International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 4 Issue 09, September-2015

Fast Transient Response of Battery Storage in AC Mini-Grid System to Improve Reliability and Power Quality

A. Algaddafi[1st]*, A. Rahil[2nd]
[1st] Department of Engineering,
Sirte University
Sirte, Libya
[2nd]: Institute of Energy and Sustainable Development
Queens Building, De Montfort University
Gateway Leicester, LE1 9BH

I. Daho [3rd], E. Diryak[4th]
[3rd, 4th:] Department of Engineering,
Sirte University
Sirte, Libya

***Abstract*—in rural area, communications, hospitals, and other services require a sustainable power system. A solar system, including bidirectional inverter with battery storage can be used to improve reliability and also the quality power. In this paper, the fast response of battery storage in a solar system is investigated. The scenario of having battery storage in the solar system is discussed when the variable load demand power is varied. The power quality, which is generated from solar system, and the power quality goes to the load are compared. The system consists of a bidirectional inverter with battery storage, a PV inverter with PV array emulator and a variable resistive load used as domestic loads. An off-grid system can be used where an extended transmission line or distribution network is an expensive and has limitation due to variation of terrains. Therefore, an off-grid system with storage battery is an affordable choice for the electrification of rural areas Sub-Saharan countries such as in Libya. In this paper, an AC Mini-Grid of 6 kWh is tested with a solar system and techniques to provide optimal battery storage is described. The grid connected PV inverter is modelled numerically and a controller is design using optimal control system techniques. It was found that the response of battery storage is very fast without any interruption and it provided a stable and reliable output power when a domestic load supplied whether from the solar system or the battery storage. In addition, the output current waveform improves and excess power that is generated from the solar system is stored directly in the battery and released when needed.**

Keywords—AC Mini-Grid, Battery Energy Storage System (BESS), Photovoltaic (PV), Pulse-Width Modulation (PWM), Total Harmonic Distortion (THD).

I. INTRODUCTION

Storage energy is very important in an AC-Mini-Grid system. The excess power generated (over the demand power) can be stored in a battery storage system; and when the loads need additional power; the battery storage compensates the shortage. The battery storage need to work in parallel with solar system in off-grid system to generate that availability of power even with the variable power demand of the load. More importantly, it is required to response smoothly to the charge and discharge powers. In addition, in stand-alone systems, Maximum Power Point Tracking (MPPT) is possible only if battery backup is present for the reliability of the system [1-3].

Solar energy is considered as an infinite, clean, safe and reliable source of energy. Photovoltaic (PV) systems are particularly suitable for rural areas, where a reliable distribution system might not be available. Therefore, PV generation can provide energy independence to rural areas. However, the interaction between a numbers of PV inverters may lead to an unstable system. Rural areas can include: isolated rural areas, peri-urban areas and Small Island that are separated from national grid. The off-grid or AC Mini-grid system provides independent energy source that creates distribution networks for local communities and rural areas. The PV inverter is interface between the solar generator and the rests of AC Mini-Grid. In order to test a real PV inverter in an indoor environment, the PV Array Emulator (PVAE) is required. Alternatively, Thevenin source can be used in this paper experimentally. Numerical model the PV array model is updated according to datasheet of BP Solar where the six modules are connected in series and combined in two string parallel according to circuit diagram of the solar system installed on concrete laboratory at University of Leicester.

600 million people in Sub-Saharan (SS) and North Africa lack access to electricity, while 6.5 million in developing Asia encounter the same problem [3]. Lack access to electricity is a problem which cannot be solved, even by 2030 according to [4]. This problem will not overcome unless urgent action is taken. In 2011, 1.3 billion people in the world did not have access to electricity [3].The off grid has been considered as a temporary solution for electrification and has been promoted in areas where the grid cannot reached or is unlikely to reach in the near future. Moreover, the off grid system can be stand-alone system or

local-grid systems. Also the off grid options are a cheaper than the grid electrician in many part of Africa [3].

In addition, the grid extension face a number of challenges such as the inadequate of the generating capacity of electricity in many countries. The geographical location and remoteness appear as a challenge for the grid extension. Scatters population is difficult to cover with grid extension; this limitation can be overcome, for instance, by using off-grid system [3].

In this paper, a bidirectional inverter with a storage battery has been chosen to match the variable load power. The sunny Island 6.0H inverter has been used as master in AC Mini-Grid system to achieve the aim of this paper.

The capacity of the battery is a very conceptual and essential issues. The battery capacity is measured in Ampere-Hour (Ah). For example, the battery storage has 128Ah; which means, 1.28A can be drawn from it for 100 hours. In order to determine the battery capacity, watt ratings of all appliances should be added after multiplied each by the amount of hours that it will need to operate every day [3]. This can be considered a simple way of determining the battery capacity required for a simple solar system. The battery capacity depends on its discharging current and temperature; the higher the discharging current, the lower the capacity, and vice versa. The life of battery decreases, when the temperature increase which lead to increase in the battery capacity [3]. The life of the lead acid battery is quoted as 5, 10 and 20 years [3]. The life of the battery depends on temperature band, its specific float voltage and its size (which, in turn, after its cost). The self-discharging of battery of the lead acid battery is between 4-6% per month and this need to be take into account when decided the optimal the battery size.

Mini-Grid system has some advantages such as a high reliability and a good quality of power supply and avoids greenhouse gas emission. It can enhance energy supply security. Optimized battery selection is useful in the off-grid system and Mini-Grid system. Off-grid and Mini-Grid system can improve the reliability of the power supply and increase the overall system efficiency, if it is used correctly.

This paper investigates the fast transient response of battery storage in AC Mini-Grid system to improve reliability and power quality. This paper has been organized as follows: section II is discussed the configuration of AC Mini-Grid which is tested experimentally. This includes the different elements of AC Mini-Grid, type of solar system, classification of battery storage and optimal guide line to design the AC Mini-Grid system. Section III describes simulation of PV solar system in step by step minor in order to select a LCL filter. The experimental setup is explained in the same section. The results of model simulation and experimental work are presented in section IV.

II. POWER SYSTEM CONFIGURATION OF AC MINI-GRID

AC Mini-Grid system consists of a bidirectional converter with storage batteries and a PV inverter with PV array emulator as shown in fig 1. The resistive load is connected to the local bus-bar, which is interface between the bidirectional converter and a number of the PV inverters. The resistive load represents the domestic load of the house. This paper is modelled PV inverter with an LCL filter and simulator of the PV array.

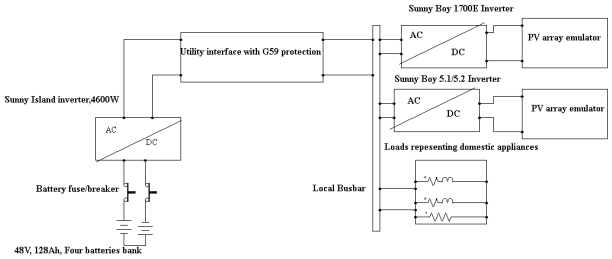

Fig. 1. AC Mini-Grid system configuration

A. *Type of solar PV system*

Solar systems can be broadly classified into three distinct types [3]:-

- Stand-alone systems:-the PV system in stand-alone system does not interact with network where the power is generated and consumed in same place such as street lighting system, solar power plants and smart design of stand-alone solar PV system.

Grid connected system: this system is connected to the main grid. It has a feature of anti-islanding for safety reasons. However this system with bidirectional energy such as sunny island 6.0H inverter can provide energy for the portion load.

- PV-hybrid system: another source of energy should be included within PV system such as wind, fuel cell, diesel and biomass. The objective of PV-hybrid system is to bring more reliability and reduce the cost. Battery provided energy storage and increase efficiency and provide permanent source of electricity that is independent from variable power generator storage energy from Renewable Energy Source (RES) and release it when needed at time when RES generator is not sufficient.

B. *Type of battery and selection of battery*

The solar module produces a power only when exposed to sunlight, thus the battery storage need to store energy during the period of sunlight and realize during the night and overcast period. There are many types of batteries such as: lead acid battery, Nickel Cadmium (NiCd), Nickel Magnesium Hydroxide (NiMH) and lithium based. The selection of batteries for off-grid and Mini-Grid systems must be correct, whereas incorrect battery selection has a significant impact on the system's performance such as high cost and safety. The PV solar system has noticed remarkable growth across the global with increasing PV installation. The technologies have the versatility and flexibility for designing PV system in different area such as rural areas. The off-grid system depends on power and energy requirement, electrical properties of the load, site specific city and available energy resource. Therefore, the off-grid should be designed to maximum efficiency, reliability and flexibility of the system at low cost. The variation of the solar resource is required storage batteries to satisfy energy demand. When the battery storage is used, there some issues need to be taken into account such as, repair and maintenance, system should be reliable,

Department of Engineering, University of Leicester, UK, Leicester, University Road, LE1 7RH

efficiency, reliability and flexibility should be account in the long term and estimating the demand energy and assessing the realistic PV resource availability are the most important step. Finally, the last section draws conclusion and presents future works

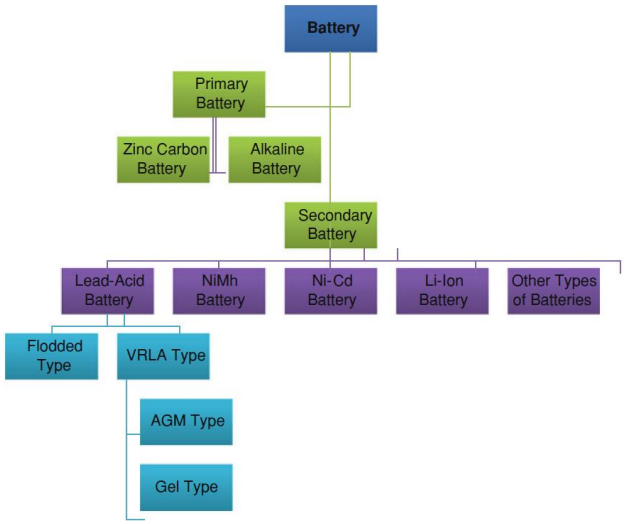

Fig. 2. classification of batteries [3]

III. SIMULATION OF PV SOLAR SYSTEM

The solar system consists of PV array model with two parasitic capacitances are connected on the + and – terminal of PV array, a large capacitor to provide DC link without intermittency due to change in weather condition and grid connected with an LCL filter and linear transformer as shown in fig.3. The linear transformer is used to galvanic isolation for DC component and boosted the DC voltage to level of grid voltage. The transformer ratio is given according technical descriptions of Sunny Boy1700E inverter to be 0.6.

The transformer ratio is given by:

$$ratio = \frac{V_p}{V_s} \tag{1}$$

Where: V_p is the primary voltage and V_s is the secondary voltage.

The parameters of the Sunny Boy 1700E inverter is changed from default in order to operate and communicate with the Sunny Island 6.0 H inverter. One of those parameters is that the feasibility to operate the PV inverter with a constant voltage rather than the MPPT. Thus the MPPT is unable. Therefore, the MPPT does not included in the numerical modelling of the grid connected inverter.

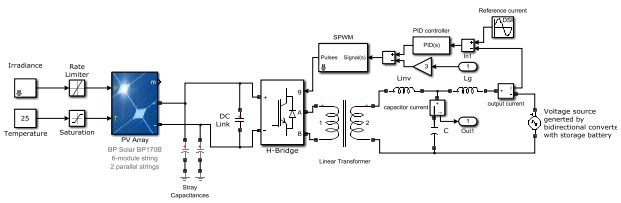

Fig. 3. PV inverter connected to source voltage instead of bidirectional inverter

Fig 3 and Table I show the standard PV inverter circuit diagram and parameters of the grid and inverter. In order to simplify the model the PV inverter and design its optimal controller, the bidirectional inverter with battery storage is assumed as a source voltage. The parameter of LCL-filters listed in table II after introducing general guide line to design LCL filter. Control circuit is described after design an LCL filter.

TABLE I: GRID AND INVERTER PARAMETERS EXCEPT LCL FILTER

Parameter	Value
Grid Voltage (V_g)	230 V
Output Power of the Inverter	1.7kW
Grid frequency (f_g)	50 Hz
Switching frequency (f_{sw})	15kHz
Input voltage (V_{DC})	270 V

A. *Designing of LCL-Filter used in grid connected inverter*

An L filter is used in gird connected inverter to attenuate the harmonic distortion. The L filter is useful when the switching frequency is very high. However, the L filter is bulky, heavy, and costly. Alternatively, the LCL is used to reduce the harmonics components at the Point of Common Coupling (PCC) [6, 7,8 9, 10, 11, 12]. The LCL filter is cheap and small filter. But, the harmonics current may cause the resonance of the LCL filter or saturated the inductor. Therefore, the LCL filter should be designed correctly.

General design of LCL-filter is given in four steps:

1-Inverter side inductanceL_{inv}

In order to select the inverter-side inductor, the output ripples currentΔI_L and the ratio r should be selected. The ripple current can be obtained by [10]:

$$\Delta I_L = 10\% * \frac{P * \sqrt{2}}{V_g} \tag{2}$$

Where: P is the active power rated of inverter, V_g is the grid voltage and its frequency is f_g. Once the ΔI_L is calculated, then the L_{inv} can be carryout by [10]:

$$L_{inv} = \frac{V_{DC}}{16 * f_{sw} *_{\Delta I_L}} \tag{3}$$

Where, V_{DC} is the DC voltage and f_{sw} is the switching frequency.

2- Grid side inductanceL_g:

The ratio between the grid inductor and inverter inductor is determined by:

$$L_g = r * L_{inv} \tag{4}$$

Where: r is desired ripple attenuation of the filter which is given as the ratio of the harmonic current generated by the inverter and the harmonic current injected in the grid respectively as $i_g(h)$ and $i(h_{sw})$ [10].The ripple attenuation factor r can be estimated from Fig. 4.

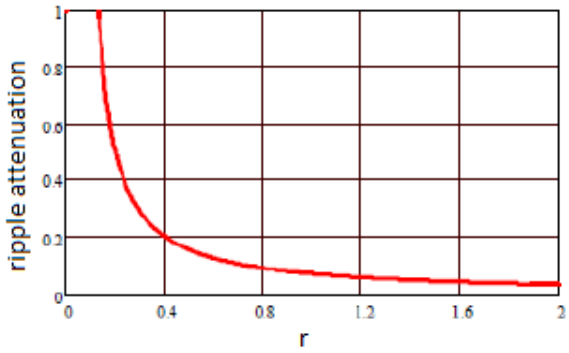

Fig. 4. Ripple attenuation as a function of the relation factor between inductances [10]

3- Filter capacitance C_f

The filter capacitor is estimated by

$$C_f = 1\% * \frac{P}{2 * \pi * f_g * V_g^2} \quad (5)$$

4-Damping resistance R_d

In order to carry out the damping resistor R_d as in Eq.8, it should find the resonant frequency f_{res} by Eq. 6. The range of resonant frequency should be satisfied with Eq.7.

$$f_{res} = \frac{1}{2 * \pi} \sqrt{\frac{L_g + L_{inv_i}}{L_g * L_{inv} * \quad C_f}} \quad (6)$$

$$10f_g < f_{res} < 0.5f_{sw} \quad (7)$$

The damping resistor is used to damping the resonance. However, the losses and dissipated power is reduced the efficiency of inverter. Therefore, the capacitor current is included in control loop as alternative solution.

$$R_d = \frac{1}{2 * \pi * f_{res} * C_f} \quad (8)$$

These parameters was selected as in example section output ripple current ΔI_L is selected 10%, inverter to grid inductor ratio is 0.6 and filter capacitance maximum power variation is chosen 1 %.

TABLE II: PARAMETERS OF LCL FILTER FOR GRID CONNECTED INVERTER

Parameters	acquired value
L_{inv}	1.78mH
L_g	1mH
C_f	1uF
R_d	25.3Ω

B. Designing Controller of solar system

In AC Mini-Grid there are two inverters. The first inverter is PV inverter, which is modelled in this paper. The second is bidirectional inverter, which is a control of current direction whether allow battery storage to charge and discharge.

The commercial PV inverter is widely used in the solar energy, fuel cell and most of the RES. The model of the grid connected inverter is shown in fig.3. The output current is measured and compared with reference current. The error passes through the Proportional-Integral-Derivative (PID) controller where it compared with the capacitor current to produce the modulation index value. Modulation index is used as reference to generate a Sinusoidal Pulse Width Modulation (SPWM) where the reference index is compared with triangle waveform to generate PWM. PWM is used to drive the full bridge converter. This simple method describes the control of PV inverter.

C. Experimental setup

The power is generated by PV inverter is equalized to the consumed power by the resistive load. This called equilibrium point. System management and control is used to ensure all energy available from RES is efficiently harvested integration of a rechargeable Battery Energy Storage System (BESS) is necessary to provide short time and power balance and/or long-term energy management. Battery Management System (BMS) is necessary to control the power flow in and out of the battery within its acceptable capacity [3].

Sunny Island 6.0H inverter has those functions of BMS and BESS. Sunny Island 6.0H inverter can be operated as off-grid system, on-grid system or stand-alone inverter. In this test, the Sunny Island 6.0H was configured in off-grid system. Sunny Island 6.0H is connected with the battery storage capacity 128AH, 48V via fuse box. The rate power of the Sunny Island 6.0H inverter is 4600W. From AC side of the Sunny Island 6.0H inverter, the Sunny Boy 1700E inverter was connected. The Sunny Boy 1700E inverter was connected to Thevenin source to represent solar system as shown in fig. 5.

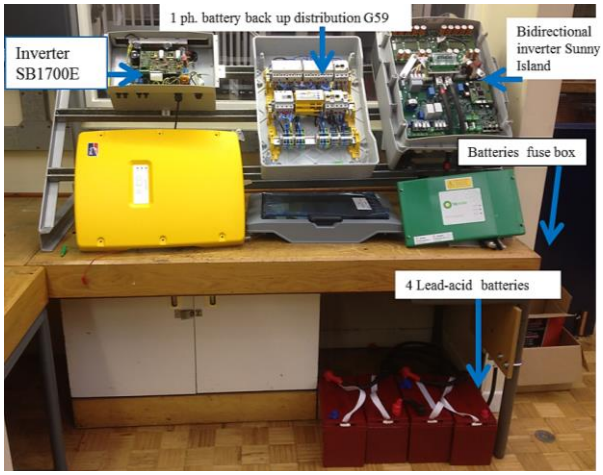

Fig. 5. Laboratory AC Mini-Grid system with PV inverter

The resistive load contains 3 banks (a, b, c), each consisting of eight resistors connected in parallel. Each resistor has a switch to connect or disconnect the resistor. The resistance and the dissipated power of each resistor are 228 Ω and 250 W respectively. The conducted experiments used two resistors connected in parallel to the local distribution, where both the Sunny Island 6.0H inverter and Sunny Boy 1700E inverter are connected. The power generated by solar energy was balanced with the power consumed by the two resistive loads as shown in Fig.6. In test fast response of bidirectional inverter along with battery storage, four resistors were used, each resistor is 228Ω

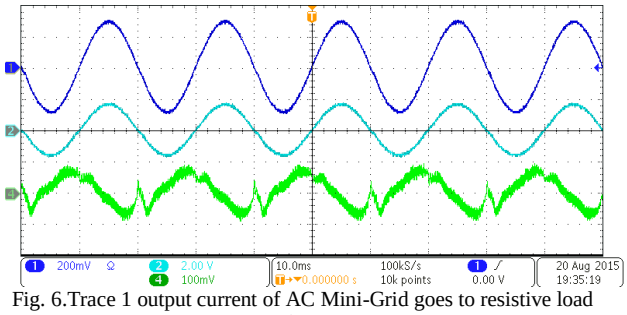

Fig. 6.Trace 1 output current of AC Mini-Grid goes to resistive load [10A/Div.], trace 2 the out voltage of AC Mini-Grid [200V/Div.] and trace 4 generated current by the bidirectional converter with battery storage [10A/Div.]

V. RESULTS

A.Numerical Model Result

The PV array block available in MATLAB Simulink. It consists of number strings of modules connected in parallel; each string consists of number of modules connected in series. The number of string and module can be chosen according the desired PV array. This block is provided by the national renewable energy laboratory (NREL, Jan 2014). This block facilitates to simulate the PV module, array and study the impact of variation of temperature and irradiation

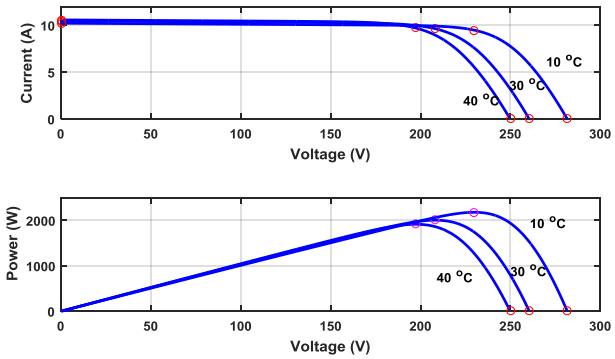

Fig. 7.Impact of varying temperature on PV array simulator

Red circuits on the figure used to identify voltage short circuit open circuit, current short circuit and maximum power point. It is clear that when temperature increased the maximum power will be reduced.

Since the LCL filter was selected correctly, the modelling of grid connected inverter gave the acceptable result where the Total Harmonic Distortion (THD) and the output current were found 2.05%, 9.2 A respectively, as shown in fig.6. But the power quality waveform and efficiency can be improved by using optimal compensator. The THD was reduced to 0.5% and the output current waveform was improved, as shown in fig.7.

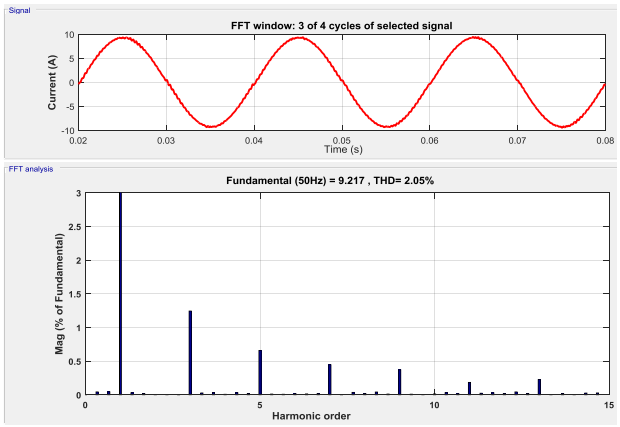

Fig. 8.Output Current generated by solar system at unit proportional gain

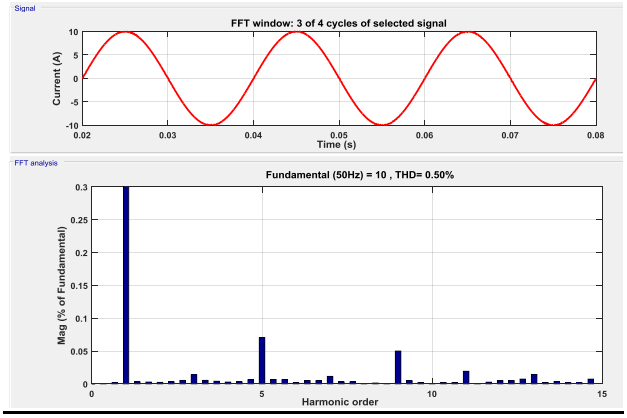

Figure (9): Output Current generated by solar system at optimal controller

B.Experimental Result

Power quality is very important criteria. Most of renewable energy depends on the environmental conditions such as Sun, Wind and tide. This causes the intermittency in the network. In AC Mini- Grid the current generated from solar system was compared with the current supplied to domestic load. Acquired results were shown in fig10 and 11 where the probe **current set to [10A/Div.]**

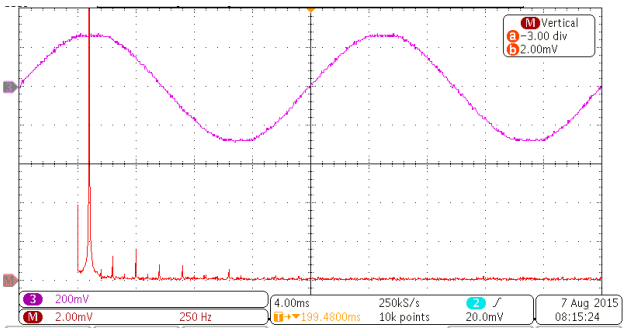

Fig. 10. Output current of the Mini-Grid goes to domestic load and THD=0.64%

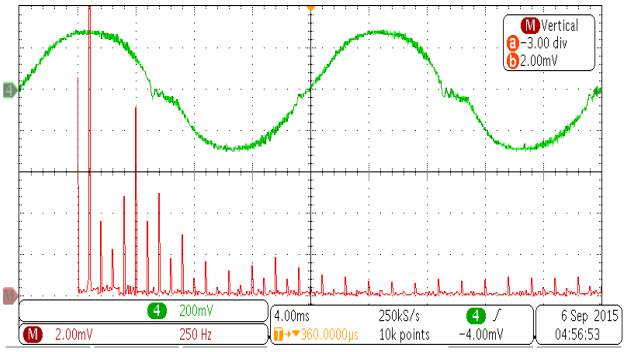

Fig. 11.Output current generated by solar system and THD=7.4%

The current waveforms is improved where the THD of current generated by solar system is 7.4%, has been improved and reduced to 0.64%. This value was measured by using PA2100 power analyser.

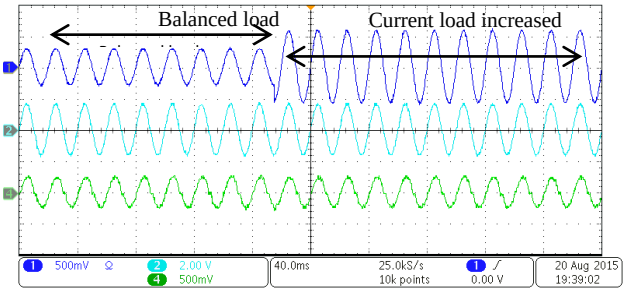

Fig. 12. Trace 1 output current of AC Mini-Grid goes to resistive load [10A/Div.]; trace 2 the out voltage of AC Mini-Grid [200V/Div.] and trace 4 current generated from solar system [10A/Div.]

Oscilloscope was triggered during the moments of changing the resistive load. The load current is rapidly changed very fast to change the load. However, the current generated by the solar system and the voltage at the local distribution do not change as shown in fig 12. However, the output current of bidirectional inverter is changed according to the load change as depicted in fig.13. This change proves the strong reliability of AC Mini-Grid system with fast response.

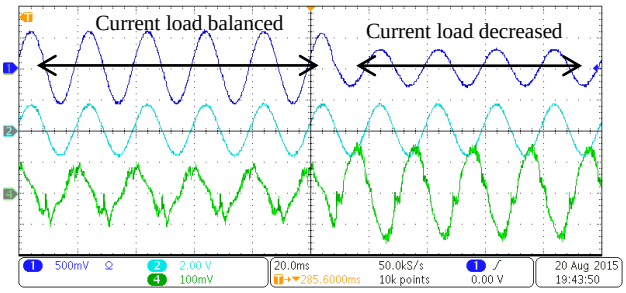

Fig. 13. Trace 1 output current of AC Mini-Grid goes to resistive load [10A/Div.], trace 2 the out voltage of AC Mini-Grid [200V/Div.] and trace 4 bidirectional current [10A/Div.]

ACKNOWLEDGEMENT

The experimental work presented in this paper was conducted at the Department of Engineering, University of Leicester, UK.

CONCLUSION

It is noticed that the current quality supplied the load is improved and the battery storage response very fast without changing in the output voltage in two cases, first case when the power demand is greater than the power generated by solar system. The second case when the power demand is less than the power generated by solar system. The numerical modelling of PV inverter included the output current controller and the capacitor current is investigated in MATLAB Simulink.Optimised battery selection for use for off-grid and Mini-Grid system improve the reliability of power supply, if it is used correctly.Increase overall system efficiency.Rural areas that include isolated rural area peri-urban areas and Small Island which separated from national grid can be used the AC Mini-Grid system which provides independent distribution networks for local community.Battery provided energy storage and increase efficiency and provide permanent source of electricity that is independent from variable power generator storage energy from RES and release it when needed at time when RES generator is not sufficient. The future work will be investigated the interaction between a number of PV inverters in the weak grid connection. Modelling and characterizing the bidirectional converter with battery storage will be investigated.

REFERENCES

[1] M. Abusara, J. M. Guerrero, and S. M. Sharkh, "Line-interactive UPS for microgrids," Industrial Electronics, IEEE Transactions on, vol. 61, pp. 1292-1300, 2014.

[2] M. Das and V. Agarwal, "A Novel Control Strategy for Stand-alone Solar PV Systems with Enhanced Battery Life," Industry Applications, IEEE Transactions on, vol. PP, pp. 1-1, 2015.

[3] S. C. Bhattacharyya, Mini-Grids for Rural Electrification of Developing Countries: Analysis and Case Studies from South Asia: Springer, 2014.

[4] R. Carnieletto, D. B. Ramos, M. G. Simoes, and F. A. Farret, "Simulation and analysis of DQ frame and P+Resonant controls for voltage source inverter to distributed generation," in Power Electronics Conference, 2009. COBEP '09. Brazilian, 2009, pp. 104-109.

[5] H. B. Massawe, "Grid Connected Photovoltaic Systems with SmartGrid functionality", MSc, Norwegain University of Science and Technology,2013.

[6] S. V. Araújo, A. Engler, B. Sahan, and F. Antunes, "LCL filter design for grid-connected NPC inverters in offshore wind turbines," in Power Electronics, 2007. ICPE'07. 7th Internatonal Conference, pp. 1133-1138, 2007.

[7] J. Bauer, "Single Phase Voltage Source Inverter Photovoltaic Application," Acta Polytechnica, vol. 50, 2010.

[8] J X. Wei, L. Xiao, Z. Yao, and C. Gong, "Design of LCL filter for wind power inverter," in World Non-Grid-Connected Wind Power and Energy Conference (WNWEC), pp. 1-6,2010.

[9] H. B. Massawe, "Grid Connected Photovoltaic Systems with SmartGrid functionality", MSc, Norwegain University of Science and Technology,2013.

[10] K. Jalili and S. Bernet, "Design of Filters of Active-Front-End Two-Level Voltage-Source Converters," Industrial Electronics, IEEE Transactions on, pp. 1674-1689, 2009.

[11] M. Liserre, F. Blaabjerg, and R. Teodorescu, "Grid Impedance Estimation via Excitation of LCL -Filter Resonance," Industry Applications, IEEE Transactions, pp. 1401-1407, 2007.