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 (RESSs). The proper control strategy is needed to effectively maintain the power balance between the RESSs, 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 (RESSs) [1]. Solar photovoltaic (PV) and the wind are the two commonly known RESSs. 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 RESSs 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.

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 $R_L$. $i_{sw_a}$, $i_{sw_b}$, $i_{sw_c}$ and $i_{sw_d}$ are representation of the control switches used for DC-DC converters. The $i_{pv}$, $i_b$, $i_{sc}$ and $i_L$ represent the PV, 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,

$$ \bar{P}_{avg} + \hat{P}_{tran} = P_{tot}, $$

where $P_{tot}$ is the total power supplied by the HESS, and $P_{avg}$ and $P_{tran}$ are the average and transient power respectively. This total current demand to be supplied by the HESS is given by

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

where $\bar{i}_{avg}(t)$ is the average current component obtained by subtracting the transient current component from the total current. The average current component $\bar{i}_{avg}(t)$ is given by

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

where $\omega_c$ 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 $2\pi*5$ rad/sec, as presented in [29]. The average current is handled by the battery controller and bidirectional DC-DC converter, the uncompensated power from the battery system is observed.

Therefore, the uncompensated power by the battery system is given as
ensures the stability of the SC current control loop. The 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 rate of charge/discharge of SC is faster compared to PV current response to the change in the DC link voltage. The dynamic behaviour of the DC link voltage during supply to regulate the DC link voltage as fast as possible, while the change in the DC link voltage can be represented as follows,

\[ \Delta v_{dc} = G_b \Delta i_b + G_{sc} \Delta i_{sc} + G_{pv} \Delta i_{pv}, \]  

where \( \Delta v_{dc} \) 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.

### 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,

\[ \Delta v_{dc} = G_b \Delta i_b + G_{sc} \Delta i_{sc} + G_{pv} \Delta i_{pv}, \]  

where \( \Delta v_{dc} \) 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.

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#### 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,

\[ G_{ol,sc} = G_{pi,sc} G_{id,sc} H_{sc} \]  
\[ G_{cl,sc} = \frac{G_{pi,sc} G_{id,sc}}{1 + G_{pi,sc} G_{id,sc} H_{sc}} \]  

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,

\[ G_{ol,b} = G_{pi,b} G_{id,b} H_b \]  

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 control loop are \( K_{p,b} = 0.18 \) and \( K_{i,b} = 1030 \).
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.

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,

\[
G_{ol,vdc} = G_{pi,vdc} G_{cl,sc} G_{sv,sc} H_{vdc}
\]

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 \( K_{i,vdc} = 1720 \).

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 (17 Ah, 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 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 experiment, the load resistance \( (R_L) \) is kept constant at 60 Ω with \( i_L = 0.8A \).
### TABLE III

**System Parameters for Experimental Study**

<table>
<thead>
<tr>
<th>PV array simulator</th>
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<tr>
<td>Open circuit voltage ($v_{pv}$)</td>
<td>30.2 V</td>
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<tr>
<td>Short circuit current ($i_{pvs}$)</td>
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<tr>
<td>Mpp voltage ($V_{mpp}$)</td>
<td>29 V</td>
</tr>
<tr>
<td>Mpp current ($I_{mpp}$)</td>
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<tr>
<td>Mpp power ($P_{mpp}$)</td>
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<td>Ah capacity</td>
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<td>Terminal Voltage ($v_t$)</td>
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<tr>
<td>No of batteries in series</td>
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</table>

<table>
<thead>
<tr>
<th>SC specifications</th>
<th>Values</th>
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<td>Type</td>
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<tr>
<td>Terminal voltage ($v_{sc}$)</td>
<td>15V</td>
</tr>
<tr>
<td>Capacitance ($C_{scint}$)</td>
<td>58F</td>
</tr>
<tr>
<td>No of SC in series</td>
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<table>
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<tr>
<th>DC-DC converters parameters</th>
<th>Values</th>
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<tr>
<td>$L_{mpc}$ = 10 mH, $L_{b}$ = 6.3 mH, $L_{sc}$ = 5 mH</td>
<td></td>
</tr>
<tr>
<td>$C$ = 440 $\mu$F</td>
<td></td>
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</table>

| Nominal load resistance ($R_L$) | 60 $\Omega$ |
| Nominal load power ($P_L$) | 38.4 W |

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Fig. 6. Experimental result for step increase in PV generation: (a) conventional control strategy and (b) proposed control strategy. $v_{dc}$ ~ 5 V/div, $v_{pv}$ ~ 2 A/div, $i_L$, $i_b$, $i_{sc}$ ~ 1 A/div, $\Delta i_{pv}$ ~ 2 A, $\Delta t_{pv}$ = 250 ms.

Fig. 7. Experimental result for step decrease in PV generation: (a) conventional control strategy and (b) proposed control strategy. $v_{dc}$ ~ 5 V/div, $v_{pv}$ ~ 2 A/div, $i_L$, $i_b$, $i_{sc}$ ~ 1 A/div, $\Delta i_{pv}$ ~ 2 A, $\Delta t_{pv}$ ~ 250 ms.

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At time instant $t_1$, the PV generation is increased from 2 A to 4 A, 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 630 ms. 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 260 ms. 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 60 $\Omega$ with $i_L = 0.8 A$.

At time instant $t_1$, the PV generation is intentionally decreased from 4 A to 2 A 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 590 ms. The proposed control strategy shows two times faster response compared to the conventional one with the response time of 250 ms, 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 ($R_L$) = 60 $\Omega$ to ($R_L$) = 30 $\Omega$. 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 conventional strategy as shown in Fig. 9(b). The total time taken by the proposed control to restore the DC link voltage is 240ms.

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 ($R_L$) = 30 $\Omega$ to ($R_L$) = 60 $\Omega$. The step change in load demand has significant influence on the DC link voltage ($v_{dc}$).

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 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.

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