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A Dynamic Evolution Control Based Power Sharing Method for Hybrid Energy Storage System

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Abstract: In this paper, a new dynamic evolution control (DEC) based power sharing method is proposed for hybrid energy storage system (HESS) with photovoltaic in the isolated DC grid application. The proposed control approach solves the current controller conflict problem in HESS and provides faster DC link voltage restoration. A DEC method is implemented to control the battery current, supercapacitor current and DC link voltage. A DEC method uses a predictive term and feed-forward term to regulate the current and voltage in the system. In the proposed control method, the battery supports the average power demand in the system. The supercapacitor supports the transient power demand, uncompensated power from the battery and error voltage term. Thus, result in faster DC link voltage restoration and less stress in the battery system. The detailed design of the system parameters and controller parameters are presented in the paper. Simulation and experimental studies validate the effectiveness of the proposed control method.

1 Introduction

The environment-friendly renewable energy sources (RESs) are gaining more attention in the modern electric grid. DC microgrid is one of the emerging technologies which provide easy integration of RESs and energy storage devices. The large integration of RESs affects the electric grid in many ways. The fast variation in RESs causes voltage fluctuations which may result in degraded power quality in the modern electric grid. The frequent voltage deviation affects the sensitive electronics devices in telecommunication and industrial applications which rely on high power quality power supplies [1–3].

The variation in the RESs cannot be avoided. To solve the varying power fluctuation problem energy storage devices are used as an energy buffer. The ideal energy storage systems possess both high power density capability and high energy density capability. However, in the existing energy storage devices both the properties cannot be realised at once. Hence, the hybrid energy storage system (HESS) is used to meet the high power density and high energy density requirement [4].

The battery with high energy density and the supercapacitor (SC) with high power density combination is used to form a HESS. The battery and SC combination is effective in restoring the DC link voltage faster as SC can respond to fast changing power demand. The quick response of SC also reduces stress in the battery system. This helps to increase the lifetime of the battery system. The battery and SC combination is applied in multiple applications like renewable source integrated microgrid systems, electrical vehicle (EV) applications, and uninterruptible power supply applications.

One of the critical aspects of HESS is the power sharing and control of different energy storage devices. The efficiency and effectiveness of the HESS depend on the power sharing and control method adopted for HESS. The fundamental idea of power sharing is that the battery supports the slow changing average power demand and SC supports the transient power demand in the system. Literature review shows that researchers have used various techniques to control the power from HESS in many applications. In [5], a model predictive control (MPC) for HESS has been proposed for DC microgrid. In the proposed approach, the state of charge (SOC) limits

of the battery and SC are operated in safe operating regions. However, the implementation of the MPC is computationally intense as it relies on discrete system model and cost function. In the proposed method, the quadratic programming method is used to obtain the optimal duty cycle variable. The quadratic programming method is difficult to implement in digital signal processor board as it requires larger computational time to provide optimal controller parameters.

In [6], the multi-mode fuzzy logic control has been applied for HESS. In the proposed method, the fuzzy logic control is divided into two parts. The first part handles the power sharing between the battery and SC. The second part maintains the SOC of SC in a predefined limit. However, the practical application of multi-mode fuzzy logic control is still an issue. The voltage deviation and system instability problems when the fuzzy logic control changes its mode from one to another are not discussed.

In [7], an adaptive fuzzy logic control method has been applied for the HESS in the hybrid EV system. The adaptive fuzzy logic control method is used to calculate the power references for the HESS. This helps to maintain the overall power balance in the system. In the proposed method, the membership functions are tuned online. Thus, the generation of power references does not require the past EV driving cycle information. The proposed control method is effective in reducing the battery current ripple. It also maintains the SOC limit of SC in the safe operating region. However, the proposed method requires considerable computational resources.

In [8], the adaptive neural network (ANN) control technique has been implemented for the control of HESS current in an EV application. In the proposed method, the ANN control is trained with various datasets for the given load condition. The ANN control generates the optimal current references for the given load condition to be handled by HESS. However, its performance depends on the number of datasets used to train the ANN and requires large computational resources.

In [9], two-stage rate limit controller for HESS has been presented. The main advantage of the two-stage rate limit control is an extension of the battery lifetime compared to the constant rate limit control approach. The sliding mode control approach for HESS has been presented for EV application [10] and microgrid application [2]. The unified control approach considering the SOC limit of the

battery and SC in grid connected HESS is presented in [11]. However, the detail stability analysis is not discussed. In these controllers, the proportional-integral (PI) controller are implemented to control the current and voltage in the system. The performance of the system depends upon the PI controller parameters selection and is sensitive to the operating point variation. Another issue with the above methods is the current controller conflict which makes the system unstable and also creates larger voltage deviation as mention in [9].

In [12], Kollimalla *et al.* presented a modified PI control method for HESS in the DC grid application. In the proposed method, the battery error term is used as a feed-forward term to the SC current controller. The proposed method provides better dynamic performance compared to the conventional control methods [13, 14]. In [15], the new control method for HESS has been presented for the dynamic energy management of the HESS with a high gain PV converter in the DC microgrid application. In the proposed method, the voltage loop PI compensator and LPF are used to generate current references for the battery and SC. The current references are then regulated based on the dynamic converter equations. The advantage of the proposed method is the use of weighting factor in the dynamic converter equations. The weighting factor provides the flexibility to control the power from the battery and SC effectively. The weighting values can be determined based on the ratings of the ESSs.

In [16], the extended droop control (EDC) method has been used to generate current references for HESS. The EDC method is the extension of virtual resistance droop control to the virtual capacitance droop control. The current references are then regulated using a PI based control method. The EDC method is applied for the decentralized dynamic power sharing between the ESSs in the autonomous DC microgrids.

In [17], the DEC has been implemented in a bidirectional converter control for interfacing SC to a fuel cell system. The proposed control approach shows the better result than the traditional PI control approach. The DEC is applied to use the SC as axillary power sources. The DEC has been implemented in [18] to control the synchronous DC-DC buck converter. In [19] DEC has been used to improve the dynamic performance of the boost converter which improves the power factor in the system. The PWM block method has been used to control the SC system in [20]. The advantage of the PWM block method is it provides the seamless and smooth transition between the charging and discharging mode of operation. In these control methods, the PI controller is used to control the DC link voltage. The DC link voltage stability is affected if the PI controller parameters for DC link voltage control are not selected properly. The DC link voltage has to be maintained in a prescribed limit in all conditions to integrate the system with the AC grid [21].

To solve the above issues, a new DEC based power sharing method is proposed. The current and voltage control for HESS is regulated based on DEC method. In the proposed control approach, the predictive term and feed-forward term is used to calculate a duty cycle for a bidirectional DC-DC converter in each time step. Hence, it is computationally intense than discrete MPC approach and provides better dynamic performance. The rest of the paper is organised as follows. The system architecture is presented in Section 2. The system parameters and controller parameters design are discussed in Section 3. The detail simulation results are presented in Section 4. The experimental results are presented in Section 5 followed by conclusions in Section 6.

2 System Architecture

The overall system architecture used in this paper is shown in Fig. 1. The PV system is connected to the DC link with the boost DC-DC converter. The battery and SC system is connected to DC link with the bidirectional DC-DC converter. The bidirectional DC-DC converter enables the power flow from and into the energy storage devices depending upon the system condition. In Fig. 1, i_{pv} , i_b , i_{sc} and i_{dcl} represent the PV, battery, SC and DC load current respectively. L_{pv} , L_b and L_{sc} are the PV, battery and SC connected converter's filter inductor parameters respectively. C_{dc} and R_{dc} represent the total DC link capacitance and load resistance. v_{pv} , v_b , v_{sc}

Fig. 1: System architecture

Fig. 2: Block diagram representation (a) Conventional control approach and (b) Proposed control approach

and v_{dc} are PV system, battery, SC and DC link voltage respectively. S_1 , S_2 , S_3 , S_4 and S_5 represent the converter control switches.

3 Controller Design

The block diagram representation of the conventional control approach used for HESS control is shown in Fig. 2 (a). In the conventional control approach, the dual loop voltage control is used to control the DC link voltage of the system. The inner current control loop is used to control the current from the battery and SC [11, 12, 14]. In the conventional control approach, the DC link voltage (v_{dc}) is compared with the DC link voltage reference (v_{ref}). The error voltage obtained after comparison is fed to PI compensator. The PI compensator generates the total current reference (i_t) to be supplied/absorbed by the HESS. i_t is then divided into the average current demand and the transient current demand using a low pass filter (LPF) as shown in Fig. 2 (a). The average current (i_{br}) is fed as a current reference for the battery current controller, and transient current (i_{scr}) is fed as a current reference for SC current controller. The controller bandwidth of the voltage and current PI compensator must be carefully selected to avoid the converter controller conflict problem. Moreover, these controllers are designed to operate at certain operating points and their performance degrades if the operating points are changed.

With the proposed control the afore-mentioned problems are addressed. The block diagram representation of the proposed control approach is presented in the Fig. 2 (b). In the proposed control approach a simple power balance equation is applied to generate the power reference for HESS. The power balance equation to generate the total power for HESS (P_H) is explained in Section 3.2.1. The total power is divided into average power demand (P_{av}) and

Table 1 Nominal DC-DC converter parameters

Symbols	v_{pv}	v_b	v_{sc}	R_{dc}	C_{dc}	f_{sw}
Value	32V	24V	30V	48Ω	220μF	10 KHz
Symbols	δ_{pv}	δ_b	δ_{sc}	L_{pv}	L_b	L_{sc}
Value	0.34	0.5	0.375	3.6mH	5mH	5.7 mH

transient power demand (P_{tr}) using a LPF as shown in Fig. 2 (b). The average power demand is divided by the battery voltage (v_b) to generate the current reference for the battery converter control. The transient power demand is divided by the SC voltage (v_{sc}) to generate the transient current reference for the SC connected converter control. The SC current reference consists of transient current demand, uncompensated power from the battery and voltage error term. The battery and SC currents are controlled using the DEC method. The proposed control approach is discussed in detail in following sections. The features of the proposed control approach are emphasized as follows.

1. Faster DC link voltage restoration compared to the conventional control strategy.
2. Simple to design without any PI compensator parameters selection for control purpose.
3. Ability to suppress the overshoot in DC link voltage during a step change in load and generation.

3.1 Design of Converter Parameters

The bidirectional DC-DC converters filter parameters are designed as given in [22]. The bidirectional DC-DC converters are assumed to be operated in a continuous current conduction mode. Thus, the inductor value (L_{in}) for the bidirectional DC-DC converter parameters are obtained as follow,

$$L_{in} = \frac{(v_{in} \delta_i)}{(2 \Delta i_{in} f_{sw})}, \quad (1)$$

$$\delta_i = (1 - \frac{v_{in}}{v_{dc}}), \quad (2)$$

where v_{in} , δ_i and f_{sw} are the input voltage, duty cycle and switching frequency of the bidirectional DC-DC converter. Δi_{in} is the input current ripple percentage of the bidirectional DC-DC converter. The bigger value of inductor will contribute to lesser input current ripple. The larger inductor will increase the overall system cost and the loss. So the input current ripple (Δi_{in}) is limited to 3% for both battery and SC converters. The output filter capacitor value (C_o) for the bidirectional DC-DC converter are obtained as follows,

$$C_o = \frac{(v_{dc} \delta_i)}{(2 \Delta v_{dc} R_{dc} f_{sw})}. \quad (3)$$

The output capacitor value is dependent on the output voltage ripple (Δv_{dc}). The bigger value of the capacitance will contribute less output voltage ripple. During the design, the output voltage ripple is limited to 1% for both the bidirectional DC-DC converter connected to the battery and SC. The DC link voltage is chosen to be 48V in this paper. The nominal system parameters and calculated filter parameters for the PV and HESS are given in Table 1. Here, $C_{dc} = C_{pv} + C_b + C_{sc}$. Where, C_{pv} , C_b and C_{sc} are PV, battery and SC connected converter's filter capacitance. δ_{pv} , δ_b and δ_{sc} are the duty cycle of the bidirectional DC-DC converter connected to PV, battery and SC respectively.

3.2 Proposed Control Approach

3.2.1 Reference Current Generation: The DC link voltage reflects the power balance among the RESs and HESS. The DC link voltage tends to increase if the generation is higher than the load demand and vice versa. The overall DC link power balance equation

is given in (4).

$$P_H = P_{dc} - P_{pv}, \quad (4)$$

where P_H , P_{dc} and P_{pv} are the HESS, DC link load and PV generation power respectively. In the proposed method, P_H is calculated as in (5)

$$P_H = \frac{(i_{dcl} * v'_{dc})}{v_{dc}} * v'_{dc} - i_{pv} * v_{pv}. \quad (5)$$

The DC link voltage tends to fluctuate depending upon the system condition. To respond to change in the DC link voltage a simple voltage balance condition is calculated as follows,

$$v'_{dc} = \begin{cases} v_{ref}, & \text{if } (v_{dc} < v_{ref}) \\ v_{dc}, & \text{otherwise} \end{cases} \quad (6)$$

As shown in Fig. 2 (b), the LPF is used to generate the average power demand and transient power demand to be supplied/absorbed by the HESS. The battery and SC reference currents are calculated as given in (7) and (8).

$$i_{br} = \frac{LPF.(P_H)}{v_b}, \quad (7)$$

$$i_{scr} = \frac{(1 - LPF.(P_H))}{v_{sc}} + \frac{v_b}{v_{sc}} \Delta i_b + \beta v_e, \quad (8)$$

where $LPF(.)$ represents the first order LPF function. The time constant of the LPF depends on the response time of the battery system. It should be greater or equal to the battery response time [16]. Thus, we choose the cut-off frequency of the LPF as $2\pi * 5$ rad/s [23, 24]. i_{br} and i_{scr} represent the battery and SC current references. Here, $\Delta i_b = i_{br} - i_b$, $v_e = v'_{dc} - v_{dc}$ and β is chosen to be 5 to smoothen the DC link voltage variation by diverting the ripple content to the SC system. To avoid the large voltage sag or swell due to slow dynamics of the battery system controller, the uncompensated power from the battery converter is diverted to the SC system in the proposed control approach. This ensures the faster DC link voltage regulation in spite of the slow battery dynamics.

3.2.2 Battery Current Controller: The dynamics of the inductor current over a period of a switching cycle for the buck and boost mode of bidirectional DC-DC converter are given in [15], and shown as follow,

$$\frac{di_b(t)}{dt} = \frac{(v_{dc} - v_b)}{L_b} \delta_b(t) - \frac{v_{dc}}{L_b} (1 - \delta_b(t)), \quad (9)$$

$$\frac{di_b(t)}{dt} = \frac{v_b}{L_b} \delta_b(t) - \frac{(v_{dc} - v_b)}{L_b} (1 - \delta_b(t)). \quad (10)$$

In the unified controller, the bidirectional DC-DC converter switching devices are operated in a complementary fashion. Therefore, it is sufficient to analyse the boost mode of operation to design a controller [25]. The duty cycle of the bidirectional DC-DC converter connected to the battery for the boost mode of operation can be obtained by simplifying (10) and is given as

$$\delta_b(t) = \frac{(v_{dc} - v_b)}{v_{dc}} + \frac{L_b}{v_{dc}} \frac{di_b(t)}{dt}. \quad (11)$$

In (11) the first term is the feed-forward term, and the second part is the predictive term, and the coefficients of these parts are not constant. The dynamics of the controller vary with the DC link voltage resulting in faster control action.

3.2.3 SC Current Controller: The SC current control scheme plays an important role in achieving a faster DC link voltage restoration. The dynamics of the SC current control also affects the stress level on the battery system. Based on the state-space average model, the voltage and current dynamics during boost mode of operation

Fig. 3: Dynamic evolution path for voltage error control

of bidirectional DC-DC converter connected to SC are given in (12) and (13).

$$v_{sc} = L_{sc} \frac{di_{sc}(t)}{dt} + v_{dc} (1 - \delta_{sc}(t)), \quad (12)$$

$$\frac{di_{sc}(t)}{dt} = \frac{v_{sc}}{L_{sc}} \delta_{sc}(t) - \frac{(v_{dc} - v_{sc})}{L_{sc}} (1 - \delta_{sc}(t)). \quad (13)$$

The SC current reference consists of transient current, uncompensated power from battery and voltage error term. To control the voltage and current, a DEC method is implemented. The main advantage of the DEC is it controls the dynamic characteristic of the system to operate on the target equation [18]. In this paper, an exponential evolution path is chosen as shown in Fig. 3 and the corresponding equation is given as

$$v_e^*(t) = v_{eo} \cdot e^{-mt}, \quad (14)$$

where v_e^* represents the dynamic characteristic of the system. v_{eo} is the initial value of the error voltage and m is the rate at which the system responds to minimize the error voltage. Thus, the dynamic evolution function of the proposed controller can be written as follow,

$$\frac{dv_e^*(t)}{dt} + m v_e^*(t) = 0, \quad m > 0. \quad (15)$$

To ensure the voltage error to zero with the proposed evolution path, the synthesis process is conducted. In the power electronic application, the state error function is needed to be defined. The function can be either of error current or error voltage. The linear function of the error voltage is selected for our application and is given as follows,

$$v_e^*(t) = k \cdot v_e(t), \quad k > 0, \quad (16)$$

where k is the positive gain coefficient. By substituting (16) to (15), it can be obtained as follows,

$$k \cdot \frac{dv_e(t)}{dt} + m \cdot k \cdot v_e(t) = 0. \quad (17)$$

Subtracting v_e to both sides in (17) the relation between the v_{dc} and error function can be obtained as follows,

$$k \cdot \frac{dv_e(t)}{dt} + (m \cdot k - 1) \cdot v_e(t) + v_{dc}' = v_{dc}. \quad (18)$$

By combining (12) and (18),

$$v_{sc} = L_{sc} \frac{di_{sc}(t)}{dt} + k \cdot \frac{dv_e(t)}{dt} + (m \cdot k - 1) \cdot v_e(t) + v_{dc}' - v_{dc} \cdot \delta_{sc}. \quad (19)$$

Rearranging (19) the expression for duty cycle is obtained for the control of DC link voltage and the SC current. The expression for

δ_{sc} is given below,

$$\delta_{sc}(t) = \frac{(v_{dc}' - v_{sc})}{v_{dc}} + \frac{(m \cdot k - 1)}{v_{dc}} v_e(t) + \frac{k}{v_{dc}} \frac{dv_e(t)}{dt} + \frac{L_{sc}}{v_{dc}} \frac{di_{sc}(t)}{dt}. \quad (20)$$

The control expressed in (20) consists of four parts. The first part is feed-forward term which calculates the duty cycle based on the previous sampling instant. This helps to compensate the input voltage variation in the system. The second term acts as a proportional term of the voltage error. The third term is the voltage error derivative term. The coefficients of these terms vary with the output voltage resulting in faster DC link voltage restoration. The fourth term is used to control the inductor current. The duty cycle equation for SC connected converter control shows that the proposed controller compensates the input voltage variation, output voltage variation and the inductor current variation in the system. This contributes to the better dynamic response of the system. In the proposed control approach PI compensator are not used which simplifies the design of controller.

4 Simulation Results

The detailed simulation study is carried out to study the performance of the proposed control approach. The nominal simulation parameters are given in Table 2. The block diagram representation of the implementation of DEC method in Matlab/Simulink is presented in Fig.4. In DEC method, the controller gains k and m are tuned such that the faster transient response is achieved in the system. The transient response of the system depends mostly on the m value. The controller response faster with the increased m value. However, the high overshoot in the system is observed when the m value is increased above certain limits. In general, the best m value is the maximum value before the overshoot appears in the system [17–19]. The similar procedure is applied to calculate the controller gains for the HESS. The step change in voltage reference is applied with different m values and the responses are observed. The m value which satisfies the system requirement before the overshoot occurs in the system is selected. The step response of the voltage controller and the voltage error with different m values are shown in Fig. 5(a) and (b). The simulation results show that the increase in m value improves the performance of the overall system. In the simulation study, the m values are $m_1 < m_2 < m_3 < m_4 < m_5$. Thus, the controller response is better with m_5 value and the error voltage converges faster.

In our proposed method, the SC current reference also contains the voltage error compensation factor β . Thus, the β and m values are tuned to get the desired transient response in the system. These parameters minimize the voltage error in the system. In the proposed control method, only two parameters are required to obtain the desired system response compared to six parameters to be tuned in PI based control methods [11, 14]. Thus, the proposed method is simple to design and also provides better dynamic performance.

During the simulation, the SOC limits of the battery and SC are kept within the safe operating region. The execution time during the simulation study (T_s) is chosen to be $1\mu s$. The communication delay (τ_{cd}) in the system is also considered and chosen to be $1\mu s$. The delay functions are used to represent the measurement delay in the experimental setup during the simulation study to obtain more accurate simulation results [26]. The delay functions are not used during the implementation of the proposed control method in the experimental platform.

4.1 Performance under Step Change in Load Demand and Generation

The step change in the load demand and the generation are done to observe the performance of the proposed control approach. At time $1s$, the load resistance is decreased from $R_{dc} = 48\Omega$ to $R_{dc} = 24\Omega$. The step change in a DC load resistance creates a power deficit situation in the DC link. The variation in the generation and load demand is handled by the HESS to make the system stable. The SC responds to the fast changing variation and the battery current slowly

Fig. 4: Block diagram representation of DEC method for HESS in Matlab/Simulink.

Fig. 5: Simulation result for a step change in voltage reference from 48V to 60V with different m values. (a) controller response to a step change in voltage reference, (b) error voltage response to a step change in voltage reference. $R_{dc} = 48\Omega$, $i_{pv} = 2A$, $\beta = 2e^{-4}$, $k = 0.0315$, $m_1 = 2e^4$, $m_2 = 5e^4$, $m_3 = 1e^5$, $m_4 = 2e^5$ and $m_5 = 2.85e^5$.

risers to make the system stable as shown in Fig. 6 (b). The DC link voltage is stable in this condition with the overshoot of less than 1% as shown in Fig. 6 (a). At time 2s, the step decrease in load demand is made by increasing the load resistance from $R_{dc} = 24\Omega$ to $R_{dc} = 48\Omega$. In this condition, the system performance is stable with SC taking the transient power demand and the battery taking the average power demand. The system operates in an excess power mode with the generation higher than the load demand. The excess power is fed to the HESS. The overshoot in the DC link voltage is less than 1% in this case as well.

In time 3s, a step change in the PV generation is made by increasing the current reference to a PV converter from 2A to 4A. In this

Table 2 System parameters of DC grid

PV array parameters	Values
Open circuit voltage (v_{pv})	32 V
Short circuit current (I_{pv})	5.5 A
Mpvt voltage (V_{mpvt})	30V
Mpvt current (I_{mpvt})	5 A
Mpvt power (P_{mpvt})	150 W
Lead acid battery specifications	Values
Ah capacity	17 Ah
Terminal Voltage (v_b)	12 V
No of batteries in series	2
Supercapacitor specifications	Values
Terminal voltage (v_{sc})	30V
capacitance (C_s)	29F
DC link voltage (v_{dc})	48V
Switching frequency (f_{sw})	10KHz
β, m, k	5, 31.74, 0.0315

condition, the load resistance is kept constant at 48Ω . In this situation as the generation is higher than the load demand, the excess power is stored in the HESS. The PV generation, DC link, SC and battery powers in the system are shown in Fig. 6 (c). The DC link voltage is well maintained during the step changes in load demand and generation. The proposed system is immune to the current controller conflict which is generally creating instability in the system with many converters.

4.2 Performance under Long-Term Generation Variation

The performance of the proposed control approach is evaluated in long-term power variation scenarios. Fig. 7 (a) shows the PV irradiation data recorded every minute from 10:00 to 16:30 on April 11th, 2011 in Singapore. The long-term scenario is studied to show the effectiveness of the proposed control to deal with the real power variations. The PV irradiation data is scaled down to apply for our application. During the simulation study, the SOC limits of the HESS is kept under safe operating region.

The PV generation power is varied as shown in Fig. 7 (d) for 60 s to observe the performance of the proposed control approach in long-term power variation scenario. The step change in load demand

Fig. 6: Performance of proposed control approach in step change in load demand and generation. (a) v_{dc} (b) i_{sc} and i_b and (c) PV power (P_{pv}), DC link load power (P_{dc}), SC power (P_{sc}) and battery power (P_b).

Fig. 7: Performance of proposed control approach under long-term generation variation. (a) PV irradiance pattern, (b) v_{dc} (c) i_{sc} and i_b and (d) P_{pv} , P_{dc} , P_{sc} and P_b .

is also done at time t_1 and t_2 along with the PV power variation to study the practical scenario. i_{sc} and i_b profiles obtained to meet the long-term power variation are shown in Fig. 7 (c). The high frequency power fluctuations are diverted to the SC system while the battery system takes the average power demand. As shown in Fig.

Fig. 8: Hardware setup

Fig. 9: (a) Performance of conventional control approach under step change in load demand and (b) Performance of proposed control approach under step change in load demand.

7 (b) the DC link voltage is well maintained at 48V during random generation power variation. The DC link voltage deviation is less than 1% during the entire simulation period.

5 Experimental Results

The experiment setup is shown in Fig. 8. To build DC-DC converters, the Semikron SKM 75GB12T4 control switches are used. LEM transducers are used to measure the currents and the voltages. Regulated power supply is used in this experiment as a PV generator. The two series combination of lead acid battery (17Ah, 12V) and two series combination of Maxwell BMOD0058 E015 B01 SC (58F, 15V) are used to form the HESS. The controller is implemented in real time dSPACE 1103 controller platform. The SOC limit of the battery and SC are kept within the safe operating region during the experiment. The execution time (T_s) during the experimental study is $20\mu s$.

(a)

(b)

Fig. 10: (a) Performance of conventional control approach under step change in PV generation and (b) Performance of proposed control approach under step change in PV generation.

5.1 Load Regulation

The experimental results for load regulation are shown in Fig. 9. The performance of conventional control approach is given in Fig. 9 (a) and the performance of the proposed control approach is shown in Fig. 9 (b). In Fig. 9, R_{dc} is decreased from 48Ω to 24Ω , and i_{dcl} is increased from $0.96A$ to $1.96A$ correspondingly. 100% load increment is done to observe the performance of the proposed control approach. i_{pv} is kept constant at $4A$. To keep the DC link voltage constant during the power variation due to a step change in load demand is supplied by HESS. i_{sc} supply the transient current demand and i_b slowly increases from $-2.2A$ to $-0.4A$.

From the experimental results, it can be observed that the change in voltage (Δv_{dc}) is $2.5V$ in the conventional control approach with settling time (Δt_{ss}) of $0.35s$. In this case, the Δv_{dc} of the proposed control approach is less than $0.5V$ and the settling time (Δt_{ss}) is less than $0.02s$. The proposed control approach is more robust compared to the conventional control approach.

5.2 Generation Variation Regulation

The experimental results for a step change in the PV generation are shown in Fig. 10. The performance of the conventional control approach and proposed control approach is shown in Fig. 10 (a) and Fig. 10 (b) respectively. During the experiment, the DC load resistance R_{dc} is kept constant at 48Ω . The PV generation is changed from $4A$ to $2A$ as shown in Fig. 10. The variation in generation is controlled by HESS to maintain the system stable. i_{sc} supplies the transient current demand. i_b slowly increases from $-2.2A$ to $-0.25A$ to compensate the average power fluctuations.

From the experimental results, it can be observed that with the conventional control approach the DC link voltage overshoot is about 5.3% and the Δt_{ss} is $0.35s$. With the implementation of the proposed control approach, the better DC link voltage regulation is achieved. The M_p with the proposed control method is less than 1.1% and the Δt_{ss} is less than $0.02s$. The results show the better

Fig. 11: Performance of proposed control approach under random generation variation.

Fig. 12: Performance of proposed control approach under a step change in DC link voltage reference.

performance with the proposed control approach compared to the conventional control approach.

The experimental study is also carried out with the random variation in the PV generation. i_{pv} is varied as shown in Fig. 11. The experimental results show that v_{dc} is well maintained in all condition with the DC link voltage overshoot less than 1.1% and settling time Δt_{ss} less than $0.02s$. During the random PV generation variation, the average power demand is supplied by the battery and the transient power is handled by the SC system. The results obtained show that the proposed control approach is able to handle the sharp changing random PV generation.

5.3 Response to Output Voltage Reference Change

The experimental results for the response of the proposed controller during change in the DC link voltage reference are shown in Fig. 12. The output voltage is step changed from $48V$ to $60V$. In this condition, the R_{dc} is kept constant at 48Ω . The PV generation is made constant at $4A$. The smooth transition in the output voltage is observed. It is observed that the required power to maintain the system stable is supplied by the HESS. i_b slowly increases from $-2.2A$ to $-1.8A$ to compensate the average power fluctuations. i_{sc} supports the transient current demand. i_{dcl} increased from $0.96A$ to $1.25A$ with a step change in the DC link voltage. It is observed from the experimental results that the proposed controller is able to cope with the step change in the output voltage reference.

5.4 Comparison with the Conventional Control Approach

The comparison between the proposed control approach and conventional control approach is presented in Table 3. Voltage overshoot ($M_p = \frac{\Delta v_{dc}}{v_{dc}} * 100\%$) and settling time (Δt_{ss}) during step change in load demand and generation is studied based on the experimental results shown in Fig. 9 and Fig. 10. It is observed that the proposed

Table 3 Comparison of DEC method with conventional control methods

Conditions	Performance parameters	MPC [5]	Conventional [11, 14]	Proposed
Load Change	M_p	-	5.3%	1.04%
	Δt_{ss}	-	0.3s	0.02s
	T_s	0.01s	75 μ s	20 μ s
PV Change	M_p	-	5.3%	1.10%
	Δt_{ss}	-	0.35s	0.02s
	T_s	0.01s	75 μ s	20 μ s

control approach provides the faster DC link voltage restoration with lesser DC link voltage variation.

The transient response of the proposed control method and the counterpart in [11, 14] for a step change in the load and generation demand is tabulated in Table 3. The average M_p for the conventional control method during a step load change and PV generation change is around 5.3%. The average M_p for the proposed control method is around 1.07%. The settling time for the conventional control method is around 0.32s while that of the proposed control method is around 20ms. Thus, the proposed control method shows a better transient performance compared to the PI-based control methods [11, 14]. The execution time (T_s) for the conventional control method is around 75 μ s and for the proposed control method is around 20 μ s.

The proposed control method is also compared with the conventional MPC method [5]. In the conventional MPC method, the execution time (T_s) is around 0.01s. The execution time depends on the complexity of the control method. This includes system model, prediction approach and the optimization technique used. Thus, T_s value for the proposed control method is around 20 μ s as it uses a simple control equation to calculate the desired duty cycle for the converters. This validate that the proposed control method can provide a faster dynamic response with less computational resources.

6 Conclusion

The new DEC based power sharing method has been proposed in the paper for PV system with HESS. The proposed control approach is based on the predictive term and feed-forward term to control the battery current, SC current and DC link voltage. The proposed control approach is more robust, provides faster DC link voltage restoration and simple to design compared to PI based control methods. The simulation and experimental results for a step change in load and generation variation as well as long-term power variations are presented. The less ripples in the DC link voltage and the battery current is obtained as the voltage error term, and the uncompensated power from the battery is diverted to the SC system in the proposed control approach.

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8 References

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