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Experimental Works to Improve Power Quality of the Existing PV Solar Inverters

***Ali Algaddafi* [1], *Abdelrahim N. Esgiar* [1], *Eljaroshi Diryak* [1] and *I.M. Saleh*[2]**

[1] *Electrical and Electronics Department, University of Sirte, Sirte – Libya.*
[2] *Engineering Mechanics of Aeronautics, Power and Production Department, University of Sirte, Sirte – Libya.*

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A B S T R A C T

Solar energy development has attracted significant research attention, due to it offering many advantages that include being a safe, clean, and non-finite resource with no operational costs or moving parts. Therefore, solar systems are expected to play a significant role in the future of electricity supply, but, the power electronics used to connect these resources to the grid may face problems. This paper presents improving the power quality of the existing PV inverter by integrating it with a bidirectional inverter along with a battery storage system. A 6 kWh AC Mini-Grid is developed and tested with a PV inverter. The experimental works found that the PV inverter has high the Total Harmonic Distortion (THD) of the output current that may reach up to 24%, while when this PV inverter was connected to the proposed system, the THD of the output current of the PV inverter was reduced to 0.64 %. The response of the battery storage is very smooth and fast, providing a stable and reliable output power in both cases when a domestic load is supplied from the solar system or the battery storage.

1 Introduction

Global energy use is expected to double during the first half of the twenty-first century, against a backdrop of increasingly constrained oil supplies [1], with significant challenges confronting the world's electricity suppliers currently and in the future. Climate change and the security of electricity are thus issues that require greater investigation in order to achieve reliable systems. Furthermore, there are 1.3 billion people globally living without electricity [2]. As such, it is pertinent to investigate the potential for improving Photovoltaic (PV) systems with battery storage to enhance reliability and safeguard the security of electricity.

Recently, power electronic inverters or converters have been utilized in the standalone inverter or grid-connected inverter (PV inverter) [3]-[5]. The inverter is an interface between Renewable Energy Sources (RESs) and the grid, with RES defined as energy harnessed from natural processes such as the sun's rays, waves, and the wind. However, due to the nonlinearity of power electronics and intermittency of renewable sources may bring challenges and cause instability for the network distributions. Hence, many control techniques have been implemented, e.g., in the grid-connected inverter, the two loops are used such as the internal current loop and the external voltage loop [6]-[10], the internal current loop control is used to improve the Power Quality (PQ) and current protection, where it is designed at high bandwidth to give fast response, while the output voltage is controlled by the external loop to ensure stable system and improve the dynamic performance. The information about the phase of the grid voltage is essential to transform the grid variables from the natural reference frame to the synchronous reference frame, where it is easy to deal with DC variables in the control of AC voltage and current [11]. Synchronous reference frame

***Corresponding author*: E-mail:** anasser6474@yahoo.co.uk

control was used in [12]-[16], where the control variables become DC values, hence the control will be easier to accomplish. Also, the active and reactive power delivered to the grid can be controlled, if the reactive power is not required to inject into the grid, then the Iq is set to zero. This procedure is still very poor with the PI controller.

In general, the power that is generated by renewable energy sources can be converted into the grid according to different control procedures as described in [11]. The control procedures can be classified into [10], [11], [14], [17]-[20]:1) Control DC sides, such as Maximum Power Point Tracker (MPPT) techniques or protect the sources of energy. 2) The grid side is usually required to protect the network and the workers who are working on the network interrupt the grid. It has many controllers such as grid synchronization, control reactive power, control DC–link voltage, guarantee high power quality injected into the grid, frequency regulations and so further on. There are various control methods for grid-connected inverters, among these methods are Linear Quadratic Gaussian control [21], predictive control [22], and capacitive current control of the stand-alone system, which is validated to the grid-connected inverter as presented by the authors in [23]-[25]. However, this approach cannot able to ensure system robustness due to the grid voltage disturbances depending on the feed-forward techniques.

Recently, enhancing the frequency of current control for grid-connected inverters was presented by the authors in [3]. It has shown that the control gain for current control should be infinite to achieve good control [3], [11]. However, the one limitation is that it does not show how to obtain the parameters of current control in the proportional resonant controller, and repetitive controller to determine the optimal performance of a second-order-generalized Integrator-based phase-locked loop. Another technique is a sliding mode controller [26]. This technique for the grid-connected inverter may not be able to guarantee robustness and has limitations as described in [27]. The u-synthesis system for grid-connected inverter was presented in ref. [27], [28] and an optimal current controller design for a grid-connected inverter was presented in [29]. Although the results show a good dynamic performance, the system would be useful if tested with a nonlinear load such as a full rectifier circuit. The time delay may not be taken into account, which makes it a serious challenge in practice. Further, the maxim percentage deviations were assumed.

In light of the above issues, this paper presents testing a commercial PV inverter and then proposed an AC Mini-grid to enhance the power quality of the existing PV inverter by integrating with a bidirectional inverter along with battery storage. The present study pursues the following objectives: 1) Designing a PV Array Emulator (PVAE) with a faster response than the available commercial PV inverter. The PVAE should logically be faster than the response of the PV inverter in order to investigate the effectiveness of the MPPT feature. Moreover, the PVAE assists in experimenting in an indoors' environment. An Analogue Computation Circuit (ACC) is employed to design the PVAE. 2) A Fast Fourier Transform (FFT) analysis is used to analyze the waveforms, while the Total Harmonic Distortion (THD) and the fundamental of the output voltage and current are used to evaluate the performance of the PV inverter. 3) Finally, the configuration of the entire AC Mini-Grid system and testing the response of the entire system. This paper is organized as follows: Section II presents the impact of high harmonic distortions in the network, while section III describes the framework system. Section IV shows the experimental setup and section V shows the proposed AC Mini-Grid system. Section VI discusses the obtained results, and the last section concludes the paper.

2 Impact of High Harmonic Distortion of Waveforms in Electricity Network

The THD of the voltage and current waveforms is a measurement of the harmonic distortion of these waveforms. These powerful tools facilitate the evaluation of the PQ of electric power systems because it is defined as the ratio of the square root of the sum of all the harmonics except the fundamental harmonic, divided by the fundamental harmonic. The harmonic components of both the voltage and current in the electrical power system may be caused by the source of the load, according to Sultani [12]. There are many negative consequences of higher harmonic distortion levels, which may lead to stress and problems for the network distribution system, and in particular the transformer, where the temperature may increase. This excess temperature may affect the isolation and performance of the transformers. Furthermore, the high harmonic distortions may cause the shutting down of important plant equipment, together with the motor and wire insulation breakdown and failure. Ultimately, the harmonic reduces the motor life and leads to the inability to fully load motors. For the transformer, the high harmonic distortions increase the losses and reduce the useful capacity [29]. Increased noise and possible insulation failure are likely, most notably through thermal degradation. The key to all of this, as we introduce switching power electronics into legacy systems, is the need for equipment to run as cool as was originally intended.

The voltage and current harmonics of the source imply power losses, electromagnetic interference, and pulsating torque in AC motor drives. In general, appliances can be categorized as having a linear or non-linear load. The linear load can draw current as a pure sinusoidal waveform, while the non-linear load can draw current that is not a perfectly sinusoidal waveform, so the voltage waveform may be distorted [30], [31]. The output current with a THD of AC voltage is <2% and must be ≤3% [32]. The low THD values on a system will further guarantee the proper operation of the equipment and increase its lifespan.

3 Description of The Framework System

The aim of this paper is to improve the power quality of the existing PV inverter. Therefore, the procedure of experimentation consists of one PV inverter and a bidirectional inverter with a battery storage system. The PV inverter was connected to the grid firstly from the AC side while the DC side was connected to the PV array emulator. The PV array emulator was designed as presented in [21]. The first step was to measure the THD of the output voltage and current of the Sunny Boy 700 inverter without connecting the proposed system. The second step is connecting the Sunny Boy 700 inverter to the local grid with a bidirectional inverter along with a battery storage system as shown in Fig.1.

The commercial PV inverter has high harmonic distortion. Thus, the proposed system, inclusive of a bidirectional inverter with battery storage, is implemented by connecting the commercial PV inverter to improve power quality and reduce THD. According to the quality power produced by the solar panel connected to the PV inverter, the proposed system can produce active and reactive power to reduce the distortion of both waveforms the output voltage and current. The AC Mini-Grid system consists of a PVAE, grid-connected inverter, bidirectional inverter and a storage battery.

3.1 Frame to Mount the AC Mini-Grid Elements

The AC Mini-Grid system that is considered in this paper consists of an automatic transfer switch (offering protection for the network (G59 switch box)), the Sunny Island (SI) 6.0H inverter, and a battery bank. Furthermore, additional elements such as local loads, the PV inverter and the utility grid connection could be integrated to create a centralized battery storage solar system. The AC Mini-Grid system is described in Fig. 9 and illustrated in the schematic diagram in Fig.1.

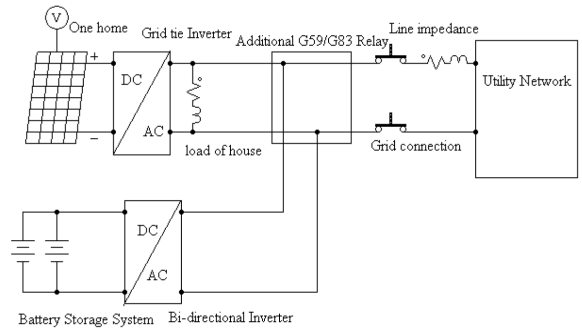

Fig. 1. Circuit diagram of the AC-Mini-Grid system

To clarify, the AC Mini-Grid solar system developed in the Laboratory of Engineering at the University of Leicester features the SB700 inverter, a single-phase battery backup distribution G59 switch box, and the SI 6.0H inverter with the storage batteries. Therefore, the mounted frame needed to be designed according to the dimensions of the different components. A steel frame was thus designed to ensure ease of access and facilitate the connection between the different components of the AC Mini-Grid system.

The frame was designed using SOLIDWORKS software, relying on strain cables and facilitating experimentation to maintain the relevant measurements. Those cables were as short as possible in order to avoid parasitic resistance and reduce costs. This frame was designed in six parts in accordance with the components' dimensions, as described in their respective manuals [33], [34]. Fig. 9 illustrates the physical configuration of the AC Mini-Grid system.

3.2 Development of Battery Storage in PV Systems

Battery storage converts electrical energy into chemical energy during charging and vice versa [36]. A battery cell typically comprises three primary elements: two electrodes (negative and positive) immersed in an electrolyte. Four batteries (Rolls Solar, Absorbed Glass Mat (AGM)) are used in this project, having the following features: all parts are included inside and sealed; there is no threat of acid spill; they have a deep cycle and low internal resistance, and thus the charge time is rapid. These batteries must be kept in an upright position at all times and be properly charged to maximize the battery life. It is important to determine a proper battery bank capacity to meet the load; however, any oversized battery bank may lead to sulphation issues. As a battery system with multiple parallel batteries may suffer from an imbalance of charge [35], the batteries in this system are connected in series. The four batteries have a free maintenance feature [35]. There are a number of parameters that require consideration when selecting the optimum battery size: depth of discharge, the efficiency of charge, battery life, and coulometric capacity (amp-hours). The characteristic of the battery storage can be represented by using the Simulink battery block in MATLAB. Fig. 2 presents the characteristics of the batteries used in the four-battery bank in this paper.

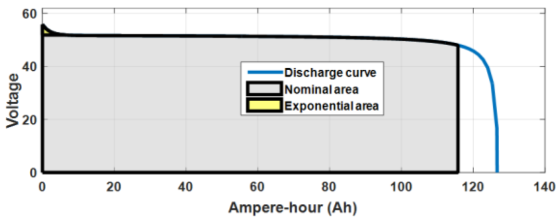

Fig. 2. Cut-off voltages for a typical battery

Batteries utilized in the solar system should have the capability for deep cycle and discharge. Solar batteries differ from conventional car batteries, which are required to provide a large amount of current for a short period [38]. Therefore, the capacity of the battery will be smaller with larger discharge current rates. The other parameter is the State-Of-Charge (SOC). A fully charged battery has a SOC of 100%, while a fully discharged battery has a SOC of 0% [36], [39].

3.3 Limitations and Challenges of the PV Array Emulator

Due to the limitations of testing a PV inverter with a real PV array, where the actual PV array depends on the climatic conditions, it may not be possible to repeat the experiment under the same condition. Thus, the design of the PVAE is presented by employing an ACC. The PVAE is defined as an electronic circuit that provides the characteristic of a real PV array, such as the I-V or P-V curves of the solar array. While researchers identify, that solar power offers the potential for producing electricity, there are limitations such as a dependency on the weather and unavailability during night periods. Furthermore, under cloudy conditions the efficiency of solar power will be reduced; thus, the energy produced by solar energy is variable and intermittent [40]. Currently, the high cost of solar energy is the main challenge; however, this is expected to decrease in future. Solar energy is one of RES that has many advantages such as being a non-finite resource, safe, clean, and continuously available while having no operational costs or moving parts. Solar energy is thus considered an elegant solution to supplying rural areas with electricity. The PV modules are connected to form a PV string or an array. Those PV modules face challenges in mismatching power during varying climatic conditions such as clouds and shadows. Changing conditions may lead the power against the voltage to have multiple peaks, which may fail the MPPT algorithm in power condition devices. Therefore, the maximum power produced by the inverter will be reduced. The PVAE is utilized to evaluate the performance and behaviour of electronic devices, such as a DC/DC converter or DC/AC inverter. These electronics have different MPPT algorithms in order to extract the maximum power from the PV array. Many studies were published to explore MPPT algorithms [12], [41]-[44]. There are a number of limitations to using a real PV array, such as:

1- Solar radiation may not be available and is uncontrollable.

2- Repeating the same experimentations may not be possible due to changing conditions.

3- The high cost of a real PV array and installation may present a problem.

Therefore, the term PV emulator arose as a result of the above limitations. There are two commercial companies offering a PVAE: Agilent with their E4360 [45], and Magna-Power Electronics with their PV Power Profile Emulation (PPPE) [46]. The high cost of these PV emulators and the limitations of their power makes them impracticable, according to Entwistle [44]. Many researchers have paid attention to developing a PVAE at low cost [44], [47], [48], with research being conducted to gain further improvements with respect to the cost, speed of response, efficiency and reliability of the PVAE [47], [49], [50]. To date, there is no established method for testing and assessing the MPPT.

Chavarría, et al. [48] employed a boost converter and a lookup table to design a PVAE. However, the boost converter may not be a suitable solution, particularly when the duty cycle reaches a unity factor. On the other hand, any DC voltage level can be obtained by utilizing a linear transformer with a rectifier circuit. Thus, the DC-DC buck converter is an acceptable choice to design a PV emulator due to its simplicity and reliability [7]. The other issues in designing a PVAE are a non-linear relation between the I-V and/or P-V curves, together with the cooling of a power switch and a diode at a high power level. The ACC can be implemented to overcome some of these limitations; however, the speedy response of a PVAE is presented as an additional challenging matter as it depends on the output capacitor value of the emulator. The output voltage ripple is increased when the output capacitor is very small. The optimal choice of the DC-DC buck converter elements that are used to design PVAE is considered in this paper, in order to overcome those limitations.

3.4 Designing PV Array Emulator

A PVAE consists of a DC/DC buck converter with the output feedback voltage controller. The I-V characteristic generator of the PVAE is utilized as the desired reference, as shown in Fig. 3 and described by the authors in ref. [44], [51], [52].

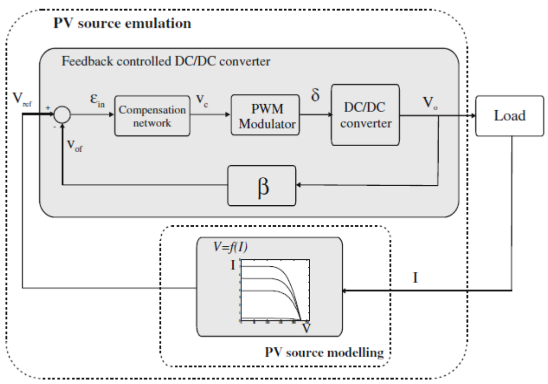

Fig. 3. Block diagram of a PV array emulator [26]

The effectiveness of the ACC was tested experimentally by supplying the variable resistive load, where the current passed through the Hall effect sensor. The variable resistance was varied to decrease to zero ohms and the output voltage of the I-V curve, and the load current were observed.

The ACC generates an acceptable curve that is like a realistic solar cell curve. This analogue curve is utilized in its analogue state, where there is no need to take the time to arrange a processor operation, such as in a digital signal. This procedure, therefore, is utilized as a reference signal to control the PVAE. After combining all the elements of the PVAE, the test was achieved with a low input-variable supply voltage (30 V, 6 A) for safety reasons and to avoid damaging the PVAE elements, including the buck converter.

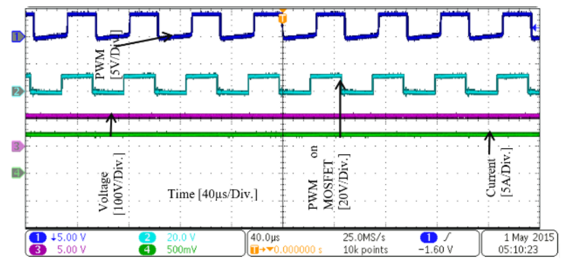

Fig. 4. Experimental measurements of the buck converter at input voltage=300V [24]

Fig. 4 shows the PWM in trace 1, which is generated by the function generator. The PWM of the output driver circuit of the MOSFET in trace 2, the output voltage of the buck converter in trace 3 and the output current of the buck converter in trace 4 were acceptable when the input voltage was 300 V and the performance of the control circuit as shown in Fig.5. Following this test, the PVAE was connected to the SB 700 inverter.

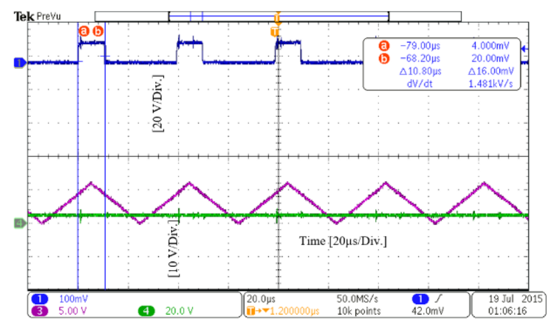

Fig. 5. The performance of the control circuit, trace 3 and trace 4 are the triangular signal and error signal respectively and trace 1 is generated PWM waveform

The SB700 inverters were provided by SMA Solar Technologies, which was connected to the designed PVAE. The output and input of the voltage and current of the SB700 inverter, which was observed via an oscilloscope (Tektronix MDO3024) and the THD was measured by using a PA2100 power analyzer. According to the technical description of the SB700 inverter [32], three ranges of PV voltage can be adapted to operate the inverter: 125–250 DCV, 100–200 DCV and 75–150 DCV. The latter range was selected in this thesis. The results of this test of the SB700 inverter are shown in Fig. 6.

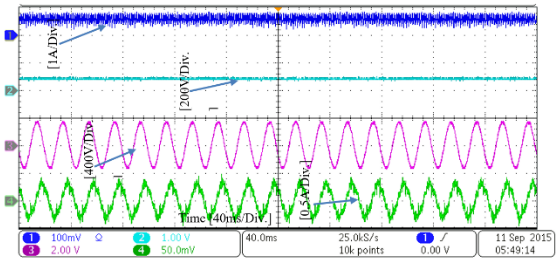

Fig. 6. Testing the SB700 inverter with the PVAE: trace 1 is the input current [10A/Div.], trace 2 is the input voltage [200V/Div.], trace 3 is the output voltage [200V/Div.], and trace 4 is the output current [10A/Div.]

As this paper aims to evaluate the PQ generated by the PV inverter, an analysis of the output voltage and current is conducted by using FFT analysis, as shown in Fig. 7 and Fig. 8.

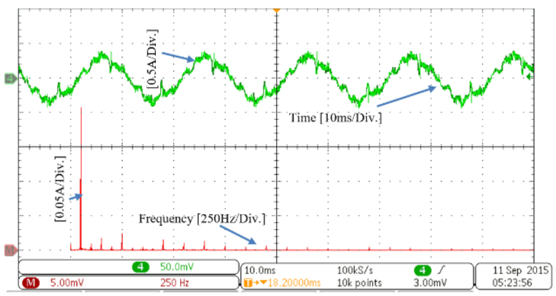

Fig. 7. Output current waveform of the SB700 inverter [10A/Div.] when connected to the PVAE and its FFT analysis, along with the THD which was found to be 24%

The output current was found to be 0.28 A and the fundamental current at 50 Hz was 0.21 A. The fifth harmonic current is the dominant harmonic at approximately 0.025 A. The THD of the output current was provided by [53]:

$$I_{THD} = \frac{\sqrt{\sum_{K=2}^{max} I(K)^2}}{I(1)} \quad (1)$$

Where: I(1) is a fundamental current at 50 Hz. The ITHD was found to be 24%when the PV inverter was connected to the PVAE. The output voltage of the PV inverter is shown in Fig. 8 and it is noticed that the THD of the output voltage when the PV inverter is connected to the PVAE is high. This is due to the main transformer in the network being located close to the Concrete Laboratory, where experimental works are carried out in the Department of Engineering at the University of Leicester. The THD of the output voltage was provided by [53]:

$$V_{THD} = \frac{\sqrt{\sum_{K=2}^{max} I(K)^2}}{V(1)} \quad (2)$$

here: V(1) is a fundamental voltage at 50 Hz. The VTHD was found to be 4.5% when the PV inverter was connected to the PVAE, which does not comply with the IEEE-519-2014 standard. Although those harmonics can be eliminated by using a small LC filter, they have been created by the current distortion and impedance of the network. Therefore, the next section introduces the AC Mini-Grid system that can reduce the harmonic distortion of the voltage and current.

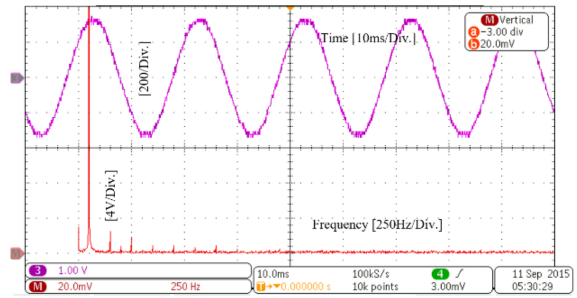

Fig. 8: Output voltage waveform of the SB700 inverter [200V/Div.] when connected to the PVAE and its FFT analysis, along with the THD which was found to be 4.5%

4 Proposed Ac Mini-Grid System to Improve Reliability and Power Quality

From previous analyses of the output waveforms, it was noticed that the THD does not comply with the IEEE 1547 and IEEE-519-2014 standards. This research, therefore, proposes the AC Mini-Grid system to improve the PQ and also enhance the output of a commercial PV inverter. There are two possible topologies for providing continuous electricity to rural regions via solar systems: the centralized battery system and the decentralized battery system. The centralized battery system is employed in this paper to investigate the interaction between two or more PV inverters and improve the power quality. This represents the AC Mini-Grid system, as shown in Fig. 9, which is implemented to facilitate the experimental investigation of the PQ.

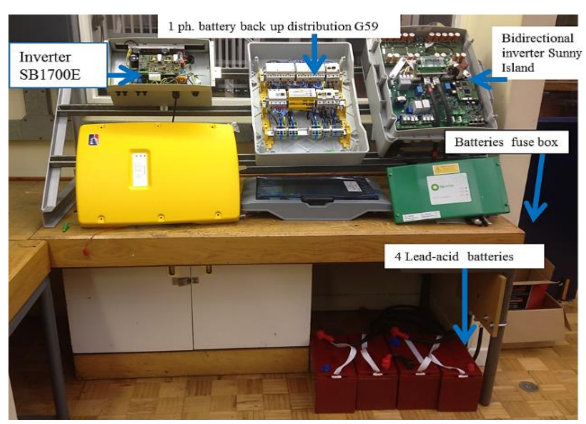

Fig. 9. Batteries located under the AC Mini-Grid system.

In future, this system will be used to explore the interaction between a number of PV inverters and use Variable Frequency Power Supply/Variable Frequency Power Source. The PVAE was connected to the SB700E inverter, then connecting this inverter to a small local network. The bidirectional inverter was connected to battery storage via a fuse box. The other side of the bidirectional inverter was connected to an automatic transfer switch (the additional G59/G83 relay), which was utilized to offer protection to the network and workers. In addition, the automatic transfer switch was also deployed to protect the elements of the PV system. The small local network was connected to a resistive load (two resistors, each 228 Ω). The commercial PV inverter (SB700) was then connected to an SI 6.0H inverter to measure the improvement of the PQ.

5 Discussion of The Obtained Results

The PQ is a critical criterion. The majority of renewable energy resources depend on environmental conditions such as the sun, wind, and tide, which causes intermittent in the network. In the AC Mini-Grid, the current generated from the solar system was compared with the current supplied to the domestic load. The improved results are presented in Fig. 10 and Fig. 11.

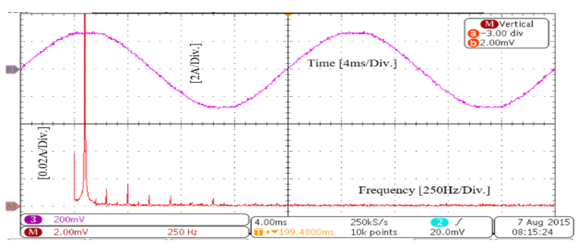

Fig. 10. Output current [10A/Div.] of the Mini-Grid goes to the domestic load and THD=0.64%

The observation in these experiments is that the THD of the output current reduced from 7.4% to 0.64%, and thus improved; this means that the THD output current improved by 8.6%. Moreover, this allows the THD of the current to comply with IEEE-519-2014. The THD value of the current was measured via the PA2100 Power Analyzer.

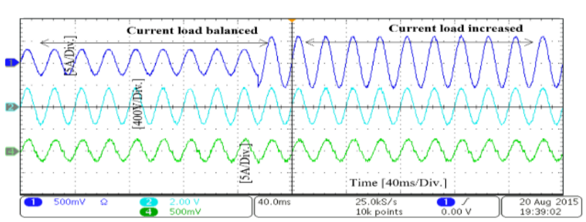

Fig. 11. Trace 1 is the output current of the AC Mini-Grid going to the resistive load [10A/Div.], trace 2 is the output voltage of the AC Mini-Grid [200V/Div.], and trace 4 is the current generated from the solar system [10A/Div.]

Future An oscilloscope was triggered during the moments of changing the resistive load. The load current was altered rapidly to change the load. However, the current generated by the solar system and the voltage at the local distribution did not change, as shown in Fig.11, while the output current of the bidirectional inverter did change according to the load change. This change proves the strong reliability of the AC Mini-Grid system with a fast response.

The AC Mini-Grid is configured and mounted on the assembly frame. The output voltage and current between the SI 6.0H inverter and PV inverter are measured, together with the current injected into the battery, where the voltage is fixed at 48 V; hence, the battery voltage is not included where the battery charge current has two components: AC components and DC components. The charge current should be a DC current with a small ripple. This ripple current has a frequency twice that of the grid and thus may cause damage to the battery and also reduce its lifespan. This is considered to be the main limitation of the AC Mini-Grid, as discussed in [54]. The proposed AC-Mini-Grid system can be operated in both off-grid and on-grid systems. It can provide virtually an Uninterruptible Power Supply (UPS) function. Commercial UPS is used to respond rapidly to secure power provision for small machines such as computers and printers. However, for a large load, the fast response of the Uninterruptible Power Supply function is challenged. E.g., the AC Mini-Grid takes five seconds to respond. Fig. 12 presents the response of the AC Mini-Grid during an interruption in the network. Also, when the system is recovering from the grid system to a stand-alone system, the peak current and voltage appear, which could cause problems for the connecting appliances.

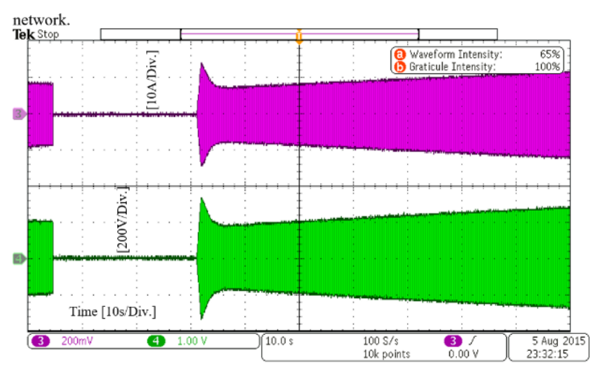

Fig. 12. Response of the AC Mini-Grid when transferring from on-grid to off-grid: trace 4 is the output voltage [200V/Div.], trace 3 is the output current [10A/Div.]

This system can work perfectly, although the solar system has a number of limitations, such as fluctuation in intensity and unavailability during night periods, it is considered an elegant solution to supplying electricity to rural areas such as those found in southern Libya. In summary, the PV system can be used in rural areas where the main electrical grid may not be available. The stand-alone inverter in the PV system has been used in a variety of applications, such as supplying electricity to a critical load and continuing to supply power where the grid connection is absent or intermittent. This research thus resonates with the scenario of rural Libya.

The surplus power of the solar system is directly conserved in the battery storage, and so when the power demand is higher than the produced power, the battery storage compensates. Moreover, the proposed system can be operated in off-grid and on-grid modes, and thus can be deployed in remote and isolated areas where the grid is unavailable. The solar system is a solution for increasing self-consumption and reliable backup power.

It can be integrated with the existing system and ensures continuous power supply to all consumers, which guarantees the security of electricity. If the grid fails, the backup power is harnessed to provide security for the electricity supply.

6 Conclusions

The key features of the power electronic inverter are used to facilitate the integration of different renewable energy sources and manage power flows between the generator, the load, and the grid while providing a reasonable Power Quality (PQ) to the grid or the load. The integration of a renewable energy source into distribution networks greatly impacts the grid performance, particularly the PQ of the grid and the harmonic distortions. This paper, therefore, has studied and proposed the AC Mini-Grid to improve the PQ. However, the fluctuation of renewable energy resources such as the impact of cloudy days on the solar system may lead to degradation of the efficiency and distortion of the PQ. Therefore, improving the PQ and designing an optimal controller for the solar system to improve reliability were studied here, taking into account the cost and output power.

To evaluate the proposed system improvements, achieved in the AC Mini-Grid system, the experimental works in the laboratory were implemented and validated by using real testing at the University of Leicester as follows: The design and construction of a Photovoltaic Array Emulator (PVAE) were presented The PVAE control was used the I-V curve to develop the PVAE. The Sunny Boy 700 inverter as a commercial PV inverter was tested experimentally. The commercial PV inverter was found to have high harmonic distortion. The proposed system, which includes a bidirectional inverter with battery storage, is integrated with the commercial PV inverter to improve the PQ and reduce the total harmonic distortion. The proposed system can produce both active and reactive power, according to the quality of the power produced by the solar system. The surplus power from the solar system is transferred to the battery storage when the power demand is higher than the produced power; then, the battery storage compensates for any reduction in produced power as required. Furthermore, the proposed system can be operated in both off-grid and on-grid scenarios; thus, the proposed system can be deployed in remote and isolated areas when access to the grid is unavailable. This paper accounts for the limitations and challenges of grid-connected inverters that include the island feature, power factor, harmonic components, and commercial PV inverters. To be precise, the output current harmonic of a commercial PV inverter was found to be higher than the requirements of IEEE-519-2014. Thus, this paper proposes an AC Mini-Grid that can be utilized to reduce the harmonic current in order to reduce the harmonic voltage, with acceptable results realized. Moreover, these results comply with the IEEE-519-2014 standard's requirements. The output current waveform improves, and any excess power that is generated from the solar system is stored directly in the battery, and then released when required. The development of the bidirectional converter and testing of the fast-transient response of the battery storage is then tested in the AC Mini-Grid system.

In fact, rural areas can include isolated rural areas, peri-urban areas and small islands that are separated from the national grid. The off-grid or AC Mini-Grid system provides an independent energy source that creates distribution networks for local communities and rural areas. This system can be implemented in rural zones such as villages in Libya, where the extension of existing transmission lines proves both cost-intensive and challenging. However, limitations of the AC Mini-Grid system such as the ripple current on the DC side need to be eliminated, and an attempt was made by using a central transformer with a capacitor. However, this is a complicated method that is still inapplicable with the AC Mini-Grid system. Thus, seeking an affordable method to reduce this ripple is recommended. Also, the Variable Frequency Power Supply/Variable Frequency Power Source does not available at present time, which helps to study in detail the effect of changing frequency, which will be a part of future work.

Conflict of interest: The authors declare that there are no conflicts of interest

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