Model Predictive Voltage Control for Seamless Transfer of DC-DC Converters in ESS Applications

Duc Dung Le and Dong-Choon Lee
Dept. of Electrical Engineering, Yeungnam University

ABSTRACT

In this paper, a model predictive voltage control (MPVC) for the DC-DC buck-boost converters is proposed. It provides a fast seamless bidirectional control method to maintain the DC grid voltage, battery voltage and current within predefined limits. In addition, an inner current control loop is not employed, so that the bandwidth of controller can be higher compared with the PI controller.

1. Introduction

DC microgrid usually consists of a combination of distributed energy resources and energy storage system (ESS), which can be applied in the areas of rural, marine and university campus. In DC microgrid, the distributed energy resources play a critical role in power generation; however, it makes no sense without the integration of ESS in DC microgrid.

The bidirectional DC-DC converters (BDDC) are applied to transfer energy between ESS and DC grid. The function of BDDC in the ESS is to keep the DC grid voltage constant in the case that the energy from distributed energy resources is not sufficient for load consumption. To operate the BDDC at desired requirements, various control methods have been proposed such as classical PI controller, hysteresis-based controller and sliding-mode controller. These control methods have been proved to fulfil the operation requirements of BDDC in ESS; however, there are some obstacles including parameter tuning as well as low bandwidth of the controller. In order to cope with these issues, the MPVC is proposed in this research.

In this paper, the mathematical model of the buck-boost converter in discrete-time domain is derived. Then, the MPVC is suggested to control the DC grid voltage and battery voltage/current. The simulation results are shown to verify the validity of the proposed method.

2. Model Predictive Control

2.1 Discrete-time model of the buck-boost converters

A model of dc-dc buck-boost converter is derived in discrete time domain [1], where a zero-order-hold technique is applied, as

$$\begin{aligned} x(kT_s+T_s) &= \Phi_1 x(kT_s) + \Gamma_1 u(kT_s) \quad \text{with } S_1 = 1,\ \overline{S}_1 = 0 \\ x(kT_s+T_s) &= \Phi_2 x(kT_s) + \Gamma_2 u(kT_s) \quad \text{with } S_1 = 0,\ \overline{S}_1 = 1 \end{aligned} \tag{1}$$

where

$$x(kT_s+T_s) = \begin{bmatrix} i_B(kT_s+T_s) \\ v_{dc}(kT_s+T_s) \end{bmatrix},\quad u(kT_s) = \begin{bmatrix} v_B(kT_s) \\ i_{in}(kT_s) \end{bmatrix}$$

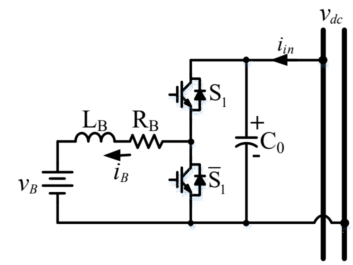

Fig. 1. Bidirectional DC-DC converter.

$$\Phi_1 = \begin{bmatrix} 1-\dfrac{R_B T_s}{L_B} & \dfrac{T_s}{L_B} \\ -\dfrac{T_s}{C_0} & 1 \end{bmatrix},\quad \Phi_2 = \begin{bmatrix} 1-\dfrac{R_B T_s}{L_B} & 0 \\ 0 & 1 \end{bmatrix},\quad \Gamma_1 = \Gamma_2 = \begin{bmatrix} -\dfrac{T_s}{L_B} & 0 \\ 0 & \dfrac{T_s}{C_0} \end{bmatrix}$$

2.2 Model predictive voltage control

In a model predictive control, the discrete-time model is employed for predicting the future behavior of the control variables. In addition, a cost function is defined depending on the desired behaviors of the system. Then, an optimization process is performed by minimizing the cost function [2]. In this MPVC, two cost functions are introduced for the DC grid voltage and battery condition. If the DC grid voltage is higher than the reference value, the cost function is selected for battery charging as

$$J = \sum_{j=k}^{k\ N-1} f\left(\left|i_B^* - i_B(j+1)\right|,\ u(j+1)\right) \tag{2}$$

If the DC grid voltage is lower than the reference value, another cost function is applied to regulate the DC grid voltage, as

$$J = \sum_{j=k}^{k\ N-1} g\left(\left|v_{dc}^* - v_{dc}(j+1)\right|,\ u(j+1)\right) \tag{3}$$

A sequence of switching states (1 or 0) for N predefined horizon steps in time is **u** = [u (k+1), … , u(k+N)], which can be applied to (2) and (3) to find the minimum of the cost function J. The output is the sequence of switching states; however, only the first element, u(k+1), is used for the switching of converter.

Since the MPVC is performed without the inner current control loop, the deviation of v_{dc} is severe at the beginning of the sudden change of v_{dc}^*. So the system easily becomes unstable. To handle this issue, the long prediction intervals, NT_s, are needed to generate correct switching states, in order that the output voltage can follow its reference well. However, the prediction for long intervals, NT_s, takes a long computation time. To reduce this burden, there have been some existing strategies including the move blocking technique [3], which is applied to this work.

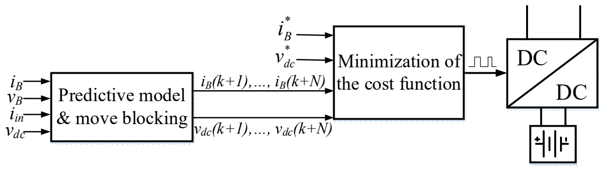

Fig. 2. Block diagram of the MPVC.

In the move blocking strategy, the NT_s sampling intervals are separated into two parts of N_1T_s and N_2mT_s, where N_1 and N_2 are the numbers of steps in each part. In the first part which is close to the step k, the prediction is performed at every T_s. However, in the second part which is far from the step k, it is carried out at every multiple of T_s, i.e., mT_s.

The block diagram of the proposed control scheme is shown in Fig. 2, where v_{dc}, i_{in}, v_B, and i_B are the DC grid voltage, the current input of converter, the battery voltage and the battery current, respectively. These feedback signals are inputs of the predictive model. With the predictive model and move blocking strategy, the future behaviors of the controlled variables $i_B(k+1), \ldots, i_B(k+N)$ and $v_{dc}(k+1), \ldots, v_{dc}(k+N)$ are predicted. Then, the optimal switching states are determined by the cost functions according to the controlled variables and their references.

3. Simulation Results

For simulation, the BDDC is applied to connect a battery to the DC microgrid with a DC load. The parameters of the system are listed in Table I.

Fig. 3 shows the performance of the MPVC when a grid disconnection occurs at 0.2s. In Fig. 3(a), before 0.2s, the power from the distributed resources is supplied to the DC grid voltage and the battery. After the grid disconnection occurs at 0.2s, the battery will transfer the power to the DC grid. In the transient period, the DC grid voltage deviation is 1.3V. In Fig. 3(b), the battery is charged during grid-connected stage, so the BDDC operates in buck mode. On the other hand, the BDDC operates in boost mode during islanding stage. The charging and discharging currents of battery are shown in Fig. 3(c).

Fig. 4 shows the mode switching in the buck-boost converter. In Fig. 4(b), mode I, II, and III represent charging, floating and discharging mode, respectively. The battery operation moves to the floating mode if the SOC is full. At 0.2s, the grid disconnection occurs. The floating mode of battery is changed to the charging mode quickly. In Fig. 4(c), the charging current in the floating mode is low, so the battery voltage increases slowly compared with the charging mode.

4. Conclusions

This research has investigated the model predictive voltage control of BDDC for ESS application. The MPVC not only performs well during the transient period but also provides the fast seamless bidirectional control method for both charging and discharging modes of converter.

This research was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (No. 2014R1A2A1A11052748).

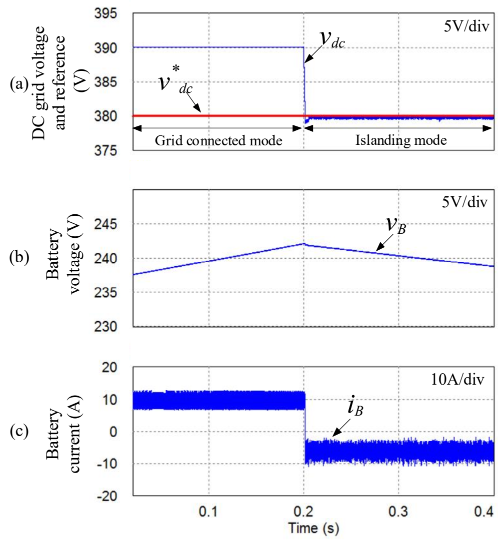

Fig. 3. Response of the MPVC under grid disconnection.

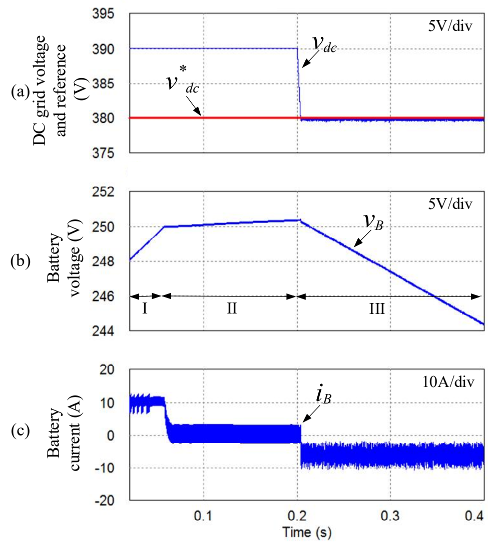

Fig. 4. Modes switching in the buck-boost converter.

Table I. Parameters of BDDC and ESS

BDDC		Battery	
L_B	5 mH	Battery capacity	10.8 Ah
R_B	1 Ω	V_{batt_nom}	222 V
C_0	1500 uF	I_{max_charge}	21.6 A

References

[1] 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.*, vol. 29, no. 2, pp. 968–978, 2014.

[2] J. Rodriguez and P. Cortes, *Predictive control of power converters and electrical drives*, 1st ed. New York: Wiley-IEEE Press, 2012.

[3] R. Cagienard, P. Grieder, E. C. Kerrigan, and M. Morari, "Move blocking strategies in receding horizon control," *J. Process Control*, vol. 17, no. 6, pp. 563–570, 2007.