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INTEGRATION OF FULLY RECONFIGURABLE SINGLE-INDUCTOR DC/DC CONVERTER WITH ACGRID FOR RENEWABLE ENERGY APPLICATIONS

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ABSTRACT

This work presents a compact but fully functional design of a simplified single inductor converter structure by combining and integrating basic converters, keeping minimum number of operating switches. This gives a fully reconfigurable structure of converter where all possible power flow combinations among the PV panel and load are achieved by various switching patterns.

Keywords: three port converter, Renewable energy, storage, topology.

1. INTRODUCTION

Now-a-days, tri-port converters are dominating the picture where renewable energy applications integrated with load and energy storage are concerned. Loads of converter topologies have been proposed in recent times apart from existing ones. A converter comprising of single stage power conversion with very small amount of losses is in demand. From [2]-[4], non-isolated TPC can be derived from generic multi-input and multi-output structure. In [5], a review of the existing TPC topologies such as partly-isolated, isolated and non-isolated is done and comparison characteristics are provided. Conventionally in multi-stage conversion, the renewable energy source is connected to the load via a conventional DC/DC converter and the energy storage element is connected to the converter via a bi-directional DC/DC converter for charging or discharging. Due to the usage of an additional converter, there arises a problem of increased size, low efficiency and relatively high cost. Partially-isolated converter provides high voltage gain but the power flow paths are limited. In isolated TPCs, high voltage gain is achieved, high power operations and galvanic isolation is provided but the three-winding transformer and a large number of switches increases the losses and complexity in the system. Some DC loads exist which have dynamic braking capabilities which can be used to charge the source. Also, some hybrid AC grids are there which can be used (via inverter) to sate the load demand when the produced at PV panel is very less (at dusk) and the battery is also not initially charged.

A non-isolated three port converter (TPC) is proposed in this work. The objective of this topology is to integrate an AC grid and an AC load with the photovoltaic battery system. Earlier either a separate DC-DC converter or an isolated three port converter for bidirectional power flow between any two ports was used [1]. These conventional methods have many switches in their circuit configuration which increase the control complexity and the size of the converter. In this work, a compact but fully functional design is being presented by integrating basic converters to form a single inductor converter structure which is quite a simplified one with minimum number of switches. A simulation analysis has been done and different possible modes of power flow have been catalogued. A downsized prototype of hardware was also made and tested.

In the existing models, single PV energy is utilized with unidirectional flow of energy. This energy is transferred with the use of coupled inductors. This inturn leads to high inductive losses in the system.

2. PROPOSED BLOCK DIAGRAM

The TPC is used in here to facilitate the bidirectional flow of energy between PV panel, battery and the inverter.

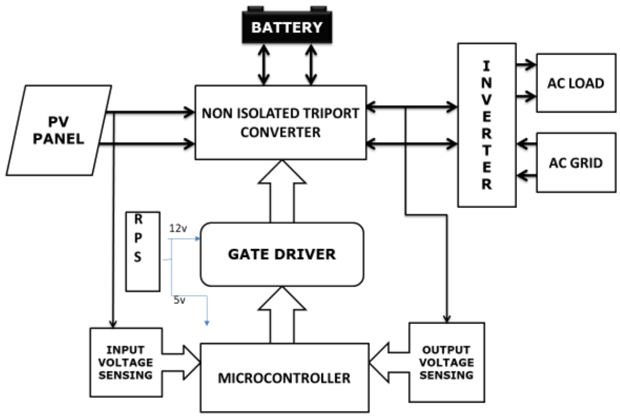

Figure-1. Proposed block diagram.

The micro controller compares the input and the required output voltage value and the error is calculated. Necessary changes are made by the gate driver. The RPS supplies 5V to micro controller and 12V to gate driver. The AC load and AC grid are attached to the system through the H bridge inverter. The converter can be flexibly reconfigured into single-input single output (SISO), dual-input single-output (DISO) and single-input dual-output (SIDO) modes, to fulfil all possible power flow combinations among the three ports.

In the proposed circuit, six different modes of operations are possible. In Mode1, when ample amount of

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power is produced at PV panel, the battery gets charged and load is also supplied. So, power flow is there from PV panel to battery and load. In Mode2, when slightly less amount of power is derived from PV panel as compared to Mode1, then the power flow is there from PV panel to load. In Mode3, when even lesser amount of power is there as compared to Mode2 and battery is initially charged to some percent, the power flow is there from PV panel and battery to load. In Mode 4, when negligible amount of power is derived from PV panel and battery is initially charged to some extent, the power flow is there from battery to load and is very less in magnitude. In Mode 5, when negligible amount of power is there at the PV panel and battery is initially not charged, AC grid supplies power to load as well as battery. In all the above mentioned five modes, the load is in ON state. In Mode 6, when load is in OFF state and ample amount of voltage is produced at the PV panel, the power flow is there from PV panel to Battery.

3. CIRCUIT CONFIGUARATION

As shown in the Figure-2, the converter comprises of three ports denoted by $V_{pv,}V_b$ and V_{ac}. Here in the existing system the input port is the PV panel which is unidirectional port whereas the other two are bi-directional ports. The battery port is also a bidirectional one which is used for balancing the power flow between the other two ports. To facilitate a proper operation of converter, integrated buck-boost topology is used. AC load and AC source is connected to the system through the H-Bridge inverter. Inductor L1 is used for stepping up or down the voltage to meet the desired output voltage as it is the main energy storage element here.

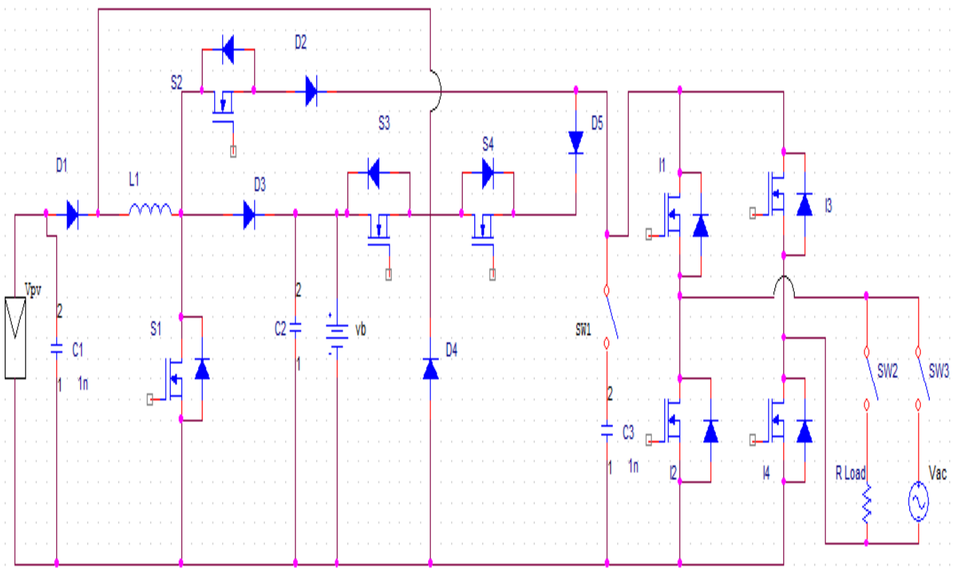

Figure-2. Circuit configuration.

Capacitors C1, C2, C3 act as filter capacitors for PV panel, battery and DC bus respectively. Diode D1 is used to block any current flow back to the PV panel from either battery or the ac source. D2 is used as output rectifier of the boost converter for the load as well as allows unidirectional current flow into the branch by disabling the body diode of S2. D3 acts as output rectifier of the boost converter for the battery. D4 acts as fly wheel diode used for buck operation while D5 is used to block the battery current from flowing back to ac source. S1, S2, S3, S4 are the power MOSFET switches. S1 here is used for helping the inductor to store energy during boost operation as well as achieving MPPT. S2 is used for current control to the load. S3 is used for permitting the battery to discharge while S4 permits the ac source to act as input source. SW1 is closed to keep the load in ON state and SW2 is used to connect the ac source to the circuit when the load is in OFF state. This circuit was designed in ORCAD Capture Lite software.

4. OPERATIONAL ANALYSIS

A. PRINCIPLE OF OPERATION

As the proposed converter has bi-directional port, it is capable of operating in six modes. The power accumulated at the PV panel is used to satisfy the load and when it is not enough then battery is used. Based upon the availability of power at PV panel, the initial state of charge of battery and the ON/OFF state of load, the mode of operation is chosen. The required output voltage is fed as reference value in the microcontroller. The input voltage and output voltage are sensed via the voltage sensing unit. The difference in the output voltage value and the reference voltage value is calculated via comparator and given in the form of pulses from controller to the gate driver. For boosting up the voltage and providing isolation between controller and gate driver circuit, an optocoupler is used.

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The gate driver takes low power input from the controller IC and gives high current input for power MOSFET.

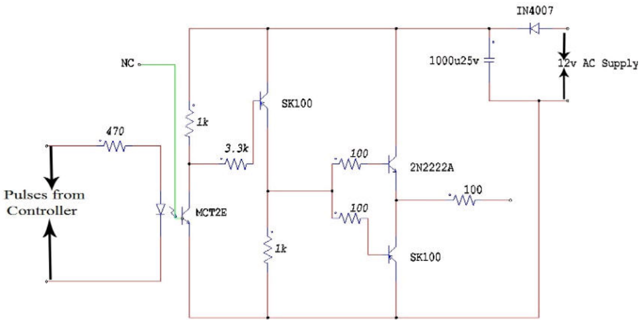

Figure-3. Design of Gate driver circuit.

Maximum voltage, $V_m = \sqrt{2}\ V_s$
Supply voltage, $V_s = 12V$
$V_m = 12\sqrt{2} = 16.97V$

Average Voltage, $V_{av} = \frac{16.97}{\pi} = 5.40V$

Output voltage of the gate driver, $V_{out} = 5.40*1.414 = 7.6356$ V

To find the capacitance value,

$V_{out} = V_m\left[1 - \frac{1}{4fRC}\right]$,

where f= 50 Hz, R=16Ω

C= 568.07μf ≈ 1000μf

The Gate driver provides the corresponding input gate pulses to the power MOSFET used in the tri port converter. And accordingly, the power is converted and the required output is achieved.

B. SIMULATION ANALYSIS

For cataloguing the voltage range for the various modes of operation, simulation analysis was done in MATLAB. In PID controller the reference output voltage was set as 30V.

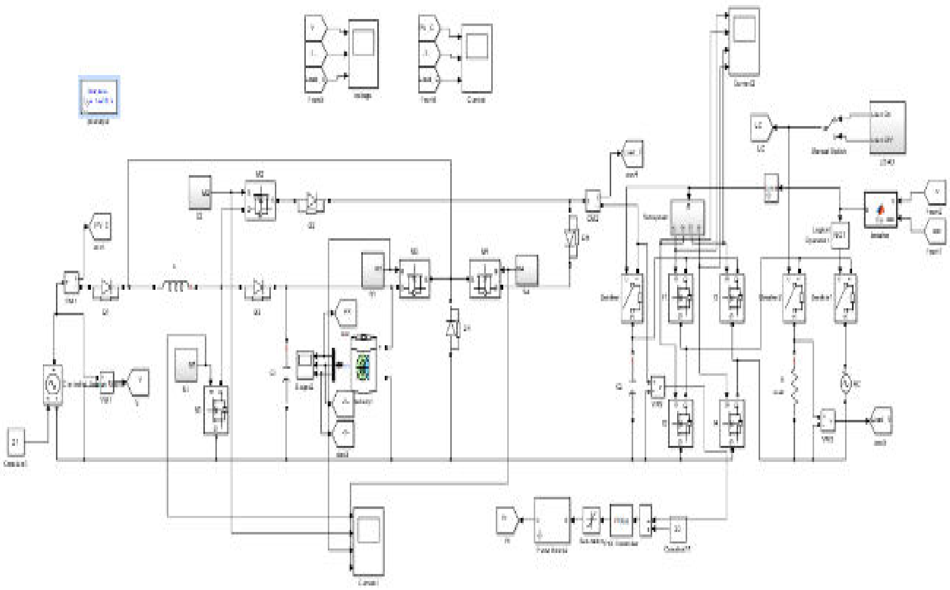

Figure-4. Simulation circuit.

Mode 1

As the maximum voltage that can be analyzed from the PV panel practically is 24V, that was taken as V_{pv} initially and the initial state-of-charge of battery was kept at 15% i.e. the battery was initially charged to some extent. The load in ON state. Then the simulation was run.

From Figure-5, the battery voltage graph is found to be rising to some extent which shows that the battery is being charged.

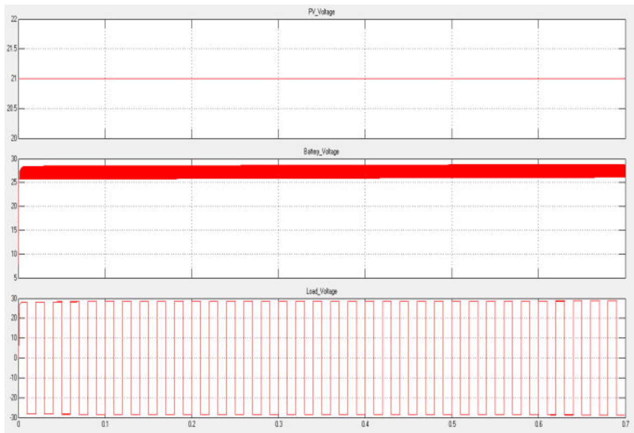

Figure-5. PV, battery and load voltage vs. time respectively.

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Also, the load voltage is found to be 30V so the required load demand is also fulfilled. Thus, in this mode, power flow occurs from PV to Battery and load. The voltage range in which this mode can be facilitated was found to be (21-24) V.

Mode 2

The load was in ON state and now V_{pv} was assumed as 18V that is slightly reduced value was taken. The battery voltage was found to be constant which means that there was no power flow to or from the battery.

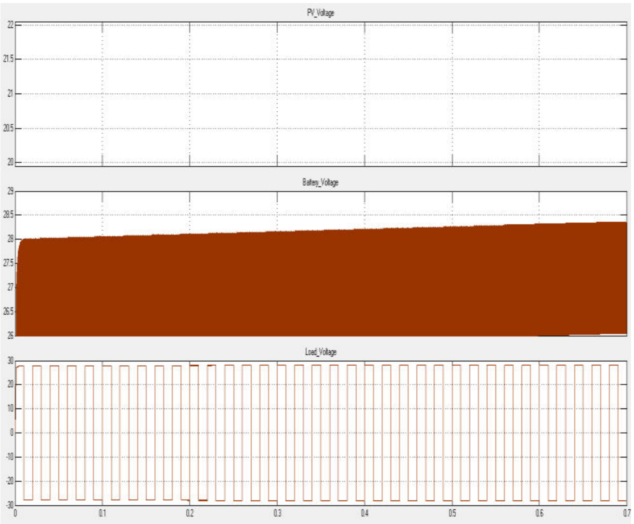

Figure-6. PV, battery and load voltage vs time respectively.

The load voltage was found to maintained at 30V.Thus in this mode power flow was there from PV to load, and the voltage range in which this mode is realized was found to be (18-20) V. Thus, when PV panel voltage reduces slightly then the power flow is there from PV directly to the load.

Mode 3

The load in ON state and the PV voltage was now taken as 10V.

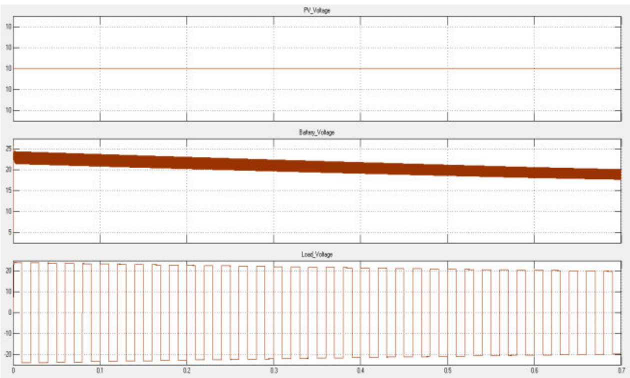

Figure-7. PV, battery and load voltage vs time respectively.

The battery voltage was found to be decreasing which shows that battery is getting discharged in this mode. The load voltage is found to be slightly above 20V but not the required 30V output. So, the power flow was there from PV panel and battery to load. This mode can be operated in the voltage range of (2-10) V. Thus, when very less amount of power is produced at the PV panel, then the battery also discharges to meet the required power demand at the load.

Mode 4

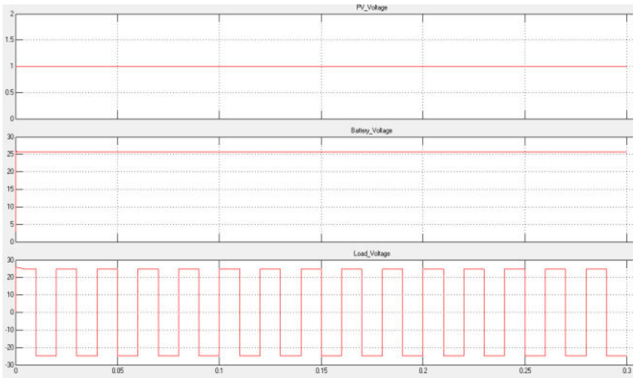

Figure-8. PV, battery and load voltagevs time respectively.

When V_{pv} was kept at bare minimum, of about 1V then the battery was found to be discharging as can be seen from the decreasing battery voltage graph. But the load voltage is very less, (in the order of 10^{-5} V). So, the power flow was there from battery to load, even if it is very less. This mode can be operated in the voltage range of (0-1) V and when the initial state-of-charge (soc) of battery is kept above 10%.

Mode 5

Here also, V_{pv} is kept bare minimum around 1V but the initial state-of-charge is also decreased, i.e. it is kept as 5%. The load voltage was found to be 30V and is a sine wave which shows AC grid is supplying the power to the load. So, in this mode, the power flow is there from AC grid to load and battery. This mode can be facilitated in the voltage range of (0-1) V and the initial state-of-charge is kept below 10%.

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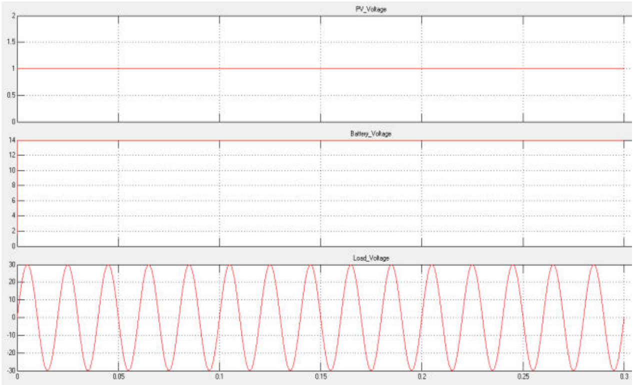

Figure-9. PV, battery and load voltagevs time respectively.

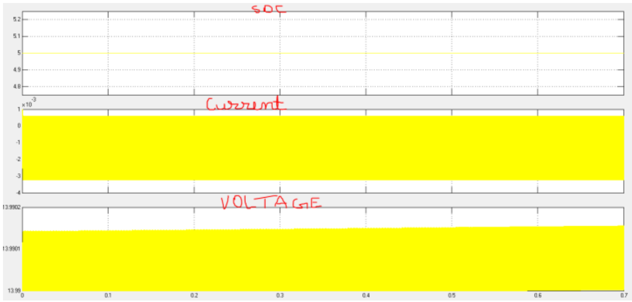

Figure-10. Battery soc, current and voltage respectively.

Mode 6

Here the load is kept in OFF condition and so whatever be the voltage produced at PV panel, the battery will be getting charged in this mode as is shown by the battery current graph in (-ve) direction and increasing battery voltage. So, here the power flow is there from PV to Battery. The load voltage is 0 V. This mode is operated when load is in the off state.

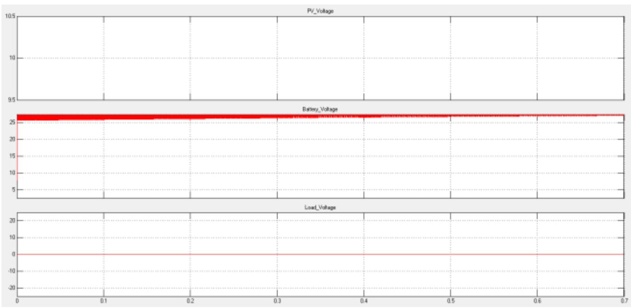

Figure-11. PV, battery and load voltage vs time respectively.

C. HARDWARE VERIFICATION

Figure-12. Hardware prototype.

A hardware prototype was built and tested. An analog circuit comprising of a capacitor bank (of 2200µf, 25V capacitor each) was used as battery source. Battery voltage is a very closely associated with state-of-charge so, in order to determine the battery capacity, battery voltage is assessed. The Input and output voltages are sensed by voltage sensing units realized via analog circuits. The gate driver for pulse width modulation of MOSFETs (IRF540) is realized by analog circuits while the control is performed by microcontroller (PIC 16F887). Four MOSFET switches are used as an H-bridge inverter with a 22K, 5W resistor as load. A 2-channel relay circuit was used to provide 5V supply for the functioning of microcontroller.

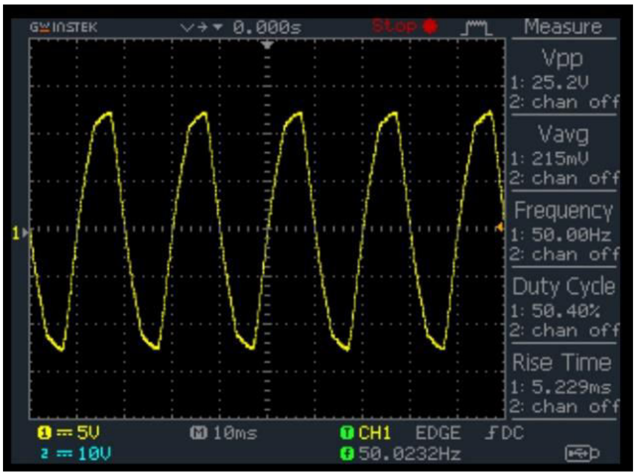

Figure-13. Output oscillograph when power flow is there from AC grid to load and battery.

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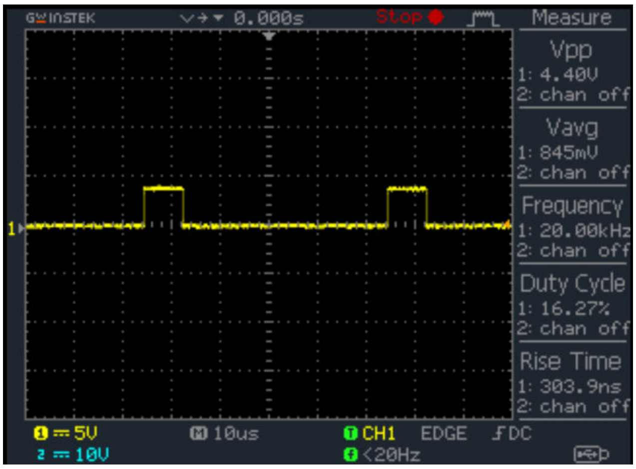

Figure-14. Output oscillograph when power flow is there from PV panel to battery and load.

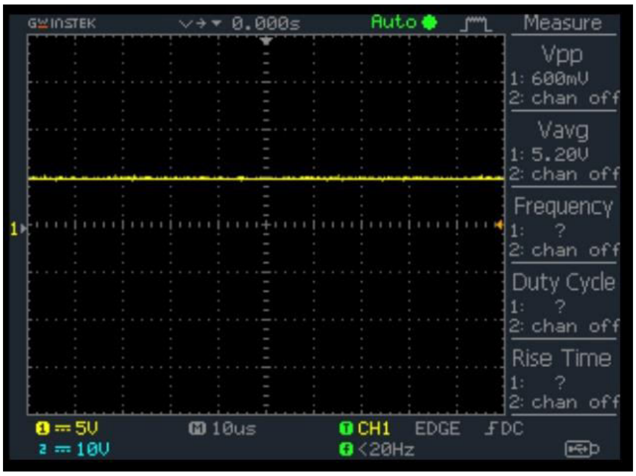

Figure-15. Output oscillograph when power flow is there from battery to load.

According to the voltages available at the PV panel, the selection of operating mode was done by the microcontroller and the flexible power flow between the ports took place and the load was provided with the power. More numbers of PV panels and batteries can be stacked up together to scale up the converter.

Thus, the proposed topology was realized and verified via a downsized hardware prototype.

5. CONCLUSIONS

A simplified three-port single-inductor converter topology has been presented in this work by combining and integrating basic converters. The converter is completely reconfigurable where a number of bidirectional power flow paths among the PV panel, battery and load is possible by various switching patterns. The proposed system is stable in all the modes. Less inductive losses are there as compared to existing systems due to the usage of single inductor in the design. Here, hybrid energy can also be used in the system as AC source. The converter can work in SISO, SIDO or DISO mode, depending upon the voltage obtained at PV panel. The key feature of the converter, which is single- stage power conversion between any two ports, is preserved. Operation of the system in described in detail and the operating voltage ranges for various modes is provided. Simulation analysis was performed and the experimental results are given.

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