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Article

Power Balancing Control for Grid Energy Storage System in PV Applications—Real Time Digital Simulation Implementation

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Abstract: Grid energy storage system for PV Applications is connected with three different power sources i.e. PV Array, Battery and the Grid. It is advisable to have Isolation between these three different sources to provide safety for the equipment. The configuration proposed in this paper provides the complete isolation between the three sources. A Power Balancing Control (PBC) for this configuration is proposed to operate the system in three different modes of operation. Control of a dual active bridge (DAB) based battery charger which provides a galvanic isolation between batteries and other sources is explained briefly. Various modes of operation of a Grid energy storage system are also presented in this paper. Hardware-In-Loop (HIL) Simulation is carried out to check the performance of the system and the PBC algorithm. Power circuit (comprises of inverter, dual active bridge based battery charger, grid, PV cell, batteries, contactors and switches) is simulated and the controller hardware and user interface panel are connected as HIL with the simulated power circuit through Real Time Digital Simulator (RTDS). HIL simulation results are presented to explain the control operation, steady state performance in different modes of operation and the dynamic response of the system.

Keywords: active power control; battery charging; dual active bridge; energy storage system; hardware-in-loop

1. Introduction

In solar power plants, active power transfers from PV array to the grid during daytime and PV array loses its capability of generating power during night time or when the irradiation is weak. To supply power to the grid during night time also, energy storage is required. Since the power requirement during night time is much lesser than that of the daytime, energy storage with 25% of rated power of PV array may be selected for 24-hour operation. Block diagram of a grid energy storage system in a solar PV power plant is shown in Figure 1.

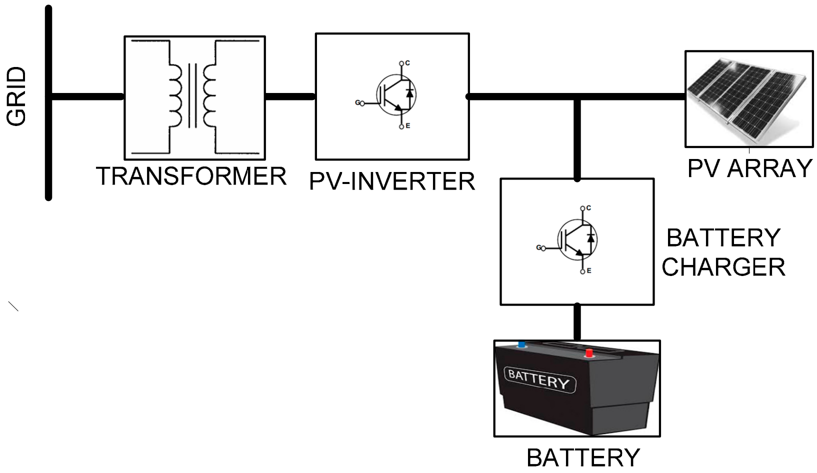

Figure 1. Generalized block diagram of a Grid energy storage system in PV applications

Modes of operation of the above system are explained below.

Mode1: During day time, PV Array feeds active power to the grid through an inverter and provides charging current to batteries through the Battery charger.

Mode2: Battery is in charged condition and the PV array cannot feed full power to the grid i.e. during Partial clouds or during Night time or when irradiation is weak. In this mode of operation, PV array feeds the power based on Maximum power point (MPP) to the Grid and the batteries also feed active power to the grid.

Mode3: Battery is in fully discharged state and the PV array cannot provide the charging current to the batteries i.e. during Night time. In this mode of operation, Grid provides the charging current to Batteries through Inverter and Battery charger.

With such systems, it is also possible to charge the batteries from grid during non-peak load hours and the batteries along with PV array feed power to the grid during peak load hours. Since the system is connected with three different power sources i.e. PV array, battery and the grid, it is necessary to have isolation between these three power sources to provide safety for the equipment. Existing energy storage systems for PV applications using a Buck-Boost chopper based battery charger are briefly explained below.

In configuration presented in [1], A DC-DC converter is connected between PV array and PV inverter and the battery is connected across DC Link as shown in Figure 2(a). In such systems, DC/DC converter needs to be designed for the maximum capacity of PV Array even though the battery capacity is very less when the system operates in Mode3, the Inverter should act like an active rectifier to charge the batteries and there is no isolation between PV array and the batteries. In the configuration shown in Figure 2(b), PV array and PV inverter are connected to the DC Link and battery is connected to the DC link through a Buck-Boost chopper. In this case, charger needs to be rated only for the rating of the battery. In the configuration presented in [2] and [3], Independent DC-DC converters are required to connect battery and PV array to DC link as shown in Figure 2 (c).

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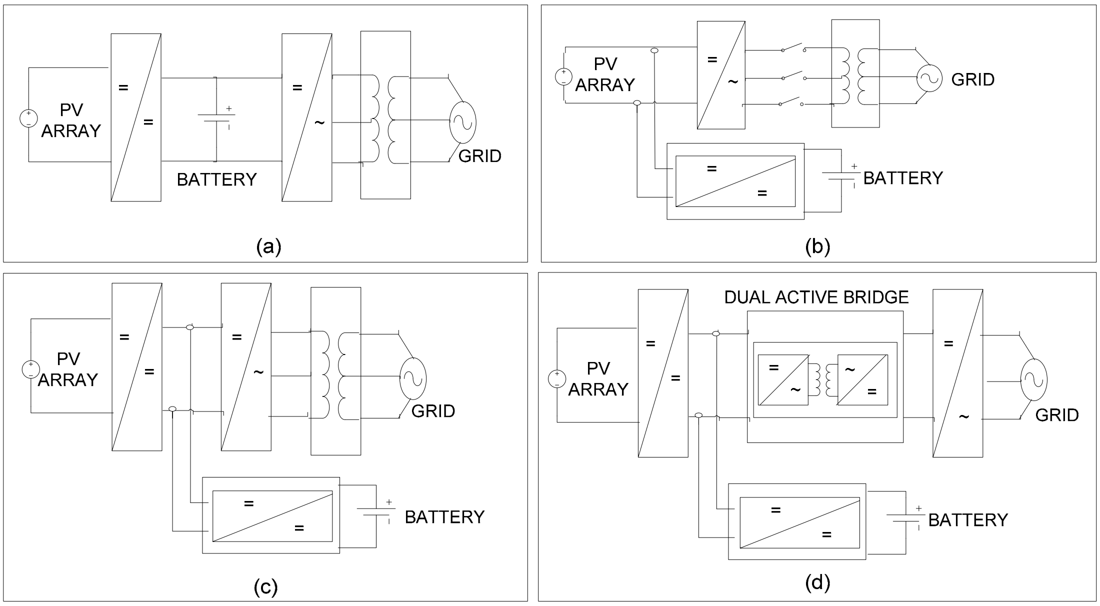

Figure 2. Various configurations of Buck-Boost Chopper based ESS for PV applications

An optimized operation of a Dual Active bridge (DAB) converter feeding a PV inverter connected to the grid is presented in [4] and [5]. Isolation between Grid and DC side is provided through high-frequency transformer used in DAB as shown in Figure 2(d). In such configuration, DAB needs to be designed for the full capacity of PV array. Since the design of DAB is complex for high power ratings, this configuration is more suitable for low power applications. There is no isolation between DC link and the power bank with this configuration also. From the above discussions, it is observed that Buck-Boost chopper based ESS cannot provide complete isolation. In this paper, DAB based ESS for PV applications is proposed to mitigate the drawbacks of Buck-Boost chopper based systems. The proposed system is explained briefly in the next section.

2 Dual Active Bridge based ESS for PV Applications

In this configuration, PV array and PV inverter are directly connected to the DC Link and the battery is connected to the DC link through a DAB based bi-directional battery charger as shown in Figure 3. High-frequency Transformer in DAB provides isolation between DC link and the power bank. A transformer connected between Inverter and grid provides Isolation between DC sources and AC Gird.

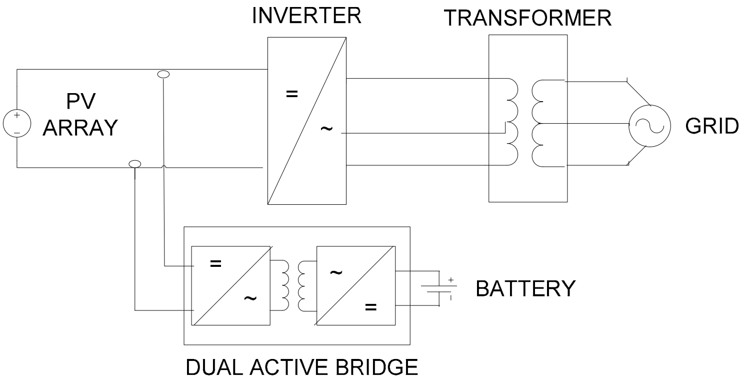

Figure 3. Dual Active Bridge based ESS for grid connected PV system

Advantages of the proposed system are as given below.

- Battery charger needs to be designed only for the battery capacity.

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- Independent controls for Battery charger and Inverter are possible.
- When the system operates in Mode3, the Inverter acts like a Simple diode Rectifier and battery charger takes care of the charging current.
- High-frequency transformer in DAB provides isolation between PV array and the battery.

2.1 Control of Dual Active Bridge based Battery Charger:

DAB based DC-DC converter consists of two H-Bridges and a high-frequency transformer. Source side H-Bridge is connected to the DC link and the load side H-bridge is connected to the battery as shown in Figure 3. High-frequency transformer is required to match battery voltage with the DC link voltage and also to provide isolation between PV array and the battery. Transformer's leakage inductance helps in boost operation [6], [7]. The transformer winding connected to the Source side H-Bridge is considered as Primary and the winding connected to the Load side H-Bridge is considered as secondary. Control block diagram of a DAB based battery charger is shown in Figure 4. During Battery charging mode, the reference battery current is generated based on the state of charge (SOC) of the battery. During discharge mode, the reference battery current is generated based on the active power required for grid and maximum power point (MPP) of PV array. Source side and load side H-bridges act like a simple square wave inverter. Square pulses with 50% duty cycle are given to load side and source side H-Bridges. Power flow through DAB is controlled using phase shift control. The pulse generator provides the Gate pulses for source side and load side H-Bridges based on the phase shift obtained through PI controller.

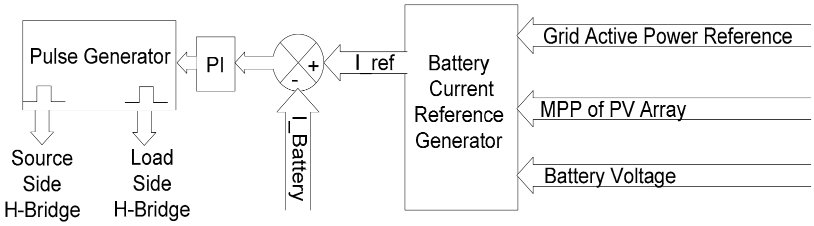

Figure 4. Control block diagram of DAB based Battery Charger.

When the battery current reference is zero, then the Gate pulses for source side and load side H-bridges will be in-phase to each other. During forward power flow i.e. for charging the battery, gate pulse of source side H-bridge will be in leading to the Gate pulse of load side H-Bridge. Similarly, during reverse power flow i.e. during battery discharging mode, load side gate pulse will be in leading. The amount of power transfer depends on the phase angle between Gate pulses for source side Bridge and Load side Bridge. As the size and cost of the high-frequency transformer are much lesser than that of a high-frequency transformer for the same power rating, Battery charger size and cost can be reduced by using a high-Frequency transformer in a DAB.

2.2 Control of Grid-Connected PV Inverter

A typical grid connected solar power conditioning system consists of three-phase two level PV-Inverter for converting DC power to AC power, a sine filter to smoothen the AC output and a Transformer to couple inverter and grid. The transformer also provides isolation between AC side and DC side. Figure 5 shows a control block diagram for a grid connected PV-Inverter. In this system, PV Array voltage and currents are to be monitored for MPP Tracking and the Grid voltage is to be monitored for Phase-locked Loop (PLL). The controller senses the charging current or discharging current of the battery and the MPP of PV Array then calculates the maximum possible power that can be fed to the Grid. Current reference is generated based on maximum possible Power and the PLL output. Three phase grid voltage is given to PLL to find out the angle wt. Angle wt obtained through PLL is used to generate Id and Iq components from Three phase grid currents. After comparing the Reference Idq currents and actual Idq currents, the error signals are given to PI controllers for the active and reactive power control. The PI controller outputs are converted back to

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Three Phase modulating signals and given to PWM Generator to generate Inverter gate pulses [8], [9]. In this work, a new power balancing control algorithm for the proposed configuration is developed and tested on the real controller with the help of Hardware-In-Loop simulations. The need of HIL Simulations, features of the Real-time digital simulator and the setup built for HIL simulation for the proposed configuration are explained in next section.

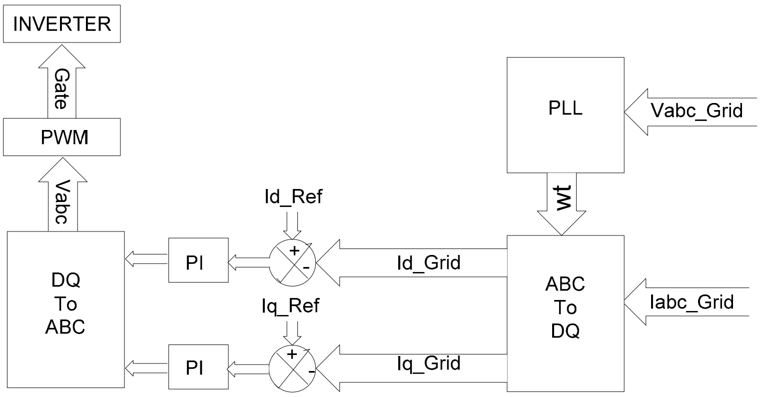

Figure 5. Control block diagram of a Grid Connected PV Inverter

3 Hardware-In-Loop Simulation setup for the proposed system

In general, controller and control software are validated by integrating the controller with actual plant hardware. In the case of any error in the control system, there are risks of personal injuries, damage to the equipment and delays. Hardware-In-Loop (HIL) simulation is a useful tool to avoid such issues. In HIL simulation, instead of a real plant a mathematical model representing the plant loaded in the Real-time simulator to act like an actual Plant. Through HIL simulations, the response of controller in real time operation can be validated [10]. Following are the advantages with the HIL Simulation. (a) Preliminary controller software can be developed with minor assumptions in the plant parameters. (b) Once the Control parameters are calculated with HIL Simulation, it is easy to tune the parameters with the actual system. (c) Reduces the design cost and time (d) System protections in Real time can be analyzed by simulating faults.

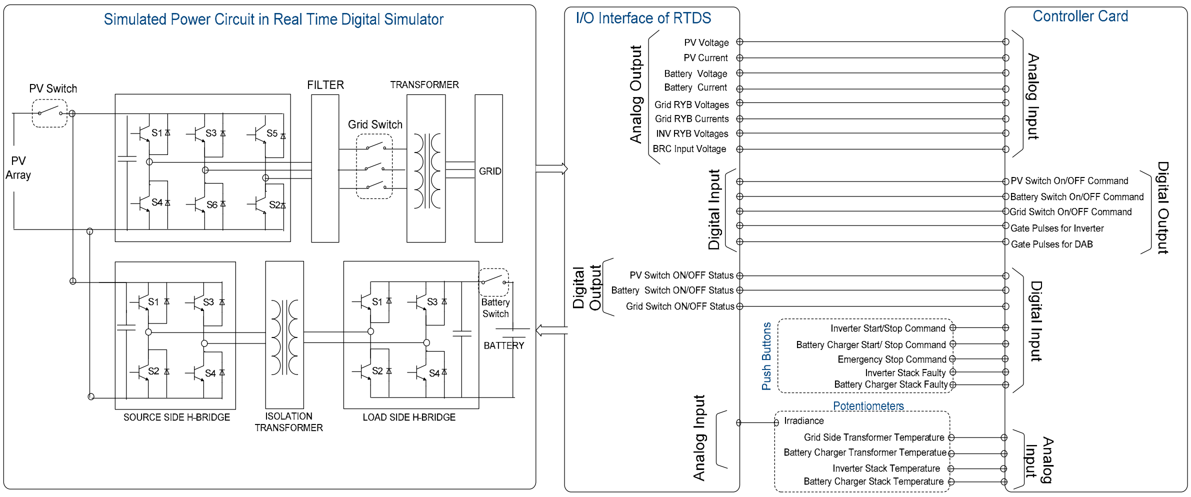

Figure 6. Block Diagram for HIL Simulation of the proposed Grid Energy storage system

To validate the control software for the proposed system, HIL simulations are carried out. The plant consists of PV array, Inverter, battery charger, isolation transformers, grid, battery and contactors are simulated in Matlab-Simulink. The simulated model is compiled and loaded in the processor of Real Time Digital Simulator (RTDS). Simulated Plant can be accessed by the external controller cards and other hardware through the I/O channels available in the RTDS. DSP based

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controller is connected as Hardware in the loop as shown in Figure 6. RTDS used for the HIL Simulations is Opal-RT make Simulator and the controller hardware is based on Texas make TMS320F2812 DSP based controller card. User interface panel consists of pushbuttons and Potentiometers (POT) is used for user commands and for simulating the faults. Figure 7 shows the Hardware setup for the HIL simulations.

3.1 *Input-Output Channels of RTDS*

Opal-RT make RTDS is equipped with Analog and Digital Input-Output modules. Voltage range for analog signals is +/- 15V whereas the voltage levels for Digital signals is Zero and +15V.

3.2 *Input-Output Channels of Controller Card*

The controller used in this work is TMS320F2812 DSP processor based controller card. Voltage range for analog signals is +/- 10V whereas the voltage levels for Digital signals is Zero and +15V.

3.3 *User Interface panel Signals*

The input to the simulated PV array is irradiance which can be given to the simulated plant through analog input channel of RTDS from a POT mounted on a user interface panel. The minimum value of POT output refers to the irradiance of Zero and the Maximum value of POT refers to 1000 W/Sq.m. From the user interface panel, Start Stop commands, Emergency stop commands are given to the controller card for the plant operations. Controller card receives temperature signals of isolation transformers and Power stacks from the user Interface panel. The possible fault signals are also given to the Controller card hence different faults can be simulated to check the functionality of controller and control algorithm.

3.4 *Signals from Simulated Plant to Controller*

The controller receives the analog signals of the plant through analog output channels of the RTDS. The controller receives PV voltage and current signals which are required for tracking MPP. Battery voltage is required for finding out the charging current reference and battery current signal is required for closed loop current control of Battery charger. Three phase Grid voltage signals are required for PLL and inverter side voltages are monitored for synchronization purpose. Three phase inverter currents are required for closed loop current control of PV inverter. Based on the start-stop commands received from user Interface panel, the controller gives the ON/OFF Commands to PV Switch, Grid Switch and Battery switches through Digital Input channels of RTDS. Switch status outputs to the Controller are given to the controller through Digital Output channels of RTDS.

3.5 *Online Plant parameter Modifications*

Online modification of simulated plant parameters i.e. Transformer parameters, filter parameters, Battery SOC, DC Link capacitor values and Load parameters etc. during the Real-time digital simulation is also possible through RT Lab main controller. Through online modifications, the optimum values of plant components can also be obtained.

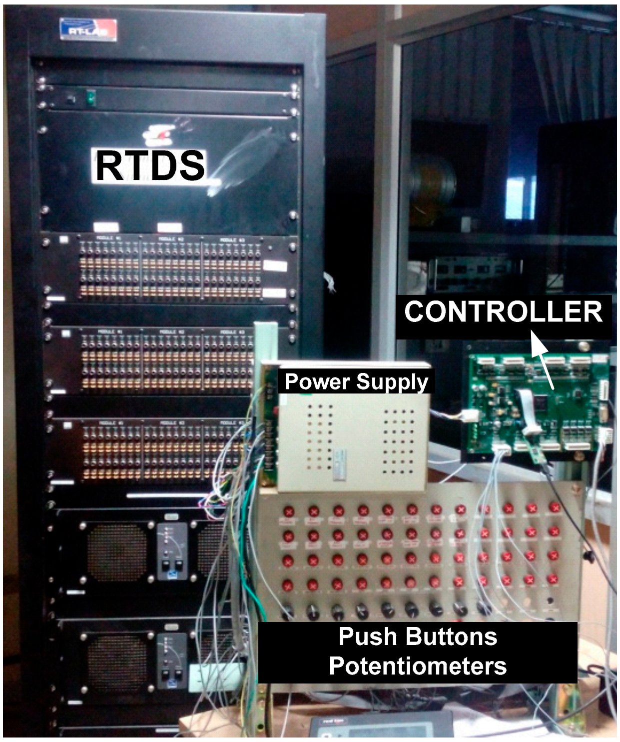

Figure 7. HIL Simulation setup for the proposed Grid Energy storage system for PV Applications

4 Power Balancing Control of Grid Energy Storage System in PV applications

Power Control of PV with ESS for Off Grid applications is presented in [11]. In the system presented, Battery and PV arrays are connected to the common AC load through independent converters i.e. as an AC Centric system. During charging of the battery, PV array supplies power to the AC load and battery. When the battery is fully charged, battery and PV arrays supply power to the common AC Load. Conditions for battery charging and discharging and control of power converters during Mode-1 and Mode-2 operations are explained briefly. Experimental results were presented to show the dynamic response of the system during Mode changeover with Lead-Acid and Li-Ion Batteries.

Control for high power PV + Fuel cell plant with hybrid energy storage consists of a battery and the super-capacitor is presented in [12]. Each energy source and energy storing element are connected to common DC link through independent converters in this configuration. Energy management among the different sources, control for charging super capacitor and batteries is explained briefly. Experimental results were presented for explaining the dynamic characteristics of system and plant performance during long load and Short load cycles. Since the system presented is for off-grid applications, Mode-3 operation i.e. charging the battery from Grid Supply is not covered in this work. Real-time simulation of the hybrid energy system with Wind-PV-Battery storage is presented in [13]. In the presented system, independent converters for Battery, PV modules, and Wind are used. Based on the power availability of all the sources, an algorithm is developed for battery charging, discharging and load shedding.

The systems presented in [11], [12] and [13] are for Off-Grid Applications hence the control during Mode-3 of operation is not covered. System configurations presented in above works require independent converters for each source which may increase the cost of the system and also may increase the complexity of control algorithm. The above-mentioned drawbacks can be mitigated with the proposed system configuration and with the power balancing control algorithm explained in the next subsection.

The proposed system is the combination of three phase PV inverter and a DAB based battery charger explained in section-2. Power flow through inverter can be controlled over a wide range through current control. Battery current can be controlled in both directions through DAB using a

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phase angle control. Power balancing among three sources in the presently proposed system is achieved by controlling the power flow through battery charger and inverter. Power balance control algorithm shown in Figure 8 is explained below.

1. Once the system is ready and Start command is given by the user, the controller reads the Gird voltages for determining wt through PLL.
2. Controller Initialize the value of Inverter reference current (Id_Inv_Ref) and Battery reference currents (I_Batt_Ref) as Zero.
3. Controller reads the PV voltage (Vpv), PV Current(Ipv), Battery voltage(VBatt) and Battery Current (I Batt)
    - If the PV voltage (Vpv) is less than Minimum PV voltage required (Vpv_Min) then MPP of PV Array is Zero.
        - In this case, if the battery voltage is also less than the Nominal Battery Voltage Vb_Nominal then the system is in mode-3.
        - In this mode, Battery needs to be charged but the PV array cannot give any power for battery charging. So the Grid shall supply the Power required for Battery charging.
        - In this mode of operation, the Inverter acts like a simple Diode rectifier to provide DC Input to the Battery charger.
        - Based on the SOC of battery, reference battery charging current I_Batt_Ref is obtained.
    - If the PV voltage (Vpv) is more than Minimum PV voltage (Vpv_Min) then controller tracks the MPP of PV Array by monitoring PV voltage and current.
        - In case MPP is more than minimum value i.e. P_PV_Min then the system is in mode-1.
        - In this mode of operation, Battery will be in charging state and PV array gives the power for battery charging.
        - The remaining power after battery charging will be fed to the Grid.
        - Based on the SOC of Battery, reference battery charging current I_Batt_Ref is obtained.
        - Through Power balancing equation Inverter reference current Id_Inv_Ref is calculated based on MPP and Battery current.
    - If the MPP is less than the minimum value (P_PV_Min) but the Battery is in charged condition then the system is in mode2.
        - In this case based on Backup time adjusted by the user, reference Battery current I_Batt_ref is calculated.
        - Through Power balancing equation Inverter reference current Id_Inv_Ref is calculated based on MPP and Battery current.
        - When PV voltage is more than Minimum DC Link Voltage, then Battery charger is operated with closed loop current control to maintain I_Batt = I_Batt_Ref.
        - When PV voltage is less than the minimum DC Link voltage then battery charger operates with closed loop voltage control to maintain a constant DC Link voltage i.e. Vdc_Link = Vdc_Link_Ref.
4. After determining the Battery reference current I_Batt_Ref and Inverter reference current Id_Inv_ref, Controller implements the closed loop current control through PI controllers and releases the Gate pulses to Inverter stack and Battery charger stack.

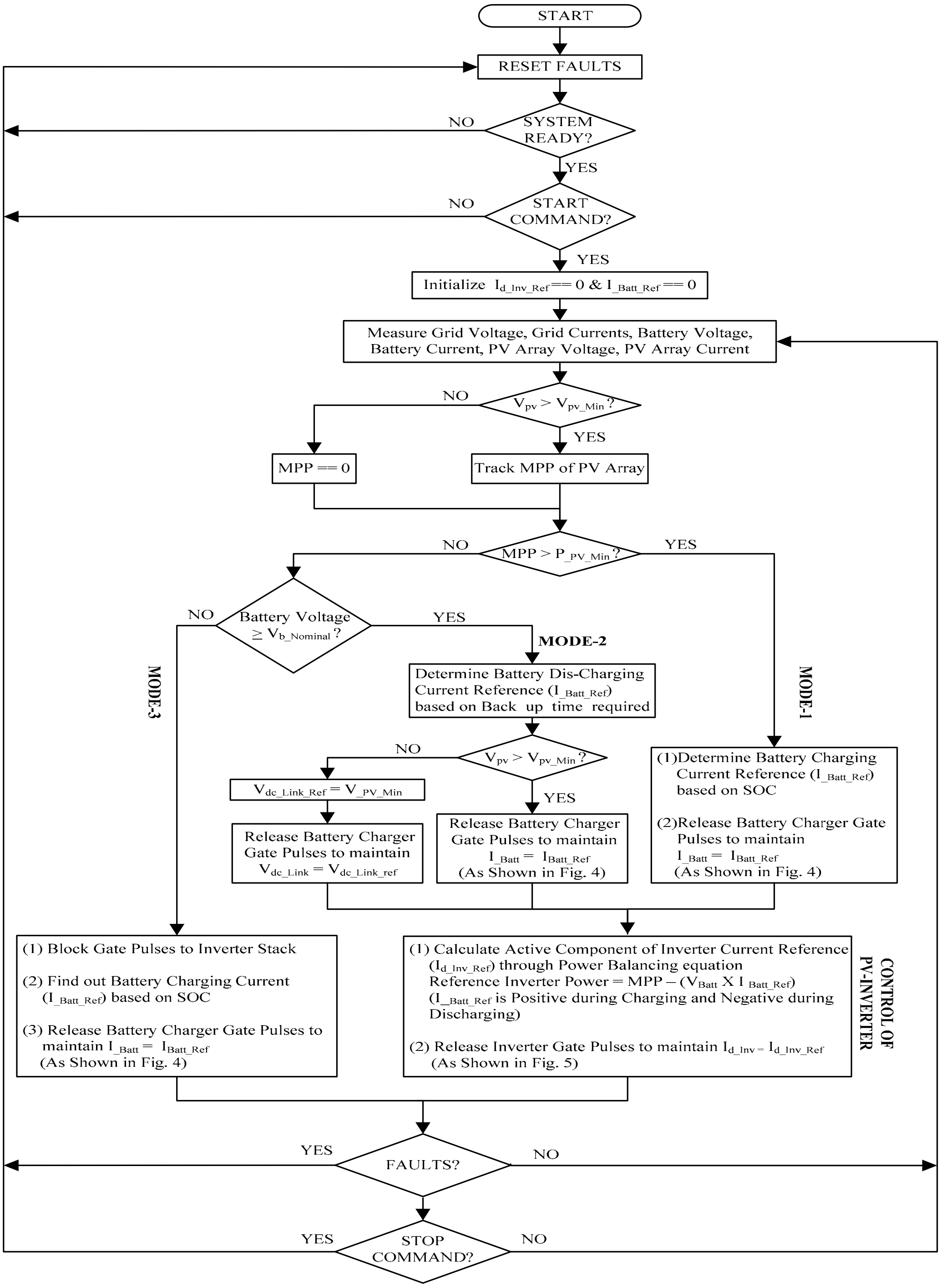

Figure 8. Algorithm for Power Balancing Control of Grid Energy Storage System in PV Applications

5 Results & Discussions

5.1 Inverter, Grid and Load Currents in different modes of Operation

Figure 9 shows the current waveforms in Mode-1 of operation. Since the PV array can produce more than the minimum power required for charging the battery and feeding internal loads connected to the plant, the additional power produced from the PV array is supplied to the Grid. An Irradiance of 1000 W/Sq.m is adjusted on the user interface panel; hence the PV array is producing the maximum possible power. From the presented result, it can be observed that the grid current is phase displaced by 180 degree to the inverter current.

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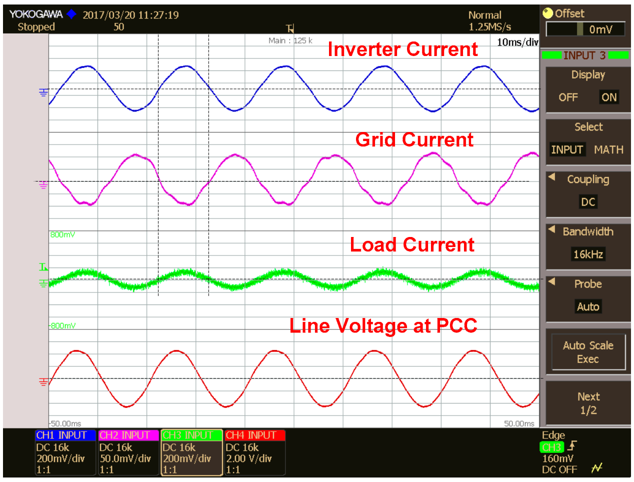

Figure 9. Currents of Inverter, Grid, Load and voltage at PCC in Mode-1 of operation

In Mode-2 of Operation, an Irradiance of Zero W/Sq.m is adjusted on the user interface panel; hence the PV array cannot produce any power. The battery is in charged condition and supplies the power to the load based on the Ampere-Hour rating of the Battery and the discharging time or backup time adjusted by the user. Since the Local Loads consume more than the inverter supplied current, the remaining current is drawn from the Grid as shown in Figure 10. Since the load is drawing current from both the sources, the grid current and the inverter current are in phase with each other.

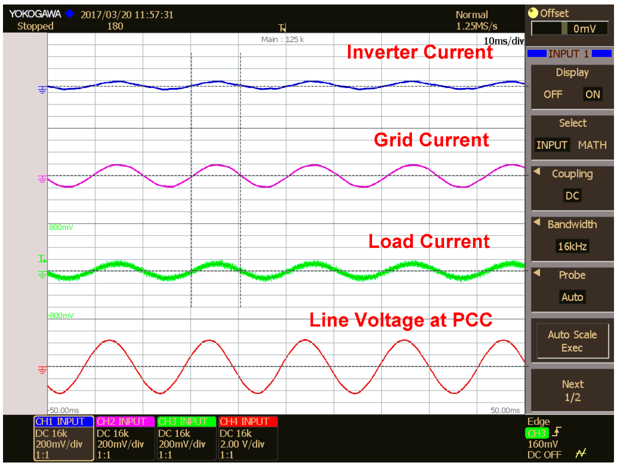

Figure 10. Currents of Inverter, Grid, Load and voltage at PCC in Mode-2 of operation

In Mode-3 Operation, the PV Array cannot produce any power and the battery is in discharged condition. Since the Battery is to be charged, the Grid supplies the necessary charging current to the Battery and the current required for the Local Loads as shown in Figure 11.

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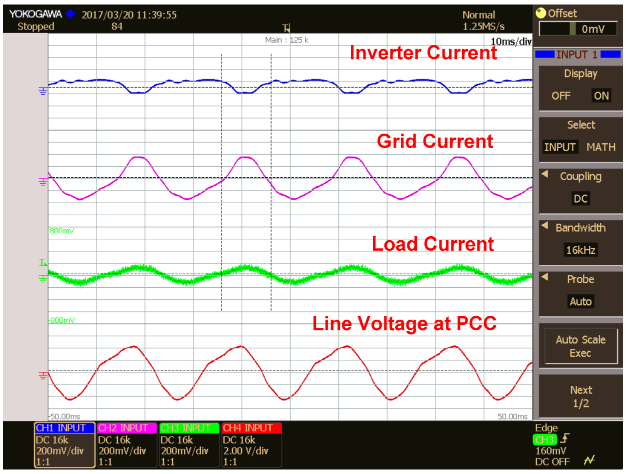

Figure 11. Currents of Inverter, Grid, Load and voltage at PCC in Mode-3 of operation

The dynamic response of the system to a step change in inverter reference power is shown in Figure 12. When the inverter power reference is more than the local load requirement then the inverter is supplying current to grid and load. Since the grid is receiving the current, phase displacement is 180 degree between grid and inverter currents. After a step change in the reference power, since the reference power is less than the load requirement, the load current is supplied from both the inverter and the grid, hence the both the currents are in phase with each other. With the present controls, the system is coming to the steady state within one cycle time.

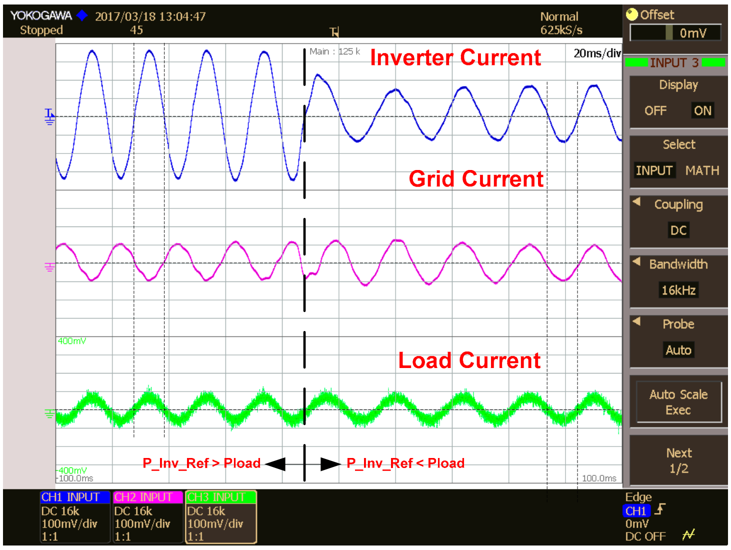

Figure 12. Currents of Inverter, Grid, Load for a step change in reference power.

5.2 *Battery Charger Input and Output Currents in different modes of Operation*

Battery Current is considered as positive during charging and Negative during Discharging of the Battery. The battery will be in charged Condition in Mode-1 and Mode-3 of operations as explained earlier. During charging, depending on the SOC of the battery, the charging current reference is obtained and the controller carries the closed loop current control of the battery charger. The battery Charger Input and Output currents for different modes of operation are discussed below. In mode-1 operation, since the battery is in charging condition, battery Current and the average value of Battery charger input current are positive as shown in Figure 13.

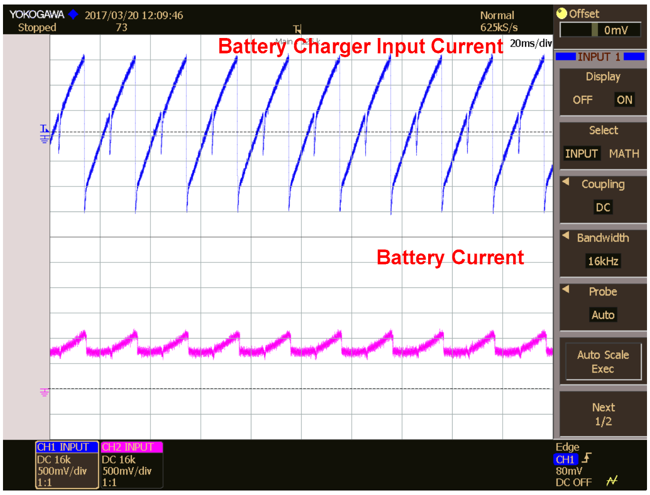

Figure 13. Battery Charger Input and output currents in Mode-1 operation

In Mode-2 of operation, when the PV array voltage is less than the minimum DC Link voltage then the battery charger operates with closed loop voltage control and maintains a constant DC Link voltage. The current through the battery depends on the Id Reference of the Inverter which is obtained through the Amp-Hour rating of the battery and the backup time required for the user. since the battery is in discharging condition, battery Current and the average value of Battery charger input current are negative as shown in Figure 14.

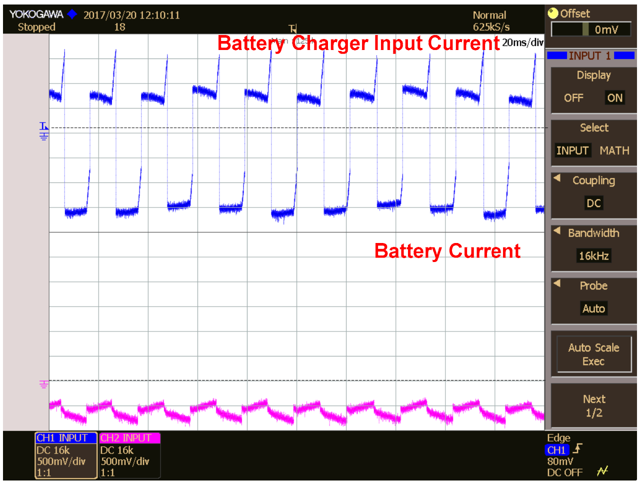

Figure 14. Battery Charger Input and output currents in Mode-2 operation

Similar to mode-1, in mode-3 operation also, battery Current and the average value of Battery charger input current are positive as shown in Figure 15. Charging current required for the battery is provided from grid supply in this case.

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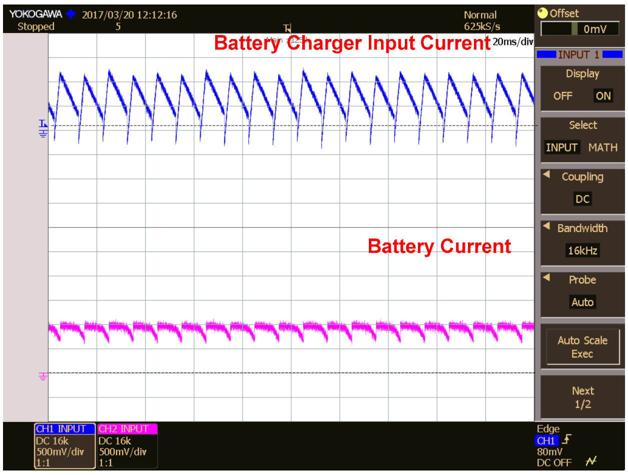

Figure 15. Battery Charger Input and output currents in Mode-3 operation

The dynamic response of the battery charger system is observed by applying a step change in the battery current reference. The system takes approximately 250 millisecond time to come to the steady state as shown in Figure 16.

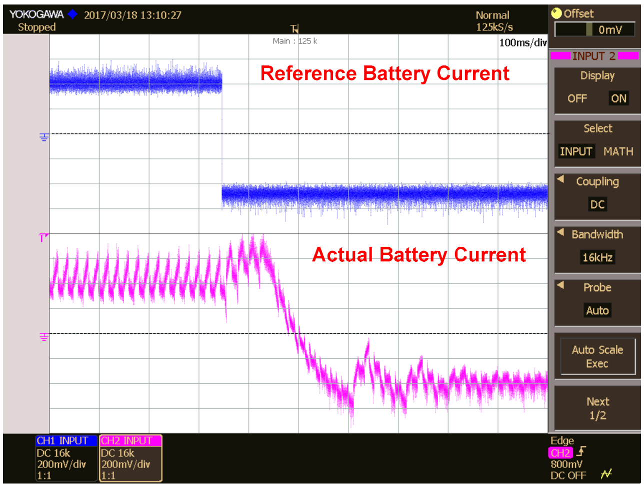

Figure 16. Battery Charger reference and actual currents for a step change in reference current.

6 Conclusions

In this paper, a power balancing control for a grid energy storage system is presented. PBC technique is implemented on a TMS320F2812 processor based controller card and tested. Dynamic responses of the inverter and battery charger system are verified by applying a step change in the reference values. From the presented HIL results, it is observed that the performance of PBC control is satisfactory in all the three modes of operation and good dynamic performance is also achieved using this technique. As the controls are tested through HIL simulations in this work, plant parameters are considered as ideal whereas the plant parameters vary with operating temperatures in real time operation. Hence, minor modifications in plant parameters and tuning of control parameters are required to implement on the real system. The same system can be extended further to have the feature of reactive power compensation through the modified PBC control.

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