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Design and Real-Time Simulation of an AC Voltage Regulator Based Battery Charger for Large-Scale PV-Grid Energy Storage Systems

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ABSTRACT In a conventional energy storage system in a grid-connected solar power stations, solar power is transferred to the grid through a PV-Inverter, and the battery is charged and discharged through a bi-directional converter. In this paper, a novel grid energy storage system for large-scale PV systems is discussed. With the proposed configuration, the battery charging and discharging are carried out through an AC voltage regulator which is connected in series to the line. For this system, cascaded H-bridge (CHB)-based PV-Inverter which is suitable for a high power application is selected. In case of failure in one H-Bridge of a CHB inverter, it is difficult to integrate solar inverter with the grid as the voltages of inverter and grid are not matched. Fault tolerant operation of the CHB-based PV-Inverter can also be achieved through the proposed configuration. In this paper, basic operation and control of a voltage regulator, application of the voltage regulator in grid energy storage systems, fault tolerant operation of a CHB inverter through the voltage regulator are presented. To validate the performance of the controls proposed, Real-time simulations are carried out by interfacing the simulated power circuit with the real controller card with the help of an Opal-RT make real-time simulator. Performance of the proposed system is analyzed through presented results.

INDEX TERMS Battery charger, cascaded H-bridge, energy storage, PV-inverter, real-time simulator, voltage regulator.

I. INTRODUCTION

In photovoltaic (PV) power stations, PV-Array with a series-parallel combination of multiple solar modules provide the desired DC voltage to the inverter. Different configurations of grid-connected solar inverters are shown in Fig. 1. A two-stage PV power conditioning system is shown in Fig. 1(a), in which the first stage of conversion is required for regulating the DC voltage and for maximum power point tracking (MPPT). The second stage of conversion i.e. DC to AC conversion is required for the grid connectivity. Due to multi-stage conversion, the number of components is more which reduces the efficiency and the reliability of the system. A boost chopper based two-stage PV power conditioning systems are discussed in [1] and [2]. Cost and size of such systems are high. Due to two stages of power conversion. The overall cost of the system can be minimized by reducing the number of conversion stages. Fig. 1(b) shows a single stage grid-connected PV power conditioning system in which PV array is connected across the DC link of the inverter and the power flow through the inverter is regulated by current control. A single stage PV system is presented in [3]. Conventionally Two-Level or three level inverters are used for such systems. The DC input to the configurations single stage and two stage power conditioning systems is the series-parallel combination of multiple PV modules erected over a large area. MPPT for such systems is not so efficient and results in the wastage of solar energy due to the partial shading and mismatch in the series connected PV modules. So these systems are not preferable for high power applications where PV modules are large in number. For large-scale PV-systems, independent MPPT strategy for each module is required for efficient energy extraction from PV arrays and this can be

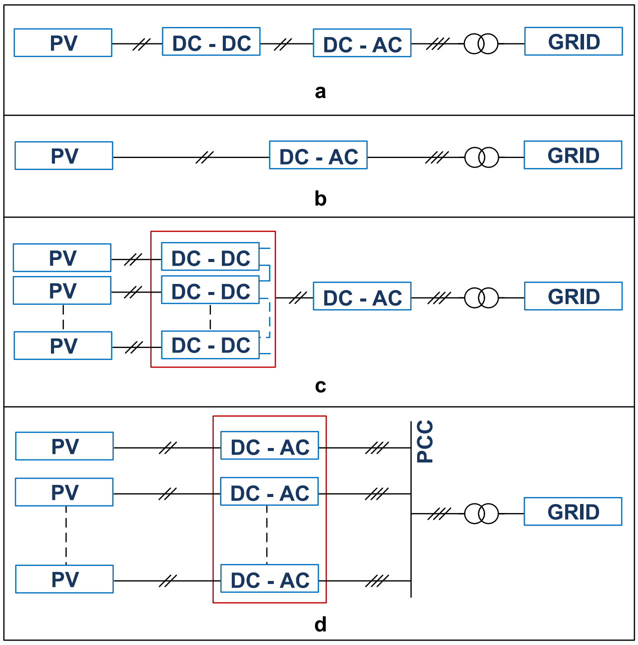


FIGURE 1. **(a) Two Stage Solar power conditioning system (b) Single Stage Solar power conditioning system (c) DC side cascaded PV-inverter (d) PV String inverter.**

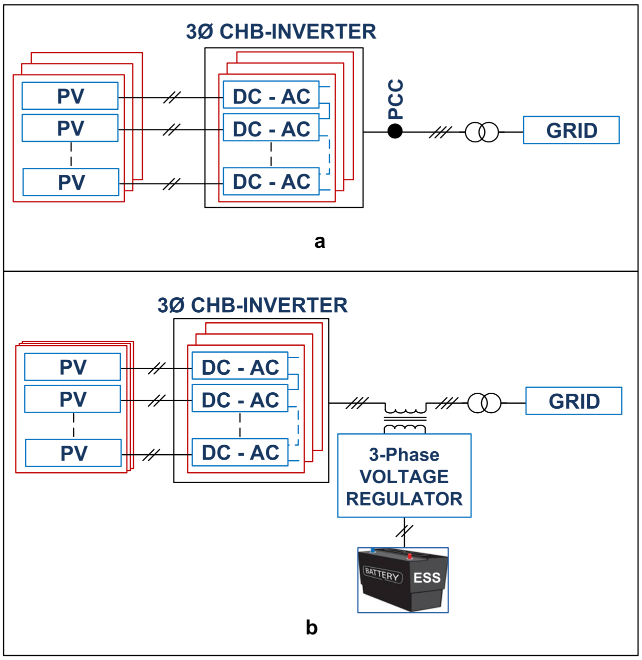


FIGURE 2. **(a) AC side cascaded PV-inverter (b) Block diagram of a proposed voltage regulator based energy storage system for a CHB based PV-Inverter.**

achieved through string inverters and cascaded configurations [4], [5]. Fig. 1(c) shows the block diagram of DC side cascaded inverters. Typically DC-DC converter used in such systems is a buck-boost chopper. This is required for regulating the DC voltage and for MPPT. Generally, inverters used in a DC side cascaded system are conventional two or three-level inverters. Since DC side is cascaded, systems are rated for high voltage applications. A Two-Level Inverter for DC to AC conversion stage is not preferable due to high dv/dt, high device losses and higher filter size requirement. A Two-level inverter also requires multiple devices in series for high voltage applications. To avoid above mentioned drawbacks of a two-level inverter, multilevel inverter topologies need to be used for DC to AC conversion stage. An isolated DC-DC converter based on quasi Z-source for a DC side cascaded PV systems with a modular multilevel converter (MMLC) for DC to AC conversion is presented in [6]. Fig. 1(d) shows a Grid-connected power conditioning systems with string inverters which are an alternative for independent MPPT of PV modules. A comparison study on low power PV-inverter configurations such as string inverters, microinverters and power optimizers are carried out in [7]. String inverters are rated for the low voltage and low power applications. For high power applications, so many such string inverters need to be connected in parallel to the grid and each inverter is fed from independent PV array. Conventionally a Two-Level inverter is used for such applications. Power quality of the overall system is a major concern, as so many such two-level inverters are connected to the grid in parallel.

AC side cascaded inverters can overcome the drawbacks of DC side cascaded inverters and string inverters. In the case of AC side cascaded system shown in Fig. 2(a), cascaded H-bridge (CHB) based multilevel inverter is used for DC to AC conversion. Multiple H-Bridges connected in cascade on AC side are fed from independent DC sources i.e. PV-Arrays. A review on cascaded H-Bridge inverter based PV-systems is presented in [8]. Independent MPPT controls for CHB based PV-inverters are explained in [5] and [9]. For large scale applications, AC side cascaded systems have the following advantages over other configurations (a) Since the inverter is a multi-level configuration, Output THD and filter size is less (b) Single Stage conversion from DC to AC hence cost is less (c) Even though the system is rated for higher voltage, module level voltage is very low which is safe to operate (d) Maintenance and replacement is easy due to Modular construction (e) Independent MPPT control is possible.

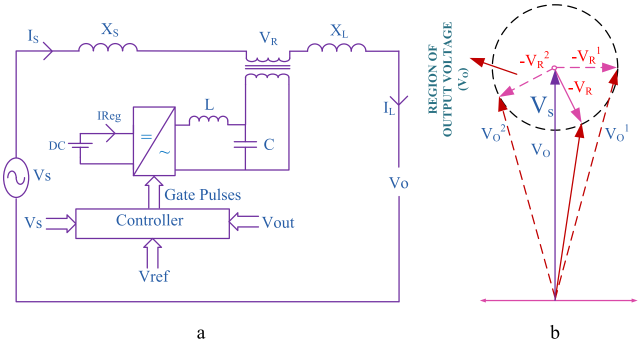
In an AC side cascaded systems, magnitude, and phase angle of Inverter output AC voltage are adjusted for the active power control. The following are the drawbacks with such systems. In the case of failure in one H-Bridge or a failure in a PV Array, it is difficult to transfer power to grid as the voltages of Inverter and Grid are not matched. This problem can be mitigated by cascading an extra H-Bridge. But this redundant module also needs to be fed from an independent PV Array which will increase the cost and the space requirements of the system. Moreover, this makes the system to operate at lower modulation index. Instead of using redundant modules in each phase, redundant operation using one common H-bridge is explained in [10]. In [11], the redundant operation of CHB inverter through an Auxiliary module i.e. a three-leg inverter module along with bypass switches is proposed. Instead of using redundant modules, the above problems can also be mitigated through the proposed configuration shown in Fig. 2(b). Proposed configuration consists of CHB inverter and an voltage regulator. AC voltage regulator serves the following (a) It acts as a battery charger and by controlling the voltage regulator, and regulates the battery current in both directions. (b) It can regulate the voltage applied to the AC terminals of CHB inverter. AC voltage can be boosted to operate the system at higher modulation index and can also be made less than the grid voltage during partial clouding or in the case of failure in any H-bridge.

Details of the proposed configuration are explained in the next sections. In Section-2, the basic operation of a voltage regulator, the application of voltage regulator as a battery charger is explained. Application of voltage regulator in energy storage system (ESS) in PV power systems and the control philosophy for such systems are explained in Section-3. The design of voltage regulator based ESS for Grid-connected CHB inverter for PV applications is explained in Section-4. Experimental validation for proposed system and its controls are explained through results in Section-5.

II. STATIC VOLTAGE REGULATOR AS A BATTERY CHARGER

A. OPERATION OF A STATIC VOLTAGE REGULATOR

An automatic voltage regulator is a closed loop system consists of one measuring unit and one control unit. Generally, the voltage regulator can be used to achieve one of the following (a) To maintain load voltage constant with a variable input voltage or (b) To convert a fixed input AC voltage to variable AC output voltage. In both the cases frequency of input and output are maintained constant. Static voltage regulators based on power electronic converters are used. Static series voltage regulator for voltage regulation in a distribution system is presented in [12]. A modular series voltage compensator and the operating scenarios are presented in [13].The operation of the voltage regulator to obtain a variable output voltage from a fixed input AC voltage is explained briefly in this subsection. Block diagram of the voltage regulator system is shown in Fig. 3(a). In this system, regulation of output voltage is carried out by using an inverter fed from a separate DC source. The primary winding of a step-down transformer is connected to AC output terminals of the voltage regulator and the secondary winding is connected in series with the input AC source. Based on the voltage range of the battery, the voltage rating of transformer primary is decided. The range of output voltage to be regulated decides the transformer secondary voltage rating. Minimum secondary rated current is equal to the rated load current. If the output voltage V_O of the system is to be regulated in the range of $(1\text{-a})V_S$ to $(1\text{+a})V_S$ (where $a < 1$), then the voltage regulator power rating needs to be at least "a" times the rated load. Transformer winding on the voltage regulator side should always be a closed circuit since the transformer acts as a current source. When the system is healthy, then the transformer primary current flows through a voltage regulator and the battery. But in the case of failure in the H-bridge, then a bidirectional switch consists of two thyristors connected in anti-parallel provides the closed path for transformer primary winding.



a b

FIGURE 3. **(a) Block diagram of a single-phase voltage regulator (b) Phasor-diagram of a single-phase voltage regulator.**

Fig. 3(b) shows the phasor diagram of the voltage regulator. Voltage drops across source/line inductances and resistances are neglected for simplification. Source voltage (V_S) is constant and the magnitude of the voltage regulator output (V_R) can be controlled over a wide a range depends on secondary winding voltage rating. The frequency of voltage regulator is maintained equal to the source frequency. The above phasor diagram shows the variation in the output voltage (V_O, V_O^1, V_O^2) for different values of regulator output voltages(V_R, V_R^1, V_R^2) respectively. Since the phase angle of regulator output voltage V_R can be controlled from Zero to 360 degree, the region of the output voltage is as shown in Fig. 3(b).

For better understanding, a single-phase voltage regulator connected to the pure resistive load is simulated. Waveforms of the input voltage, regulator voltage and the load voltage for different reference load voltages are shown in Fig. 4. Rated input voltage Vs is considered as 1 per unit (P.U). During the time interval of 0 to 0.06 sec reference output voltage is adjusted to 0.85 P.U. To obtain the output voltage of 0.85 P.U., the voltage regulator output is controlled to maintain at – 0.15 P.U. Similarly, the reference output is set at 1 P.U during the Time interval of 0.06 to 0.12 sec. In this case, the regulator voltage is Zero as the source voltage and the load voltage are equal. During the time interval of 0.12 to 0.18 sec, reference output voltage is adjusted to 1.15 P.U. To obtain the output voltage of 1.15 P.U., the voltage regulator output is controlled to maintain at + 0.15 P.U. From the above discussion, it is concluded that the load voltage can be varied over a wide range depending on the power rating of the voltage regulator.

B. VOLTAGE REGULATOR AS A BATTERY CHARGER

Regulation of output voltage is discussed in the previous subsection and how this regulator can be used as a battery

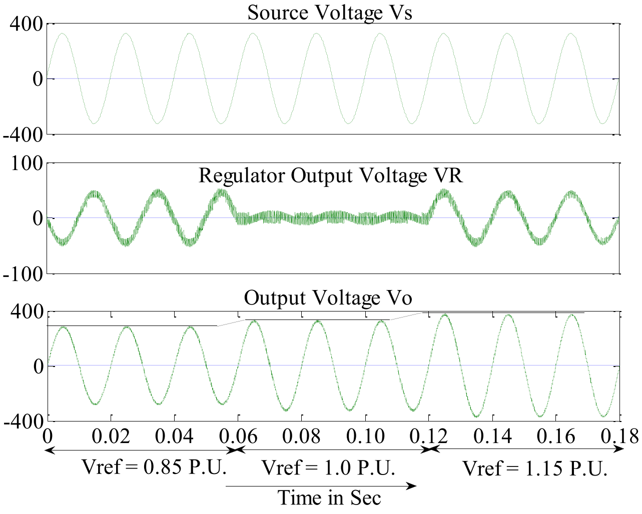


FIGURE 4. **Source voltage, Regulator voltage and Output voltage for different reference voltage outputs.**

charger is explained this subsection. From Fig. 4, during a time interval of 0 to 0.06 sec input voltage is 1 P.U. and the output voltage is 0.85 P.U. since the current flowing through the source and load are same, the output power (0.85 P.U) is lesser than the source power (1 P.U.), the remaining power (−0.15 P.U) is transferred to the DC source i.e. battery. Since the battery power is negative, battery current I_{Batt} is negative. Hence the battery is in charging mode during this operation. Similarly, during a time interval of 0.06 to 0.12 sec, source power and load power are equal, so the battery power is zero. Hence battery is in idle state during this operation. During the time interval of 0.12 to 0.18 sec, since the output power (1.15 P.U) is more than the source power (1 P.U.), the additional power required is to be supplied from the DC source (0.15 P.U). Hence the battery will be in discharging mode during this operation.

From this, we can conclude that the power flow to the battery in both the directions can be controlled by regulated the voltage regulator output. The above discussion is based on the case when the purely resistive load is connected across the output terminals. In the case of an R-L Load, if regulator voltage and source voltage are in-phase with each other, then reactive power also flows through the regulator. To avoid the reactive power flow through the regulator when it is to be used as a battery charger, the following points to be taken care

(a) Phase angle of Regulator voltage: Since the regulator needs to carry only active power voltage regulator output voltage (VR) should be in phase or with 180 degree out of phase to the inverter output current (I_S) during discharging and charging modes respectively.

(b) The frequency of Regulator voltage: The frequency of regulator output voltage (V_R) is always to be maintained equal to the Grid frequency.

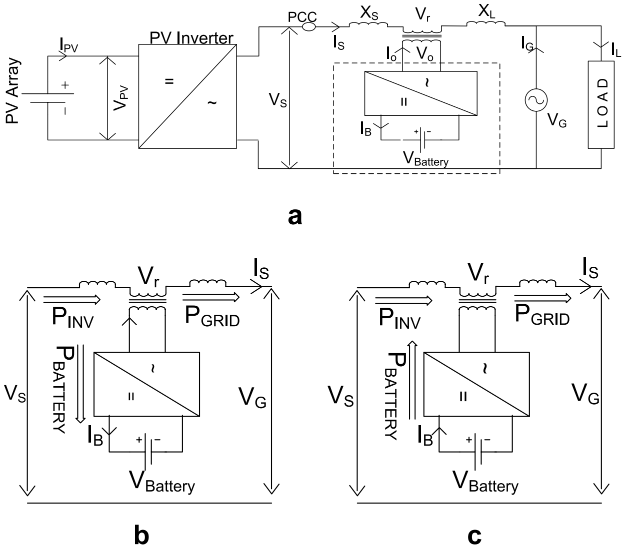


FIGURE 5. **(a) Block diagram of a single-phase PV-Inverter along with a voltage regulator for a Grid energy storage system (b) Power flow diagram when $V_S > V_G$(c) Power flow diagram when $V_S < V_G$.**

III. APPLICATIONS OF AN VOLTAGE REGULATOR IN A GRID ENERGY STORAGE SYSTEM FOR PV APPLICATIONS

The voltage regulator explained in the previous section can be used in applications such as grid energy storage in solar power stations. Application of voltage regulator with a two-level solar power inverter for low power applications is explained in this section. The control algorithm for power transfer and for the battery charging is explained briefly. This concept is extended for CHB MLI for the fault tolerant operation of the inverter during a failure in any H-bridge module in the CHB inverter.

A. VOLTAGE REGULATOR BASED ESS WITH A CONVENTIONAL PV INVERTER

Block diagram of voltage regulator based ESS with a conventional grid-connected PV inverter is shown in Fig. 5(a). When the solar power is more than the power required for a local critical load then the battery takes power from the PV Array for and gets charged. Similarly when the available solar power is less than the power required for a local critical load then the battery needs to supply the additional power required for load, hence the battery will be in discharging mode. In this system, Grid voltage is always constant and the Inverter input AC voltage is varied by controlling the regulator. By making inverter side AC voltage at a higher level than the grid voltage, then the battery will be in charging operation, as the power on the inverter side is more than the load power as shown in Fig. 5(b). Similarly, as shown in Fig. 5(c), the battery will be in discharging mode of operation, if the inverter side voltage is lesser than the grid side voltage, to meet the additional power requirement of the load. Battery Power is Zero when Inverter voltage and Grid voltage are maintained equal.

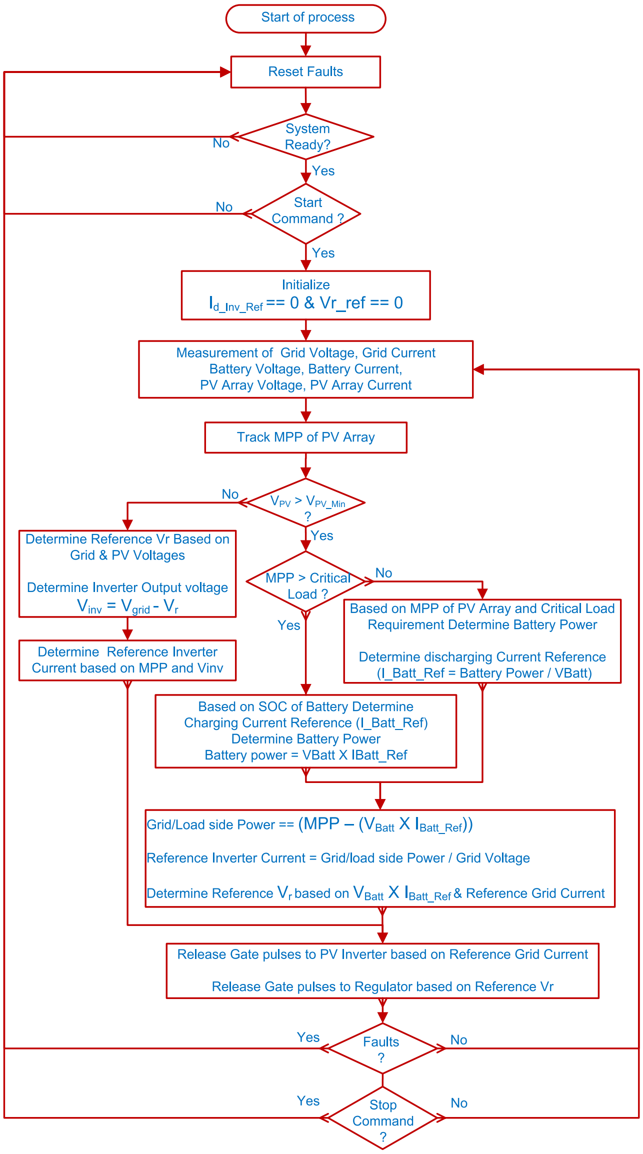


FIGURE 6. **Control Algorithm for the proposed PV-Grid Energy storage system.**

Similar to a conventional PV System, for tracking the maximum power point, current and voltages of PV array are monitored. In this system Perturb and Observe method for MPPT is considered. Algorithms presented in [14] and [15] can also be used for improving the accuracy and speed of the tracking of maximum power point. After tracking the maximum power point, reference grid power is calculated based on the maximum power of PV array and the SOC of the Battery. Subsequently, reference grid current is obtained and the current controller regulates the power flow through the PV inverter. Battery charging/discharging is carried out through regulating the Regulator output voltage. Control Algorithm for the system proposed is shown in Fig 6.

a) If PV voltage is below the Minimum DC Voltage required, then the inverter side input AC Voltage should be maintained lesser than the Grid voltage. Reference Vr (Vr_Ref) is determined based on the PV Voltage and Grid voltage. Controller Generates Gate pulses to the voltage regulator to maintain Vr equal to Vr_Ref. Based on MPP and Inverter voltage (Vinv = Vgrid – Vr), the reference current for the inverter is determined. Controller Generates Gate pulses to the PV Inverter based on Inverter current reference.

b) If PV voltage is higher than the minimum DC Voltage and the available solar power is lesser than the local critical load requirements of the plant, then the battery needs to supply additional power to the Load.

Grid/load side power is the addition of Battery power and the MPP of PV source. From the calculated Grid/load power and the Grid voltage, the reference Inverter current is generated. Controller Generates Gate pulses to the PV Inverter based on Inverter current reference. Through Power balancing, based on Battery Power and Reference Inverter current, reference Vr is determined. Controller Generates Gate pulses to the voltage regulator to maintain Vr equal to Vr_Ref.

c) If PV voltage is higher than the minimum DC Voltage and the available solar power is also more than the local critical load, then the Battery will be in charging mode. The reference charging current is determined based on the SOC of the battery. Reference Battery power which is negative during charging mode is calculated from the battery voltage and reference battery current.

Grid/load power is the addition of Battery power and the MPP which is lesser than MPP as the Battery power is negative. From the calculated Grid/load power and the Grid voltage, the reference Inverter current is generated. Controller Generates Gate pulses to the PV Inverter based on Inverter current reference. Through Power balancing, based on Battery Power and Reference Inverter current, reference Vr is determined. Controller Generates Gate pulses to the voltage regulator to maintain Vr equal to Vr_Ref.

The operation of the proposed configuration at different operating points is explained through simulation results shown in Fig. 7. As shown in Fig. 5, a constant critical load on the grid side is connected. Since the grid voltage is constant, the current drawn by the Load is also constant at all the operating points.

Case 1: From Time 0 to 0.1 Sec, System is in normal operating condition (PV Voltage > Minimum DC Voltage && MPP > critical load)

- Since the Inverter power is more than the Grid/load side power and since the current through Inverter and Grid/Load is equal, the voltage on the Inverter output should be more than Grid voltage which will be regulated by the voltage regulator. Hence the Voltage Vr is in phase with the grid voltage to maintain inverter voltage more than grid voltage.
- Since MPP is more than critical load requirement, the Battery is in charging condition hence the Battery current is negative. Since Battery gets charged/ discharged through Regulator, the regulator output is negative.

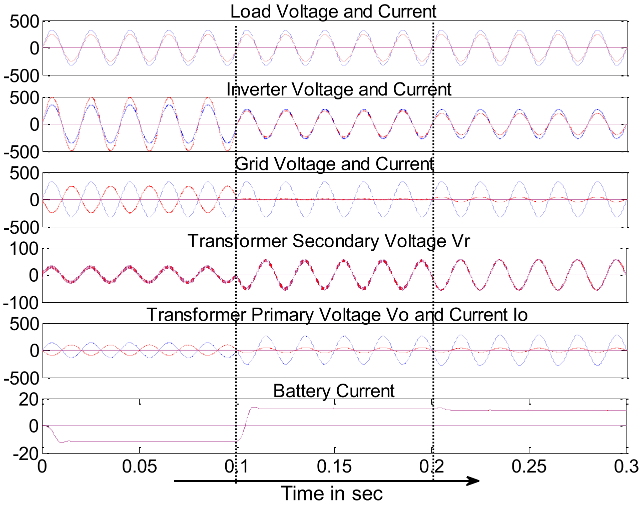


FIGURE 7. **Voltage and current waveforms at Different operating conditions of PV-Inverter along with a voltage regulator for a Grid energy storage system.**

So the output voltage and current of the regulator are 180 degree out of phase.

- Since Inverter power is more than the critical load, the additional power remaining after the battery charging is transferred to the Grid. Hence the Grid voltage and Currents are 180 degree out of phase, so the Grid power is negative.

Case 2: From Time 0.1 to 0.2 Sec, the PV Voltage is more than minimum PV Voltage required but MPP is less than the critical load requirement. (PV Voltage > Minimum DC Voltage && MPP < critical load)

- Since MPP is less than critical load requirement, the Battery is in discharging condition hence the Battery current is positive. Since Battery gets discharged through Regulator, the regulator output is also positive hence the output voltage and current of the regulator are in phase with each other.
- Since the Inverter power is less than the Grid/load side power the voltage on the Inverter output should be less than Grid voltage. The Voltage Vr is 180 degree out of phase with the grid voltage to maintain inverter voltage less than the grid voltage.
- Since Inverter power is less than the critical load requirement, the battery supplies the balance power required for the load. If PV Power and the battery power are sufficient to meet the critical load requirement, then the Grid current will be Zero. If the power supplied from PV array and Battery is still less than the critical load requirement, the Grid needs to supply the remaining power.

Case 3: From Time 0.2 to 0.3 Sec, the PV Voltage is less than minimum PV Voltage required and MPP is less than the critical load requirement. (PV Voltage < Minimum DC Voltage && MPP < critical load)

- Since PV Voltage is less than minimum PV Voltage required, the Inverter output voltage will be lesser than the Grid voltage. Hence Voltage Vr is 180 degree out of phase with the grid voltage to maintain inverter voltage less than the grid voltage.
- Since the Inverter voltage is less than Grid voltage, Inverter Power is less than Grid/load side Power. Hence the Battery will supply the power to Grid/load side. Since the power supplied from PV array and Battery are less than the critical load requirement, the Grid power is positive as shown in Fig. 7.
- Since the Battery is in discharging mode, Battery current is positive. The regulator output voltage and current are in phase with each other.

B. VOLTAGE REGULATOR WITH A CHB BASED PV INVERTER

A CHB Inverter based PV power conditioning system is fed from independent PV Arrays. In the case of failure in one H-Bridge or a failure in a PV source, it is difficult to transfer power to the grid as the voltage of Inverter and Grid are not matched. This problem can be mitigated by cascading an extra H-Bridge. But this redundant module also needs to be fed from an independent PV Array which will increase the cost and the space requirements of the system. Instead of providing a redundant H-Bridge module, it is possible to control inverter side input AC voltage by using an AC Voltage regulator discussed in previous sections. From the previous discussions, it was observed that by using a voltage regulator along with a PV Inverter the following can be achieved

- Energy can be stored in the Battery when the available solar power is more than the requirement.
- The battery can feed the stored energy to the Grid when PV Array cannot feed sufficient amount of Power.
- Operating PV Voltage range can be increased i.e. by adjusting PCC voltage, the Minimum PV Voltage level can be reduced further.

If the control algorithm shown in Fig.6 is extended for the CHB Inverter, Fault redundant operation of CHB Inverter can also be achieved in addition to the above-mentioned advantages. Block diagram of a single-phase CHB based PV-Inverter along with a voltage regulator for a Grid energy storage system is shown in Fig. 8. Active Power flow control through the single-phase CHB inverter is presented in [16]. An advanced control strategy for single-phase CHB inverter is explained in [17]. A DC-side sensorless CHB inverter for PV applications and the controllers are explained briefly in [18].

The operation of the system during a Fault condition is explained through results shown in Fig. 9.

Case 1: From Time 0 to 0.1 Sec, System is in normal operating condition i.e. all three H-Bridge modules are Healthy. The MPP of all PV arrays together is more than the critical load requirement.

- Since MPP is more than critical load requirement, the Battery will be in charging mode hence the current is negative. Since Battery gets charged/ discharged through

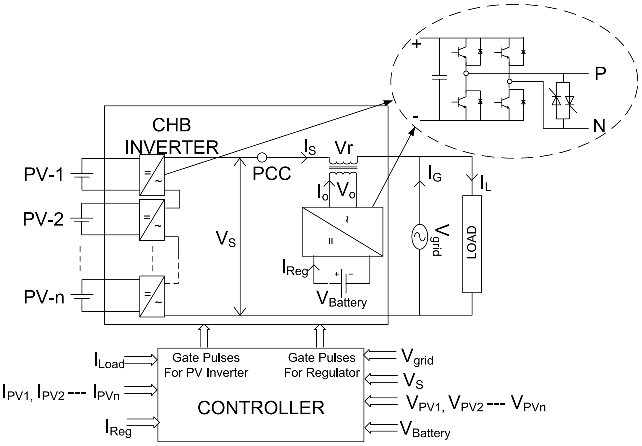


FIGURE 8. Block diagram of a single-phase CHB based PV-Inverter along with a voltage regulator for a Grid energy storage system.

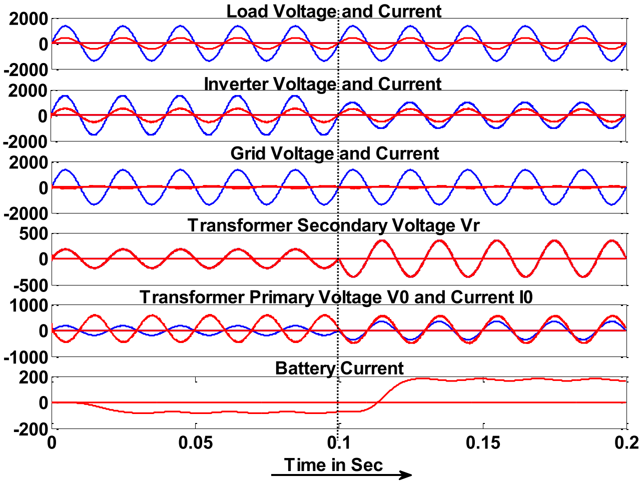


FIGURE 9. Voltage and current waveforms of the system at Different operating conditions of PV-Inverter along with a voltage regulator for a Grid energy storage system.

Regulator, the regulator output is negative. So the regulator current and voltages are 180 degree out of phase.

- Inverter power remaining after the battery charging is transferred to the Grid. Since the grid is taking the power, the Grid power is negative.
- To make inverter side AC voltage greater than grid voltage, Vr is maintained in phase with Vgrid.
- Since Three H-bridges are in cascade and all Three H-bridges are in the Healthy state, the number of Levels on the Output Voltage is Seven i.e. (2N+1) where N is the number of healthy H-bridges connected in cascade.

Case 2: From Time 0.1 to 0.2 Sec, H-Bridge-3 is Faulty.

- Since one H-Bridge is faulty; the number of Level on the Output Voltage is Five.
- MPP is the sum of MPPs of PV sources associated to the two Healthy H-Bridges.
- In this case, Since the MPP is less than critical load requirement; the Battery supplies power to the load, so the battery current is positive.

TABLE 1. Electrical specification of the PV-Grid energy storage system.

Electrical Parameter	Value	Units
Grid Voltage (V_G)	1100	V
Grid Frequency (F)	50	Hz
Maximum Power to be transferred	1000	kW
Battery Backup Power	250	kW

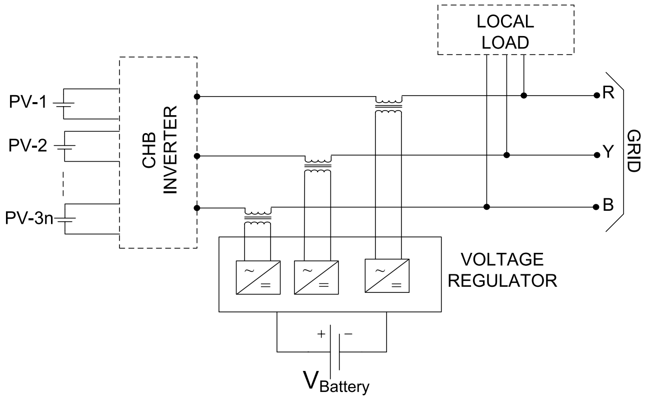


FIGURE 10. Three-phase grid connected CHB MLI based PV-Inverter along with a voltage regulator as a battery charger.

- Since Battery gets discharged through Regulator, the regulator output is positive. Since the regulator output is positive, so the regulator and currents are in phase with each other.
- To maintain inverter input AC voltage lesser than grid voltage, Vr is 180 degree out of phase with the grid voltage.

IV. DESIGN OF VOLTAGE REGULATOR BASED ESS FOR THREE-PHASE CHB MLI BASED PV-INVERTER

In the previous section, the basic operation of voltage regulator based ESS for grid-connected PV applications; different modes of operation, battery charging control and fault tolerant operation of CHB MLI based PV inverters are explained considering a single phase system. In this section, design calculations for a three-phase system are presented and controls for the system are also discussed briefly for the specifications of the system shown in Table 1.

As shown in Fig. 10, in this system, Independent PV arrays are connected to each H-Bridge and the battery is connected on the AC side through an voltage regulator. A local load is connected to the 1100V, three-phase grid. An L-C filter smoothens the PWM voltage of the inverter. Additional Inductance provided by regulator transformer reduces the current harmonics from the inverter. Design calculations for the proposed configuration for a grid power rating of 1000 kW and energy storage of 25% capacity are presented in this paper.

A. DESIGN OF VOLTAGE REGULATOR

Detailed calculations for the design of voltage regulator based battery charger are presented in Table 2. Since the backup power requirement is 25%, the voltage regulation needs to

TABLE 2. Design calculations for voltage regulator based battery charger.

Parameter		Units	Remarks
Battery Backup Power			
% Voltage Regulation	25	%	Equal to % Battery Power
Ratings of Regulator Transformers			
Secondary Voltage (Vsec)	160	V	Max Regulation voltage
Secondary Current (Isec)			
Power Rating (Preg)	85	kW	Voltage X Current
Primary Voltage (Vpri)	160	V	Considering 1:1 Ratio
Primary Current (Ipri)	525	A	Considering 1:1 Ratio
Ratings of Regulator Inverter			
Switching Frequency	5	kHz	Fsw_Reg
Corner Frequency (F_C)	1.25	kHz	Selected equal to Fsw_Reg/4
Filter Voltage Drop	6	%	
Regulator Output Voltage	170	V	Vpri + Filter voltage drop
Regulator RMS Current			
Filter Inductance (L)	60	uH	Obtained from filter drop
Filter Capacitance (C)	265	uF	$(Fc = 1/(2 \times PI \times \sqrt{LC})$
Minimum Battery Voltage	225	V	Vbatt_Min = Vac /0.71
Ratings of Battery			
Type of Battery selected			Lithium-ion
Minimum Battery Voltage	225	V	> 87.5% Vbatt_Nom
Nominal Battery Voltage	256	V	
Maximum Battery Voltage	300	V	116% of Vbatt_Nom
Battery Power	250	kW	
Battery Nominal Current	977	A	Battery Power/ Vbatt_Nom
Battery Ah Rating	1954	Ah	For 2 hour backup time

TABLE 3. Design calculations for CHB MLI based PV inverter.

Parameter		Units	Remarks
Ratings of each CHB Inverter			
Minimum Power Rating	1250	kW	Grid + Battery Power
Maximum Filter drop	3	%	
Max Inverter AC Voltage	1408	V	Vgrid + Vreg+Filter Drop
Inverter phase voltage	813	V	$Vph = Line\ voltage/\sqrt{3}$
No.of H-Bridges per Phase	3.00	No	Hn_Ph
Ratings of each H-Bridge			
Max AC Voltage (Vac)	271	V	Vph/ No of H-Bridges
Minimum DC Link voltage	382	V	Vdc_Min = Vac / 0.71
RMS Current (Iac)	525	A	Rated Grid Current
Power Rating	142	kW	P_H =Vac × Iac
Switching Frequency	1	kHz	Fsw_H
L-C Filter Design			
Switching Frequency (Fsw)	6	kHz	2 × Fsw_H × Hn_Ph
Cut-Off Frequency (Fc)	1.5	kHz	Selected equal to Fsw_Reg/4
Filter Inductance	200	uH	Obtained from filter drop
Filter Capacitance	165	uF	$(Fc = 1/(2 \times PI \times \sqrt{LC})$

be carried out for 25% of rated voltage. Since three single phase regulator transformers are used in this system, secondary of each transformer is rated for 25% of rated phase voltage. Rated secondary current of regulator transformer is equal to the rated grid side current. Regulator transformer of turn's ratio 1:1 is selected in this system; hence the primary and secondary winding ratings are same. Since the voltage regulator system is connected in series, a suitable L-C filter is used at regulator output for avoiding the injection of voltage harmonics. The lithium-ion battery is selected for energy storage and the minimum battery voltage is selected based on the voltage rating of regulator transformer and filter drops.

B. DESIGN OF CHB MLI BASED PV-INVERTER

Detailed calculations for the design of CHB MLI based PV-Inverter is presented in Table 3. Three H-Bridges per phase are selected in this system. Rating of CHB inverter is decided based on the power required for the Grid and the battery. An L-C filter smoothen the PWM output of CHB inverter and the inductance of secondary winding of regulator transformer provides additional inductance to the system which helps in reducing the current harmonics.

C. DESIGN CALCULATIONS FOR PV ARRAY

Design calculations for the PV array in a conventional PV power conditioning system are explained in [19]. In similar lines, design calculations for the PV arrays in CHB system are explained in this section. In a CHB Inverter, independent PV arrays for each H-Bridge are required. Since the number of H-bridges in this system are Nine numbers, Nine PV arrays which consist of a series-parallel combination of 435 watt PV module are selected. In Table 4, design calculations for each PV array are explained in detail.

D. CONTROL BLOCK DIAGRAM

Fig. 11 shows the control structure for the proposed configuration and the control philosophy is explained as below

- ➢ Voltage and currents of each PV array are monitored for independent MPP Tracking. Perturb and Observe method is adapted for MPPT in this system.
- ➢ Overall MPP of Three Phase system is calculated based on independent MPP of each PV array.
- ➢ From overall MPP of PV arrays, direct current reference (Id_Ref) is obtained and the quadrature reference current (Iq_Ref) is obtained from the reactive power reference.
- ➢ Inverter input AC voltage is monitored for determining the angle 'ωt' through phase locked loop (PLL).
- ➢ Three-phase Inverter currents (Iabc) and 'ωt' are given to ABC to DQ converter to obtain Idq components of inverter current.
- ➢ Power control is carried out through PI controllers by comparing the dq components of reference

TABLE 4. Design calculations for CHB MLI based PV inverter.

Parameter		Units	Remarks
Selection of each PV Array			
Number of PV Arrays	9.00	No's	3 × Hn_Ph
Max Power Rating	142	kW	H-Bridge rating
Minimum PV Voltage	382	V	Vdc_Min
Maximum PV Current	364	A	Power / Vdc_Min
PV-Module Details			
Manufacturer Name			M/s Sunpower
Model/Type No			SPR-435NE-WHT-D
Operating Temperature			25 -55 Deg C
Parameters of selected PV-Module at 25^{O}C			
Rated Power	435	W	P_module
Open circuit voltage Voc_25	85.6	V	
MPP Voltage Vmpp_25	72.9	V	
Short circuit current Isc_25	6.43	A	
MPP Current Impp_25	5.97	A	
PV module Temp Coefficients			
Power	-0.38	%/K	
Voltage	-233.5	mV/K	
Current	3.5	mA/K	
Parameters of selected PV-Module at 55^{O}C			
Rated Power	385.4	W	
Open circuit voltage Voc_55	78.59	V	
MPP Voltage Vmpp_55	65.89	V	
Short circuit current Isc_55	6.53	A	
MPP Current Impp_55	6.07	A	
Minimum voltage Vmod_min	65.89	V	MPP Voltage at 55^{O}C
PV-Array Selection			
Minimum No of Modules (Nmin)	320	No's	Rated power/ P_module
No. of series modules (Nse)	6	No's	Vdc_Min/ Vmod_min
No. of parallel modules (Np)	60	No's	Nmin/ Nse
Total No of Modules	360	No's	Nmod = Nse × Np
Maximum Power (Pmax)	156.6	kW	P_module × Nmod
Operating DC Link Voltage			
Minimum	395.4	V	MPP at 55^{O}C
Maximum	513.6	V	Voc at 25^{O}C
Maximum PV Current	392.1	A	Isc at 55 Deg X Np

inverter current with dq components of actual inverter current.

- ➢ The output of PI controllers generates the reference output voltage required for the CHB inverter.
- ➢ Based on MPP of each PV array and the overall MPP, independent voltage references for each H-Bridge is obtained.
- ➢ PWM block generates gate pulses for each H-Bridge in the CHB inverter based on the independent voltage reference. The level shifted PWM generation technique is adopted in this system.
- ➢ Battery voltage and currents are measured to obtain SOC and battery instantaneous power.

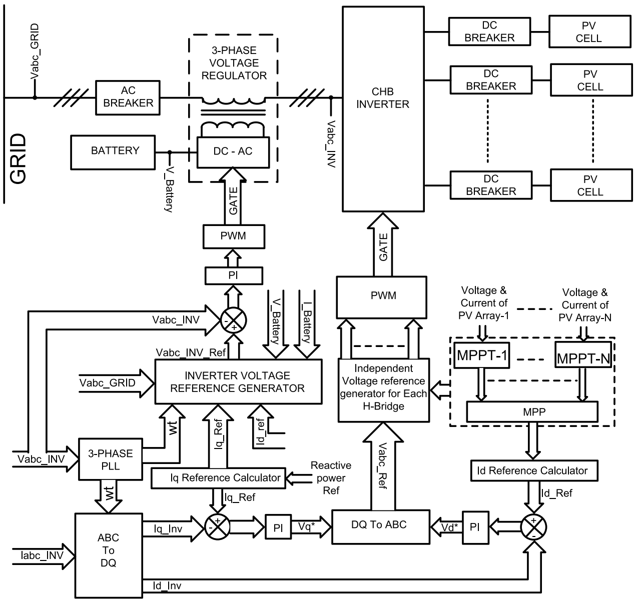


FIGURE 11. Control Block Diagram for Voltage regulator based ESS for Three-phase CHB MLI based Grid connected PV-Inverter.

- ➢ Since the battery charger needs to handle the active power alone, regulator voltage output should be in-phase or 180 degree out of phase with the regulator transformer primary side (Regulator side) current.
- ➢ In this system, regulator transformer primary current is equal to the inverter line current.
- ➢ Battery charging current reference is determined from the SOC of the battery.
- ➢ From battery voltage and the reference battery current, the battery reference power is calculated.
- ➢ Reference regulator output voltage is calculated through the power balancing on the battery side and the regulator output side.
- ➢ Inverter side AC reference voltage is the vector sum of Grid and regulator reference voltages.
- ➢ Error signal obtained after comparing the actual and reference inverter side AC input voltages is given to the PI controllers for closed-loop voltage control.
- ➢ The PI controller output voltage is applied to the pulse generator blocks of inverter and voltage regulator.

V. EXPERIMENTAL VALIDATIONS AND RESULTS

To validate the proposed controls for a 7-Level, Three-phase, grid-connected CHB MLI along with the voltage regulator, a controller in loop setup is built using a real-time simulator as shown in Fig. 12. Opal-RT make Real-Time Simulator is used in this setup. This simulator can be interfaced with the real controller card with the help of I/O interfacing. With this simulator, the power circuit can be modeled in Matlab-Simulink platform and can be loaded into the high-speed CPU which can be operated at the speed of real-time operation. The high-speed CPU used in this simulator is based on Intel

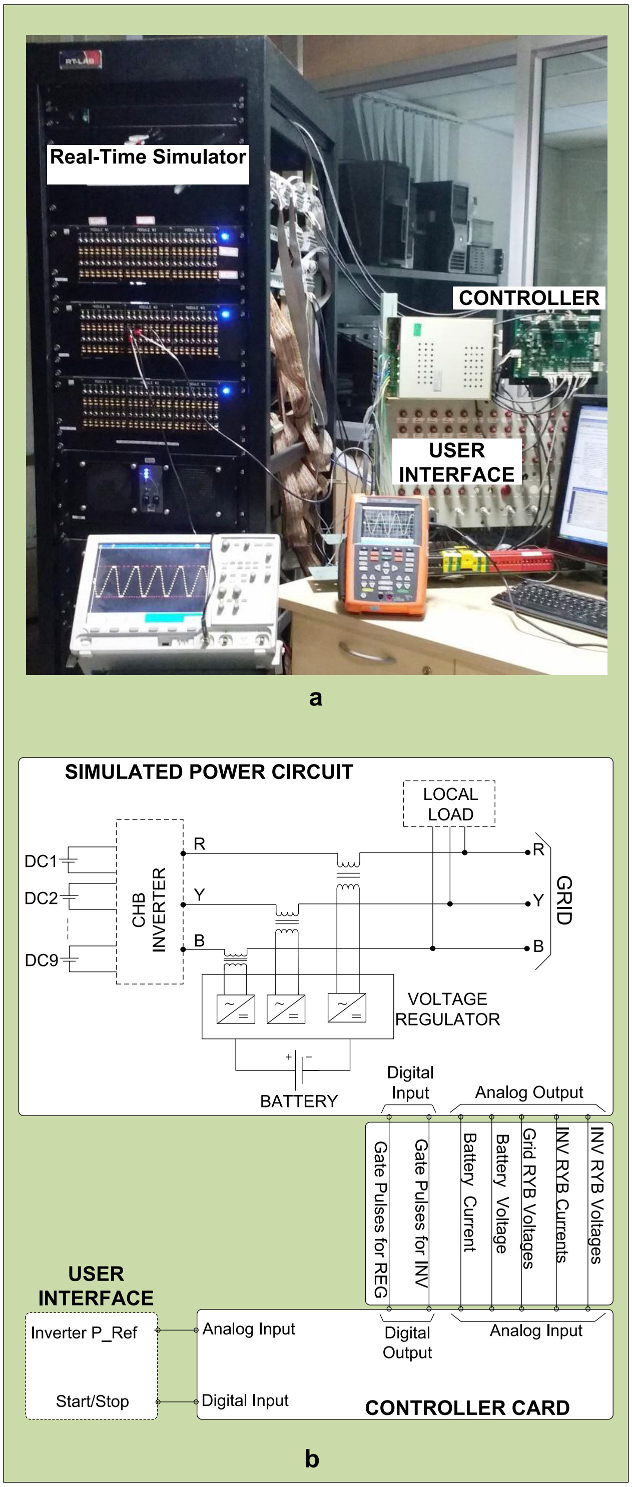


FIGURE 12. (a) Controller in Loop Simulation setup (b) Block diagram of Controller in loop simulation for the proposed configuration.

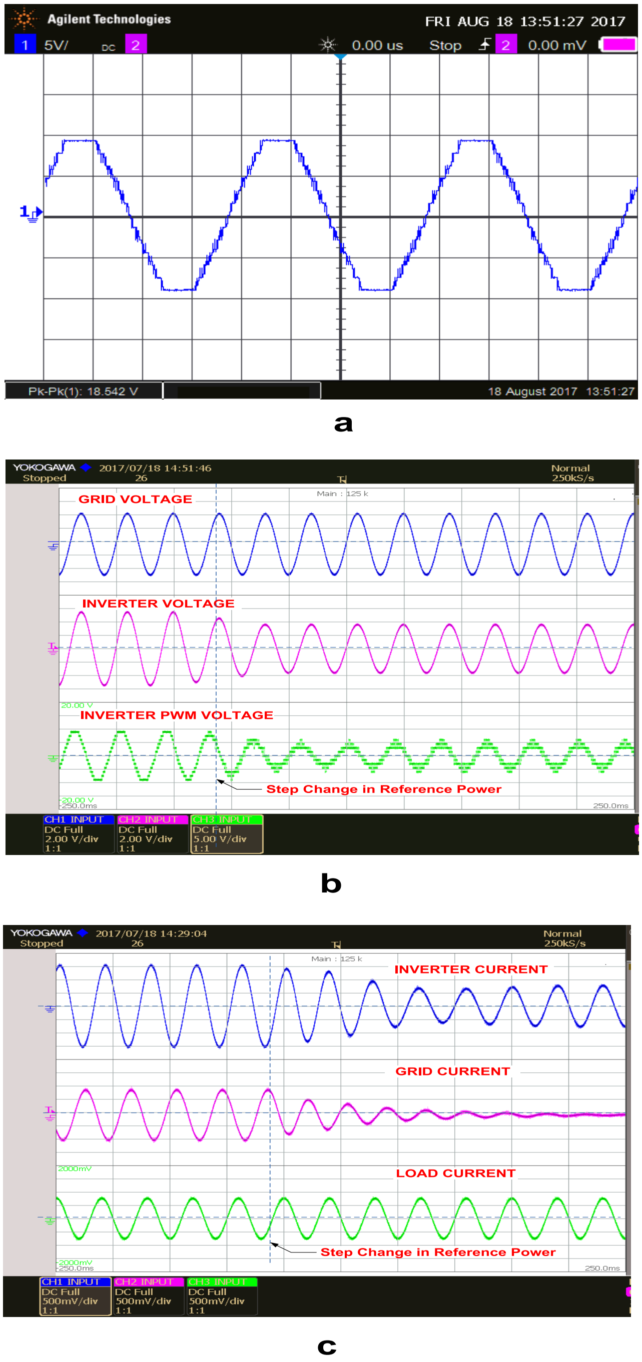


FIGURE 13. (a) 7-level output of CHB Inverter (b) Voltages of Inverter and Grid at two different reference inverter powers (c) Currents of Inverter, Grid and the Load at two different reference inverter powers.

Xeon Quadcore 2.50 GHz processor and the I/O interface is based on FPGA. Controls for this system are programmed in the TMS320F2812 DSP processor based controller card and the Digital inputs and Analog output channels of the real-time simulator are used for interfacing with this controller hardware. The voltage range of Analog output channels of the real-time simulator is −15V to +15V and the digital inputs logic low is Zero volt and Logic high is +15V. Analog input, digital input and digital output channels of controller card are used for interfacing with the simulated power circuit and the mimic panel consisting of pushbuttons and potentiometers. Voltage levels of an analog input channel of the controller card are −10V to +10V which will be further converted into 0 to 3.3V as an input to the DSP processor. Controller card digital channel voltage levels are identical to the digital channels of real-time simulator hence no interfacing cards are required. Parameters of simulated power circuit can also be varied online to check the system response for different values of the components. In this work, the power circuit which consists of three H-Bridges per phase, DC Sources, sine filter, voltage regulator, battery, AC Grid and a fixed R-L load connected to Grid is modeled in the Matlab-Simulink with a sample time of 10 microsecond and the controls are programmed in the processor. Initially, the simulated power circuit is compiled and executed in the high-speed processor in the Opal-RT simulator. Since the Matlab model of power circuit model gets executed in a high-speed processor, real-time values of voltage and current signals from the simulated plants can be obtained from the real-time simulator. The processor card receives the analog signals such as voltage and current signals of the grid, inverter, battery and PV sources from the simulated plant through Analog out (AO) channels of the real-time simulator.

Control software is programmed, compiled and executed on the controller card. User commands such as Start/Stop signal and reference inverter power signal are given to the controller card through the user interface. Based on the reference power, the reference current is obtained by the processor. Real-time values of inverter current are received from the simulator analog output channels and the processor compares the actual and reference currents. Then based on the current controller output, reference phase voltages are generated in the processor. Then the gate pulses are generated by the processor. The controller gives Gate pulses to the simulated CHB inverter and the voltage regulator through the DI channels of simulator system. On receiving the gate pulses from the processor, simulator converts these electrical signals into data and fire the IGBTs in the power circuit in real-time.

Fig. 13(a) shows the CHB output voltage. Since three H-bridges are used per phase the maximum number of levels that can be obtained from the CHB inverter is Seven. A step change is applied in the reference inverter power, and the response of inverter voltage is as shown in Fig. 13(b). Initially, reference inverter power is adjusted at rated value. In this case, the Magnitude of Inverter voltage is more than the Grid voltage and the number of levels in the PWM output of the inverter is also maximum i.e. Seven levels. PV inverter is supplying power to the local load, grid and to the battery. Reference inverter power is reduced instantaneously and adjusted to a value lesser than the local load requirement. In this case, the PV inverter and battery are supplying power to the local load. In this case, the Magnitude of Inverter voltage is less than the Grid voltage. A number of levels in the PWM output of inverter also reduced as AC voltage applied at inverter AC terminals is less.

The response of inverter and grid currents for a step change in the reference inverter power is shown in Fig. 13(c). Initially, reference inverter power is adjusted at rated value, inverter feeds the power to the load and the additional current is transferred to the grid. Reference inverter power is reduced instantaneously and adjusted to a value lesser than the local load requirement, then Inverter and battery together supply power to the local load and there is no current flowing to the grid. The response of battery current for a step change in the reference inverter power is shown in Fig. 14(a). Initially, reference inverter power is adjusted at rated value, then the battery is in charging mode and the battery current is negative. Reference inverter power is reduced instantaneously and adjusted to a value lesser than the local load requirement, then Inverter and battery together supply power to the local load and there is no current flowing to the grid, then the battery needs to provide additional power required for the local load.

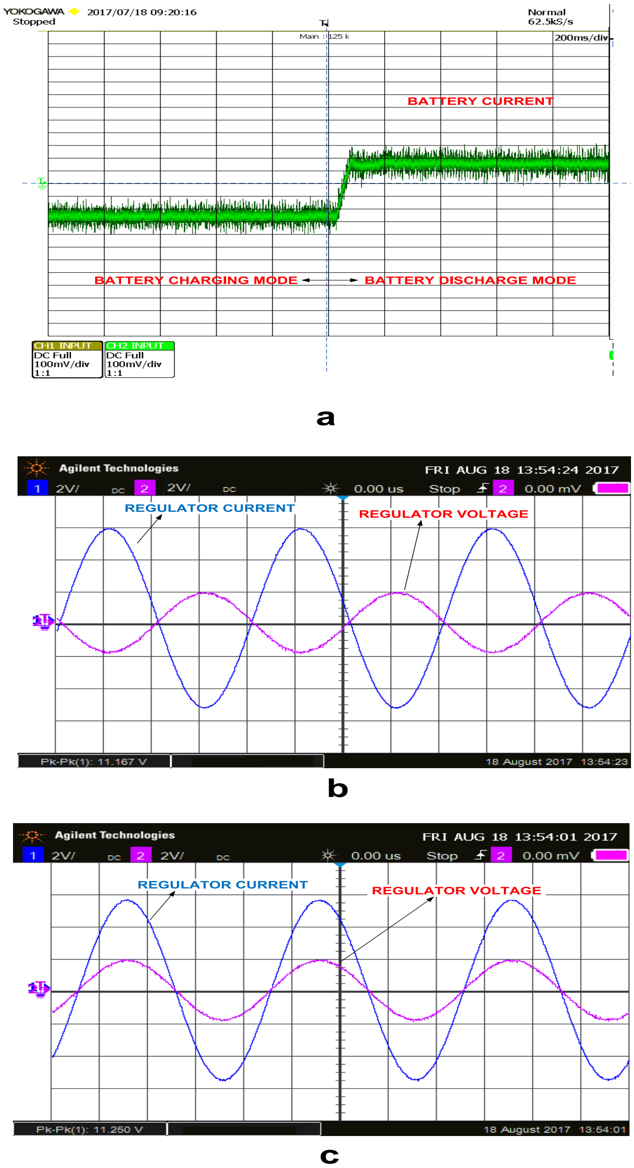


FIGURE 14. **(a) Battery Current for a step change in reference inverter power (b) Voltage regulator voltage and current waveforms during Battery charging mode (c) Voltage regulator voltage and current waveforms during Battery dis-charging mode.**

Hence the battery will be in discharging mode and the current is positive. Voltage and current waveforms of R-Phase voltage regulator transformer secondary winding during charging and discharging modes of operation are shown in Fig. 14(b) and Fig. 14(c) respectively. As discussed earlier, since the regulator power is negative during battery charging, voltage and currents are 180degree out of phase as shown in Fig. 14(b). Similarly during battery discharging mode, since the regulator power is positive, voltage and currents are in phase with each other.

A. CHALLENGES INVOLVED IN THE DESIGN

The following are the challenges involved in the design of the proposed system

(a) Unlike the DC coupled energy storage systems, in an AC side coupled energy storage system; there is the possibility of disturbances in the grid. As the voltage regulator in the proposed configuration is a series compensator, it may cause additional voltage harmonics. Hence the output side filter for the regulator is to be designed accurately.
(b) Regulator control should be so accurate to maintain the output frequency of the voltage regulator equal to the Grid frequency.
(c) Transformer Winding on the voltage regulator side should always be a closed circuit, as it acts as a current source.
(d) Regulator output may cause unbalance in the three-phase inverter input AC voltage. Since the PLL input is taken from the Inverter AC terminals, the Voltage regulator may cause the disturbance to the PLL.
(e) Control of Battery charger is not decoupled with the Control of PV-Inverter.

B. FUTURE SCOPE

(a) The controls proposed in this system are for grid-connected applications. This configuration can also be adapted for Standalone systems with minor modifications in the control algorithm.
(b) The work can be extended for reactive power compensation.
(c) The proposed configuration can also be extended for Hybrid PV- Fuel cell systems.

VI. CONCLUSION

In this paper, voltage regulator based energy storage system and its controls are presented. The controls are executed through a controller card based on TMS320F2812 processor and validated through the controller in loop simulations. The proposed system enables the feature of Energy storage and Fault-tolerant operation for a Grid-connected CHB based Inverter for large-scale PV systems. This configuration also improves the system dynamics during grid fluctuations. The main drawback of the system is the control of battery charger is always tied with the control of PV-inverter. Operation and control during charging and discharging modes are explained briefly. Transient responses of the systems are validated and found satisfactory from the presented results.

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