Hybrid energy storage system using bidirectional single-inductor multiple-port converter with model predictive control in DC microgrids

Wang, Benfei; Xian, Liang; Manandhar, Ujjal; Ye, Jian; Zhang, Xinan; Gooi, Hoay Beng; Ukil, Abhisek

2019

Wang, B., Xian, L., Manandhar, U., Ye, J., Zhang, X., Gooi, H. B., & Ukil, A. (2019). Hybrid energy storage system using bidirectional single-inductor multiple-port converter with model predictive control in DC microgrids. *Electric Power Systems Research*, 173, 38-47. doi:10.1016/j.epsr.2019.03.015

<https://hdl.handle.net/10356/143254>

<https://doi.org/10.1016/j.epsr.2019.03.015>

© 2019 Duke University Press. All rights reserved. This paper was published by Elsevier B.V. in *Electric Power Systems Research* and is made available with permission of Duke University Press.

Downloaded on 26 Apr 2023 22:51:57 SGT

Hybrid Energy Storage System using Bidirectional Single-Inductor Multiple-Port Converter with Model Predictive Control in DC Microgrids

Benfei Wang^{a,b}, Liang Xian^b, Ujjal Manandhar^b, Jian Ye^b, Xinan Zhang^b, Hoay Beng Gooi^b, Abhisek Ukil^c.

^a School of Intelligent Systems Engineering, Sun Yat-sen University, Guang Zhou, China

^b School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore

^c Department of Electrical and Computer Engineering, University of Auckland, New Zealand

Abstract—This paper presents a bidirectional single-inductor multiple-port (BSIMP) converter for integrating hybrid energy storage system (HESS) into DC microgrids, where the HESS is the combination of different types of energy storages (ESs). A control method based on model predictive control (MPC) is proposed to regulate the BSIMP converter for the HESS. With the MPC-based method, the ESs are controlled following their characteristics. Simultaneously, the DC microgrid bus voltage can be maintained against the fluctuations of the load consumption and renewable generation. Compared to conventional bidirectional single-input single-output converters, the proposed BSIMP converter significantly reduces the component count, system size and cost to integrate the HESS into DC microgrid. To verify the performance of the proposed BSIMP converter with MPC-based method, a series of hardware-in-loop (HIL) experimental cases are studied. Moreover, the comparison with previous works is conducted. The HIL experimental and comparison results demonstrate the successful regulation of HESS using the BSIMP converter in DC microgrid.

Key Words— single-inductor multiple-port converter, model predictive control, HESS, DC microgrid.

1. INTRODUCTION

The hybrid energy storage energy systems (HESS) have been widely adopted in varieties of applications, including microgrids, electric ships and vehicles [1]-[16]. HESS incorporates different types of energy storage (ES) devices with diverse energy density, power density and ramp rate [6]. Hence, HESS optimally utilize the ESs with different response time, including batteries or supercapacitors, to mitigate the mismatch of energy generation and consumption. The lifespan of the ESs can be extended since each ES in HESS is operated to follow its characteristics [3]-[6]. To achieve the effective integration of the ESs as the HESS into DC microgrid, the bidirectional converters with corresponding control methods have been implemented for the charge and discharge operations of HESS [6]-[16]. In addition, the general HESS operational principle is that the ESs with low ramp rate provide the long-term power, and the ESs with high ramp rate compensate the transient power, which has been adopted in [6]-[13].

In [6], the hierarchical control strategy has been proposed including the centralized control and distributed control for the HESS with different types of batteries in DC microgrids,

which enhances the system reliability. Moreover, the centralized control contains the online iteration, voltage control and autonomous state-of-charge (SOC) restoration. A dynamic energy management has been proposed to control the HESS with high-gain PV converter in [7], where the fast DC bus voltage regulation, reduced burden on battery, effective energy management, and the maximum power point tracking (MPPT) control of the renewable energy source (RES) PV can be achieved. Additionally, the stability analysis is presented for the proposed management method. The authors have further extended the dynamic energy management for a grid-connected HESS in [8]. Different operational modes, including deficit power mode, excess power mode and floating power mode, have been defined to specify the energy management strategies based on different conditions of the microgrid and HESS. A decentralized dynamic power sharing method based on an extended droop control strategy has been presented in [9]. Virtual resistance droop control and virtual capacitance droop control are adopted in the proposed method so that power for ESs with different response time can be decoupled. In [10], a supervisory power management strategy has been developed for a grid-connected hybrid microgrid including the HESS. The variations in renewable power and load, and electricity pricing are taken into consideration in the proposed method. A smart energy management algorithm (SEMA) has been presented in [11], and SEMA can simultaneously achieve power equilibrium of microgrid, maximum power point racking for PV and optimal of battery.

In [6]-[11], all the different strategies for HESS management, however, are based on the proportional-integral (PI) control strategy. Nevertheless, the PI control has the sluggish response to sudden disturbances, which is frequently caused by load and renewable energy sources, for example, photovoltaics (PV). In [12], [13], a model predictive control (MPC) method is utilized to the hybrid battery-supercapacitor power source. The proposed MPC method incorporates the constraints on the current and SOC of the battery, and the operation of the supercapacitor are regulated within the preset ranges. However, the classical MPC adopted in [12], [13] with whole system state-space models result in significantly high computational capability and long execution time to obtain the optimal control

Fig. 1. The proposed BSIMP converter for integration of HESS into DC microgrid.

actions. In [5]-[13] all research works adopt the bidirectional single-input single-output (BSISO) converters. However, in the circumstance of the large number of ESs in HESS, the number of BSISO converters is increased accordingly resulting in bulky size and high cost.

One possible solution is to replace the conventional BSISO converter by the multiple-input converter as reported in [14]-[17]. However, there are several drawbacks of the solutions in [14]-[16]: a) increment in the number of inductors when integrating more ESs, b) low capability of extension to an arbitrary number of ESs. The multiple-input converter proposed in [17] has the capability of extension, but it also needs lots of inductors with the same number as the ESs. Additionally, it only allows unidirectional power flow, which is not suitable for DC microgrid.

A bidirectional single-inductor multiple-port (BSIMP) converter is developed in this paper for integrating HESS into DC microgrid as the extension of the previous work [18]. One main contribution of this work is that the proposed BSIMP converter achieves the integration of HESS into DC microgrids with significantly reduced component count, system size and cost. Considering the topology of the proposed BSIMP converter, the input voltage values vary dramatically among the different ESs' terminal voltage values, which requires a control strategy with fast response to dynamics. Recently, a great number of research works have illustrated the effectiveness of MPC for power electronics converters [19], ranging from basic converters, e.g., boost converters [20], to advanced converters, such as bidirectional converters and single-inductor multiple-port converters [21]-[25]. MPC has the features of fast dynamic response, online optimization and easy incorporation of constraints. Hence it is superior to the conventional PI control method, which is the basis of strategies for HESS proposed in [6]-[11]. Therefore, a MPC-based method is proposed to control the BSIMP converter, resulting in the successful regulation of various ESs and the better DC bus voltage control over the previous works. In summary, the combination of the advantages of BSIMP converter and MPC can be obtained in this paper

simultaneously. Moreover, to validate the proposed method, the hardware-in-loop (HIL) experimental verification of various operations is conducted.

2. HESS USING BSIMP CONVERTER IN DC MICROGRID

2.1 System Architecture

Fig. 1 presents the proposed BSIMP converter for integrating HESS into DC microgrid. The HESS includes n ES devices, and any ES_i is allocated with one small filter inductor L_i , one filter capacitor C_i and one switch S_i . The filter inductor L_i and the filter capacitor C_i will form the EMI filter to eliminate the EMI resulting from the sudden deviations of the inductor current due to the operation of the switches ($S_1, S_2, \dots, S_i, \dots, S_n$). The switch S_i consists of two switches, which forms a bidirectional-blocking structure (BBS). Hence, the charge/discharge of ES_i can be achieved only when the two switches in S_i are both turned on. In other words, the BBS can eliminate the uncertain power flow of ESs. Moreover, the power extracted from/injecting to each ES_i can be accurately regulated by S_i . The HESS is connected to the single inductor L_{hess} and two switches $S_{hess,1}$ and $S_{hess,2}$, which are connected to the DC bus. The DC bus voltage is regulated to track the target reference by controlling $S_{hess,1}$ and $S_{hess,2}$. The switches ($S_1, S_2, \dots, S_i, \dots, S_n$), $S_{hess,1}$, $S_{hess,2}$ and inductor L_{hess} forms the BSIMP converter. A boost converter, formed by an inductor L_{pv} , a capacitor C_{pv} , a switch S_{pv} , and a diode D_{pv} , is adopted to for integrating a PV array into the DC microgrid. The symbols ($i_{in,1}, i_{in,2}, \dots, i_{in,i}, \dots, i_{in,n}$), ($v_{in,1}, v_{in,2}, \dots, v_{in,i}, \dots, v_{in,n}$), i_L , v_{pv} , i_{pv} , i_{Load} and v_{Bus} represent current and voltage of ES, inductor L_{hess} current, voltage of PV, output current of the PV boost converter, load current and bus voltage respectively. It is noticeable that $i_{in,i} > 0$ when ES_i is discharged, and $i_{in,i} < 0$ when ES_i is charged. In addition, v_{in} represents the voltage at the common joint point of switches ($S_1, S_2, \dots, S_i, \dots, S_n$). The other parameters related to ES_i are response time rt_i , state of charge SOC_i , SOC upper limit $H_{SOC,i}$ and SOC lower limit $L_{SOC,i}$.

The comparison of component number between the proposed BSIMP converter and the power converters for

TABLE I COMPARISON OF COMPONENT NUMBER BETWEEN THE PROPOSED BSIMP CONVERTER AND PREVIOUS WORKS

References	BSISO Converter	Multiple-Input Converter			BSIMP Converter
	[5]-[11], [16]	[12]	[13]	[14]	
Inductor	n	n	n	n	1
kW/Inductor	n (1 pu)	n(1 pu)			1 (1pu)
Capacitor	2n	n+1	n+1	n+1	n+1
V/Capacitor	n of $v_{in,i}$; n of v_{Bus}	n of $v_{in,i}$; 1 of v_{Bus}			n of $v_{es,i}$; 1 of v_{Bus}
Switch	2n	2n	2n+1	n+2	2n+2
kW/Switch	2n of (1pu)	2n of (1pu)	2n+1 of (1pu)	n+2 of (1pu)	2n+2 of (1pu)
Diode	0	0	0	n	0

*The number of ESs n is greater than 2. 1pu is defined the maximum load demand of the DC microgrid.

Fig. 2. The basic operation rule of the proposed BSIMP converter.

HESS in the previous works is presented in Table I. Moreover, the ratings of the inductors (kW/Inductor), capacitors (V/Capacitor) and switches (kW/Inductor) are also presented in the Table I. To guarantee the operation of DC microgrid, the power converters for HESS should handle the extreme scenario, which is zero PV power generation, maximum load demand (1pu) and only one ES is available. Moreover, this extreme scenario can happen to any ESs in the HESS. Hence, the ratings of inductors and switches can be obtained as shown in Table I. In addition, the ratings of capacitors are diversified among $v_{in,i}$ and v_{Bus} based on their positions. It can be seen that the adoption of BSIMP converter reduces the number of inductor and capacitor without increasing the ratings, compared to [6]-[13], especially when the number of ESs n is large.

It is noteworthy that the basic operation rule of the proposed BSIMP converter is that there is only one ES is connected to the DC bus via the shared inductor at any given instant. The corresponding figure is presented in Fig. 2 illustrate the basic operation rule. It can be seen that the i -th ES _{i} is connected to shared inductor by turning on S_i , and the other switches including $S_1, S_2, \dots, S_{i-1}, S_{i+1}, \dots, S_n$ are turned off.

Fig. 3. The proposed MPC-based method block diagram.

2.2 MPC-based Method for BSIMP Converter

From Fig. 3, it can be seen that the proposed method includes HESS current control and DC bus voltage regulation.

1) Current Control for HESS

To control the HESS current, the modulation index δ_i is adopted for the generation of the control signal q_i for S_i of ES _{i} . As shown in Fig. 4, the moving average filter (MAF) processes the current $i_{in,i}$ for the ES _{i} [25], because the MPC-based method generates the control signals with variable switching frequency [25]. Based on [25], the MAF can be set as a low pass filter. After the process by MAF, the average current and the current reference $i_{Ref,i}$ are transmitted to the PI controller, so that δ_i can be obtained, and the generation of $i_{Ref,i}$ will be discussed in detail in Section II-C. It can be seen from Fig. 4 that, to strictly conduct the ESs in sequence and exclusively, the accumulated modulation index δ'_i ($i = 2, 3, \dots, n-1$) is defined and expressed as follows:

Fig. 4 Block diagram for HESS current control

$$\delta'_i = \sum_{k=1}^i \delta_k, 2 \leq i \leq n, 0 \leq \delta_k \leq 1 \quad (1)$$

With $(\delta_1, \delta_2', \dots, \delta_i', \dots, \delta_n')$, the control signals $(q_1, q_2', \dots, q_i', \dots, q_n')$ are obtained by the synchronized pulse-width-modulation (PWM) generator. The period of the carrier in the PWM generator is t_{ps} . For the applicable control signals $(q_2, \dots, q_i, \dots, q_n)$, the logic XOR gates are adopted as shown in Fig. 3, so that q_i can be expressed as follows:

$$q_i = q_i' \text{ XOR } q_{i-1}', 2 \leq i \leq n \quad (2)$$

From Fig. 4, it can be seen that q_1 is directly obtained since ES_1 is the first ES to be conducted. As shown in Fig. 3, The control signals $(q_1, q_2, \dots, q_i, \dots, q_n)$ not only regulate the power from the ESs, but also determine the input voltage v_{in} which is given in (3).

$$v_{in} = \sum_{i=1}^n q_i \cdot v_{in,i} \quad (3)$$

It is noticeable that there is only one ES connected to DC bus via the shared inductor L_{hess} at a given instant, since $(q_1, q_2, \dots, q_i, \dots, q_n)$ are exclusive to each other.

2) Voltage Regulation for DC Bus

From (3), it indicates that the value of input voltage v_{in} varies dramatically due to the exclusive switching pattern of $(q_1, q_2, \dots, q_i, \dots, q_n)$. The BSIMP converter can be regarded as a SISO boost converter with varying input voltage, so that a control strategy with fast dynamic response is required. Therefore, the MPC method is employed in this paper considering its features of fast dynamic response and online optimization, and its successful applications on converters with single-inductor topology [23]-[25].

With the data $(v_{in}, v_{Bus}, i_{pv}, i_L)$, v_{Bus} can be controlled to follow v_{Ref} using the optimal control signals $q_{hess,1}$ and $q_{hess,2}$,

as shown in Fig. 3. Moreover, $q_{hess,1}$ and $q_{hess,2}$ are mutual exclusive.

The equations in continuous-time domain for describing the BSIMP converter are expressed in (4) and (5) to conduct the implementation of the proposed MPC-based method.

$$L_{hess} \frac{di_L}{dt} = \sum_{i=1}^n q_i \cdot v_{in,i} - q_{hess,1} v_{Bus} \quad (4)$$

$$C_{Bus} \frac{dv_{Bus}}{dt} = q_{hess,1} i_L + i_{pv} - i_{Load} \quad (5)$$

Considering that the proposed MPC-based method is executed in discrete-time domain and the time step is t_s . (4) and (5) need to be discretized using the forward Euler method, which are expressed as follows:

$$i_L(k+1) = \frac{t_s}{L_{hess}} \left[\sum_{i=1}^n q_i \cdot v_{in,i}(k) - q_{hess,1}(k) v_{Bus}(k) \right] + i_L(k) \quad (6)$$

$$v_{Bus}(k+1) = \frac{t_s}{C_{Bus}} \left[q_{hess,1}(k) i_L(k) + i_{pv}(k) - i_{Load}(k) \right] + v_{Bus}(k) \quad (7)$$

When the sampling frequency is sufficiently high, i_{pv} and i_{Load} in (6), (7) can be regarded as the constants [22], and their discretization can be obtained as follows:

$$i_{pv}(k+1) = i_{pv}(k) \quad (8)$$

$$i_{Load}(k+1) = i_{Load}(k) \quad (9)$$

According to the analysis above, the state-space model can be obtained as shown in (10).

$$\begin{aligned} \mathbf{x}(k+1) &= [\mathbf{A} + \mathbf{B}q_{hess,1}(k)] \mathbf{x}(k) + \mathbf{C} \sum_{i=1}^n q_i(k) \cdot v_{in,i} \\ \mathbf{y}(k) &= \mathbf{D}\mathbf{x}(k) \end{aligned} \quad (10)$$

where $\mathbf{x}(k) = [i_L(k) \ v_{Bus}(k) \ i_{pv}(k) \ i_{Load}(k)]^T$, $\mathbf{y}(k) = [i_L(k) \ v_{Bus}(k)]^T$, and the coefficient matrices are

Fig. 5 Block diagram for move-blocking technique.

$$A = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & \frac{t_s}{C_{Bus}} & -\frac{t_s}{C_{Bus}} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, B = \begin{bmatrix} 0 & -\frac{t_s}{L_{hess}} & 0 & 0 \\ \frac{t_s}{C_{Bus}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, C = \begin{bmatrix} \frac{t_s}{L_{hess}} \\ 0 \\ 0 \\ 0 \end{bmatrix}, D = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}^T$$

The prediction of the possible future v_{Bus} values can be conducted using the state-space model in (10). Based on the MPC strategy, a cost function is defined in (11).

$$J = \sum_{j=1}^{N_c} [v_{Ref} - v_{Bus}(k+j)]^2 \quad (11)$$

where N_c is the control horizon. Because the BSIMP converter adopts the shared inductor L_{hess} , it is imperative to enhance the protection of the inductor to avoid the inductor fault, which will lead to the disconnection of HESS from DC microgrid. To implement the inductor protection, the inductor current constraint needs to be considered. As reported in [24], [25], MPC has the features of easy constraint incorporation. i_{LR} is defined as the current rating for the inductor. Hence, (12) gives the constraints for the inductor current as shown below, which indicates that the inductor current is always maintained less than i_{LR} .

$$\text{Max}(|i_L(k+1)|, |i_L(k+2)|, \dots, |i_L(k+j)|, \dots, |i_L(k+N_c)|) < i_{LR} \quad (12)$$

If one group of predicted v_{Bus} values can minimize (11) and predicted i_L absolute values can satisfy the constraint in (12),

the corresponding control signal is the optimal one, which will be utilized to regulate the BSIMP converter.

The basic unit of the BSIMP converter is the bidirectional buck/boost converter, and it is a non-minimum phase system as discussed in [19]. Hence, the move-blocking technique (MBT) is required to apply MPC for regulation of the proposed BSIMP converter. In the process of prediction, the MBT multiplies t_s with a suitable integer, so that it can predict the future status of the BSIMP converter further with less prediction steps. Fig. 5 illustrates the MBT adopted in the MPC-based method in the form of a binomial tree with the depth of N_c+1 . It can be seen that the time step t_s in (6) and (7) is dynamically adjusted with different integral times of time step T , and the integer are $n_1, n_2, \dots, n_j, \dots, n_{N_c}$ respectively. The relationship of n_j follows (13) below.

$$n_1 < n_2 < \dots < n_j < \dots < n_{N_c}, n_j \in \mathbb{N}^+ \quad (13)$$

It is noticeable that time step T is restricted by the practical processor for hardware implementation. Hence, the real optimal control action can be identified. Moreover, the enumerated technique is adopted for various works of applying MPC on power converters to relieve the computational burden due to the minimization [20], [24], [25]. In detail, all possible future status are predicted and substituted into (11) and (12). If one future status (i.e., one group of predicted v_{Bus} and predicted i_L) can minimize the cost function and meet the inductor current constraint respectively, the corresponding set of control signals is the optimal one. The number of enumeration is decided by N_c

[24], which is 2^{N_c} as shown in Fig. 5. Hence, for lower computational complexity, it is better to adopt a proper small value of N_c .

2.3 Current Reference Generation for HESS

MPPT operation is applied to the PV array and its power generation is P_{pv} . HESS power and the load power consumption are defined as P_{hess} and P_{load} . Hence relationship of P_{pv} , P_{hess} and P_{load} can be expressed as follows:

$$P_{hess} = P_{load} - P_{pv} \quad (14)$$

According to [8], two modes can be defined, including deficit power mode (DPM) and excess power mode (EPM). Moreover, P_{hess} is greater than 0 and HESS is discharging to provide the deficient power in DPM. P_{hess} is less than 0 and HESS is charging to handle the excess power in EPM. Hence, only ES_i , whose SOC_i is greater than $L_{SOC,i}$, will participate the discharge process in DPM, and the ES_i whose SOC_i is less than $H_{SOC,i}$ will participate in the charge process in EPM. Hence, an auxiliary coefficient ρ_i is defined to indicate whether ES_i is available in DPM or EPM, and the values of ρ_i are given by (13) and (14).

$$\text{DPM} \begin{cases} \rho_i = 1, \text{ if } SOC_i > L_{SOC,i} \\ \rho_i = 0, \text{ if } SOC_i < L_{SOC,i} \end{cases} \quad (15)$$

$$\text{EPM} \begin{cases} \rho_i = 1, \text{ if } SOC_i < H_{SOC,i} \\ \rho_i = 0, \text{ if } SOC_i > H_{SOC,i} \end{cases} \quad (16)$$

Using the auxiliary coefficients, the response time rt_i can be updated as ρrt_i which is expressed as follows

$$\rho rt_i = \rho_i \times rt_i \quad (17)$$

Among all ρrt_i , the minimum non-zero value is defined as ρrt_{min} . The ES with ρrt_{min} is marked as ES_{min} , and the corresponding subscript is m .

For the ES_i , whose ρrt_i is greater than ρrt_{min} , the reference current can be obtained in (18) following the algorithm in [9].

$$i_{Ref,i} = \frac{\rho_i I_{max,i}}{I_{max} (1 + s \rho rt_i)} (i_{Load} - i_{pv}), i \neq m \quad (18)$$

where I_{max} is the available maximum HESS output current and $I_{max,i}$ is the maximum ES_i output current, and I_{max} is expressed as follows:

$$I_{max} = \sum_{i=1}^n \rho_i I_{max,i} \quad (19)$$

For ES_{min} , the corresponding current reference is given as

$$i_{Ref,m} = \left(1 - \sum_{j=1}^{m-1} \frac{\rho_j I_{max,j}}{I_{max} (1 + s \rho rt_j)} - \sum_{j=m+1}^n \frac{\rho_j I_{max,j}}{I_{max} (1 + s \rho rt_j)} \right) (i_{Load} - i_{pv}) \quad (20)$$

With the current references, the PWM index δ_i defined in subsection 2.2 can be generated as shown in Fig. 4. Consequently, the power provided or absorbed by the ESs of

Fig. 6. Illustration of control scheme for the MPC-based method.

HESS can be properly regulated by $(q_1, q_2, \dots, q_i, \dots, q_n)$, which are determined by $(\delta_1, \delta_2, \dots, \delta_i, \dots, \delta_n)$.

2.4 MPC-based Method Control Scheme

Based on the previous analysis, the control scheme to illustrate the MPC-based method for HESS using BSIMP converter is presented in Fig. 6. In Fig. 6, t_{PS} is defined as the power-sharing time constant, and the switching frequency can be obtained as $1/t_{PS}$ for the PWM generation in Fig. 3. It can be seen that $(q_1, q_2, \dots, q_i, \dots, q_n)$ regulate the switches ($S_1, S_2, \dots, S_i, \dots, S_n$) to be turned on sequentially, and then the value of v_{in} can be determined. The updated v_{in} and i_L assist to calculate the optimal $q_{hess,1}$.

3. HIL EXPERIMENTAL SETUP

To validate the BSIMP converter for HESS and the proposed MPC-based method, the HIL experimental setup is built as shown in Fig. 7, including the OP5600 real-time digital simulator from OPAL-RT and the MicroLabBox all-in-one controller from dSpace. It is noticed that OP5600 and MicroLabBox both support the standard modules in the Matlab/Simulink library. Consequently, the HESS using BSIMP converter and the MPC-based method are implemented using these standard modules and then compiled as C/C++ codes for the real-time operation. Moreover, it can be seen that the proposed DC microgrid including the HESS with BSIMP converter is simulated in real time using OP5600. The MicroLabBox execute the proposed MPC-based method. The system data are transited from OP5600 to MicroLabBox via the analog output ports and the ADC ports. The digital I/O ports is utilized to communicate the control signals from MicroLabBox to OP5600. The HIL experiments using real-time simulators have been widely adopted [27]-[29]. These research works demonstrate that the HIL experiments can be trusted to validate newly designed power converters or control methods for the applications of microgrids. Hence, the HIL setup is adopted for the validation.

Fig. 7. HIL experimental setup of OP5600 and MicroLabBox. (a) Schematic of setup. (b) Photo of setup.

The HIL experimental setup parameters are listed in Table II. In the HIL experimental setup, HESS consists of 3 ESs. And the HESS includes lithium-ion battery (ES₁), nickel-metal-hydride battery (ES₂) and lead-acid battery (ES₃) respectively. The maximum output current and nominal voltage of these batteries are all set as 8A and 50V. However, different response times are adopted, i.e., $rt_1=0.01s$, $rt_2=0.02s$ and $rt_3=0.05s$ respectively. In the proposed BSIMP converter, the main inductor and capacitors are 1.5mH and 2200 μ F respectively. The switching frequency of ($S_1, S_2, \dots, S_i, \dots, S_n$) is 5kHz, which is the cut-off frequency for the EMI filter. Consequently, the filter inductors L_1, L_2 and L_3 can be calculated as 0.5 μ H.

The DC bus voltage reference is 80V. For the proposed MPC-based method, the time step is 35 μ s and the power sharing time constant is 200 μ s. The PV array is the SunPower SPR-305-WHT, whose open circuit voltage and short circuit current is 64.2V and 5.96A respectively.

4. HIL EXPERIMENTAL RESULTS

The HIL experimental results including the steady-state operation and dynamic operation are analyzed in this section.

TABLE II. HIL EXPERIMENTAL SETUP PARAMETERS

Parameters			Values	
BSIMP Converter			n	3
			t_s	35μs
			t_{PS}	200μs
			$C_{in,1}, C_{in,2}, C_{in,3}, C_{Bus}$	2200μF
			L_{hess}	1.5mH
			V_{ref}	80V
HESS	ES ₁ (lithium-ion)	$V_{in,1}$	50V	
		$I_{max,1}$	8A	
		rt_1	0.01s	
	ES ₂ (nickel-metal-hydride)	$V_{in,2}$	50V	
		$I_{max,2}$	8A	
		rt_2	0.02s	
	ES ₃ (lead-acid)	$V_{in,3}$	50V	
		$I_{max,3}$	8A	
		rt_3	0.05s	
PV Array			V_{OC}	64.2V
			I_{SC}	5.96A

V_{oc} is PV open circuit voltage and I_{sc} is PV short circuit current.

Fig. 8. HIL experimental results of steady-state operation in DPM.

4.1 Steady-State Operation

In this subsection, the steady-state operation of DC microgrid is presented in Fig. 8 and Fig. 9, including DPM and EPM. Moreover, the HIL experiments are conducted on the condition of $L_{SOC,i} < SOC_i < H_{SOC,i}$, so that all three ESs are discharged or charged in DPM or EPM, i.e., $\rho_1=\rho_2=\rho_3=1$.

Fig. 9. HIL results of steady-state operation in EPM.

The HIL experimental results of steady-state operation in DPM are shown Fig. 8. It can be seen that $i_{pv}=1.0A$ and $i_{Load}=2.0A$. Hence, the HESS is discharged with $i_{ES,1}=0.5A$, $i_{ES,2}=0.5A$ and $i_{ES,3}=0.5A$, which follow the current references in (18) and (20). Moreover, v_{Bus} is regulated to 80V, which tracks the voltage reference tightly. The control signals (q_1 , q_2 , q_3) and $q_{hess,1}$ in DPM are presented in Fig. 9, following the control scheme in Fig. 7.

The HIL experimental results of steady-state operation in EPM are shown Fig. 9. It can be seen that $i_{pv}=3.0A$ and $i_{Load}=2.0A$. Consequently, the HESS is charged with $i_{ES,1}=-0.5A$, $i_{ES,2}=-0.5A$ and $i_{ES,3}=-0.5A$, following the current references in (18) and (20). Similarly, v_{Bus} is regulated to follow the voltage reference 80V tightly. The control signals (q_1 , q_2 , q_3) and $q_{hess,1}$ in EPM are also shown in Fig. 9, which follow the control scheme in Fig. 6.

4.2 Dynamic Operation

In this subsection, the dynamic operation is studied including HIL experiments with varying PV power generation, varying load power consumption and varying of number of available ESs.

1) HIL Experiments with Varying PV Power Generation

Fig. 10 shows the results with varying PV generation with the condition of $\rho_1=\rho_2=\rho_3=1$. It can be seen that three

Fig. 10. HIL results with varying PV power generation.

sudden variations of i_{pv} are applied, and they are from 1.0A to 1.5A at t_1 , from 1.5A to 2.5A at t_2 , and from 2.5A to 1.0A at t_3 respectively. The system is in EPM during (t_2 , t_3), and the DC microgrid is in DPM in the other time duration. According to Table II, rt_1 , rt_2 and rt_3 are 0.01s, 0.02s and 0.05s respectively. Hence, the ESs references are given in (21)-(23) according to (18) - (20):

$$i_{Ref,3} = \frac{1}{3(1+0.05s)}(i_{Load}-i_{pv}) \quad (21)$$

$$i_{Ref,2} = \frac{1}{3(1+0.02s)}(i_{Load}-i_{pv}) \quad (22)$$

$$i_{Ref,1} = \left(1 - \frac{1}{3(1+0.02s)} - \frac{1}{3(1+0.05s)}\right)(i_{Load}-i_{pv}) \quad (23)$$

In Fig. 10, the waveforms of $i_{in,1}$, $i_{in,2}$ and $i_{in,3}$ follow (21)-(23). At the time point t_1 , t_2 and t_3 , ES₁ immediately reacts to balance the system power mismatch and maintain the bus voltage. Then, ES₂ and ES₃ gradually responds and follow their characteristics.

In the time duration (0 , t_1), the three ESs are discharged to compensate the deficit power with $i_{ES,1}=0.5A$, $i_{ES,2}=0.5A$ and $i_{ES,3}=0.5A$. In the time duration (t_1 , t_2) the PV power generation is increased, however, P_{pv} still cannot fully meet P_{Load} . Hence, the three ESs continue to be discharged with decreased current values of $i_{ES,1}=0.25A$, $i_{ES,2}=0.25A$ and $i_{ES,3}=0.25A$. In the time duration (t_2 , t_3), the three ESs are charged to absorb the excess power with $i_{ES,1}=-0.25A$, $i_{ES,2}=-0.25A$ and $i_{ES,3}=-0.25A$. After t_3 the microgrid enters DPM

Fig. 11. HIL results with varying load power consumption in DPM.

again. It can be observed from the zoom-in figures on the bottom of Fig. 7 that there are three overshoot of v_{Bus} due to the variation of PV power generation, which are 0.9V, 1.2V and 2.0V. Moreover the settling time T_{ST} [8] for the recovery of v_{Bus} are 250ms, 300ms and 350ms respectively. Hence, the MPC-based method for HESS using BSIMP converter can effectively balance the power and regulate the bus voltage.

2) HIL Experiments with Varying Load Power Consumption

The HIL experimental results with varying load power consumption, with the condition of $\rho_1=\rho_2=\rho_3=1$, are presented in Fig. 11 and Fig. 12.

Fig. 11 shows the waveforms in DPM with $i_{pv}=1.0A$. The load power consumption has two step changes at t_1 and t_2 , i.e., i_{Load} increases from 2.0A to 3.3A and then decreases to 2.0A. Similarly, following (21)-(23), the three ESs respond to the step changes of load power consumption following their response time as shown in Fig. 11. ES₁ takes actions at t_1 and t_2 firstly followed by ES₂ and then ES₃, so that the bus voltage is regulated to the target reference in spite of the load power consumption sudden variations. The zoom-in figures on the bottom of Fig. 11 show that there are two overshoot of DC bus voltage v_{Bus} because of the varying load power consumption, which are 1.0V and 1.3V, and the corresponding settling time T_{ST} are 250ms and 150ms.

Fig. 12 shows the response in EPM with $i_{pv}=3.0A$. Similarly, the load power consumption has two step changes at t_1 and t_2 , i.e., i_{Load} varies from 2.0A to 2.8A and then goes back to 2.0A. Following (21)-(23), the three ESs react based on their

Fig. 12. HIL results with varying load power consumption in EPM.

response time very well as shown in Fig. 12. ES₁ responds immediately at t_1 and t_2 , then ES₂ and ES₃ gradually compensate the deficient power, so that the bus voltage is maintained approximate to $v_{Ref}=80V$. Similarly, there are two overshoot of v_{Bus} resulting from the load power consumption step changes from the zoom-in figure on the bottom Fig. 9, which are 1.2V and 1.4V, and the corresponding settling time T_{ST} are 200ms and 120ms, respectively.

3) HIL Experiments with Varying Number of Available ESs

The HIL experimental results with varying number of available ESs in DPM and EPM are presented in Fig. 13 and Fig. 14 respectively.

As discussed in Section II-C, there are SOC upper limit $H_{SOC,i}$ and SOC lower limit $L_{SOC,i}$ for the ESs to determine the values of ρ_1 , ρ_2 and ρ_3 , which indicate whether the ESs will participate the discharge process in DPM or charge process in EPM. Consequently, the ESs in the HESS are protected from over-discharge and over-charge.

In Fig. 13, the DC microgrid works in DPM with $i_{pv}=1.0A$ and $i_{Load}=2.0A$. The SOC₃ is intentionally set less than $L_{SOC,3}$ at t_1 , so that ρ_3 is changed from 1 to 0 following (15). The number of available ESs is changed from 3 to 2 in DPM. Accordingly, the current references for the two available ES₁ and ES₂ are updated as follows:

$$i_{Ref,2} = \frac{1}{2(1+0.02s)}(i_{Load}-i_{pv}) \quad (24)$$

Fig. 13. Response to variation of number of available ESs in DPM.

Fig. 14. Response to variation of number of available ESs in EPM.

$$i_{Ref,1} = \left(1 - \frac{1}{2(1+0.02s)}\right) (i_{Load} - i_{pv}) \quad (25)$$

It can be observed from Fig. 10 that $i_{in,3}$ gradually decreases from 0.5A to 0. Following (24) and (25), ES_1 responds immediately at t_1 and followed by ES_2 . In addition, ES_1 and ES_2 , each shares the half of the deficient power portion due to the absence of ES_3 .

In Fig. 13, the DC microgrid works in EPM with $i_{pv}=3.0A$ and $i_{Load}=2.0A$. Similarly, the SOC_3 is intentionally set greater than $H_{SOC,3}$ at t_1 , so that ρ_3 varies from 1 to 0 as indicated in (14). The number of available ESs is changed from 3 to 2 in

(a)

(b)

Fig. 15 Efficiency of the proposed BSIMP converter. (a) HESS in DPM. (b) HESS in EPM.

EPM. Consequently, $i_{in,3}$ gradually increases from -0.5A to 0. Simultaneously, ES_1 and ES_2 equally absorb the extra excess power because ES_3 retreats from EPM. Moreover, the responses of ES_1 and ES_2 also track the current references given by (24) and (25).

In practical situation, the batteries in HESS are usually equipped with battery management system (BMS). The fault conditions, for example the fault in input filter capacitor C_i , will trigger the BMS to shut down the battery. Moreover, the BMS also can be triggered by mechanisms such as over-voltage protection, over-current protection, over-temperature protection, etc. Therefore, all these scenarios will reduce the number of available ESs in HESS. Based on the HIL experimental results, it can be concluded that the proposed MPC-based method has the capability to control the BSIMP converter to handle the variations of number of available ESs.

4) Efficiency of the Proposed BSIMP converter

The efficiency of system is investigated in DPM and EPM. The efficiency data are captured from the HIL experiments and presented in Fig. 15. It can be seen that the efficiency is maintained greater than 96%. Compared to 92% in [7], and 81%~91% in [11], the proposed BSIMP converter can improve the efficiency since less components are adopted for the same number of ESs in HESS.

4.3 Comparison with Previous Works

The comparison with previous works has been conducted and the results are tabulated in Table III. M_p is defined as the

TABLE III COMPARISON WITH PREVIOUS WORKS

References	[5]	[8]	[10]	[13]	[16]	This Work
Execution Time Step T	-	-	-	0.01s	-	35 μ s
T_{ST} PV Step Change	>1min	~250ms	1.56s	-	>1s	250ms, 300ms, 350ms
M_P PV Step Change	-	5.3%	2%	-	8%	1.1%, 1.5%, 2.5%
T_{ST} Load Step Change	>1min	~250ms	-	-	-	250ms, 150ms, 200ms, 120ms
M_P Load Step Change	3.9%	5.3%	-	-	-	1.25%, 1.63%, 1.5%, 1.75%

DC bus voltage regulation performance index and T_{ST} is the settling time [8]. The definition of M_P is given in (26), where Δv_{Bus} is the overshoot voltage.

$$M_P = \frac{\Delta v_{Bus}}{v_{Bus}} \times 100\% \quad (26)$$

It can be seen that this work has smaller M_P values in PV step changes and load step changes than [5], [8] and [16], and less settling time T_{ST} compared to [5], [10] and [16]. Moreover, the execution time of the proposed MPC-based method is 35 μ s and much less than the 0.01s in [13], resulting from the highly reduced computational complexity of MPC. There are two factors contribute to the lower computational complexity. This first one is that the adoption of MBT for predication and the enumeration method for optimization reduce the computational requirement. In [13], the prediction and optimization involves large matrix calculation, and consumes long time for computation. The other factor is that the proposed BSIMP converter for the integration of ESs as HESS enables the simple state-space model for MPC. In other words, the state-space model of the proposed MPC-based method is a basic unit of the BSIMP converter, i.e. the bidirectional buck/boost converter. However, in [16], two state-space models for two conventional bidirectional buck/boost converters are required for MPC. Therefore, the proposed BSIMP converter with MPC-based method has better performance with less components, smaller circuit size and lower cost. Moreover, it is feasible for hardware implementation due to its lower computational complexity.

5. CONCLUSION

A BSIMP converter has been proposed in this paper to integrate HESS for DC microgrid. The BSIMP converter significantly reduces the number of components, system size and cost. A MPC-based method has been developed to control the BSMIP converter for the power balance and the bus voltage regulation of the DC microgrid. The validation of the proposed BSIMP converter for HESS has been conducted using HIL setup based on OP5600 and MicroLabBox.

The performance of steady-state operation and dynamic operation have been investigated based on HIL studies. For steady-state operation, the HIL experimental results in DPM and EPM have been discussed. For dynamic operation, three different test cases have been conducted with varying PV power generation, varying load power consumption, and varying number of available ESs respectively. Based on the HIL experimental results, the comparison with previous works has been presented, and the comparison results indicate that the proposed MPC-based method can control the BSMIP converter to successfully integrate HESS into DC microgrid with better performance, less component, smaller size and lower cost.

REFERENCES

- [1] T. Dragičević, X. Lu, J. C. Vasquez and J. M. Guerrero. DC microgrids—Part I: A review of control strategies and stabilization techniques. *IEEE Trans Power Electron*, 31 (7) (2016), 4876-4891.
- [2] C. R. Lashway, A. T. Elsayed, O. A. Mohammed, Hybrid energy storage management in ship power systems with multiple pulsed loads, *Electr. Power Syst. Res.*, 141 (2016), 50-62.
- [3] Y. Yuan, C. Sun, M. Li, S. S. Choi, Q. Li, Determination of optimal supercapacitor-lead-acid battery energy storage capacity for smoothing wind power using empirical mode decomposition and neural network, *Electr. Power Syst. Res.*, 127(2015) 323-331.
- [4] M. Ortuzar, J. Moreno, and J. Dixon. Ultracapacitor-based auxiliary energy system for an electric vehicle: Implementation and evaluation. *IEEE Trans Ind Electron*, 54 (4) (2007), 2147-2156.
- [5] G. Wang, M. Ciobotaru, and V. G. Agelidis. Power smoothing of large solar pv plant using hybrid energy storage. *IEEE Trans Sustain Energy*, 5 (3) (2014), 834-842.
- [6] J. Xiao, P. Wang and L. Setyawan. Hierarchical control of hybrid energy storage system in DC microgrids. *IEEE Trans Ind Electron*, 62(8) (2015), 4915-4924.
- [7] N. R. Tummuru, M. K. Mishra and S. Srinivas. Dynamic energy management of hybrid energy storage system with high-gain PV converter. *IEEE Trans Energy Con*, 30 (1) (2015), 150-160.
- [8] N. R. Tummuru, M. K. Mishra and S. Srinivas. Dynamic energy management of renewable grid integrated hybrid energy storage system. *IEEE Trans Ind Electron*, 62 (12) (2015), 7728-7737.
- [9] Q. Xu, X. Hu, P. Wang, J. Xiao, P. Tu, C. Wen, and M.Y. Lee. A decentralized dynamic power sharing strategy for hybrid energy storage system in autonomous dc microgrid. *IEEE Trans Ind Electron*, 64 (7) (2017), 5930-5941.
- [10] S. Kotra and M. K. Mishra. A supervisory power management system for a hybrid microgrid with HESS. *IEEE Trans Ind Electron*, 64 (5) (2017), 3640-3649.
- [11] A. Aktas, K. Erhan, S. Ozdemir, E. Ozdemir, Experimental investigation of a new smart energy management algorithm for a hybrid energy storage system in smart grid applications, *Electr. Power Syst. Res.*, 144 (2017), 185-196.
- [12] B. Hredzak and V. G. Agelidis. Model predictive control of a hybrid battery-ultracapacitor power source. *International Power Electronics and Motion Control Conference*, (2012) 2294-2299.
- [13] B. Hredzak, V. G. Agelidis and M. Jang. A model predictive control system for a hybrid battery-ultracapacitor power source. *IEEE Trans Power Electron*, 29 (3) (2014), 1469-1479.
- [14] J. J. Jose and U. B. Manthathi. Two-input bidirectional converter controlled hybrid energy storage system (HESS) for micro grids. *IEEE International Conference on Power Electronics, Intelligent Control and Energy Systems* (2016), 1-4.
- [15] M. Momayyezani, B. Hredzak and V. G. Agelidis. A new multiple converter topology for battery/ultracapacitor hybrid energy system. *Annual Conference of IEEE Industrial Electronics Society*, (2015), 464-468.
- [16] F. Akar, Y. Tavlasoglu, E. Ugur, B. Vural and I. Aksoy. A bidirectional nonisolated multi-input DC–DC converter for hybrid energy storage

- systems in electric vehicles. *IEEE Trans Veh Technol*, 65 (10) (2016), 7944-7955.
- [17] A. Deihimi, M. E. S. Mahmoodieh, R. Iravani, A new multi-input step-up DC–DC converter for hybrid energy systems, *Electr. Power Syst. Res.*, 149 (2017) 111-124.
 - [18] S. M. Tan, B. Wang, U. Manandhar, K. Chaudhari, A. Paudel and H. B. Gooi, Model predictive control for hybrid energy storagesystem using single-inductor dual-input single-output converter, *IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia)*, (2018) 97-102.
 - [19] S. Kouro, M. A. Perez, J. Rodriguez, A. M. Llor, and H. A. Young. Model predictive control: MPC's role in the evolution of power electronics. *IEEE Ind. Electron. Mag.*, 9 (4) (2015), 8-21.
 - [20] P. Karamanakos, T. Geyer, and S. Manias. Direct voltage control of DC-DC boost converters using enumeration-based model predictive control. *IEEE Trans Power Electron*, 29 (2) (2014), 968-978.
 - [21] Jianfeng Liu, Qing Yan, Xiaohui Qu, Fei Jiang, Weirong Liu, and Zhiwu Huang "Explicit model predictive control of bidirectional DC/DC converter for ultracapacitors energy storage unit applied to light rail vehicle," *IFAC Proceedings Volumes*, 47(3) (2014), 10293-10298.
 - [22] A. Pirooz and R. Noroozian. Model predictive control of classic bidirectional DC-DC converter for battery applications. *IEEE Power Electronics and Drive Systems Technologies Conference* (2016) 517-522.
 - [23] B. Wang, K. T. Tan and P. L. So. Low cross regulation SIMO DC/DC converter with model predictive voltage control. *IEEE Power & Energy Society General Meeting* (2013) 1-5.
 - [24] B. Wang, V. R. K. Kanamarlapudi, L. Xian, X. Peng, K. T. Tan, and P. L. So. Model predictive voltage control for single-inductor multiple-output DC–DC converter with reduced cross regulation. *IEEE Trans. Ind Electron*, 63 (7) (2016), 4187-4197.
 - [25] B. Wang, L. Xian, V. R. K. Kanamarlapudi, K. J. Tseng, A. Ukil and H. B. Gooi. A digital method of power-sharing and cross-regulation suppression for single-inductor multiple-input multiple-output DC–DC converter. *IEEE Trans Ind Electron*, 64 (4) (2017), 2836-2847.
 - [26] S. Golestan, M. Ramezani, J. M. Guerrero, F. D. Freijedo, and M. Monfared. Moving average filter based phase-locked loops: performance analysis and design guidelines. *IEEE Trans. Power Electron*, 29 (6) (2014), 2750-2763.
 - [27] M. Hanif, V. Khadkikar, W. Xiao, and J. L. Kirtley. Two degrees of freedom active damping technique for *LCL* filter-based grid connected PV systems. *IEEE Trans Ind Electron*, 61 (6) (2014), 2795-2803.
 - [28] Q. Ye, R. Mo, and H. Li. .Multiple resonances mitigation of paralleled inverters in a solid-state transformer (SST) enabled ac microgrid. *IEEE Trans Smart Grid*, 2017.
 - [29] Y. Mi, C. Ma, Y. Fu, C. Wang, P. Wang, and P. C. Loh. The SVC additional adaptive voltage controller of isolated wind-diesel power system based on double sliding mode optimal strategy. *IEEE Trans Sustain Energy*, 2017.