed in Simulink is studied in [20]. They developed the PV model is tested by using the real solar irradiance data taken from UTeM laboratory, and were experimentally tested to validate the model. Results showed that the developed PV model is able to predict the PV system behavior, particularly on THD. Studies have been conducted in the literature using the regression between harmonic analysis and radiations [21], in these studies, the coefficient of the fourier equation was determined by solar data [22] and solar data prediction was made [23,24]. Harmonic analyzes from solar data [25] are also shallowly available in the literature, However, harmonic estimation using hourly solar data is not available to our knowledge. This study brought a new perspective to harmonic estimation, and highly accurate results were obtained in its prediction.

Considering the existing literature, main contributions in this work are;

1) Real micro grid design was implemented by using 250 kW PV plant connected in a distributed system by taking account of specific needs of the university campus while measuring current harmonics at the PCC point of the PV system were analyzed.
2) With the best of our knowledge, the relationship between current harmonics and temperature data has been discussed and verified in previous studies [15,24], but harmonic estimation has never been studied with these data. In our study, this gap in the literature was filled, harmonic estimation was made with hourly radiation and temperature data using ANN and NARX methods, and the results were proved with satisfactory accuracy.

This article is organized as follows: Detailed PV integrated campus implementation and explanation on harmonics estimation are introduced in Section 2. The results obtained from proposed campus implementation and harmonic estimation are presented in Section 3, and conclusions are given in Section 4.

3. Designing PV system for campus

3.1. Grid connected PV system for campus

In this study, the effect of the electrical energy supplied to the grid by the PV power plant with an installed power of 250 kW in Konya on the power quality parameters was investigated. In the analysis, real-time measurements were taken with the Fluke 435 device and the label values of the equipment in the system were modeled in the Matlab / Simulink environment. Simulation and measurement results were analyzed according to TS EN 50,160 [26].

Konya with an installed power of 250 kW and Necmettin Erbakan University Köyceğiz Campus; Three main faculties, namely the PV plant, the Faculty of Engineering and Architecture, the Faculty of Aviation and Space and the faculty of Social Sciences and Tourism, are fed and are shown in Fig. 1. 5 inverters are used in the system, 230 panels in 23 series and 10 parallel are connected to each inverter, and there are 1150 panels in total. Label values of the panel and inverter used are given in the appendix section.

3.2. System simulation

A simulation study was carried out to perform analyzes on the system. In the simulation studies, first of all, the PV system was analyzed. The circuit shown in Fig. 2 was designed and the parameters were calculated. In the circuit you have seen, the voltage booster obtained from the PV panel is amplified and fixed with a DC-DC converter. The obtained

Fig. 1. 250 kW PV plant site.

Table 1
Calculated parameters of converter.

Calculated Parameter of Converter	Value
Coil	1.81110–3H
Capacitor	3.98410–4 F
Doluluk oranı (D)	0.255
Effective value of capacitor current	36.5 A
Average value of the semiconductor power switch	15.93 A
Effective value of the semiconductor power switch	31.5 A

constant DC voltage was sent to the inverter block and converted to AC voltage. With the help of LCL filter, it is integrated into the network.

Converter input voltage, in other words, panel output voltage is 596 Vs, converter output voltage, in other words, inverter input voltage is 800 Vs. Converter load rating (R) 12.8 Ω, converter switching frequency (fs) 5 kHz, converter output power (P0) 50 kW, Peak-to-peak fluctuation of inductance current (ΔIL) rate 20%, Peak-to-peak fluctuation of the capacitor voltage (ΔVc) ratio is 1%.

$$\mathrm{C} = \frac{\mathrm{I0max} * \mathrm{D}}{\Delta\mathrm{Vc} * \mathrm{fs}} \tag{1}$$

$$\mathrm{L} = \frac{\mathrm{Vgmin}}{\Delta\mathrm{IL} * \mathrm{fs}} \tag{2}$$

$$\mathrm{D} = 1 - \frac{\mathrm{Vg}}{\mathrm{V0}} \tag{3}$$

$$\Delta\mathrm{I_L} = \frac{\mathrm{Vgmin}}{\mathrm{L} * \mathrm{fs}} \tag{4}$$

Converter parameters were calculated using the above equations [27] and values and are listed in the Table 1. Perturb and observation algorithm were used as MPPT algorithm in the control part of the power switch of the DC / DC converter. The choice of this algorithm is due to the fact that it is the most widely used algorithm today and its implementation in our active installed system. The MPPT Control block is a voltage-based algorithm that outputs D occupancy data. The first D value of the MPPT Control block parameters is calculated as D_init = 0.255. Our input voltage is calculated as D_max = 0.285 and D_min = 0.225 by adding ± 24Vs to 596 V. The occupancy information from the MPPT control block is transferred to the PWM generator block and a switching signal is sent to the power switch on the DC/DC converter.

Inverter connection is made to convert DC energy from DC/DC converter to AC. The simulation uses a 3-bridge voltage-controlled inverter and a constant DC voltage is connected to the inverter inputs.

Inverter switching is done with the VSC control block and provides network integration with the PLL block. After converting the voltage fixed with DC/DC inverter to alternating voltage with DC/AC inverter, we regulated the obtained voltage with LCL filter. The rated power (Pnom) of the inverter is 50 kW, the frequency (Fnom) is 50 Hz, the voltage (Vnom) is 800 V and the DC voltage value is 400 V.

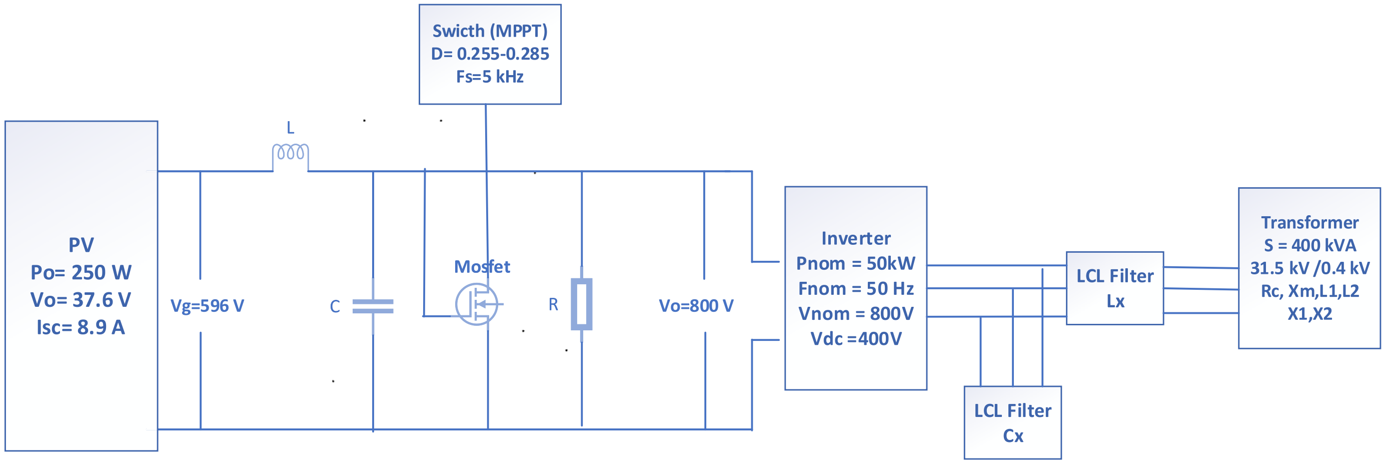

Fig. 2. Block diagram of the system.

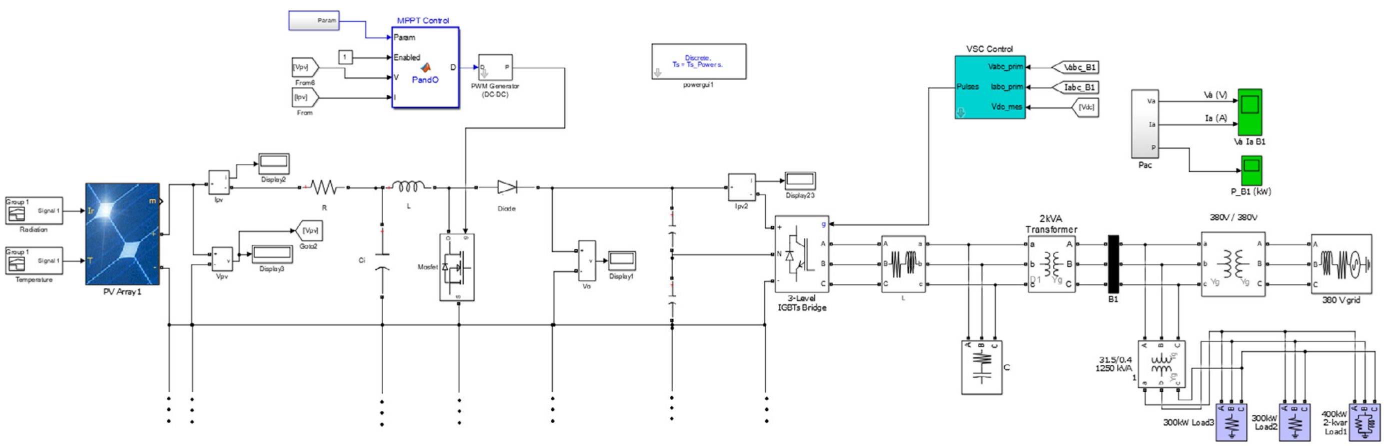

Fig. 3. 250 kW system simulation with mains connection.

Table 2
Calculated parameters of LCL filter.

Calculated Parameter of LCL Filter	Value
Coil	Lx= 1.52 mH
Impedance	Rx =4.8 mΩ
Reactive Power	Qc = 5 kVAr
Active Power	Pc = 100 W

Table 3
Calculated parameters of transformers.

Calculated Parameters of Transformer	Value
Iron resistance (Rc)	502.4 Ω
magnetization reactance (Xm)	135.34Ω
Primary inductance (L1)	0.883 H
Secondary inductance (L2)	47.14 μH
Primary reactance (X1)	277.35 Ω
Secondary reactance (X2)	0.0148Ω

LCL filter parameters were calculated using the equations given below [28] and listed in the Table 2.

$$R_x = 0.0015 * V_{nom}^2 / P_{nom} \tag{5}$$

$$L_x = 0.15 * V_{nom}^2 / P_{nom} / (2 * \pi * F_{nom}) \tag{6}$$

$$Q_C = 0.1 * P_{nom} \tag{7}$$

$$P_C = Q_C / 50 \tag{8}$$

There is a 400kVA 31.5 / 0.4 kV transformer in the installed system. With the values taken from the manufacturer, transformer winding resistance, inductance, magnetic resistance and magnetic inductance were calculated with the help of the equations given below [29] and listed in the Table 3.

$$P_k = U_k I_k \cos(\alpha) \tag{9}$$

$$Z_k = U_k / I_n \angle \phi_k \tag{10}$$

$$P_0 = U_n I_0 \cos\left(\phi_k\right) \tag{11}$$

$$Y_E = I_0 / U_n \angle - \phi k \tag{12}$$

After calculating all the values of our system installed on campus, simulation studies were started in Matlab/Simulink environment and are shown in Fig. 3 but only 1 inverter layer images are shown for better understanding of simulink operation consisting of 5 inverter layers.

3.3. ANN – NARX model

Today, ANNs are successfully applied in many areas. A classical ANN consists of three parts: an input layer, hidden layers and an output layer [30]. If we talk about the ANN modeling step by step, the basic step

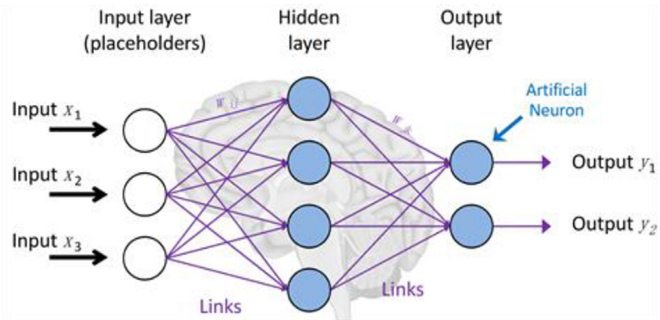

Fig. 4. ANN Neural Network Architecture [31].

Table 4
PV Output Power and THD.

Time	$t = 1$	$t = 1.5$	$t = 2$	$t = 2.5$	$t = 3$
PV Output Power(kW)	76.23	184	219.38	172.97	60.912
Nominal Power(kW)	250	250	250	250	250
P/P_n(%)	30.49	73.6	87.7	69.18	24.36
Radiation (W/m^2)	311	730	889	694	247
%THD	10.89	4.95	4.23	6.01	19.27

Fig. 5. Measurement of data.

is to obtain input and output data. The data is then split into tarining, validation and test data. Data are normalized in the range 0–1 or - 1–1. The hidden layers of the ANN and the number of neurons here are determined and the data is trained with different learning algorithms. Performance is calculated by making statistical error analysis. ANN model is completed by aiming to minimize error values. Fig. 4 shows architecture of ANN.

NARX model is a dynamic recurrent neural network that have layers with feedback connections, and have the same layers input, hidden and output layers. As a first step, data is obtained and input and output data are created. The data are divided into training, validation and testing, and normalization is done. Select the number of tapped delay lines and neurons in hidden layers. series parallel NARX network structure is obtained and the data is trained with different learning algorithms. series parallel NARX network structure is obtained, then analysis is started and if the error value is not at the desired value, the algorithm is returned to the head and the neuron numbers are determined again, the operations are repeated, if the error value is still not at the desired level, the parallel NARX is converted to the network. continue until the error value reaches the desired value. The inputs represents measurements of weather, in our case, and the outputs are the estimations of harmonics of inverter current. In this study, with a multi-layer feed forward ANN [32, 33] and NARX [34] to estimate the harmonics caused by PV inverters. Input and output variables of ANNs are solar radiation, temperature and%THD. Because the working ranges of PV inverters have effects on the harmonics that occur.

4. Results and discussion

In this study, a PV system with 250 kW installed power, which is active in Necmettin Erbakan University campus, is modeled. In addition, power quality measurements of PV system were made on 05.09.2021. These measurements were continued for 7 days. These measurements were recorded and uploaded to the program written in Power Log. The

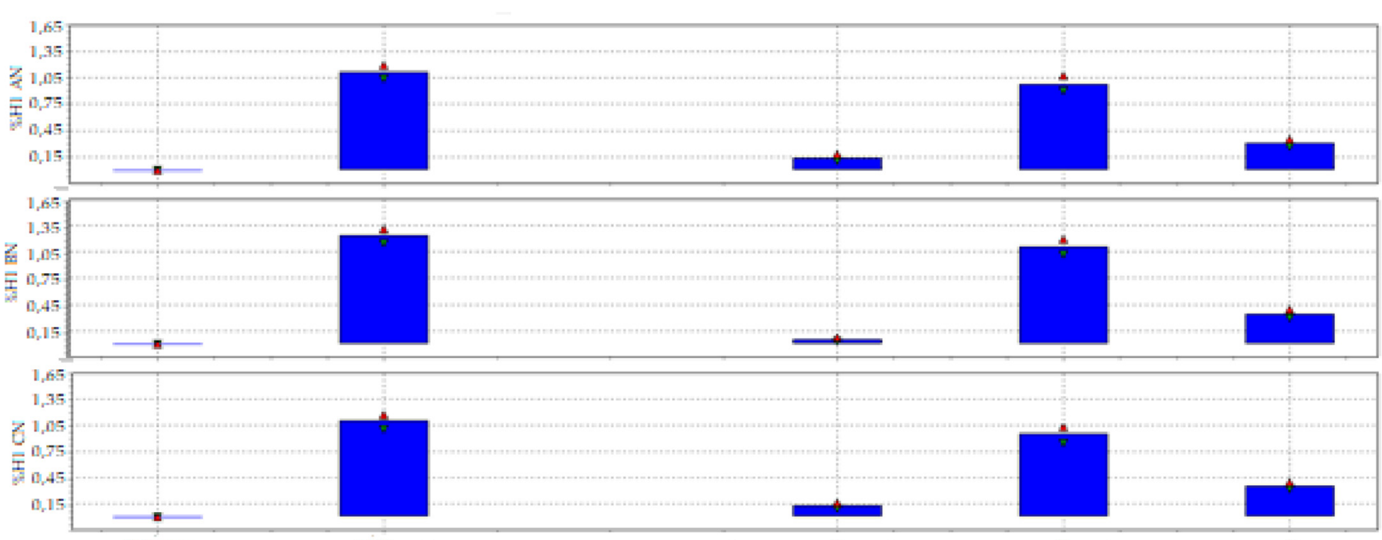

Fig. 6. Fluke Meter Voltage Harmonic Analysis.

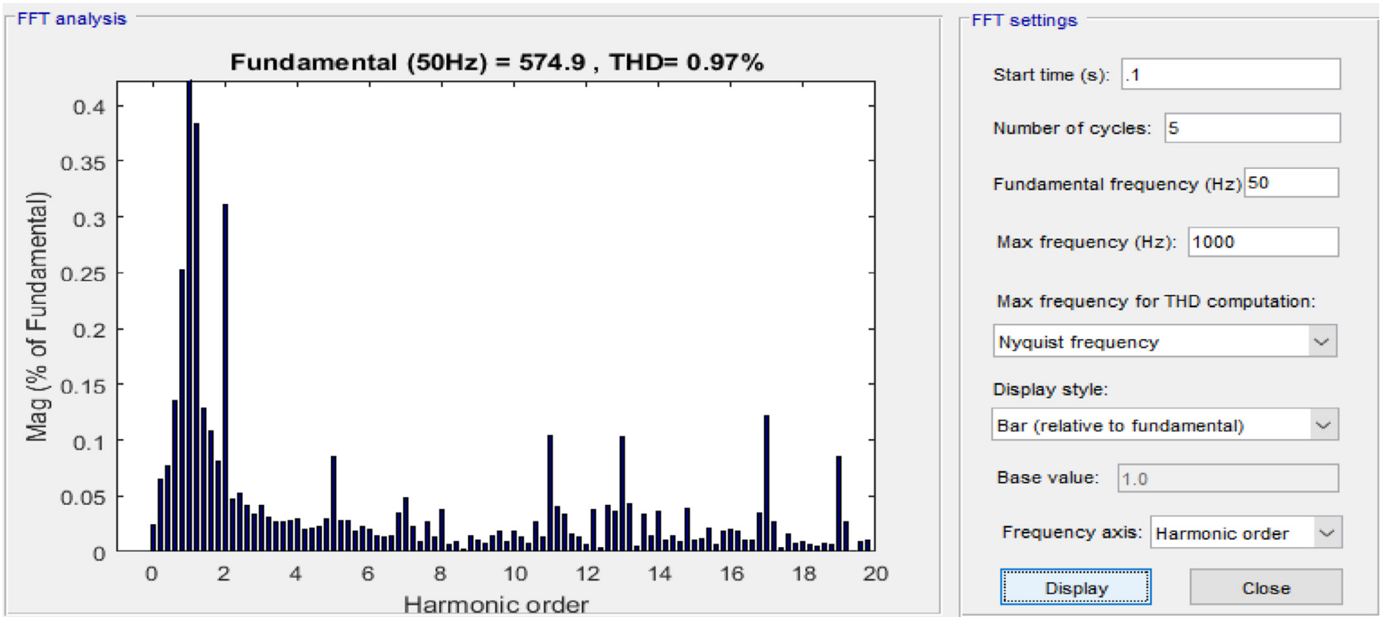

Fig. 7. Matlab/Simulink LV Voltage Harmonic Analysis.

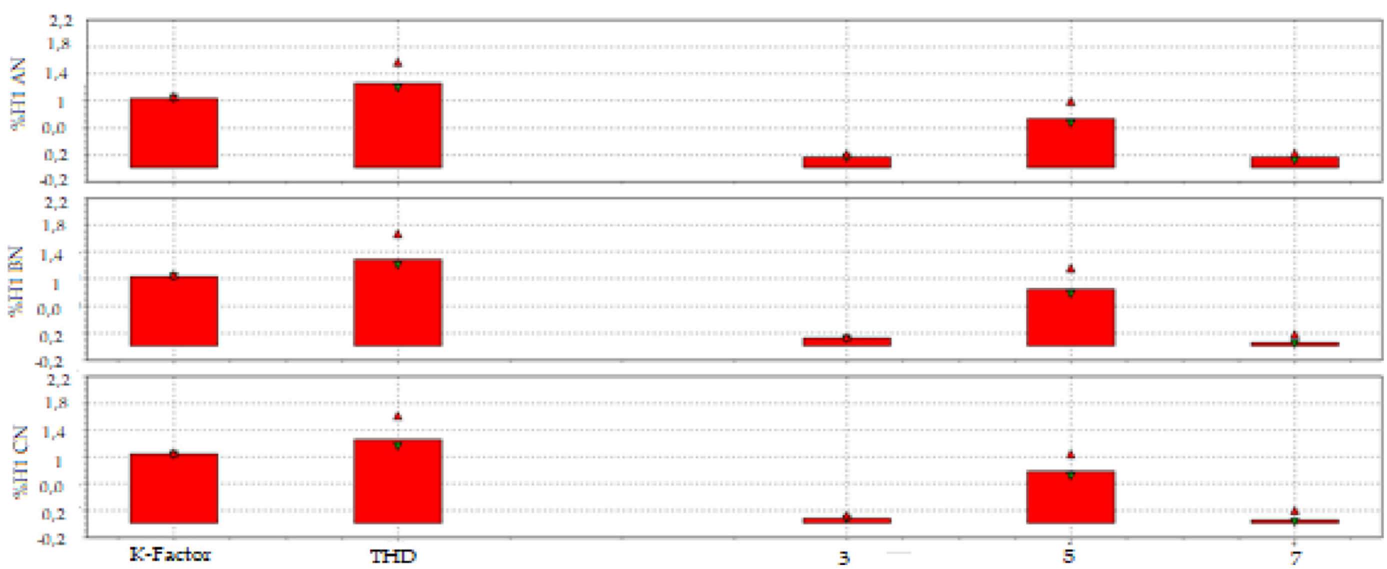

Fig. 8. Fluke Meter Current Harmonic Analysis.

Table 5
The Parameters of ANN and NARX.

The name of method	ANN	NARX
The number of inputs	2	2
The number of outputs	1	1
Hidden layer	2	2
Activation function	Logarithmic sigmoid function	Logarithmic sigmoid function
Training algorithm	Levenberg-Marquardt	Levenberg-Marquardt
The number of neurons in hidden layers	17/7	8/9
The number of iterations	767	767
Estimation Accuracy	%98	%96

Power Log program provides a graphical view of the loaded data. In order to prove the accuracy of the simulation, real and simulation comparisons were made on voltage, current, power and harmonic values. As seen in Fig. 5, harmonic measurements were made on LV side of the transformer with the Fluke 435 measuring device.

4.1. Harmonic comparison

In this study, in order to examine the effect of distributed generation facilities on power quality, harmonic measurements were made on the LV side of the transformer in the field and are shown in Fig. 6. In

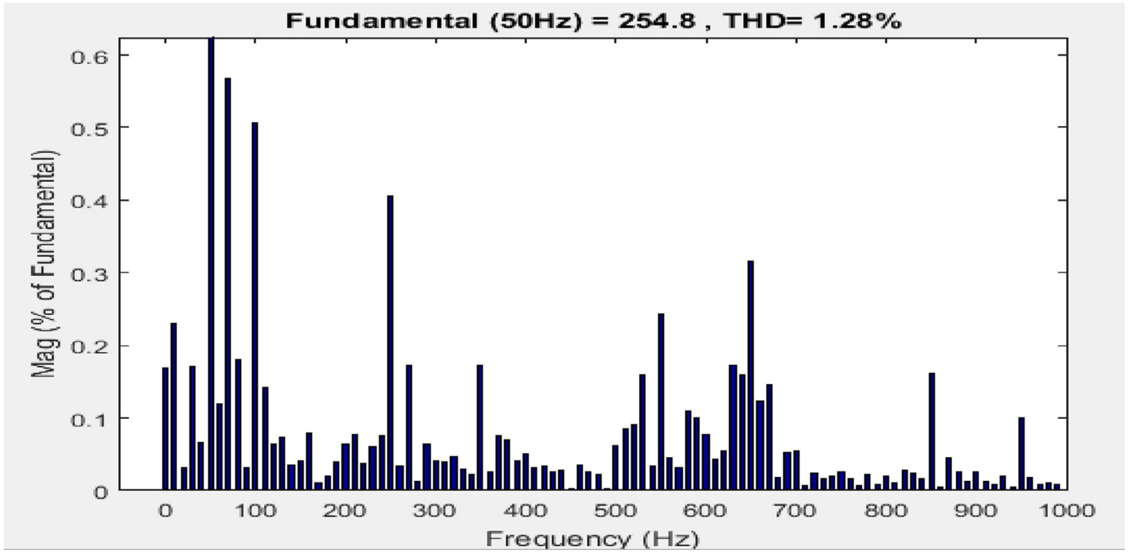

Fig. 9. Matlab / Simulink LV Current Harmonic Analysis.

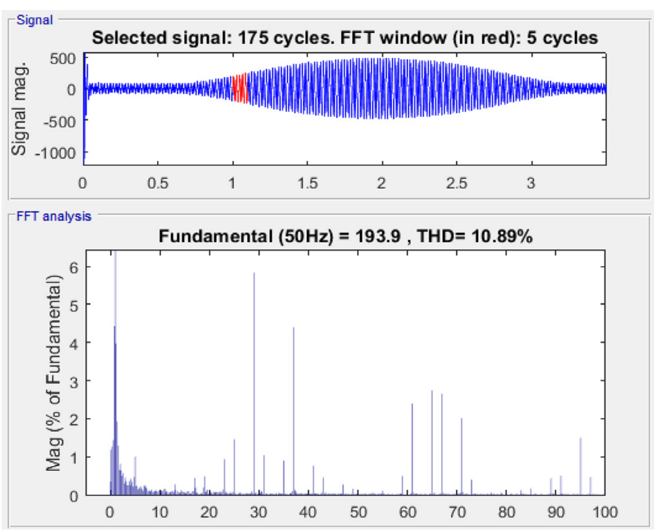

Fig. 10. Matlab / Simulink Harmonic Analysis.

the simulation made in Matlab / Simulink environment, harmonic analysis was performed on the LV side of the transformer and is shown in Fig. 7. Similarly, Fig. 8 shows the current harmonic measurement and Fig. 9 shows the current harmonic simulation result.

Harmonic analysis, which is one of the power quality parameters, is an important subject of distributed generation facilities. Concerns about harmonic distortion caused by increased PV inverters are increasing. As a result of the literature studies, it was observed that total harmonic distortion increased while working under light load conditions due to low sunlight of PV inverters. In order to monitor PV panel output, one day radiation data as in 05.09.2021 was taken from NASA's solar radiation database and then integrated it to our PV panel. Then, harmonic analysis was performed on the instantaneous values of the generated power.

The first graph in Fig. 10 shows the PV inverter output current obtained when a log radiation data is input to the PV panel as radiation data; the second graph shows the harmonic analysis at $t = 1$.

Table 4 shows the harmonic changes that occur when the THD analysis is performed at regular intervals in the inverter output current obtained by entering a daily radiation and temperature values of the PV system. It is the%THD change in the morning and evening hours that

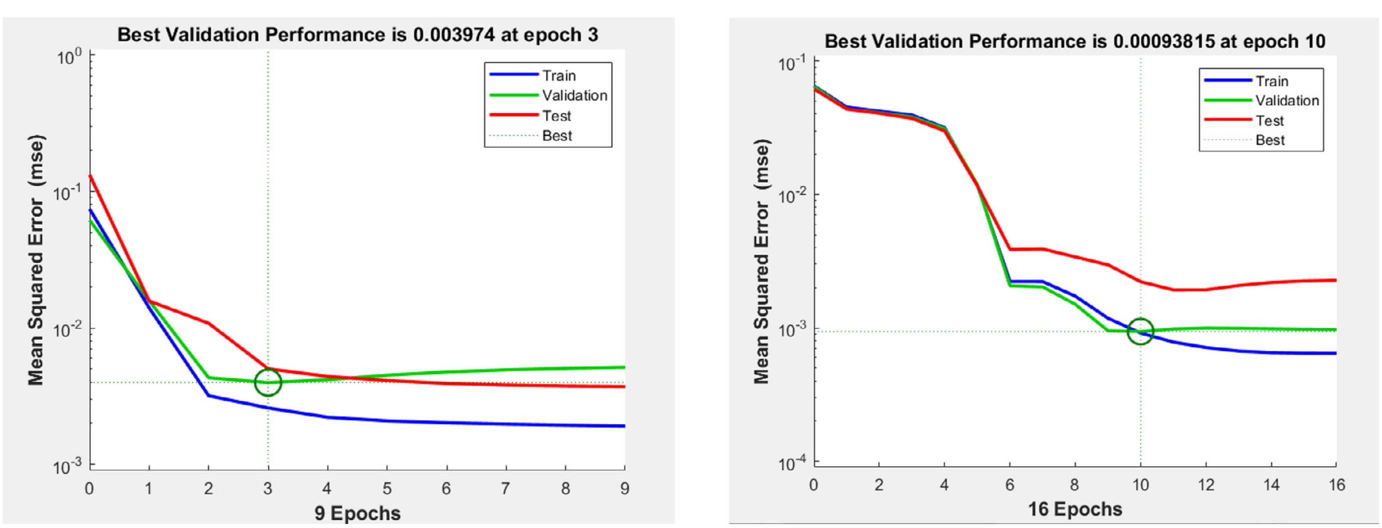

Fig. 11. Training, Validation, Test Graph with ANN method, $R = 0.98$, With NARX method, $R = 0.96$.

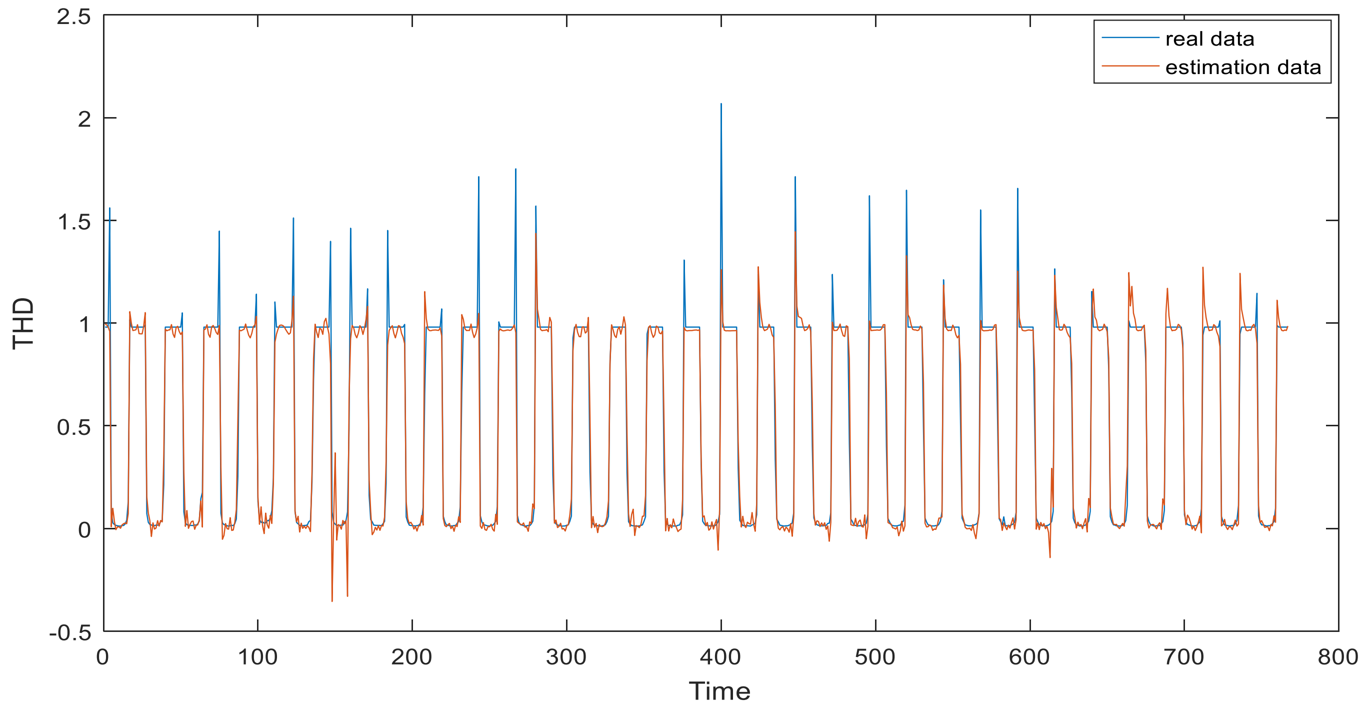

Fig. 12. Comprasion pf real data and estimation data of THD.

are desired to be observed with these changes. The relationship between THD, generated power and radiation was also evaluated seasonally, and August to January was compared. It has been observed that the harmonic distortion in January is higher than in August.

4.2. Harmonic analysis prediction

ANN and NARX parameters designed to estimate PV harmonics are given in Table 5. Inputs are radiation, temperature, ouput is%THD of PV inverter. These parameters were determined by trial and error method. Statistical performance measures such as Mean Absolute Percent Error (MAPE), correlation coefficient (R), Square Mean Error (RMSE) and Mean Absolute Error (MAE) were used to measure the performance of the predictions. Designed for harmonic prediction, ANN was made between 05.08.2021–05.09.2021, hourly harmonic measurements were made with the Fluke measuring device from the PV system and 767 data were obtained by taking radiation and temperature data from NASA's network on the same day. In both estimation algorithms, 70% of the data is devoted to training. The data was normalized in the range 0–1. The estimates obtained by ANN and NARX method is shown respectively in Fig. 11. Correlation coefficient values are 0.98 and 0.96 respectively, which is a very large accuracy value. Fig. 12 shows the comparison of the actual data with the forecast data.

5. Conclusion

Environmental concerns and government incentives have increased renewable energy deployment projects. PV based generation, whether it be large-scale power plants or small-scale residential systems, is the most popular technology due to its low-cost and easy installation. Increasing number of such systems in the power grid would disrupt normal operation. Therefore, it is important to study their impacts before actual installation and take necessary precautions. Considering the number of such projects and research items related to this field, such studies are an integral part of renewable energy's future.

Addressing this need, in this study, a real-time analysis was performed to observe the effects of the PV system on the power quality of the grid. As a result of the studies, it has been observed that the THD value increases as the output power of the PV inverter decreases and is supported by field measurement studies. The THD results were calculated by ANN and NARX method and the accuracy of prediction with ANN is better than NARX. As a continuation of this study, a dynamic control and switching study based on time and radiation variables is planned in inverter design.

The systematic approach taken in this paper to explain analysis process of a real PV system installed in a university campus is beneficial for researchers and practitioners alike. Understanding these steps and being able to replicate them for other projects is not trivial. Furthermore, the ANN and NARX based analysis approach taken shows researchers what parts of this analysis can be modified and enriched in future studies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The authors do not have permission to share data.

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