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Validation of Faster Joint Control Strategy for Battery and Supercapacitor Based Energy Storage System

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Abstract—Energy storage system (ESS) is generally used to manage the intermittency of the renewable energy sources (RESs). The proper control strategy is needed to effectively maintain the power balance between the RESs, load demand and ESS. The conventional control strategy for the hybrid energy storage system (HESS) uses the high/low pass filter (HPF/LPF) method for system net power decomposition and the ESS power dispatch. In this paper, a new joint control strategy is proposed for photovoltaic (PV) based DC grid system, with battery and supercapacitor (SC) as a HESS. The new joint control strategy utilizes the uncompensated power from the battery system to increase the performance of the overall HESS. The advantages of the proposed control strategy over the conventional control strategy are faster DC link voltage restoration and effective power sharing between the battery and the SC. The detailed stability analysis of the proposed control strategy is also presented. The effectiveness of the proposed control strategy over the conventional control strategy is validated with the short-term and long-term experimental studies.

Index Terms—Battery control, Hybrid energy storage system, Renewable energy, Supercapacitor control.

I. INTRODUCTION

With the increased concern about fossil fuel based energy usage, the design of electrical power system focuses on increasing the utilization of renewable energy sources (RESs) [1]. Solar photovoltaic (PV) and the wind are the two commonly known RESs. PV is preferred in terms of sustainability and reliability, but its generation and stability are easily affected by intermittent operating conditions like change in irradiance, temperature, humidity and partial shadings effects [2], [3]. In real-life scenario, both the generation of RESs and the load demand are intermittent in nature. To solve the aforementioned issues, battery energy storage system (BESS) is generally used [4].

Among different types of ESSs, the battery energy storage system is easiest to implement. The BESS has relatively less impact from environmental variations. The problem with the BESS is low power density and relatively high overall system cost to meet the peak load demand. Hybrid energy storage system (HESS) is generally implemented to manage such issues. The advantages of HESS over single ESS are it can effectively utilize the properties of the different types of energy storages. The combination of battery and supercapacitor (SC) is one of the popular HESS configurations. Battery with high

energy density is used to compensate the slow average power demand. However, its lifetime is decreased if subjected to frequent transient power fluctuations [5]. The SC is used to smoothen the transient power fluctuations in the HESS. This combination can effectively and efficiently solve the varying power fluctuations, with less stress in the battery storage system. Thus, the effective control method is essential for the optimal operation of the HESS with varying load demand.

A. Literature Review

To effectively control the average and dynamic power sharing between the battery and the SC, different types of control strategies have been reported in the literature [6]–[23]. This includes fuzzy logic control [9], adaptive neuro-fuzzy inference system (ANFIS) based control [10], and model predictive control (MPC) [11]. Multi-mode fuzzy logic-based HESS controller [9] for PV system was designed and demonstrated for increased battery life. However, the stability analysis and its practical implementation are not explained. Hassan *et al.* [12] presented a non-linear controller technique for tight DC voltage regulation and effective SC current tracking for electrical vehicles (EVs) with fuel cell and SC. In [13], MPC is implemented to control the HESS currents and to maintain the state of charge (SOC) limits of the battery and the SC to predefined limits. However, the drawbacks of the proposed method are dependence on the discrete model of the system and cost function. It also uses a quadratic programming solver to calculate the optimal control, with significant computational time. Dusmez and Khaligh [14] proposed the wavelet based frequency decoupling technique for HESS control in EV application. However, the aforesaid control strategies require large computational time and resources.

Abeywardana *et al.* [15] presented the sliding mode control for the HESS. The detail controller parameters selection and SC sizing are discussed in the paper. The movement of the sliding surface of the system is insensitive to a particular kind of disturbances and model uncertainties, which is an advantage of the sliding mode control. However, the chattering effect is observed in real systems with imperfections like communication delay, hysteresis, and slow dynamic response.

Kollimalla *et al.* [16] proposed the two-state rate limit control for HESS application in standalone DC grid system. The

proposed method helps to reduce the rate of charge/discharge current from the BESS. The proposed method is effective to maintain the SOC of the battery for a longer duration. However, the rapid change in the rate of charge/discharge current may affect the battery lifetime [24]. Decentralized control strategy for dynamic power sharing between the HESS is presented in [17]. The proposed method is based on the virtual resistance and capacitance droop coefficients. The droop coefficient inherently acts as a low pass filter (LPF) for the battery and high pass filter (HPF) for the SC during generation and load variation.

Abeywardana *et al.* [18] presented a parameter selection technique for the filter based power decoupling method in HESS and SC sizing for microgrid application. HESS sizing method for EV application is presented in [19], and for uninterruptable power supply application in [20]. The study shows that the battery lifetime can be enhanced up to four times when it is operated in combination with the SC. Tao Ma *et al.* [21] presented the application of HESS in remote area RESs. The detail mathematical analysis is presented in the study.

Bazargan *et al.* [22] presented the effect in the stability of the converter connected to the battery system due to change in internal resistance and internal voltage of the battery. The study shows that the change in the internal parameters affects the battery response time as well as the DC link voltage restoration time during a load change. The change in internal parameters is generally observed due to ageing and change in the battery SOC. Stability issues of the cascaded DC-DC converter based HESS are presented in [23]. The study shows that the variation in SOC of the battery and capacity of different energy storage types could give rise to control stability problem.

B. Objective of the Study: Joint Control Strategy

The basic idea behind the aforementioned control strategies is that the battery supports the average power fluctuation, while the SC supports the dynamic high-frequency power fluctuations. However, the current tracking error present in the battery system due to slow dynamics of the battery, battery controller, and bi-directional DC-DC converter is not addressed in the control strategies. To address the aforesaid issues, a new joint control strategy is proposed in this paper, which provides faster DC link voltage restoration compared to the conventional control strategies [25]–[27]. The proposed control strategy utilizes the uncompensated power from the battery system to overcome the slow dynamics of the battery system, which includes dynamics of the battery, battery controller, and bi-directional DC-DC converter. The proposed control strategy also helps to increase the battery lifetime. The features of the proposed control approach are emphasized as follows.

- 1) Faster DC link voltage restoration compared to conventional control strategy with the utilization of uncompensated power from the battery system.
- 2) Less stress in primary energy storage system during a step change in load and generation.
- 3) Ability to suppress the overshoot in DC link voltage.

Fig. 1. Architecture of the PV system with HESS.

The remainder of the paper is organized as follows. The overall system architecture is discussed in Section II. The proposed strategy for generating reference current for HESS is discussed in detail in Section III. The controller design and stability analysis of the proposed controller are presented in Section IV. Experimental validation and discussion are presented in Section V, followed by conclusions in Section VI.

II. SYSTEM ARCHITECTURE

The overall configuration of the HESS studied in this paper is represented in Fig. 1. It consists of a standalone PV system, acting as the primary renewable energy source. The PV generated power is fed to the DC link of 48V using a unidirectional DC-DC boost converter. At 48V DC usually, no protection is required against direct contact. Such systems are also used in commercial telecommunication system [28]. The PV converter is operated with a maximum power point tracking (MPPT) algorithm in order to extract the maximum power from the PV panels. The HESS is connected to the DC link using a bi-directional DC-DC converter. The bi-directional DC-DC converter works in two modes: 1) charging mode, during surplus energy when generation is higher than load demand, and 2) discharging mode, when the generation is lower than the load demand. The HESS presented is effective in supplying the average power demand for a long duration, and transient power fluctuations for short duration. In Fig. 1, v_{pv} , v_b and v_{sc} are PV, battery and SC terminal voltage respectively. L_{pv} , L_b and L_{sc} are DC-DC converter inductor parameters for PV, battery, and SC. C_{pv} , C_b and C_{sc} are the filter capacitance of PV, battery and SC converter. The overall DC load is represented by resistance R_L . sw_a , sw_b , sw_c , sw_d and sw_e are representation of the control switches used for DC-DC converters. The i_{pv} , i_b , i_{sc} and i_L represent the PV,

Fig. 2. Conventional control strategy.

Fig. 3. Proposed control strategy.

battery, SC and load current respectively. The DC link voltage is represented as v_{dc} .

III. PROPOSED STRATEGY FOR GENERATING REFERENCE CURRENT FOR HESS

A. Conventional Control Strategy

The dynamic power sharing strategy in HESS is mainly used to regulate the power balance in the DC link as fast as possible. The conventional control strategy [25]–[27] applied in HESS is shown in Fig. 2. In conventional control strategy, the total current (i_{tot}) required to be supplied by the HESS is divided into average current component ($\bar{i}_{avg}$), and transient power component ($\hat{i}_{tran}$). This is done by using a LPF. The average current component generated from the LPF is fed as a reference current to the bidirectional DC-DC converter current controller for battery. The dynamic current obtained by subtracting the average current component from the total current is fed as a reference current to the bidirectional DC-DC converter current controller for SC.

B. Proposed Control Strategy

The block diagram representation of the proposed control strategy is shown in Fig. 3. The main purpose of the proposed control strategy is to restore the DC link voltage as fast as possible, and to reduce the stress on the battery, thus increasing the operating life of the battery system. Unlike the conventional control strategy [25]–[27], the power required to balance the overall power flow in the DC link during load and generation variation is categorized into two components, (i) average power component ($\bar{P}_{avg}$), and (ii) transient power

components ($\hat{P}_{tran}$). The power balance equation can be stated as follows,

$$P_l(t) - P_{ren}(t) = P_b(t) + P_{sc}(t) = \bar{P}_{avg} + \hat{P}_{tran}, \quad (1)$$

where, $P_{ren}(t)$, $P_b(t)$, $P_{sc}(t)$ and $P_l(t)$ are the renewable energy source, battery, SC and load power respectively. In order to maintain the DC link voltage at certain level, the net power required to be supplied by the HESS is given by (2)

$$\bar{P}_{avg}(t) + \hat{P}_{tran}(t) = v_{dc} i_{tot}, \quad (2)$$

The total current demand to be supplied by the HESS to maintain a constant DC link voltage is represented as follows,

$$i_{tot}(t) = \left(\frac{\bar{P}_{avg}}{v_{dc}} \right) + \left(\frac{\hat{P}_{tran}}{v_{dc}} \right) = \bar{i}_{avg}(t) + \hat{i}_{tran}(t), \quad (3)$$

This total current $i_{tot}(t)$ is obtained from the voltage control loop and it is given in (4),

$$i_{tot}(t) = \bar{i}_{avg}(t) + \hat{i}_{tran}(t) = K_{p_vdc} v_{er} + K_{i_vdc} \int v_{er} dt, \quad (4)$$

where K_{p_vdc} and K_{i_vdc} are the proportional and the integral constants of the voltage control loop, where v_{er} , v_{ref} and v_{dc} are the error voltage, DC link voltage reference and measured DC link voltage respectively. The effective sharing of i_{tot} is essential to achieve a faster DC link voltage restoration and effective performance of the proposed control strategy. As in conventional control strategy, LPF is employed to extract an average component from i_{tot} . The average current ($\bar{i}_{avg}$) is given by (5),

$$i_{bref}(s) = \bar{i}_{avg}(s) = \frac{\omega_c}{s + \omega_c} i_{tot}(s), \quad (5)$$

where ω_c and $i_{bref}(s)$ are the cut-off frequency of the LPF and the reference current for the battery converter control. The cut-off frequency of LPF is chosen to be $2\pi \cdot 5$ rad/sec, as presented in [29]. The average current is handled by the battery system. Due to the slow response of the battery system which includes dynamics of the battery, battery controller and bi-directional DC-DC converter, the uncompensated power from the battery system is observed.

Therefore, the uncompensated power by the battery system is given as

$$P_{b_uncomp}(s) = (i_{bref}(s) - i_b(s)) v_b(s), \quad (6)$$

where $P_{b_uncomp}(s)$ is the uncompensated power from the battery system. In the proposed control strategy we have utilized the uncompensated power from the battery to increase the performance of the SC. The oscillatory and transient effective current ($\hat{i}_{tran}$) with the uncompensated power from the battery is supported by the SC. The total reference current ($i_{scref}(s)$) for SC current controller can be obtained by (8),

$$\hat{i}_{tran}(s) = \left(1 - \frac{\omega_c}{s + \omega_c} \right) i_{total}, \quad (7)$$

TABLE I
CONTROL PARAMETERS SELECTION OF DC-DC CONVERTERS

Control loop	Cut-off frequency (Krad/s)
SC current control loop	$2 * \pi * F_{sw}/6 = 16.75$
Battery current control loop	$2 * \pi * F_{sw}/10 = 10.05$
Overall voltage control loop	$2 * \pi * F_{sw}/40 = 2.51$

TABLE II
TRANSFER FUNCTIONS FOR CONTROL OF THE PV SYSTEM WITH HESS

Duty Cycle to inductor current transfer function for SC	
$G_{id_sc}(s) = \frac{\hat{i}_{sc}}{\hat{d}_{sc}} = \frac{(C_{sc} v_{dc})s + 2(1 - d_{sc})i_L}{(L_{sc} C_{sc})s^2 + \frac{L_{sc}}{R}s + (1 - d_{sc})^2}$	
Inductor current to output voltage transfer function for SC	
$G_{iv_sc}(s) = \frac{\hat{v}_{dc}}{\hat{i}_{sc}} = \frac{(1 - d_{sc})v_{dc} - (L_{sc} i_L)s}{(C_{sc} v_{dc}) + 2(1 - d_{sc})i_L}$	
Duty Cycle to inductor current transfer function for battery	
$G_{id_b}(s) = \frac{\hat{i}_b}{\hat{d}_b} = \frac{(C_b v_{dc})s + 2(1 - d_b)i_L}{(L_b C_b)s^2 + \frac{L_b}{R}s + (1 - d_b)^2}$	
Transfer function of SC current control loop compensator	
$G_{pi_sc}(s) = K_{p_sc} + \frac{K_{i_sc}}{s}$	
Transfer function of battery current control loop compensator	
$G_{pi_b}(s) = K_{p_b} + \frac{K_{i_b}}{s}$	
Transfer function of voltage control loop compensator	
$G_{pi_vdc}(s) = K_{p_vdc} + \frac{K_{i_vdc}}{s}$	

$$i_{scref}(s) = \hat{i}_{tran}(s) + (\bar{i}_{avg}(s) - i_b(s)) \frac{v_b(s)}{v_{sc}(s)}, \quad (8)$$

The generated battery and SC reference currents are compared to the actual current. The error is then fed to the PI current control, which generates a duty ratio to follow the reference current.

IV. CONTROLLER DESIGN AND STABILITY ANALYSIS

The main objective of the proposed controller strategy is to regulate the DC link voltage as fast as possible, while maintaining the proper power flow balance in the DC link. The dynamic behaviour of the DC link voltage during supply and demand mismatch mainly depends on the SC, battery and PV current response to the change in the DC link voltage. So, the change in the DC link voltage can be represented as follows,

$$\Delta v_{dc} = G_b \Delta i'_b + G_{sc} \Delta i'_{sc} + G_{pv} \Delta i'_{pv}, \quad (9)$$

where Δv_{dc} is a small change in the DC link voltage. G_b , G_{sc} and G_{pv} are the small signal impedance of the battery, SC and PC converter respectively. $\Delta i'_b$, $\Delta i'_{sc}$ and $\Delta i'_{pv}$ are the changes in battery, SC and PV current respectively.

The rate of charge/discharge of SC is faster compared to the battery so the controller parameters are basically tuned based on the SC power stage [30]. The switching frequency (F_{sw}) for the DC-DC converter is selected as 16 kHz for our study. To ensure the overall system stability, the following bandwidths for the control loop are selected, as shown in Table I.

A. SC Current Control Loop Design

The control transfer functions for the design of the inner current control loop for SC are given in Table II. The controller parameters are designed such that it meets the bandwidth mentioned in Table I, with the phase margin of 60°. This ensures the stability of the SC current control loop. The open loop transfer function (G_{ol_sc}) and closed loop transfer function (G_{cl_sc}) of the SC current control loop are given below,

$$G_{ol_sc} = G_{pi_sc} G_{id_sc} H_{sc} \quad (10)$$

$$G_{cl_sc} = \frac{G_{pi_sc} G_{id_sc}}{1 + G_{pi_sc} G_{id_sc} H_{sc}} \quad (11)$$

In Table II, K_{p_sc} and K_{i_sc} are the proportional and integral gain for the SC current control loop respectively. In (10), H_{sc} represents the feedback gain for the SC current control loop. The bode plot of the open loop transfer function for SC current control loop is shown in Fig. 4(b). The SISO toolbox in Matlab [31] is used to design the controller parameters. The controller parameters obtained for the SC current control loop are, $K_{p_sc} = 0.301$ and $K_{i_sc} = 2900$.

B. Battery Current Control Loop Design

The control transfer function for the design of the inner current control loop for the battery is given in Table II. The controller parameters are designed such that it meets the bandwidth mentioned in Table I, with the phase margin of 60°, ensuring the stability of the battery current control loop. The open loop transfer function (G_{ol_b}) of the battery current control loop is given below,

$$G_{ol_b} = G_{pi_b} G_{id_b} H_b \quad (12)$$

In Table II, K_{p_b} and K_{i_b} are the proportional and integral gain for the battery current control loop respectively. In (12), H_b represents the feedback gain for the battery current control loop. The bode plot of the open loop transfer function for battery current control loop is shown in Fig. 4(c). The SISO toolbox in Matlab [31] is used to design the controller parameters. The controller parameters obtained for the battery current controller loop are $K_{p_b} = 0.18$ and $K_{i_b} = 1030$.

C. Overall Voltage Control Loop

The open loop transfer function (G_{ol_vdc}) of the voltage control loop is calculated using a transfer function given in Table II and closed loop transfer function of the SC current control loop given in (11). The G_{ol_vdc} is calculated as follows,

$$G_{ol_vdc} = G_{pi_vdc} G_{cl_sc} G_{iv_sc} H_{vdc} \quad (13)$$

In (13), H_{vdc} represents the feedback gain for the overall voltage control loop. The bode plot of the open loop transfer function for voltage control loop is shown in Fig. 4(a). The SISO toolbox in Matlab [31] is used to design the controller parameters such that it meets the bandwidth mentioned in Table I, with the phase margin of 60°. This ensures the stability of the overall voltage control loop in the system. The controller parameters obtained for the overall voltage control loop are $K_{p_vdc} = 1.42$ and $K_{i_vdc} = 1720$.

Fig. 4. (a) Open loop bode plot of overall voltage control loop, (b) open loop bode plot of SC current control loop and (c) open loop bode plot of battery current control loop.

Fig. 5. Experimental Setup for HESS.

V. EXPERIMENTAL RESULTS

The hardware prototype for a standalone PV system with HESS is built, as shown in Fig. 5. To build a DC-DC converter, the Semikron SKM 75GB128D switches are used. LEM transducers are used to measure the currents and the voltages. Regulated power supply (RPS) is used in this experiment as a PV generator. The step change in the input power is obtained by regulating a current through the DC-DC boost converter from the RPS. Two lead acid batteries (17Ah, 12V) in series and two Maxwell BMOD0058 E015 B01 SC (58F, 15V) in series are used as the HESS. The conventional control strategy and the proposed control strategy are implemented with dSPACE 1103 real-time controller platform. The nominal system parameters used for the experimental study are presented in Table III.

Comparative performance evaluation of the proposed and the conventional control strategy [25]–[27] under short-term and long-term scenario are carried out. The short-term scenario performance analysis is performed to study the capability of

TABLE III
SYSTEM PARAMETERS FOR EXPERIMENTAL STUDY

PV array simulator	Values
Open circuit voltage (v_{pv})	30.2 V
Short circuit current (i_{pv})	5 A
Mppt voltage (V_{mppt})	29 V
Mppt current (I_{mppt})	4.8 A
Mppt power (P_{mppt})	140 W
Battery specifications	Values
Type	Lead Acid
Ah capacity	17 Ah
Terminal Voltage (v_b)	12 V
No of batteries in series	2
SC specifications	Values
Type	Maxwell BM0D0058 E015 B01
Terminal voltage (v_{sc})	15V
Capacitance (C_{scint})	58F
No of SC in series	2
DC-DC converters parameters	Values
	$L_{pv} = 10 \text{ mH}$, $L_b = 6.3 \text{ mH}$, $L_{sc} = 5 \text{ mH}$ $C = 440 \mu\text{F}$,
Nominal load resistance (R_L)	60 Ω
Nominal load power (P_L)	38.4 W

the proposed controller to deal with sudden changes in the load demand and the generation. During short-term performance analysis, the SOC of the battery and SC are maintained within the respective safe operating regions.

A. Short-term Scenario

The short-term power management capability of the proposed controller is compared with the conventional controller for four different operating conditions as presented below.

1) *Case I. Step increase in PV generation:* The experimental results for the conventional control strategy and proposed control strategy for step increase in PV generation is shown here in Fig. 6(a) and Fig. 6(b). respectively. The PV generation is increased suddenly by changing the reference current for the PV DC-DC converter, at the time instant t_1 . During the

Fig. 6. Experimental result for step increase in PV generation : (a) conventional control strategy and (b) proposed control strategy. $v_{dc} \sim 5V/div$, $i_{pv} \sim 2A/div$, $i_L, i_b, i_{sc} \sim 1A/div$, time $\sim 200ms/div$.

Fig. 7. Experimental result for step decrease in PV generation : (a) conventional control strategy and (b) proposed control strategy. $v_{dc} \sim 5V/div$, $i_{pv} \sim 2A/div$, $i_L, i_b, i_{sc} \sim 1A/div$, time $\sim 200ms/div$.

experiment, the load resistance (R_L) is kept constant at 60Ω with $i_L = 0.8A$.

At time instant t_1 , the PV generation is increased from 2A to 4A, as shown in the Fig. 6(a) and Fig. 6(b). Due to a sudden increase in the PV generation, the DC link voltage tends to increase. The HESS controller should maintain the overall power balance, and restore the DC link voltage to its reference value as fast as possible. The conventional control strategy and the proposed control strategy are tested under the same operating condition. Result for the conventional control strategy is shown in Fig. 6(a). The settling time for the conventional controller is around 630ms. With the implementation of the proposed control strategy as shown in Fig. 6(b), we are able to restore the DC link voltage faster, with the response time of 260ms. It is observed from the result that with the diversion of uncompensated power from the battery system to the SC controller we can achieve the faster DC link voltage restoration.

2) *Case II. Step decrease in PV generation:* The experimental results for the conventional control strategy and proposed control strategy for a step decrease in PV generation is shown here in Fig. 7(a) and Fig. 7(b). respectively. The PV generation is decreased suddenly by changing the reference current for the PV DC-DC converter at time instant t_1 . During the experiment, the load resistance (R_L) is kept constant at 60Ω with $i_L = 0.8A$.

At time instant t_1 , the PV generation is intentionally decreased from 4A to 2A as shown in the Fig. 7. Due to a sudden decrease in PV generation, the DC link voltage tends

to decrease. The sudden power fluctuation in the system is handled by the HESS. The result for conventional control strategy is shown in Fig. 7(a) which shows the settling time is around 590ms. The proposed control strategy shows two times faster response compared to the conventional one with the response time of 250ms, as shown in Fig. 7(b). It is observed from the result that the proposed control strategy provides good dynamic performance compared to the conventional control strategy.

3) *Case III. Step increase in load demand:* The DC link voltage (v_{dc}) should be maintained at 48V during step change in load demand. At time instant t_1 , the load demand i_L is suddenly increased by changing the load resistance from (R_L) = 60Ω to (R_L) = 30Ω . This increases the i_L from 0.8A to 1.6A. The step change in load demand has significant influence in the DC link voltage (v_{dc}).

To maintain the power balance in the DC link, the transient and the average power demand in the DC link are required to be supplied by the HESS. In this experimental study with the conventional control strategy, the DC link voltage is restored in 450ms as shown in Fig. 8(a). With the implementation of the proposed control, we achieved about two times faster voltage restoration with less overshoot in the DC link compared to the conventional control strategy. The total time taken by the proposed control is 210ms as shown in Fig. 8(b).

4) *Case IV. Step decrease in load demand:* At time t_1 , the load demand i_L is increased by 0.8 A by with change in the load resistance from (R_L) = 30Ω to (R_L) = 60Ω . The step change in load demand has significant influence on the DC

Fig. 8. Experimental result for step increase in load demand : (a) conventional control strategy and (b) proposed control strategy. $v_{dc} \sim 5V/div$, $i_{pv} \sim 2A/div$, $i_L, i_b, i_{sc} \sim 1A/div$, time $\sim 200ms/div$.

Fig. 9. Experimental result for step decrease in load demand : (a) conventional control strategy and (b) proposed control strategy. $v_{dc} \sim 5V/div$, $i_{pv} \sim 2A/div$, $i_L, i_b, i_{sc} \sim 1A/div$, time $\sim 200ms/div$.

link voltage (v_{dc}).

Fig. 10. Experimental result for long-term scenario: (a) Input irradiation pattern, time $\sim 30 \text{ min/div}$. (b) PV change with constant load demand and (c) PV change with change in load demand. $v_{dc} \sim 20V/div$, $i_{pv}, i_b, i_L, i_{sc} \sim 500mA/div$, time $\sim 2s/div$.

The sudden power fluctuation in the system is handled by the HESS. The slow average power demand is handled by the battery system and fast changing transient power demand is handled by the SC in both the conventional and proposed control strategy, as shown in Fig. 9(a) and Fig. 9(b). With the conventional control strategy, the DC link voltage is restored in 460ms as shown in Fig. 9(a). The experimental result obtained shows with the implementation of the proposed control we can consistently achieve two times faster voltage restoration with less overshoot in the DC link compared to conventional strategy as shown in Fig. 9(b). The total time taken by the proposed control to restore the DC link voltage is 240ms.

B. Performance under Long-term Operation Scenario

The PV irradiation data is recorded every one minute on April 10th, 2011 in Singapore from 10:00 to 16:30 hr. The irradiation pattern obtained is shown in Fig. 10(a). The long-term scenario is analysed to study the performance of the proposed control strategy when operated for realistic operating

conditions. In this experiment, the SOC of the battery and the SC is maintained under safe operating region.

The experimental results to evaluate the proposed controller under long-term power variation are shown in Fig. 10(b). The respective PV current pattern is generated as per the irradiation pattern, shown in Fig. 10(a). From the experiment, it can be observed that the proposed controller is effective in managing the intermittent PV power (represented by the PV current), by effectively controlling the slow base power fluctuations from the battery (represented by the battery current), and the faster transient power fluctuations from the SC system. The DC link voltage is maintained roughly at the constant value.

The experimental results for the simultaneous variation in the renewable power generation and the load variation are shown in Fig. 10(c). At t_1 and t_3 , the PV generation is varying as shown in the Fig. 10(c), and simultaneously a step increase in load demand is applied by changing the load resistance from $(R_L) = 60 \Omega$ to $(R_L) = 30 \Omega$. During this condition, the transient power fluctuations are dealt by the SC and the average power demand is gradually taken over by the battery. The smooth transition can be observed with faster DC voltage regulation.

At time instant t_2 , the load resistance is increased from $(R_L) = 30 \Omega$ to $(R_L) = 60 \Omega$ as shown in Fig 10(c). The PV generation is varied based on the respective irradiation pattern. The DC link voltage is restored faster, and remains stable at this condition as well. The fast transient and slow base power are seamlessly handled by HESS. The experiment demonstrates that the proposed control strategy can effectively provide faster DC link voltage restoration under varying renewable generation and varying load demand condition.

C. Performance Comparison of Conventional and Proposed Control Strategy

For the performance evaluation of the proposed control strategy, the overshoot and the response time to restore the DC link voltage during a change in load and generation are considered. The graphical representation of the performance comparison of the conventional and proposed control strategy is presented in Fig. 11. This result demonstrates the advantages of the proposed control method over the conventional controller method. The proposed controller shows two times faster response compared to conventional controller [25]–[27] in all the case studies. The overshoot in the system is also reduced by 1% in all four case studies. The proposed control strategy is designed such that the SC supports the HESS until the battery comes to the steady-state condition, which makes the system more robust to the parameter variation, remaining unaffected by the internal disturbances.

VI. CONCLUSION

The comparison of the proposed joint control strategy with the conventional control strategy for various operating conditions for PV generation and load demand has been presented in this paper. The detailed experimental analysis for the faster DC link voltage stabilization with the proposed control strategy is presented. The reason behind this improvement is that the

Fig. 11. Graphical representation of performance comparison between conventional control strategy and proposed control strategy. (a) Response time and (b) voltage overshoot

SC supplies the high frequency component along with the error component of the battery system until the battery current reaches the steady-state. The proposed joint control strategy is much beneficial to enhance the life of the battery, reducing stress in the battery with some modification in the conventional control strategy. The long term test-case scenario with real PV power fluctuations is also studied. The proposed joint control strategy provides good dynamic performance compared to the conventional control strategy during a step change in load demand and generation.

REFERENCES

- [1] D. Debnath and K. Chatterjee, "Two-stage solar photovoltaic-based stand-alone scheme having battery as energy storage element for rural deployment," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 7, pp. 4148–4157, Jul. 2015.
- [2] W. Li, G. Joos, and J. Belanger, "Real-time simulation of a wind turbine generator coupled with a battery supercapacitor energy storage system," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 4, pp. 1137–1145, Apr. 2010.

- [3] K. Jin, X. Ruan, M. Yang, and M. Xu, "A hybrid fuel cell power system," *IEEE Transactions on Industrial Electronics*, vol. 56, no. 4, pp. 1212–1222, Apr. 2009.
- [4] G. Wang, M. Ciobotaru, and V. G. Agelidis, "Power smoothing of large solar pv plant using hybrid energy storage," *IEEE Transactions on Sustainable Energy*, vol. 5, no. 3, pp. 834–842, Jul. 2014.
- [5] J. Pegueroles-Queralt, F. D. Bianchi, and O. Gomis-Bellmunt, "A power smoothing system based on supercapacitors for renewable distributed generation," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 1, pp. 343–350, Jan. 2015.
- [6] J. Xiao, P. Wang, and L. Setyawan, "Hierarchical control of hybrid energy storage system in dc microgrids," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 8, pp. 4915–4924, Aug. 2015.
- [7] M. H. Nehrir, C. Wang, K. Strunz, H. Aki, R. Ramakumar, J. Bing, Z. Miao, and Z. Salameh, "A review of hybrid renewable/alternative energy systems for electric power generation: Configurations, control, and applications," *IEEE Transactions on Sustainable Energy*, vol. 2, no. 4, pp. 392–403, Oct. 2011.
- [8] D. Wu, R. Todd, and A. Forsyth, "Adaptive rate-limit control for energy storage systems," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 7, pp. 4231–4240, Jul. 2015.
- [9] X. Feng, H. B. Gooi, and S. X. Chen, "Hybrid energy storage with multimode fuzzy power allocator for pv systems," *IEEE Transactions on Sustainable Energy*, vol. 5, no. 2, pp. 389–397, Apr. 2014.
- [10] P. García, C. A. García, L. M. Fernández, F. Llorens, and F. Jurado, "Anfis-based control of a grid-connected hybrid system integrating renewable energies, hydrogen and batteries," *IEEE Transactions on Industrial Informatics*, vol. 10, no. 2, pp. 1107–1117, May. 2014.
- [11] B. Hredzak, V. G. Agelidis, and G. D. Demetriades, "A low complexity control system for a hybrid dc power source based on ultracapacitor–lead–acid battery configuration," *IEEE Transactions on Power Electronics*, vol. 29, no. 6, pp. 2882–2891, Jun. 2014.
- [12] H. El Fadil, F. Giri, J. M. Guerrero, and A. Tahri, "Modeling and nonlinear control of a fuel cell/supercapacitor hybrid energy storage system for electric vehicles," *IEEE Transactions on Vehicular Technology*, vol. 63, no. 7, pp. 3011–3018, Sept. 2014.
- [13] B. Hredzak, V. G. Agelidis, and M. Jang, "A model predictive control system for a hybrid battery-ultracapacitor power source," *IEEE Transactions on Power Electronics*, vol. 29, no. 3, pp. 1469–1479, Mar. 2014.
- [14] S. Dusmez and A. Khaligh, "A supervisory power-splitting approach for a new ultracapacitor, battery vehicle deploying two propulsion machines," *IEEE Transactions on Industrial Informatics*, vol. 10, no. 3, pp. 1960–1971, Aug. 2014.
- [15] D. B. W. Abeywardana, B. Hredzak, and V. G. Agelidis, "A fixed-frequency sliding mode controller for a boost-inverter-based battery-supercapacitor hybrid energy storage system," *IEEE Transactions on Power Electronics*, vol. 32, no. 1, pp. 668–680, Jan. 2017.
- [16] S. K. Kollimalla, A. Ukil, H. B. Gooi, U. Manandhar, and N. R. Tummuru, "Optimization of charge/discharge rates of a battery using a two-stage rate-limit control," *IEEE Transactions on Sustainable Energy*, vol. 8, no. 2, pp. 516–529, Apr. 2017.
- [17] Q. Xu, J. Xiao, P. Wang, X. Pan, and C. Wen, "A decentralized control strategy for autonomous transient power sharing and state-of-charge recovery in hybrid energy storage systems," *IEEE Transactions on Sustainable Energy*, vol. PP, no. 99, pp. 1–1, 2017.
- [18] D. B. W. Abeywardana, B. Hredzak, V. G. Agelidis, and G. D. Demetriades, "Supercapacitor sizing method for energy-controlled filter-based hybrid energy storage systems," *IEEE Transactions on Power Electronics*, vol. 32, no. 2, pp. 1626–1637, Feb. 2017.
- [19] R. E. Araújo, R. de Castro, C. Pinto, P. Melo, and D. Freitas, "Combined sizing and energy management in evs with batteries and supercapacitors," *IEEE Transactions on Vehicular Technology*, vol. 63, no. 7, pp. 3062–3076, Sept. 2014.
- [20] A. Lahyani, P. Venet, A. Guermazi, and A. Troudi, "Battery/supercapacitors combination in uninterruptible power supply (ups)," *IEEE Transactions on Power Electronics*, vol. 28, no. 4, pp. 1509–1522, Apr. 2013.
- [21] T. Ma, H. Yang, and L. Lu, "Development of hybrid battery-supercapacitor energy storage for remote area renewable energy systems," *Applied Energy*, vol. 153, pp. 56–62, Dec. 2015.
- [22] D. Bazargan, S. Filizadeh, and A. M. Gole, "Stability analysis of converter-connected battery energy storage systems in the grid," *IEEE Transactions on Sustainable Energy*, vol. 5, no. 4, pp. 1204–1212, Oct. 2014.
- [23] N. Mukherjee and D. Strickland, "Control of cascaded dc-dc converter-based hybrid battery energy storage systems; part i: Stability issue," *IEEE Transactions on Industrial Electronics*, vol. 63, no. 4, pp. 2340–2349, Apr. 2016.
- [24] A. Jossen, "Fundamentals of battery dynamics," *Journal of Power Sources*, vol. 154, no. 2, pp. 530–538, 2006.
- [25] R. Sathishkumar, S. K. Kollimalla, and M. K. Mishra, "Dynamic energy management of micro grids using battery super capacitor combined storage," in *Annual IEEE India Conference (INDICON)*, Dec. 2012, pp. 1078–1083.
- [26] H. Zhou, T. Bhattacharya, D. Tran, T. S. T. Siew, and A. M. Khambadkone, "Composite energy storage system involving battery and ultracapacitor with dynamic energy management in microgrid applications," *IEEE Transactions on Power Electronics*, vol. 26, no. 3, pp. 923–930, Mar. 2011.
- [27] E. Schaltz, A. Khaligh, and P. O. Rasmussen, "Influence of battery/ultracapacitor energy-storage sizing on battery lifetime in a fuel cell hybrid electric vehicle," *IEEE Transactions on Vehicular Technology*, vol. 58, no. 8, pp. 3882–3891, Oct. 2009.
- [28] S. I. Ganesan, D. Pattabiraman, R. K. Govindarajan, M. Rajan, and C. Nagamani, "Control scheme for a bidirectional converter in a self-sustaining low-voltage dc nanogrid," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 10, pp. 6317–6326, Oct. 2015.
- [29] M. Hamzeh, A. Ghazanfari, Y. A. R. I. Mohamed, and Y. & Karimi, "Modeling and design of an oscillatory current-sharing control strategy in dc microgrids," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 11, pp. 6647–6657, Nov. 2015.
- [30] S. K. Kollimalla, M. K. Mishra, and N. L. Narasamma, "Design and analysis of novel control strategy for battery and supercapacitor storage system," *IEEE Transactions on Sustainable Energy*, vol. 5, no. 4, pp. 1137–1144, Oct. 2014.
- [31] D. Kim, S. Choi, S. Kim, and B. Choi, "Matlab-based digital design of current mode control for multi-module bidirectional battery charging/discharging converters," in *IEEE 8th International Conference on Power Electronics and ECCE Asia (ICPE & ECCE)*, May. 2011, pp. 2256–2260.

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