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Modelling a Stand-Alone Inverter and Comparing the Power Quality of the National Grid with Off-Grid System

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***Abstract*:** Developments in power electronics have enabled the widespread application of Pulse Width Modulation (PWM) inverters, notably for connecting renewable systems to the grid. This study demonstrates that a high-quality power can be achieved using a stand-alone inverter, whereby the comparison between the power quality of the stand-alone inverter with battery storage (off-grid) and the power quality of the utility network is presented. Multi-loop control techniques for a single phase stand-alone inverter are used. A capacitor current control is used to give active damping and enhance the transient and steady state inverter performance. A capacitor current control is cheaper than the inductor current control, where a small current sensing resistor is used. The output voltage control is used to improve the system performance and also control the output voltage. The inner control loop uses a proportional gain current controller and the outer loop is implemented using internal model control proportional-integral-derivative to ensure stability. The optimal controls are achieved by using the Sisotool tool in MATLAB/Simulink. The outcome of the control scheme of the numerical model of the stand-alone inverter has a smooth and good dynamic performance, but also a strong robustness to load variations. The numerical model of the stand-alone inverter and its power quality are presented, and the power quality is shown to meet the IEEE 519-2014. Furthermore, the power quality of the off-grid system is measured experimentally and compared with the grid power, showing power quality of off-grid system to be better than that of the utility network.

***Keywords*:** Internal model control-proportional-integral–derivate controller (IMC-PID), Renewable energy system (RES), Stand-alone inverter, Total harmonic distortion (THD)

1. Introduction

According to Xue et al and the US Energy Information Administration (EIA) [1, 2], global electricity consumption will increase from 13934 TWh in 2001 to 24673 TWh in 2025 increasing annually on average by 2.35%. A Renewable Energy System (RES) can improve energy security, increase the generating capacity, reduce the greenhouse gas emissions, enhance the power quality and the overall system stability, and reduce the cost of the electricity. An RES may include e.g. wind turbines, solar power systems, fuel cells, small hydro systems and energy storage systems. The RES is considered as a sustainable alternative to using fossil fuels, and may be integrated into a distribution system, which can provide functions as follows:

- Conversion from a variable DC voltage to a fixed AC voltage.
- Improving the power quality by reducing the Total Harmonic Distortion (THD).
- Protecting the Direct Current (DC) generators from abnormal temperature, voltage, frequency, and current, along with anti-islanding protection.

- Extracting the maximum power from e.g. wind and PV modules.

Solar systems are considered one of the most important RESs, where frequently an inverter is used to connect the RES to a distribution network. The optimum requirements for small distributed power systems are high efficiency, low cost, and tolerance for a wide range of input voltage variations. An inverter can be a single stage or multiple stages. Single stage inverters offer simple structure and low cost, but suffer from a limited range of input voltage variations. Multiple-stage inverters, on the other hand, accept a wide range of input voltages but suffer from high cost, low efficiency, and complexity.

The converter in an RES can be a DC-DC converter or a DC-AC inverter. The former is used to supply DC loads, charge batteries, and provide a DC voltage for the DC Busbar, which is used to supply the DC loads directly or to convert to AC current. In addition, the DC-DC converter can be used to increase or to decrease the voltage level. The DC-AC inverter, on the other hand, can operate in island mode or as a grid connected inverter [3]. In island mode, the inverter should be able to control the amplitude and the frequency of the output inverter. The DC-AC inverter must have a fast dynamic response and must reduce the steady state error. This enables the whole RES to be islanded or grid connected, which has led to the increasing reliability of micro-grid and small-scale, low voltage supply networks designed to dependably supply electricity to for example housing estates and communities.

The output voltage of a stand-alone inverter is required to be purely sinusoidal with a minimum THD [4]. Many control strategies may be used such as repetitive, dead-beat and sliding mode controls. The deadbeat control method is sensitive to parameter variations and also is complex to use [6]. Because, the deadbeat control method requires a perfect plant model. In the real life, it is difficult to obtain the exact plant model. The repetitive control method [6-8] can achieve low THD of the output current in a few fundamental cycles; however, the dynamic performance of the inverter remains imperfect. The sliding mode control method has proved to be quite useful against uncertainty [6, 9, 10]. However, the well-known chattering problem should be considered in any analogue or digital realization of the control algorithm [4], requiring careful selection of the switching surface. Furthermore, multiple feedback loop control method was proposed by Abdel-Rahim and Quaicoe [5]. It is easy to use in theory, given a comprehensive analysis of the various controller parameters.

So that we may overcome the above limitations, we propose a multi-loop control scheme, where the inner loop is the capacitor current controller and the outer loop is an Internal Model Control-Proportional-Integral–Derivate (IMC-PID) controller. The inner current loop is designed to improve the dynamic performance and to improve the robustness and the stability. The outer loop is used to guarantee the stability of the output voltage and frequency under the variation of the load.

We conduct a comparison between the power quality of a stand-alone inverter and the power quality of the utility network, while modelling a stand- alone inverter with high power quality. This paper is organized as follows: section 2 discusses the control model of a stand-alone inverter and the experimental setup. In the same section, the procedure to test the power quality of a stand–alone inverter (off-grid system-Sunny Island (SI) 6.0H inverter) and the power quality of utility network is presented. Section 3 presents the experimental outcomes and the Simulink results. The final section lists the drawn conclusions and future work.

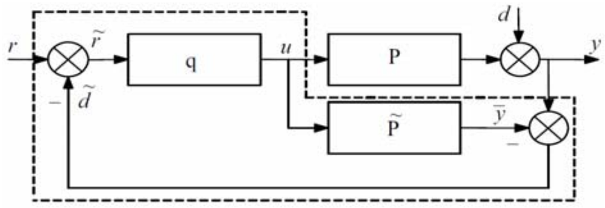

Fig. 1. Block diagram of the IMC-controller of plant [6].

2. Modelling of a Stand-Alone Inverter

2.1 Internal Model Controller

The Internal Model Controller (IMC) has advantages such as a simple structure, an excellent tracking performance, attenuation disturbance ability and the ease of designing in robustness [6].

The IMC is explained as in Fig. 1 where p is the plant that requires a design control, q is the controller, $\tilde{p}$ is the nominal model of the plant. The IMC is given by C as in Eq. (1) [6]:

$$C = \frac{q}{1 - q\tilde{p}} \tag{1}$$

The IMC–controller prevents overshoot for the process variable, sensitive to possible errors, and the tuning is very robust. Also, the IMC controller absorbs disturbances. However, it does have a limitation, this being that the integral time the controller equals the process time constant. If the process variable has a very long time constant, the resultant long controller integral time leading to slow recovery [11, 12]. The stand-alone inverter switching frequency is high, making the IMC appropriate. The Sisotool is used to design the IMC controller, which can then be compared with the PID controller structure, given by Eq. (2) [6, 11]:

$$G_{pid} = \frac{K_d s^2 + K_p s + K_i}{s} \tag{2}$$

Where: K_d is the derivate gain controller, K_p is the proportional gain controller and K_i is the integral gain controller. The derivated term is usually multiplied by a filter with a filter coefficient (N).

2.2 Inverter Model

The procedure to select a stand-alone Photovoltaic

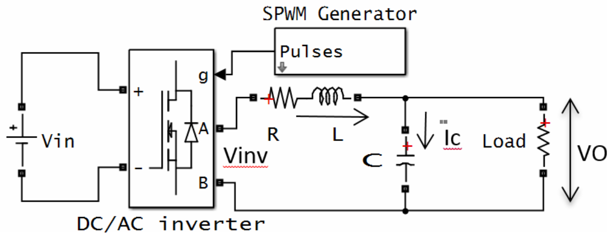

Fig. 2. Power circuit of stand-alone inverter.

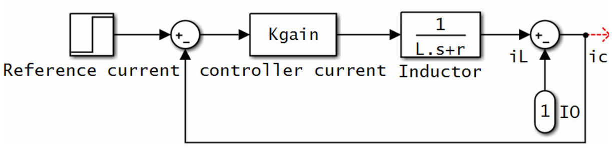

Fig. 3. Block diagram of capacitor current controller.

(PV) system has been presented by Xu [6]. Specifying and integrating PV components for an RES will include voltage and power choices to be made, storage to be selected as well as the PV modules themselves, with a vital link being the charge controller. This could be a DC-DC converter or a DC-AC inverter [13]. In this section, the stand-alone inverter is considered. A single phase example is shown in Fig. 2, consisting of the DC voltage source and the inverter full bridge, controlled by a Sinusoidal Pulse Width Modulation (SPWM) generator. The output voltage of the DC-AC inverter needs a filter to attenuate the switching harmonic components. Thus, the LC filter is used. The mathematical model of a single-phase inverter with LC filter is given by applying KVL and KCL in [6, 14, 15] as follows:

$$\frac{dV_c}{dt} = \frac{1}{c} i_L + \frac{1}{c} i_o \tag{3}$$

$$\frac{di_L}{dt} = \frac{1}{L} V_{inv} - \frac{1}{L} V_c - \frac{R}{L} i_L \tag{4}$$

At no load, the transfer function between the output and the input voltages can be given by the Eq. (5), where the output voltage V_o is equal to the capacitor voltage V_c.

$$\frac{V_o}{V_{inv}} = \frac{1}{LCs^2 + RCs + 1} \tag{5}$$

2.3 Design Optimal Controller of a Stand-alone Inverter

The capacitor current is controlled by an inner loop as shown in Fig. 3 where the inductor with parasitic resistance is used.

We propose two control loops to control the output voltage. The first loop is a capacitor current controller and the second loop is the output voltage of the stand-alone inverter controller as shown in Fig. 4.

Fig. 5 shows the numerical model of the full proposed stand-alone inverter along with two loops. The output voltage of the stand-alone inverter is assumed as desired voltage that allows this model to operate as a grid connected inverter as well. Fig. 6 shows the bode diagram of the whole system of the stand-alone inverter with its two controllers. The waveform of Simulink model in the time domain is shown in the results section.

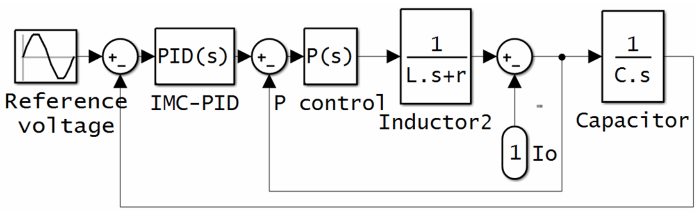

Fig. 4.Full block diagram of stand-alone inverter.

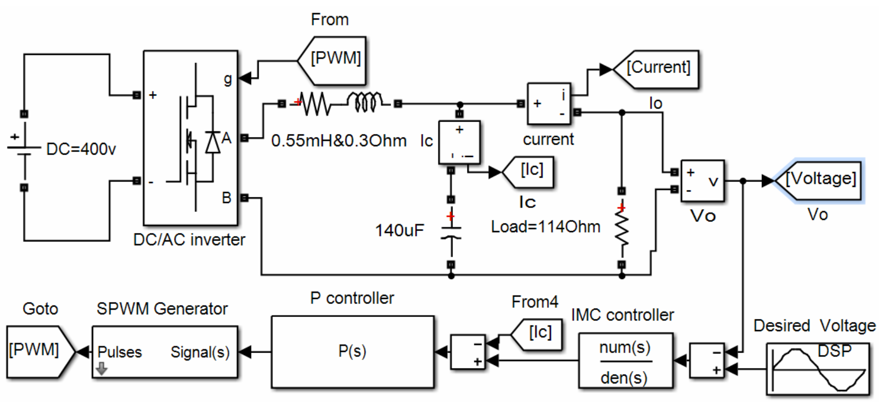

Fig. 5. Circuit diagram of stand-alone inverter with proposed controller.

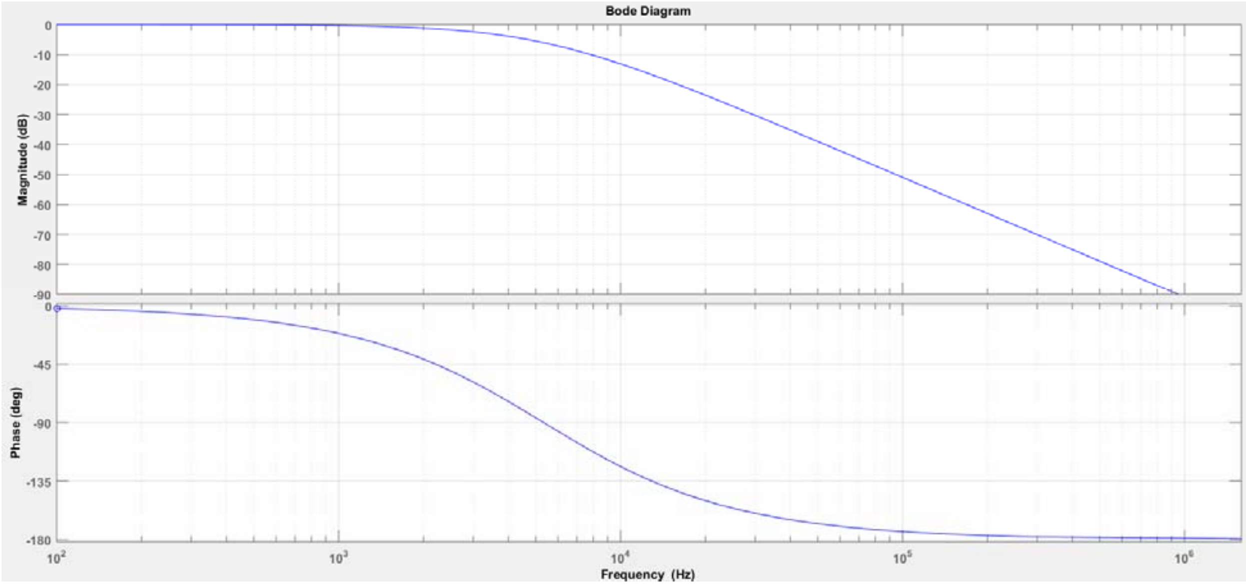

Fig. 6. Snapshot of the bode diagram of the stand-alone inverter.

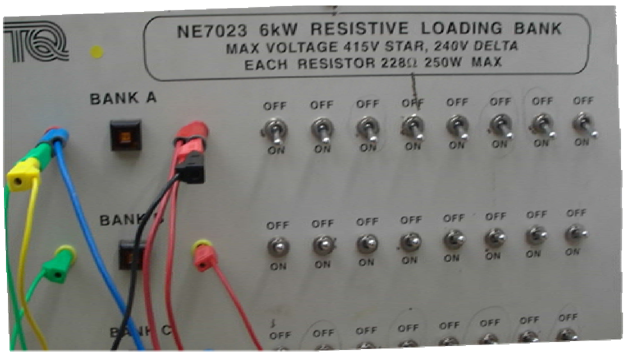

Fig. 7. Resistive loads are used in these experiments.

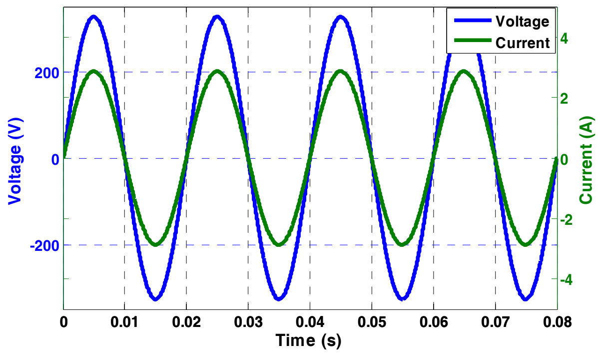

Fig. 8. Output voltage and current of stand-alone inverter.

2.4 The Experimental Set Up

2.4.1 Configuration of SI6.0H Inverter as Off-Grid System

The Sunny Island (SI) 6.0H inverter is taken as our working example, which is a bidirectional converter. It can be operated in island mode (off grid) where it forms a stand-alone system providing active and reactive power. The inverter may also run as a grid connected inverter. The conducted experiments aim to test the off-grid system power quality and to understand the inverter performance (with battery storage) and also, compare with grid power quality. Power quality in island and grid modes should meet the IEEE 519-2014 standard [16].

2.4.2 Testing the Power Quality of the Off-grid and the Public Grid

Experimental work was conducted to test the power quality in the laboratory. Two resistors of 228Ω were used in parallel to give 114 Ω. The variable resistor bank is shown in Fig. 7. Each resistive load has a switch that allows connecting or disconnecting. The inverter was conFig.d in an off-grid mode and used to supply these resistive loads. The output voltage and current were then analysed. The THD of the output voltage and current are measured using a Power Analyzer and waveform components run through Fast Fourier Transform (FFT), which is used to evaluate the stand-alone inverter performance, as presented by Neacsu [17]. The same resistive loads are supplied from the utility network and the same procedures are carried out to compare with the off-grid system.

3 RESULTS AND DISCUSSIONS

The results of this paper include numerical model results and the experimental results, which compare the on and off grid power quality.

3.1 Simulation Outcomes

To evaluate the performance of the proposed stand-alone inverter controller, the predicted output voltage and

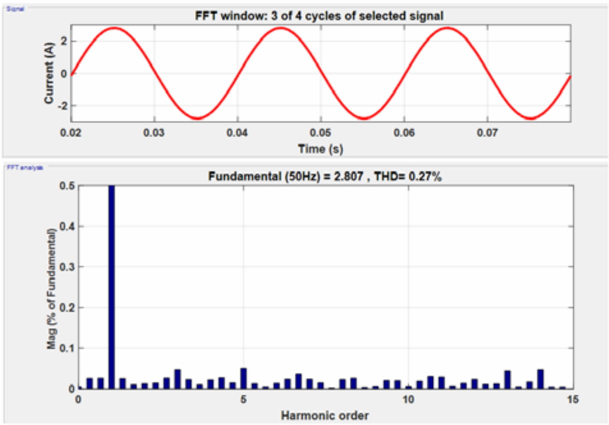

Fig. 9. Output current of stand-alone inverter and its FFT analysis.

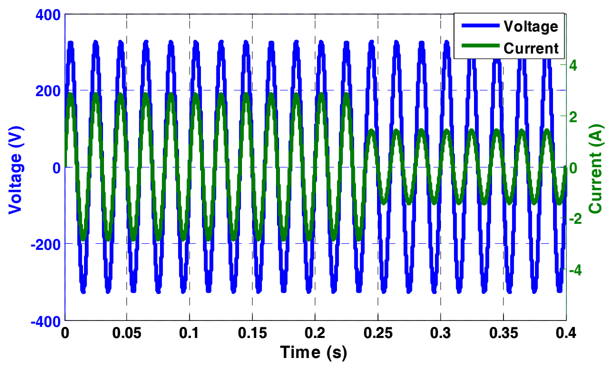

Fig. 10. The response of stand-alone inverter to reduce the load.

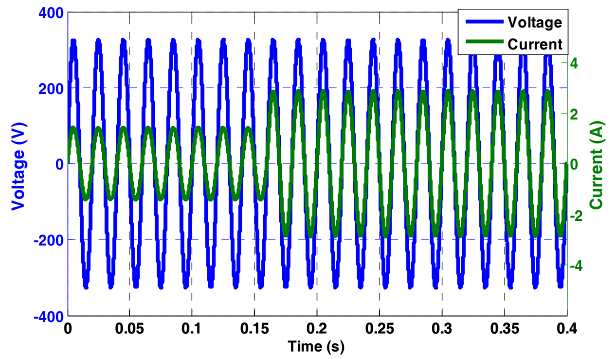

Fig. 11. Smooth response of stand-alone inverter to increase the load.

current were plotted as shown in Fig. 8. It can be seen that the stand-alone inverter works at a unity power factor. The load in Simulink is selected to be 114Ω to match the experimental work.

The THD of the output current was analysed in the frequency domain. The spectral analysis is shown in Fig. 9. The THD of the output current of the stand-alone inverter is minimal and complied with IEEE-519 standards.

In this paper, the variations of the load are only considered. A unit step with an ideal breaker is used to connect and to disconnect the load. In addition, a resistive

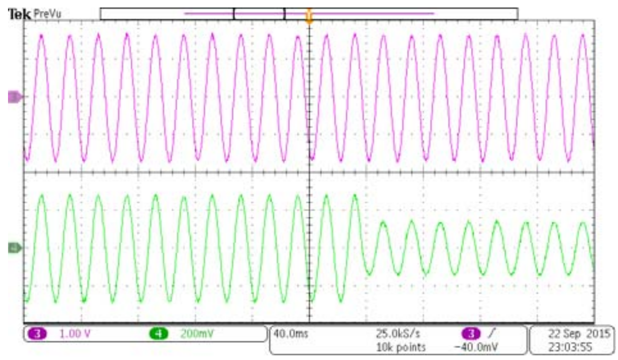

Fig. 12. Test the response of sunny island inverter to step down of the resistive load, trace 3 output voltage [200V/Div.] and trace 4 current loads [10A/Div.].

load is varied to investigate the response of the system.

The unit step function activates at 0.24s. Therefore, the output current will decrease to half as shown in Fig. 10. The response of the stand-alone inverter to reduce the load is very satisfactory, being fast and smooth. In Fig. 11, the output current responds to the increment in the load and the output voltage may not be affected. This validates the robustness of the controller.

The optimal capacitor current proportional controller gain was found to be 6.5008, which is easy to implement in practice. Poles, zeroes and gain of the IMC-PID controller were as follows:

$$IMC-PID = \frac{2.569\, s^2 + 31650 \quad + 3.324\times 10^7}{s^2 + 11530 s} \tag{6}$$

$$IMC-PID = \frac{2.569(s+11160)(s+1159)}{s(s+11530)} \tag{7}$$

It is clear that the proposed controller of a stand-alone inverter has very smooth and fast response to variations of the load when the resistive load increases or decreases.

3.2 Experimental Results

In the stand-alone inverter, the output voltage and frequency should be fixed (for example, at 230 V, 50Hz). The SI 6.0H inverter was set up as an off-grid system with battery storage.

The oscilloscope was triggered to observe the output current response to resistive load variations. When the load decreases, the current responds for this variation, as shown in Fig. 12. When the load increases the current has small distortion for a short period of time as shown in Fig. 13. It was clear that the output voltage is not affected by load variation while the current varies accordingly. This indicates that this system can be used as a grid connected inverter. Therefore, the spectral analysis of the output voltage and current of SI 6.0H inverter is analysed as shown in Fig. 14 and Fig. 15, respectively.

The network utility is used to supply the same resistive load as in previous experiments. Voltage and current, at the connected resistor with the grid, were measured and

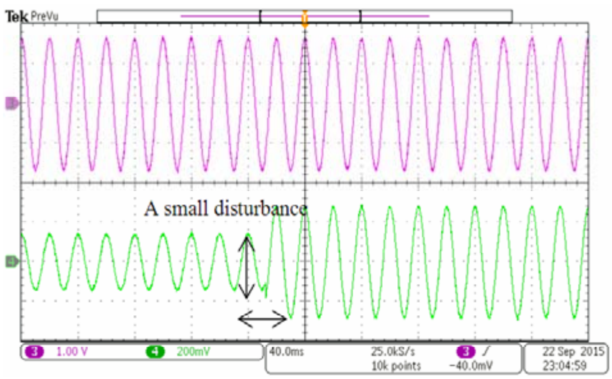

Fig. 13. Step up the resistive load of off-grid sunny island and its response, trace 3 output voltage [200V/Div.] and trace 4 current loads [10A/Div.].

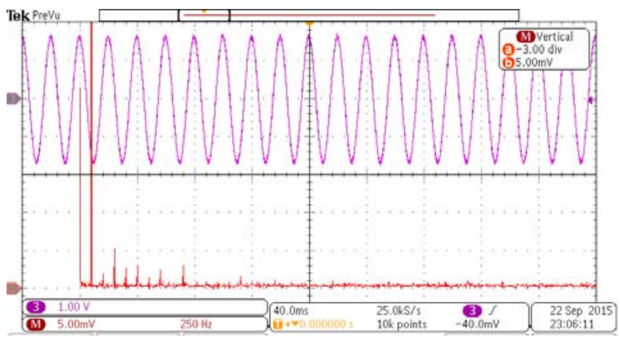

Fig. 14. Off-grid system output voltage and its FFT and THD = 1.6%.

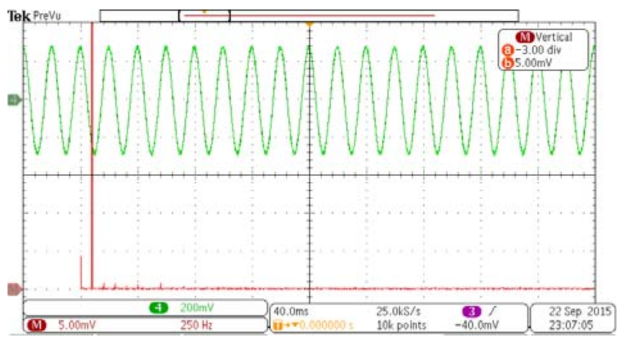

Fig. 15. Waveform of output current [10A/Div.] of the off-grid system and its FFT where the THD = 1.123%.

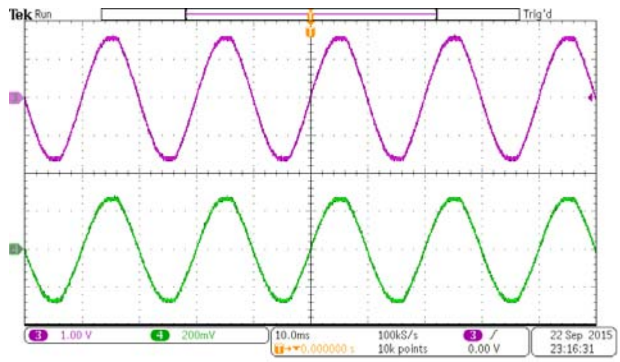

Fig. 16. Trace 3 is the network voltage [200V/Div.] and trace 4 is the load current [10V/Div.].

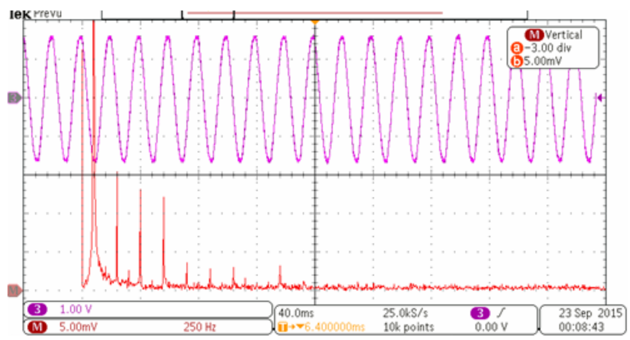

Fig. 17. The output voltage of the network and its FFT analysis [200V/Div.] and THD = 2.5%.

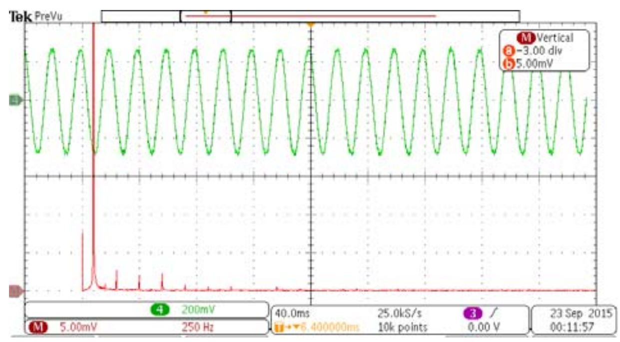

Fig. 18. Waveform of current when it is supplied by a network [10A/Div.] and its spectrum analysis where the THD = 1.5%.

the acquired results as shown in Fig. 16. From the network voltage waveforms and load current, it is clear that the network utility has high harmonic components such as the third harmonic. Therefore, those waveforms were analysed to further investigate the power quality.

Fig. 17 shows the grid voltage and its spectrum. It is interesting to compare this waveform with that of the output inverter voltage. The 3rd, 5th, and 7th harmonic of the grid voltage is higher than the output inverter voltage as shown in Fig. 14.

By comparing between the Fig. 8 and Fig. 16, it can conclude that the experimental results match the modelling results.

The THD of the output current of SI 6.0H inverter is less than the THD of the network when we compare between Fig. 15 and Fig. 18. This is due to the different loads connected to the network, such as inductive loads and resistive loads are supplied from the network and those produce the harmonic components in the network. In addition, the line impedance and the renewable energy such as solar energy cause a distortion in the network.

The main issues of the stand-alone inverter are input voltage fluctuation and load variation. The potential challenges for networks were recently presented by Munsell [18]:

1-Growth of distributed energy sources.
2-Changes in the customer preferences.
3-Expansion of energy market services.
4-Increasing regulation.

Due to those reasons, grid reliability remains as critical as ever, which remains a subject for future research.

5. Conclusion

This paper has compared the power quality of an off-grid (SI 6.0H inverter) system and that of the utility network in the UK, the off-grid system was found to have less distortion of waveforms than the grid. The numerical model of a stand-alone inverter was modelled with two loops, the inner loop being a capacitor current control and the outer loop is the output voltage controller. The inner loop does not change the tracking features of the closed-loop system; it does not only improve linear load performance but also the nonlinear load performance. The output waveform of the modelled inverter showed that the power quality is improved and gives a highly satisfactory response to load variations. Simulation results match the experimental results. In critical load or devices that require a purely sinusoidal, such as medical devices, the off-grid system, therefore, is suitable to protect those devices from abnormal voltage and frequency. Future work will analyse the impact of fluctuation of the input voltage of a stand-alone inverter. In addition, the numerical model can be used in the grid connected inverter, where the reference voltage can be generated from the grid waveform. The potential challenges for utilities, that are highlighted in this paper, will be considered as a part of future work.

Acknowledgement

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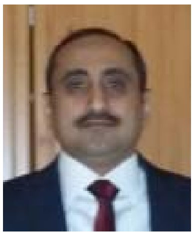

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