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An improved dynamic performance of bidirectional SEPIC-Zeta converter based battery energy storage system using adaptive sliding mode control technique

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ABSTRACT

An improved dynamic performance of DC–DC bidirectional SEPIC-Zeta converter based battery energy storage system (BESS) has been achieved using adaptive sliding mode control (SMC) technique. The micro-grid concept is gaining importance for integrating various nonconventional energy sources throughout the world. Nowadays, both DC and AC micro-grid systems are employing BESS for getting various advantages such as minimization of power fluctuations, excess or emergency power support etc. In this application, controlled charging and discharging operation of the concerned battery bank is extremely needed. In this scenario, DC to DC bidirectional converter such as combined SEPIC-Zeta converter is considered to facilitate dynamic charging and discharging operation of the concerned battery. Conventional proportional-integral-derivative (PID) controller based control strategy for the bidirectional converter can not always meet the dynamic performance requirements under charging and discharging operation cycles of the battery. Therefore, adaptive SMC action has been proposed to improve both transient and steady state behavior of the BESS. In addition to this, the proposed model can be operated satisfactorily under changed operating condition. The proposed concept is validated via various simulation studies using MATLAB-SIMULINK software. The experimental study is also performed on a prototype of the BESS to validate adaptive SMC case.

1. Introduction

In practice, the various distributed generations (DGs) [1] are integrated into low voltage (LV) electrical network [2], commonly known as micro-grid [3]. To begin with, the micro-grid is used to supply local loads. In recent scenario, it is also integrated into grid. Thus, both grid connected and grid isolated operations of micro-grid are performed in practice. In this respect, various architectures [4] of micro-grid are available in existing literatures. In general, micro-grid can be classified as DC and AC micro-grid. The battery energy storage system (BESS) is used to store surplus electrical energy [5,6], generated by DGs, which fulfills the requirements of any micro-grid. These requirements are minimization of the power fluctuations [7] caused by DGs and supply of the extra or emergency electrical power demand [8] whenever necessary. The above mentioned power management activities are discussed in several literatures [9,10]. In this respect, dynamic charging and discharging operations of concerned rechargeable battery bank are extremely necessary. The life and performance of the battery bank [11] significantly depends on the dynamic nature of charging and discharging current and the degradation phenomenon of grid connected battery is also discussed in Ref. [12].

In practical situation, various DC–DC bidirectional converters [13–15] are used to support both the charging and discharging actions of battery. In this regard, the used primitive converters are buck-boost topology, Cuk converter [16]. In advancement, SEPIC [17] and Zeta converters [18] are developed for their advantages as discussed in the paper [19]. The combined SEPIC-Zeta bidirectional DC–DC converter is chosen in this paper so that it can support wider range of operation of BESS. Besides, the current and voltage ripples of bidirectional SEPIC-Zeta converter are lesser in comparison with other bidirectional converters. It is expected that the dynamic controlling action of the DC–DC bidirectional converter in BESS should be suitably done so that charging and discharging current settles to the respective desired values quickly with less transient peaks. At first, traditional proportional-integral-derivative (PID) based con-

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Nomenclature

Abbreviations
- *AC* Alternating current
- *BESS* Battery energy storage system
- *DC* Direct current
- *PID* Proportional-integral-derivative
- *PWM* Pulse width modulation
- *SM* Sliding mode
- *SMC* Sliding mode control
- *SOC* State-of-charge

Symbol
- A, B, C, D Constants for general state matrix
- A_1, B_1, C_1, D_1 Constants for on-state state matrix
- A_2, B_2, C_2, D_2 Constants for off-state state matrix
- C_1, C_3 Battery side and output side capacitor respectively
- C_2, e Flying Capacitor and error signal respectively
- D_S, D_Z Anti-parallel body diodes of S_Z and S_S respectively
- d Duty ratio
- I_{bat}, I_{bus} Battery side and output side current respectively
- I_o, I_C Output current and capacitor current respectively
- I_{C1}, I_{C3} Battery side and output side capacitor current respectively
- I_{L1}, I_{L2} Current through the inductors of the bidirectional converter
- k_1, k_2, k_3 Adjusted coefficients for adaptive SMC
- k_P, k_I, k_D Gains of PID controller
- L_1, L_2 Inductors of bidirectional converter
- R_{in}, R_o Dynamic resistance looking from battery side and output side
- R_l Resistance of line between converter and DC bus
- S_S, S_Z Power semiconductor switch during SEPIC and Zeta operation respectively
- U, V_o, V_{ref} General input, output and reference voltage
- V_{bat}, V_{bus}, V_{os} Battery terminal, DC bus and output side voltage respectively
- V_{C1}, V_{C3}, V_{C2} Battery side, output side and flying capacitor voltage respectively
- V_{ref1}, V_{ref2} Reference voltage for discharging and charging mode respectively
- $\lambda_1, \lambda_2, \lambda_3$ Sliding coefficients

trol loop is designed for the said converter and the various dynamic responses under charging and discharging operations are observed. These responses have been significantly improved by the usage of proposed adaptive sliding mode control (SMC) strategy. Thus, the obtained smooth charging and discharging profile can help to increase life span of battery. In addition to this, the suggested strategy is flexible in changed operating conditions during charging and discharging cycles. On the other hand, under changed operating conditions, the retuning of PID controller gains is necessary but it is also very difficult to obtain under unpredictable variable conditions. The investigation on dynamic performances of SEPIC-Zeta converter based BESS under charging and discharging cycles has not been noticed in any publication to the best of author's knowledge. Apart from this, usage of adaptive SMC for improving the dynamic behavior of the said system is the new contribution of this article. The AC and DC micro-grid connected BESS is shown in Fig. 1. Here, various DGs are integrated into the common network via various converters. The BESS requires bidirectional DC–DC converter in both these schemes to support charging and discharging operations.

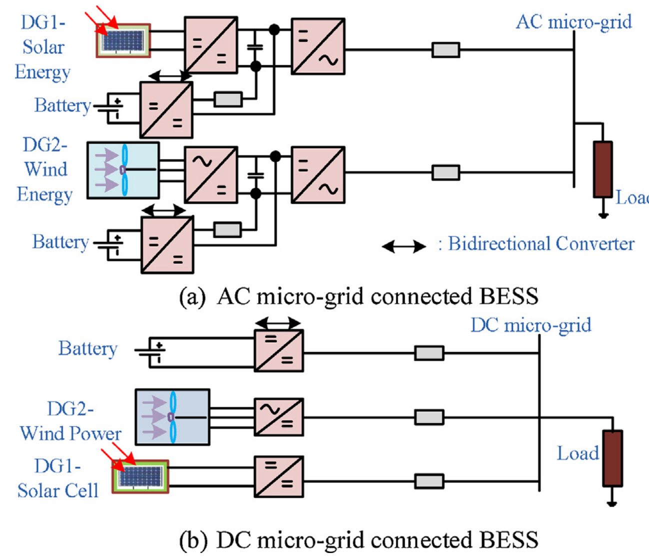

Fig. 1. AC and DC micro-grid with DC–DC bidirectional converter based BESS.

The system studied is discussed in "Section 2". The state space modeling of SEPIC and Zeta converter is described in "Section 3". The PID controller based system is presented in "Section 4". "Section 5" is devoted to present proposed adaptive sliding mode control strategy for BESS with the corresponding block diagram. "Section 6" shows the results of various simulation and experimental studies. The conclusion is presented in "Section 7". Appendices follow the conclusion.

2. Description of the system studied

The overall circuit diagram of BESS studied in this paper is shown in Fig. 2(a), which facilitates both charging and discharging of the battery with the DC bus. The symbols of components and their short description are already given in the nomenclature section. In Fig. 2(a), BESS comprises of rechargeable battery and DC–DC bidirectional SEPIC-Zeta converter. In this scheme, SEPIC configuration is activated during discharging of the battery and Zeta configuration comes into action during charging of the battery. The battery and operational modes of BESS studied are subsequently discussed as follows:

2.1. Rechargeable battery

The fundamentals, modeling and characteristics of rechargeable battery are elaborately described in Ref. [20]. The state of charge (SOC) of battery is the important quantity to be monitored to decide the initiation of charging and discharging activity of any battery. The 0% value of SOC indicates that the battery is of empty of charge and it requires immediate charging. On the other hand, 100% value of SOC points to the fully charged condition and it is ready to discharge with full capacity.

2.2. Operational modes

The BESS has two operating modes, namely charging operation and discharging operation. At first, charging operation is briefly discussed as given below:

The effective circuit diagram under charging mode of operation is shown in Fig. 2(b), which is developed from Fig. 2(a) with the activation of the switch 'S_Z' and the anti-parallel diode 'D_Z'. The circuit configuration functions as Zeta converter during charging condition. This circuit configuration operates like buck converter