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Integration of PV/Battery/ wind Hybrid Energy Conversion System to the smart Grid with Power Quality Improvement Features

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Abstract:

Grid integration of photo voltaic (PV)/Battery hybrid energy conversion system with (i) multi-functional featuresof micro grid-side bidirectional voltage source converter (µGVSC)(ii) tight volatge regulation capability of battery converter(iii) MPPT tracking performance of high gain integrated cascadedboost (HGICB) dc-dc Converter with quatratic gain andless current ripple are presented in this paper. The PV sideHGICB Converter is controlled by P&O MPPT algorithm toextract the maximum power from the variable solar irradiation.

This paper proposes a modified Instantaneous symmetricalcomponents theory to the µG-VSC in micro-grid applicationswith following intelligent functionalities (a) to feed the generatedactive power in proportional to irradiation levels into the grid(b) compensation of the reactive power, (c) load balancing and(d) mitigation of current harmonics generated by non-linearloads, if any, at the point of common coupling (PCC), thusenabling the grid to supply only sinusoidal current at unity powerfactor.

The battery energy storage system (BESS) is regulatedto balance the power between PV generation and utility grid.A new control algorithm is also proposed in this paper for thebattery converter with tight DC link voltage regulation capability.The dynamic performance of battery converter is invistegatedand compared with conventional average current mode control(ACMC).

A model of a hybrid PV Energy Conversion System isdeveloped and simulated in MATLAB/SIMULINK environment.The effectiveness of the proposed control strategies for HGICBconverter and µG-VSC with battery energy conversion systemare validated through extensive simulation studies.

I. INTRODUCTION:

Among various renewable energy resources, PV and windpower are most rapidly growing renewableenergy sources [1].The PV source is a nonlinear energy source and direct connectionof load will not give optimum utilization of the PV system.In order to utilize the PV source optimally, it is necessaryto provide an intermediate electronic controller in betweensource and load under all operating conditions [2]. Using thiselectronic controller it is possible to opearate the PV source atmaximum Power point (MPP), thus improving the energy efficiencyof the PV system. Many control algorithms have beenreported in the literature to track maximum power from thePV arrays, such as incremental conductance (INC), constantvoltage (CV), and perturbation and observation (P&O). Thetwo algorithms often used to achieve maximum power pointtracking are the P&O and INC methods [2], [3].Many DC-DC converter topologies are available to trackthe MPP in PV generating system. Cascade connection ofconventional converters provides wider conversion ratios [4].One of the major advantages of these converters is a highgain and low current ripple. However, this configuration hasa drawback that the total efficiency may become low if thenumber of stages are high, owing to power losses in theswitching devices [4]. A quadratic converter configuration isalso available that uses single switch and acheives quatraticgain [4]. An interesting attractive converter topology is a highgain integrated cascaded boost converter having n-convertersconnected in cascade using a single active switch. The instabilitycaused by the cascade structure is avoided, when comparedwith the conventional cascade boost converter [4]. This classof converters can be used only when the required number ofstages is not very large, else the efficiency will be reduced.However, this class of converters for PV applications are notreported in the technical literature.

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Micro-grid power converters can be classified into (i) gridfeeding,(ii) grid-supporting, and (iii) grid-forming powerconverters [5]. There are many control schemes reported inthe literature such as synchrounous reference theory, powerbalance theory, and direct current vector control [6], [7], forcontrol of μG-VSC in micro grid application. These algorithmsrequires complex coordinate transformations, which iscombersome. Compared to the control strategies mentionedabove, the Instantaneous symmetrical component based control proposed in this paper for micro-grid applications is simplein formulation, avoids interpretation of instantaneous reactivepower and needs no complex transformations. This paper is structured as follows: In section II, systemdescription and modeling of various components are presented.The proposed control strategies for HGICB DC-DC Converter,Battery Converter and μG-VSC are discussed in section III.The simulation results are presented in section IV. Withconcluding remarks in section V.

II. SYSTEM DESCRIPTION:

The envisaged system consists of a PV/Battery hybridsystem with the main grid connecting to non-linear and

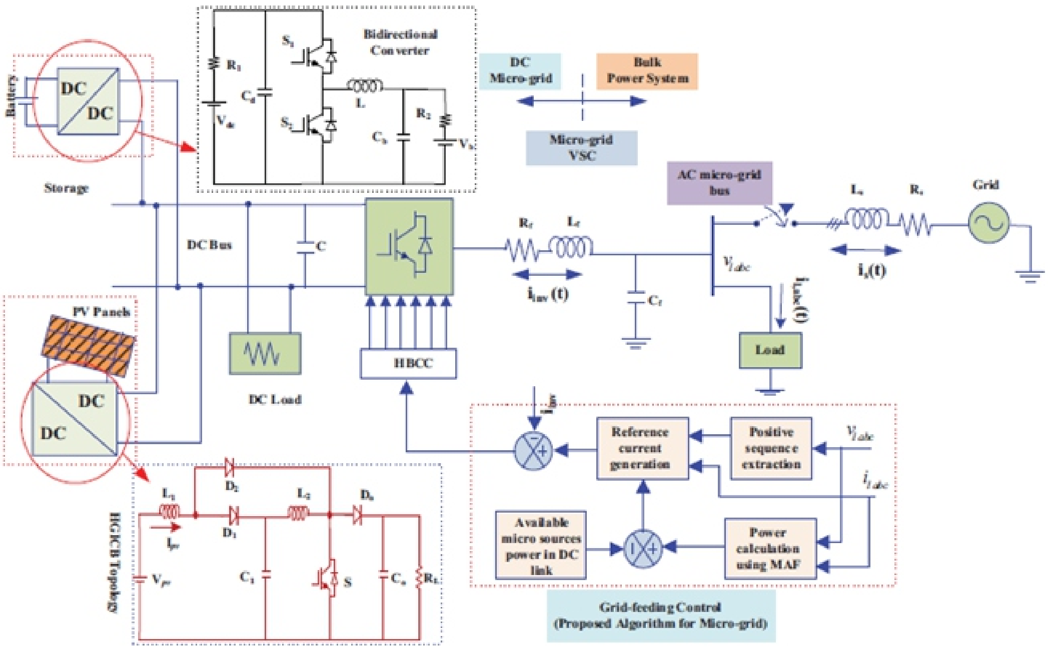

Fig.1. Hybrid Energy Conversion System under consideration

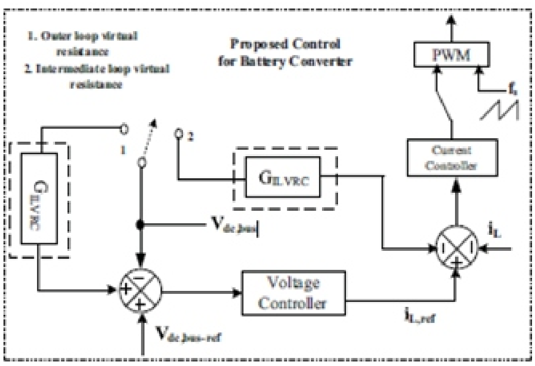

Fig.2. A new modified-ACMC control strategy for battery converter

Unbalanced loads at the PCC as shown in theFig. 1. Thephotovoltaic syatem is modeled as nonlinear voltage sources[8]. The PV array is connected to HGICB dc-dc converterand bidirectional battery converters are shown in Fig. 1, whichare coupled at the dc side of a μG-VSC. The HGICB dcdcconverter is connected to the PV array works as MPPTcontroller and battery converter is used to regulate the powerflow between dc and ac side of the system.

III. MODELING AND CONTROL:

The MPPT algorithm for HGICB Converter, control approachesfor battery converter and μG-VSC are discussed inthe following sections.

A. PV Array Model:

The mathematical model of PV system refered in [8] isused in this work.

B. Battery Converter Modeling:

The battery converter goes through two topological stagesin each switching period, its power stage dynamics can bedescribed by a set of state equations. The average state spacemodel of the converter can therefore begiven as:

$$\frac{di_L}{dt} = \frac{v_{c1}d_{(t)}}{L} - \frac{v_{c2}}{L} - \frac{(r_s + r_L)i_L}{L}$$

$$\frac{dv_{c1}}{dt} = \frac{v_{dc,Bus} - v_{c1}}{C_1 R1} - \frac{i_L d_{(t)}}{C_1} \qquad (1)$$

$$\frac{dv_{c2}}{dt} = \frac{v_B - v_{c2}}{C_2 R2} - \frac{i_L}{C_2}$$

The averaged model is nonlinear and time-invariant becauseof the duty cycle, d(t). This model is finally linearized aboutthe operating point to obtain a small-signal model is shownin Fig. 4. The following are the important transfer functionsused to design the compensators and to analize the systembehavior under small signal conditions (i) the duty-cycle-tooutputtransfer function Gcv(s), carries the information neededto determine the type of the voltage feedback compensation,(ii)the duty-cycle-to-inductor current transfer function Gci(s), isneeded to determine the current controller structure.

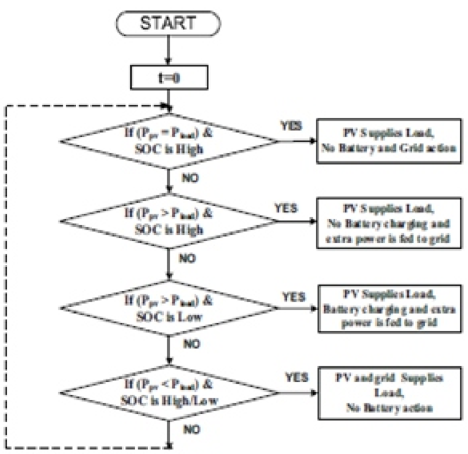

Fig3. Flow chart of power flow in hybrid system

C. Proposed Control for Battery Converter:

If AC side of µG-VSC has constant power appliances (CPAs), in the small-signal sense, CPAs nature leads tonegative incremental input-conductance which causes destabilizationof the dc-link voltage [10]. On the microgrid generationside, the inherent negative admittance dynamics of theircontrolled convertion stages challenges the dc-link voltage control and stability. This effect is more with reduced dc-linkcapacitance. Therefore, in both cases, fast and effective controland stabilization of the dc-link voltage is very crucial issue.To address this problem, many methods are reported in theliterature like (i) by large DC link capacitance (ii) by addingpassive resistances at various positions in DC LC filter (iii) byloop cancellation methods [9], [10].

In this paper, a new modified-ACMC (MACMC) controlalgorithm is proposed for effective control and stabilizationof battery converter by introducing virtual resistace (VR) inthe (i) outer loop called outer loop virtual resistance control(OLVRC) (ii) intermediate loop called inner loop virtual resistancecontrol (ILVRC) as shown in Fig. 2. The proposed virtualresitance based dynamic damping methods aim at injectinga damping signal that compensate for negative conductancecaused by CPAs without any power loss.

D. Design steps for Compensators of BESS:

The effectiveness of proposed VRCs control algorithm isinvistegated and compared with the use of traditional ACMC[11]. The flowchart for modes of operation of battery converterin grid-feeding mode is shown in Fig. 3. The design guidelinesfor inner and outer loop compensators of ACMC are givenbelow. The inner loop (current) gain can be written as:

$$T_i(s) = G_{id}(s)\, R_i\, G_{ci}(s)\, F_m \qquad (2)$$

The outter loop (voltage) gain can be written as:

$$T_v(s) = G_{vd}(s)\, G_{cv}(s)\, (1 + G_{ci}(s))\, F_m \qquad (3)$$

and the overall loop gain therefore can be written as:

$$T_1(s) = T_s + T_v \qquad (4)$$

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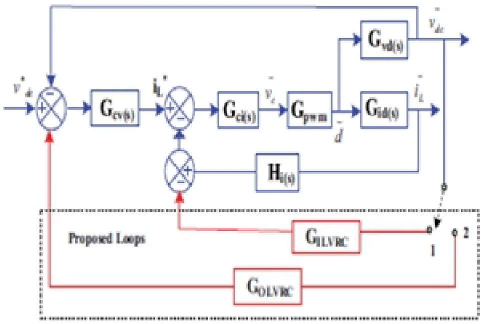

Fig.4. Inner and outter loops of battery converter with MACMC.

V oltageLoop Design Steps:

i) Place one zero as high as possible, yet not exceedin-gresonating frequency of the converter.
ii) Place one pole at frequency of output capacitor ESR tocancel the effects of output capacitor ESR.
iii) Adjust, gain of compensator to trade-off stability mar-ginsand closed-loop performance.
iv) Another pole should be place at origin to boost the dcand low frequency gain of the voltage loop.
Similar steps mentioned above are followed to design currentloop and for design of MACMC loops. Following the designprocedure given above, the inner current and outer voltageloop compensators are designed to regulate the DC linkvoltage to 920 V.

E. Generation of reference currents for µG-VSC:

The main aim of the µG-VSC control is to cancel the Ef-fects of unbalanced and harmonic components of the lo-calload, while supplying pre-specified amount of real and reactivepowers to the load. Upon successfully meeting this objective,the grid current ig will then be balanced and so will be thePCC voltage VP provided, grid volatge vg is balanced. Let usdenote the three phases by the subscripts a, b and c. Since igis balanced, we can write:

$$i_{ga} + i_{gb} + i_{gc} = 0 \,. \qquad (5)$$

From the Fig. 1, Kirchoffs current law (KCL) at PCC gives

$$i_{g,abc} + i_{inv,abc} = i_{L,abc} \,. \qquad (6)$$

Therefore, from (5) and (6), we can write as:

$$i_{inv,a} + i_{inv,b} + i_{inv,c} = i_{L,a} + i_{L,b} + i_{L,c} \,. \qquad (7)$$

Since ig is balanced due to the action of the compensa-tor, thevoltage VP will also become balanced. Hence, the instantaneousreal powers Pg will be equal to its average component.Therefore, we can write

$$P_g = v_{pa}\, i_{ga} + v_{pb}\, i_{gb} + v_{pc}\, i_{gc} \qquad (8)$$

TABLE I
SYSTEM PARAMETERS

System Quantities	Values
System voltages	325 V peak phase to neutral, 50 Hz
Linear Load	$Z_{la} = 50 + j1.57\ \Omega$, $Z_{lb} = 45 + j3.14\ \Omega$, $Z_{lc} = 40 + j4.71\ \Omega$
Non-Linear Load	Three phase full bridge rectifier load feeding a R-L load of 44Ω-3 mH
G-VSC parameters	C_{dc}=660 μF, V_{dcref}=920 V, L_f= 5 mH, R_f= 0.1Ω
Hysteresis band	0.25 A

Solving above equations, the µG-VSC reference currents areobtained as follows:

$$i^*_{inv,a} = i_{la} - \frac{v_{ga} + \beta(v_{gb} - v_{gc})}{\Delta}(P_{lavg} - P_{\mu s} + P_{loss})$$
$$i^*_{inv,b} = i_{lb} - \frac{v_{gb} + \beta(v_{gc} - v_{ga})}{\Delta}(P_{lavg} - P_{\mu s} + P_{loss})$$
$$i^*_{inv,c} = i_{la} - \frac{v_{gc} + \beta(v_{ga} - v_{gb})}{\Delta}(P_{lavg} - P_{\mu s} + P_{loss}) \qquad (9)$$

Where,

$$\Delta = \sum_{j=a,b,c} v_{gj}^2, \beta = tan\varphi/\sqrt{3} = \frac{Q_s}{P_s\sqrt{3}} \,.$$

and Qs = Ql − Qµs, and by substituting β Ps = √Qs3into theequation (9), the modified G-VSC reference current equationsin terms of active and reactive components are obtained as:

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$$
\begin{aligned}
i^*_{inv,a} &= i_{la} - \frac{v_{ga}\,P_s}{\sum_{j=a,b,c} v_{gj}^2} - \frac{(v_{gb}-v_{gc})\,Q_s}{\sum_{j=a,b,c} v_{gj}^2 \sqrt{3}} \\
i^*_{inv,b} &= i_{lb} - \frac{v_{gb}\,P_s}{\sum_{j=a,b,c} v_{gj}^2} - \frac{(v_{gc}-v_{ga})\,Q_s}{\sum_{j=a,b,c} v_{gj}^2 \sqrt{3}} \qquad (10) \\
i^*_{inv,c} &= i_{lc} - \frac{v_{gc}\,P_s}{\sum_{j=a,b,c} v_{gj}^2} - \frac{(v_{ga}-v_{gb})\,Q_s}{\sum_{j=a,b,c} v_{gj}^2 \sqrt{3}}
\end{aligned}
$$

In equations (9) and (10), Pμs, Plavg, and Ql are the availableMicrosource power, average load power, and load reactivepower respectively. Ploss denotes the switching losses andOhmic losses in actual compensator. The term Plavg isobtained using a moving average filter of one cycle windowof time T in seconds.

IV. RESULTS AND DISCUSSION:

The proposed control strategies for PV hybrid generatingsystem is developed and simulated using Matlab/SIMULINKunder different solar insolation levels. In order to capturethe transient response of the proposed control system, PVinsolation is assumed to increase from 200 to 1000 W/m2at 0.3 s, and decreases from 1000 to 200 W/m2 at 0.5 s. Thisabrupt increase or decrease is assumed in this work in orderto test the robustness of the proposed control algorithm. As aresult, the inductor current of the HGICB converter is variedto track the maxmum power accordingly and the power flow.

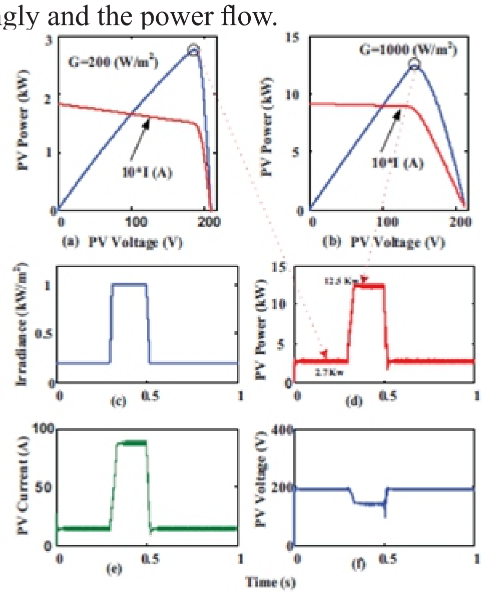

Fig.5. Simulation results: MPPT Tracking performance of HGICB Converter(a) PV Characteritic at G=200 W/m2 (b) PV Characteritic at G=1000 W/m2(c) insolation variations (d) PV Maximum Power (e) PV Current (f) PVVolatge.

TABLE II
MAXIMUM POWER TRACKING PERFORMANCE

Time (s)	G (W/m^2)	V_{pvref} (V)	I_{pvref} (A)	P_{pvmax} (kW)
0.2 – 0.3	200	190	14	2.5
0.3 – 0.5	1000	142	87	12.5
0.5 – 1	200	190	14	2.5

Between the μG-VSC, grid and load is also varied under abovethe operating conditions.

A. MPPT Tracking Performance of HGICB Converter:

The dynamic performance of HGICB converter with P&OMPPT algorithm at two different insolation levels are shownin Fig. 5. A variable PV volatge and current in proportion toinsolation levels are applied to HGICB converter and as aresult, the duty cycle is calculated using the MPPT algorithm.The PV characteristics at two insolation levels are shown inFig. 5(a)-(b).

From Fig. 5 (a), the maximum power, current andvoltage are 2.6kW, 14A and 190V respectively and thesevalues are tracked by HGICB converter which are shown inFig. 5 (d)-(f). Tracked values of PV power, voltge and currentsare given in Table II for the above operating insolation levels.From these results it can be concluded that, HGICB converteris tracking maximum power closely at all operating conditions.

B. Performance of μG-VSC with different insolation levels:

The μG-VSC is actively controlled to inject the generatedactive power as well as to compensate the harmonic andreactive power demanded by the unbalanced and nonlinearload at PCC, such that the current drawn from grid is purely

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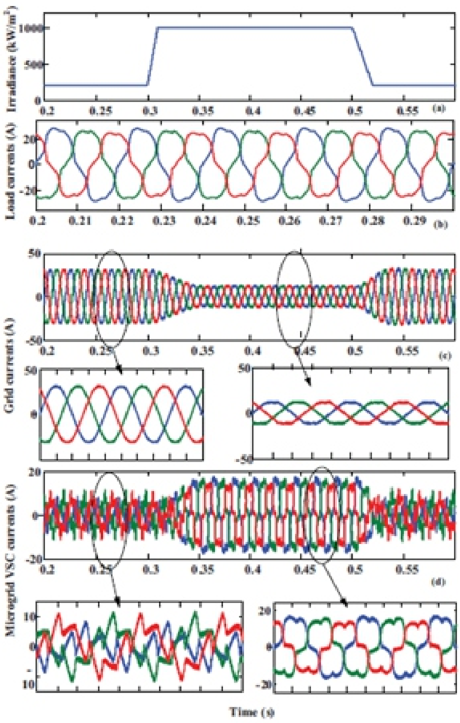

Fig. 6. Simulation results using proposed control approach for Micro-gridside VSC: (a) Insolation Changes (b) Load currents (c) Grid currents (d)µG-VSC currents.

Sinusoidal at UPF. The dynamic compensation performanceof µG-VSC using proposed control algorithm with insolationchange and nonlinear unbalanced load currents are shown inthe Fig. 6 (a)-(d) along with grid side currents. When insolationG = 200 W/m2, the maximum power extracted from PVArrays is 2.5kW and the total dc load power (4.5 kW) is partlysupplied by PV arrays and the remaining dc load power (2kW) is drawn from grid through the bidirectional µG-VSC.Here observed that the power flows from ac side to dc link asshown in the Fig. 7.

When insolation G = 1000 W/m2, themaximum power available from PV arrays is 12.5kW, partof this power (4.5 kW) is supplied to dc load and remainingpower (8 kW) is supplied to the ac load through bidirectionalµG-VSC. In this case, the power flows from dc link to acside. This shows the bidirectional power flow capability ofµG-VSC. These dynamics of power flows can be seen fromFig. 7. The corresponding variations in the grid current against grid voltage with upf are shown in the Fig. 8, along with dclink voltage variations.

TABLE III
MAXIMUM POWER TRACKING PERFORMANCE

G (W/m^2)	P_{Load} (ac+dc)(kW)	P_{pv} (kW)	P_{inv} (kW)	P_{grid} (kW)
200	13+4.5	2.5	-2	15
1000	13+4.5	12.5	+8	5

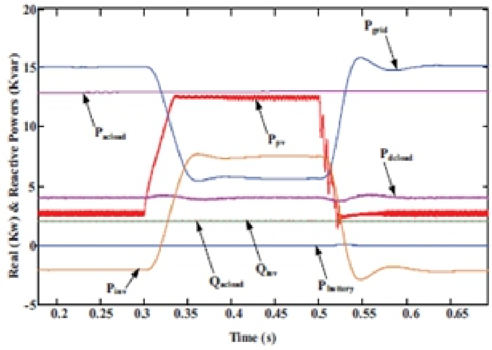

Fig.7. Real and Reactive Power flow waveforms of PV hybrid generatingsystem.

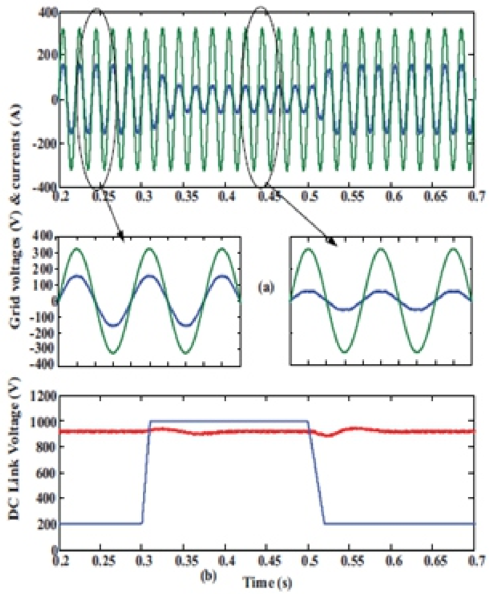

Fig. 8. Simulation results: performance of proposed control approach (a)Grid Volateges and currents (b) Dc Link Volatge Dynamics with differentinsolations

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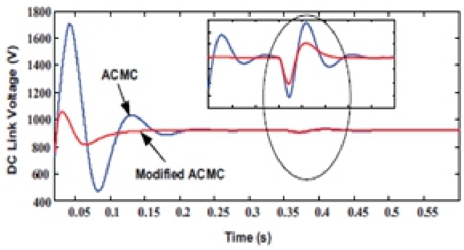

Fig.9. DC Link Voltage Dynamics using ACMC and MACMC Controlalgorithms

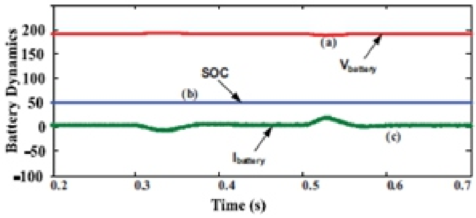

Fig. 10. Battery performance using proposed control approach to bidirectionalbattery converter: (a) Battery Voltage (b) State of charge (SOC) (c)Battery current.

C. Performance of battery converter control algorithms withDC load variations and insolation changes:

The dynamic performance of ACMC and MACMC proposedin this paper are invistegated through (i) DC loadvariations (ii) insolation changes. At t=0.35 s, the dc loadis changed from 4.5 kW to 5.5 kW. Corresponding to thesevariations, the DC link voltage regulation capability of thesetwo control algorithms are shown in the Fig. 9. From Fig. 9,it can be concluded that for dc load changes, the modified-ACMC gives better DC Link volatge regulation capabilitywhen compared to ACMC. The battery performance withreference to above changes are captured and are shown inthe Fig. 10.

V. CONCLUSIONS:

The performance of PV/Battery hybrid energy conversionsystem has been demonstrated with the application of modifiedinstantaneous symmetrical components theory to µG-VSCproposed in this paper, an efficient control strategy is alsoproposed for battery converter to regulate the dc bus voltagetightly, under varying solar insolation and dc load conditions.HGICB converter topology is used to track the MPPT withhigh gain and less current ripple. The µG-VSC is able to injectthe generated power into the grid alongwith harmonic andreactive power compensation for unbalanced non-linear load atthe PCC simultaneously. The system works satisfactorily underdynamic conditions. The simulation results under a unbalancednon-linear load with current THD of 12% confirm that the µGVSCcan effectively inject the generated active power along.

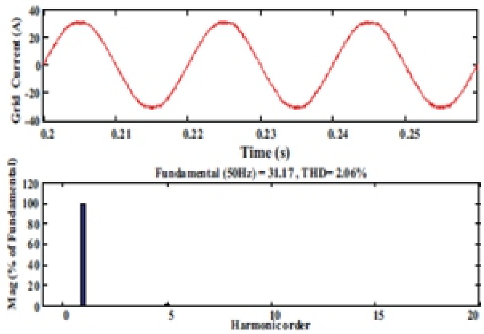

Fig.11. Simulation results: performance of proposed control approach (a)Grid currents (b) Harmonic spectrum

With power quality improvement features and thus, it maintainsa sinusoidal and UPF current at the grid side with THD of2.06% (Fig. 11).

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