Grid connected photovoltaic system impression on power quality of low voltage distribution system

W.A.A. Salem¹, Walaa Gabr Ibrahim¹, Aya M. Abdelsadek¹* and A. A. Nafeh¹

Abstract: To ensure the global energy demands and decarbonize the production of electricity, the expanded utilization of solar photovoltaics (PV) as a renewable energy resource has been increasing in recent decades, principally with the feasibility to be integrated with the conventional power grid. However, supplying clean power from PV grid-connected systems is often hampered by power quality (PQ) disturbances caused by the intermittent nature of solar radiation and other factors related to the grid, converters, and connected loads. To prevent deterioration of the power quality of the system, these disturbances must be mitigated. This paper technically studies some of these PQ issues, that is, the current total harmonic distortion (THD) which causes harmful effects on the whole connected power system and the linked loads. The case study works on a 5.5 kW grid-connected rooftop PV power system established at Benha Faculty of Engineering, Egypt, with the assistance of an installed weather station that boosts the validation of the research results. All aspects regarding the aforementioned small plant are presented including description and simulation of the whole system, review of current THD problems occurring at the point of common coupling (PCC), and a review of other disturbances observed by connected meters. A detailed examination of four techniques for harmonic mitigation, namely the on-off

ABOUT THE AUTHOR
Aya M. Abdelsadek has received her B. SC. in 2016 from Benha faculty of engineering, Benha University, Egypt and currently she is a teaching assistant in the same faculty. Her Interests are electrical power systems and electric machines.

PUBLIC INTEREST STATEMENT
This research is studying a roof-top photovoltaic (PV) plant established at Benha Faculty of Engineering, Egypt. This PV system is connected to the electrical utility grid, so that the load can be fed from PV system during periods of solar radiation, and fed from the grid at night to ensure regular electric supply for the connected loads. The system under consideration suffers from some issues related to the electric power received by the customers, resulting in negative consequences such as reduced performance of energy generation, poor functioning of the system or any of its components, and premature ageing of insulation on grid components. In this paper, the whole system is analyzed to reveal the power quality shortcomings utilizing linked meters. Then, four techniques are proposed to mitigate the adverse effects of the power problems. A comparison is set between the proposed techniques to clarify the merits and demerits of each of them.
technique, LCL filter, active power filter, and hybrid active power filter is presented with a final comparison to assess the merits and demerits of each one. This research achieved a current harmonic limitation of 1.5%.

**Subjects:** Power & Energy; Systems & Control Engineering; Electrical & Electronic Engineering

**Keywords:** Active filter; harmonics mitigation; passive filter; photovoltaic (PV) grid connected; power fluctuation; power quality; THD (total harmonic distortion)

1. Introduction

As a clean and safe source, the use of solar energy and other forms of renewable energy has proliferated and updated globally (Adak et al., 2019). It is an advanced alternative to fossil fuels that will eventually run out. Firstly, Photovoltaic (PV) panels were rarely used by citizens and were installed in space satellites and large industrial plants (Goetzberger & Hoffmann, 2005); they are currently used in household appliances, feeding power grids, communication, vehicles, and mobile lighting systems (Biswas & Kim, 2020; Tyagi et al., 2013; Zhang et al., 2012). PV power plants are classified, according to their connection with the electrical utility grid, to stand-alone systems and grid-connected PV systems. In this study, a PV grid-connected (PVGC) system is linked to the power grid by converters and works in parallel with it to feed the connected loads and limit the utilization of non-renewable resources supplying the utility grid.

The climate volatility affects the output power of the PV system; so it cannot hold-out at the maximum value. The subsequent decline in the efficiency of energy conversion in PV arrays has led researchers to inspect techniques of maximum power point tracking (MPPT) to guarantee that PV systems operate at maximum power point and maximum efficiency under variations in atmospheric conditions (Walker, 2001). In conjunction with power electronic devices, various MPPT techniques are applied under uniform radiation, such as perturb and observe (P&O; Kollimallo & Mishra, 2014), hill climbing (HC; Bahari et al., 2016, and incremental conductance (INC; Liu et al. (2018) which are the most widespread online techniques. Other indirect (offline) techniques including constant voltage, constant current, and curve fitting has been described in detail in (Bianchi & Dai Pre, 2003; Di et al., 2014; Salas et al., 2006; Tauseef & Nowicki, 2012). In the case of partial shading or non-uniform radiation, hybrid algorithms have been applied, as presented in (Ali et al., 2020; Joisher et al., 2020).

Power quality is one of the main concerns when applying PV power systems, specifically during PCC (Bouchakour et al., 2017). Variable solar irradiance and nonlinear loads with developed power electronics equipment are the essential causes of power quality issues and the emergence of voltage and current harmonics in particular (Salam et al., 2006; Tali et al., 2014). Disruption of the normal operation of the electrical network, overheating of connected equipment, decrease in electrical meter accuracy, interference with communication lines, and increase in the drawn current are unexpected influences caused by harmonic distortion on the electrical power system (Salam et al., 2006; Tareen et al., 2017).

Over the last three decades, researchers have paid close attention to the progress and analysis of PVGC systems. Bolduc et al. (Bolduc et al., 1993) studied the performance of a one-kilowatt PVGC system with battery energy storage. Enhancing the operation of a connected medium-voltage distribution network with connected PV systems was investigated in (Srissaen & Sangsawang, 2006). Tyagi et al. (Tyagi et al., 2013) reviewed the progress of PV technologies in terms of the material of utilized cells and the environmental factors affecting the efficiency of PV cells. Ferdowsi et al. (Ferdowsi et al., 2014) proposed a combinative method to limit the output power fluctuations. Figueira et al. (Figueira et al., 2015) conducted a comparative study between Brazilian standards for PVGC inverters and related standards in Europe and the United States. Pakonen et al. (Pakonen et al., 2016) experimentally clarified the nature and causes of PQ problems that emerged in PVGC
power systems. De Oliveira et al. (De Oliveira et al., 2018) used the SCICA method to analyze the voltage and current harmonics at the PCC of a grid-connected PV power plant. Vinayagam et al. (Vinayagam et al., 2019) assessed the dominance of the current THD in PV-integrated networks and proposed a harmonic management system to limit the THD within the standards. The impact of current harmonics on transformers and the rest of the distribution system was determined in (Badea & Ștefanescu, 2020).

Various techniques have been used to overcome harmonic distortions in power systems, such as passive and active power filters. Renzhong et al. (Xu et al., 2013) indicated that an LCL filter with a shunt damping resistor mitigated harmonics to 0.26%; therefore, it has more effective performance than the L and LC filters for harmonic mitigation. The hybrid damping method was presented using a digital filter together with a parallel RC circuit in (Adak et al., 2019). Mortezaei et al. (Gupta et al., 2012) studied three control methods for shunt active filters comparatively to determine their characteristics. Gupta et al. (Lei et al., 2014) reduced the current THD from 27.3% to 3.9% using a shunt active power filter with the d-q controlling technique for a designed PVGC system. Lei et al. (Yu et al., 2005) combined passive and active damping techniques to investigate the characteristics of the hybrid damping strategy, which resulted in a current THD shorthand of 3.7%. Prasad et al. (Andela et al., 2022) presented INC technique for the MPP tracking along with d-q shunt active power filter to limit the current THD within the standard limits. The proposed work used the artificial neural network controller rather than the conventional PI controller for the DC bus voltage regulation. The outcome of this methodology is simulated to show that the current THD was reduced to 3.2%. Not only filters but also another several methods may be useful for harmonic suppression. Considering the multi-level inverter (MLI) as a valid power quality conditioner, Andela et al. (Fekik et al., 2022) compared 127-level MLI with MLIs of lower levels. The 127-level MLI mitigated the current THD to 2.33%. Fekik et al. (Prasad et al., 2022) suggested a direct power control methodology to improve the functioning of the pulse width modulation (PWM) inverter and the output energy quality of a GCPV system. The simulation showed that this method has good implications.

Each research project has been applied to a different PVGC system with different surrounding conditions, but corresponding to harmonic mitigation; the common factor among them is that they all refer to IEEE-standard 519. Table 1 shows the harmonic limits for the system voltage from 120 to 69 kV. Corresponding to the PVGC system under study in this paper, only one published study has investigated the current harmonics of the plant and proposed a double-tuned passive filter that lessened the THD to approximately 20% (Gabr & Salem, 2019). This study aims to implement various techniques to solve the current THD problem and evaluate these techniques to present how each one of them can improve the performance quality of the plant. In Section 2 of this paper, the studied PVGC system is analyzed including all related measurements taken from the weather station and other

| Harmonic Order (h) | THDD |
|--------------------|------|
| 3 ≤ h ≤ 11         | 4.0  |
| 11 ≤ h ≤ 17        | 2.0  |
| 17 ≤ h ≤ 23        | 1.5  |
| 23 ≤ h ≤ 35        | 0.6  |
| 35 ≤ h ≤ 50        | 0.3  |
| h > 50             | 5.0  |

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*a* Even harmonics are limited to 25% of the odd harmonic limits above.

*b* Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

*c* All power generation equipment is limited to these values of current distortion, regardless of actual Isc/IL.
Where

\[ \text{Isc} = \text{maximum short-circuit current at PCC} \]

\[ \text{IL} = \text{maximum demand load current (fundamental frequency component) at the PCC under normal load operating conditions} \]

connected metering devices to highlight some of the power-quality problems of the studied PV plant. In Section 3, this system is simulated to match the real system using MATLAB Simulink, and harmonic spectrum analysis is performed on the output of the model scope to facilitate the selection of suitable procedures for efficient harmonic limitation. In Section 4, the on-off technique, LCL filter, shunt active power filter, and hybrid active power filter are proposed to examine and compare their effectiveness in damping emerged current harmonics.

2. Description of the deliberated grid-connected system

Figure 1 shows the studied 5.5 kW grid-connected PV system at Benha Faculty of Engineering, Egypt. The load is fed from both the power utility grid and the PVGC system where the DC boost converter raises the voltage level and the inverter turns the voltage from DC to AC form. The load absorbs active power from the PV planet during periods of good solar irradiance, appropriate weather conditions, and sufficient output power.

When the PV output power decreases, the load then is fed into the power grid. In both cases, the load receives the required reactive power from the electrical power grid causing the power factor to drop to unexpected values (Gabr & Salem, 2019; Yu et al., 2005).

To compensate for the reactive power (Q) drawn, shunt capacitor banks are connected to the system; therefore, the power factor is maintained at a reasonable rate (Sharma et al., 2019; Simpson, 2004).

Figures 2 and 3 show the power fluctuations observed from the system-dragged readings. This power intermittency is based on diverse factors, such as the topology of the PV system, location of
arrays, weather fluctuations, fineness of solar irradiance, speed and direction of the wind, and passing clouds (Anzalchi et al., 2016).

If the radiation from the sun cannot reach the solar cells properly, the output power is interrupted. Consequently, the feeders are exposed to over-and under-loading, voltage flicker, partial load damage, and incorrect prediction of output power at any time (Farhooodeh et al., 2012; Omran et al., 2011). Many researchers have investigated this snag and presented various methods and combinations of them to reduce this fluctuation such as using storage batteries, running the PV planet below MPPT (maximum power point), and applying a complementary power source (Zhang et al., 2012).

Weather conditions that have a fundamental role in output power can be tracked easily using an installed weather station that provides highly accurate measures of temperature (°C), radiation (MJ/M2 and W/M2), humidity (%RH), wind speed (M/S), and wind direction (°C). The measurements for the stations during the autumn season are shown in Figure 4.

Voltage fluctuations and imbalances are clear in the voltage records, as shown in Figures 5 and 6. this is an unacceptable result for intermittent solar irradiance and power fluctuation, specifically at the PCC (Wong et al., 2014).

In addition to active power reading, the power analyzer connected to the system measures the drawn reactive and apparent power, operating line voltage, drawn current, frequency, power factor, k factor, voltage, and current harmonics of each order, and calculates the THD. These measurements were taken during different seasons in 2020, as shown in Figures 7–9. As indicated, the current total THD, specifically at odd orders, outruns the values specified in IEEE standard-519 at PCC (Walker, 2001).

3. Simulation of studied system
On the way to reach the most operative process to overcome harmonics effect on the power quality of the system, the model of the studied system is simulated by using MATLAB SIMULINK with the parameters included in Table 2, as shown in Figure 10. Radiation and temperature readings dragged from the weather station were used as inputs to the solar panel in the simulated model. The output of the scopes was checked, as indicated in Figure 11, to validate its similarity to real readings from the power analyzer. The harmonic spectrum analysis shown in Figure 12 verifies that the current THD reaches approximately 209% at the PCC when the power supplied from the solar plant is less than 10%.

This condition transpires at sunrise and sunset, initiating several problems with the related electrical equipment (Vinayagam et al., 2019). Therefore, several practical and simulated techniques are applied to the system to obtain the most operative technique that reduces the harmonics.
to its lowest level with an appropriate outlay. As the harmonics influence the power quality of the system and corrupt the output energy delivered to consumers (Adak et al., 2019), various research projects have investigated techniques to suppress it.
Table 2. Parameters of the grid-connected system

| Parameter          | Value  |
|--------------------|--------|
| PV Output Power    | 5.5 (kW) |
| Three-Phase Voltage| 400(V)  |
| Grid Voltage       | 11(kV)  |
| Frequency          | 50(Hz)  |
4. Studied solutions for harmonics attenuation

4.1. First solution (ON-OFF method)

From the measurements shown above, the current THD was raised above the intended values at the PCC, where the current drawn from PV arrays is below 14%. Hence, the attempted technique is
to cut off the power supplied to the load at these low-current values by using the PLC control panel and its LED indicators. The outcome THD was measured by power analyzer and seemed to be terminated to approximately 20%, as shown below in Figure 13. Although this method provides helpful results, the total power delivered to the load is reduced by the amount annulled at the PCCs. The complementary part of this methodology is to improve the system leakage of power using charged batteries to ensure a continuous power supply for consumers.

4.2. Second solution (Passive filter)
A combination of capacitance, inductance, and resistance at the estimated frequency results in passive power filter.
The LCL filter with a precise design has proven to be highly efficient in suppressing low harmonics order in grid-connected PV systems (El Wahid Hamza et al., 2015). It is a shunt connection between source and the load that offers lower current ripples and a low resistive path for the intended tuned harmonic (Kahlane et al., 2014).

The data from the power analyzer indicated that the main effective harmonics were those of the 5th, 7th, and 11th orders. Hence, three passive LCL filters, as shown in Figure 14, are designed at these frequencies where $I_1$ is the current from the inverter, $I_2$ is the current to the load, $L_1$ and $L_2$ are the series inductances of the filter, and $C$ is the shunt capacitance of the filter. The resonant frequency ($f_{res}$) can be formulated as (Thamizh Thentral et al., 2018):

$$f_{res} = \frac{1}{2\pi} \left( \frac{L_1}{L_1 + L_2 + C} \right)$$

(1)

The connected passive filters can effectively improve the power quality and lessen the THD, as shown in Figures 15 and 16.

4.3. Third solution (Shunt active power filter)

The shunt active power filter (APF) is a widely used filter in electronics since it can cope with the constraints of passive filters, including consequential resonance, massive components, and
frequency boundaries (Rasul et al., 2017; Salam et al., 2006). Because a series APF is applied to lessen the voltage THD, the shunt is more usable to control the current THD. Its main function depends on injecting a compensation current that eliminates harmonic components; hence, it can handle dynamic changes in the load.

The types of APFs regarding their converters are divided into a voltage source inverter (VSI) type with connected capacitor and a current source inverter (CSI) type with connected inductor (Schwanz et al., 2016). Experiments have shown that at a high compensation current, the VSI active filter is superior to the CSI filter, and its topology and installation procedure are more familiar and common in various installations (Routimo et al., 2007).
A comparison between different active filter techniques is discussed in (Gupta et al., 2012), in which, a VSI active power filter of the d-q control technique shown in Figures 17 and 18 is applied to the PV grid-connected system. The d-q control method is based on transforming the stationary α-β-γ coordinates of the system to rotating dq0 coordinates that are synchronized with the positive sequence of the system voltage, as given in the equation below (Dey et al., 2017) where \( \omega_s \) presents the transformation angle of the system voltage positive sequence.

\[
\begin{bmatrix}
  i_d \\
  i_q \\
  i_0
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
  \sin(\omega_s t) & \sin(\frac{2\pi}{3} \omega_s t - \frac{2\pi}{3}) & \sin(\frac{2\pi}{3} \omega_s t + \frac{2\pi}{3}) \\
  \cos(\omega_s t) & \cos(\frac{2\pi}{3} \omega_s t - \frac{2\pi}{3}) & \cos(\frac{2\pi}{3} \omega_s t + \frac{2\pi}{3}) \\
  \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}
\end{bmatrix} \begin{bmatrix}
  I_{La} \\
  I_{Lb} \\
  I_{Lc}
\end{bmatrix}
\]  

(2)

The signal then appears as a DC component and an unwanted harmonic component. Thus, the harmonic components in the d-q frame can be easily extracted using a low-pass filter. The filtered active and reactive components are obtained as follows

\[
\begin{bmatrix}
  i_d AC \\
  i_q AC
\end{bmatrix} = \begin{bmatrix}
  i_d \\
  i_q
\end{bmatrix} - \begin{bmatrix}
  i_d DC \\
  i_q DC
\end{bmatrix}
\]  

(3)

This oscillating component is inversely transformed to the α-β-γ coordinates to obtain the reference current (\( I_{ref} \)).

\[
\begin{bmatrix}
  i_{dref} \\
  i_{qref} \\
  i_{eref}
\end{bmatrix} = \begin{bmatrix}
  \sin(\omega_s t) \cos(\omega_s t) \\
  \sin(\omega_s t - \frac{2\pi}{3}) \cos(\omega_s t - \frac{2\pi}{3}) \\
  \sin(\omega_s t + \frac{2\pi}{3}) \cos(\omega_s t + \frac{2\pi}{3})
\end{bmatrix}
\]  

(4)

The reference current is then fed to the APF hysteresis controller to activate the inverter and generate the compensated current. The PI controller compares the capacitor voltage and the

Figure 19. Simulation output at applied SAPF.
Figure 20. THD analysis at applied APF.

Figure 21. THD analysis at applied hybrid filter.

Figure 22. Simulation output at applied SAPF parallel with passive filter.
reference voltage to lessen the error between them. Consequently, the harmonics are limited in Figures 19 and 20 to meet the requirements of IEEE Standard 519.

4.4. **Fourth solution (Hybrid active passive filter)**

Although it is an updated technology in harmonic control, APF still has weaknesses. Owing to the application digital control, frequencies of higher orders cannot be filtered, and analog control causes signal deviation (Routimo et al., 2003). In addition, passive filters have difficulty with their massive components at low-order frequencies. Therefore, gathering the two types of filters to form a hybrid filter presents a path to lessen the shortcomings of each filter and improve the performance of the system where frequencies of low order are controlled by the APF, and frequencies of higher orders are soundly terminated by the passive filter (Abokhalil et al., 2018). In this study, the d-q active power filter is connected in parallel with the three passive filters to trim down the total current harmonics as indicated in Figures 21 and 22. The system with a connected hybrid active power filter is shown in Figure 23.

| Method                        | T.F         | Cost                        | Current harmonics limit | THD  |
|-------------------------------|-------------|-----------------------------|-------------------------|------|
| System without added techniques | -           |                             | h. 3rd  | h. 5th | h. 7th | h. 11th | 209% |
| ON-OFF method                 | Produced at PCC | Medium (Cost of PLC control) | Not simulated           | 25%  |
| LCL filter                    | Higher-order | Low                         | 3.2       | 1.9    | 1.4    | 1       | 6.7% |
| APF                           | Lower-order | High                        | 2.3       | 1.4    | 1.2    | 0.7     | 4.5% |
| Hybrid LCL & APF             | All types   | Very high                   | 0.1       | 1      | 1.6    | 0.4     | 1.5% |

Table 3. Comparison among proposed techniques
5. Conclusion

Finally, the objective of this study is to propose harmonic mitigation techniques to attenuate the current THD, which reaches 209%, for a 5.5 kW PVGC system. The acceptable percentage of THD for this system cannot exceed 8%, according to IEEE-standard 519. Table 3 shows a clear comparison of the four applied techniques.

Where T.F. is the terminated frequency, h. 3rd, h. 5th, h. 7th, and h. 11th are the percentages of these harmonics to the fundamental value. The first method used switches to cut-off power at low values of drawn current, resulting in a reduction of the THD to approximately 25%, and applied it to a real connected system using a PLC panel. This result does not meet the standard values, and the total power delivered to the load is reduced by approximately 5% of the total required power; however, the power problem may be solved by utilizing batteries during periods of power outages. The second one was to use LCL filter and the resulted THD has reached 6.7%, but on the other hand, it is bulkier at low frequencies, less sensitive, and resonance producer. Although it is a less complicated solution, it is not flexible to source and component tolerance in their values, and it has restrictions on the bandwidth.

The third method is SAPF which reduces harmonics to 4.5%, and this method is the most common nowadays because its outcome is effective and ensured. The worrisome side here is higher frequencies, where the active filters sometimes malfunction, in addition to interference with electromagnetic waves according to the high frequency of the active elements inside. The benefits of passive and active filters are obtained by a hybrid power active filter in the fourth technique, where the two filters are connected in parallel between the PV arrays and load. Although this technique requires high funding from the producer, it has consequently reduced the current THD to 1.5%. The final technique recommended for future work is to reduce voltage harmonic distortion and voltage unbalance side by side with the current harmonic distortion by applying a UPQC that contains the operation of DVR with DSTATCOM.

Author details
W.A.A. Salem1
E-mail: wailat @ bhit. bu.edu.eg
Walaa Gabr Ibrahim1
E-mail: walaa_gabr @ bhit. bu.edu.eg
Aya M. Abdelsadek1
E-mail: aya.abdelsadek @ bhit. bu.edu.eg
ORCID ID: http://orcid.org/0000-0002-4642-4496
A. A. Nafeh1
E-mail: abdelnaser. nafe @ bhit. bu.edu.eg

1 Electrical Engineering Department, Benha Faculty of Engineering, Benha University, Benha, Egypt.

Availability of data and material
The data that support the findings of this study are available on request from the corresponding author.

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Authors’ contributions
The authors confirm contribution to the paper as follows: W. A.A. Salem conceived the experimental design of the study. Aya M. Abdelsadek developed the model, analyzed the data, and wrote the manuscript with support from W.A.A. Salem and A. A. Nafeh. Walaa Gabr had the supervision of the research. W.A.A. Salem, Aya M. Abdelsadek, and A. A. Nafeh contributed to the final version of the manuscript.

The author statement
Prof. Walaa Gabr: Oversight and leadership responsibility for the research activity planning and execution, including mentorship external to the core team.

Asst. Prof. W.A.A. Salem: Project administration, design of methodology, and project Conceptualization. Eng. Aya M. Abdelsadek: System analysis, performing the experiments, application of techniques to synthesize the study data, writing the original draft, and performing the reviewers’ modifications.
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