분산제어 기반 독립형 직류 마이크로그리드 전력관리시스템의 HIL 시뮬레이션

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HIL Simulation of Power Management for Standalone DC Microgrids Based on Decentralized Control

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ABSTRACT

A hardware-in-the-loop (HIL) platform for a power management control of islanded DC microgrids is established. In order to avoid the complexity and high costs, a decentralized control based on the DC Bus Signaling (DBS) method is applied to the HIL system. The simulation results for the HIL microgrid platform have verified the effectiveness of power management strategy.

1. Introduction

Recently, HIL simulation has been successfully adopted in power electronics and microgrids. The HIL system can implement the time steps as low as tens of microseconds at the CPU, and tens of nanoseconds at the FPGA [1]. So, the HIL simulation can be used to study large and complicated power systems in different time scales.

In the islanded microgrids, the power management control is one of the main challenges. Many control strategies have been proposed to achieve the stable operation of the system. In order to avoid using the digital communication link, the decentralized control is applied to the microgrid [2]. The DC bus is used as a channel of communication and the operation mode of different units in the DC microgrid is realized by the voltage variation in the common bus.

In this paper, the HIL simulation test-bed is composed of a real time simulator PXI controller for modeling a standalone DC microgrid power system, a PC for acquiring data and DSP boards for controlling the interfacing converters. The validity of the power management strategy has been verified by the HIL simulation results.

2. Real-time simulation of DC microgrid systems

2.1 System modelling

A typical standalone DC microgrid consists of distributed generators (DG) such as PV, wind, and fuel cell, energy storage system (ESS), and loads. The DC microgrid system under study is shown in Fig. 1. The DC bus is formed by two DC-DC buck converters acting as DG units. An ESS is integrated through bidirectional half-bridge DC-DC converter. A resistor load is connected, which consumes a constant power.

In order to implement the DC microgrid with HIL simulator, the discrete-time models of the power circuits have to be built in the real-time simulator. Buck and bidirectional DC-DC converter circuits are shown in Fig. 2. By applying the Euler formula, the discrete-time state-space model of the converter is derived as

$$\begin{aligned} x(k\Delta T+\Delta T) &= \Psi_0 x(k\Delta T)+\Phi_0 u(k\Delta T) \quad (S_1=0) \\ x(k\Delta T+\Delta T) &= \Psi_1 x(k\Delta T)+\Phi_1 u(k\Delta T) \quad (S_1=1) \\ y(k\Delta T) &= \Gamma x(k\Delta T) \end{aligned} \tag{1}$$

where ΔT is the sampling interval, x is the state variable,

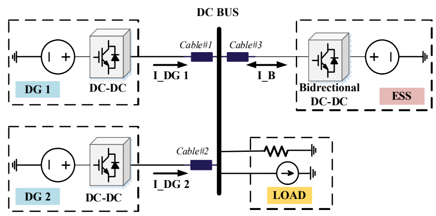

Fig. 1. Standalone DC microgrid system.

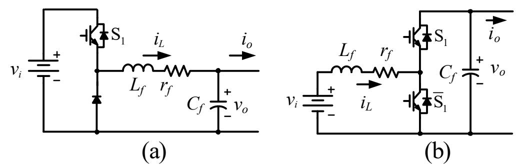

Fig. 2. DC-DC converter circuit: (a) Buck. (b) Half-bridge.

$$x(kT_s+T_s)=\begin{bmatrix} v_0(kT_s+T_s) \\ i_L(kT_s+T_s) \end{bmatrix},\ u(kT_s)=\begin{bmatrix} v_i(kT_s) \\ i_0(kT_s) \end{bmatrix}.$$

where the system matrices for the buck converter are given by

$$\Psi_{0-Buck}=\Psi_{1-Buck}=\begin{bmatrix} 1-\frac{r_f\Delta T}{L_f} & -\frac{\Delta T}{L_f} \\ \frac{\Delta T}{C_f} & 1 \end{bmatrix},\ \Gamma_{Buck}=\begin{bmatrix} 0 \\ 1 \end{bmatrix},$$

$$\Phi_{0-Buck}=\begin{bmatrix} 0 & 0 \\ 0 & \frac{\Delta T}{C_f} \end{bmatrix},\ \Phi_{1-Buck}=\begin{bmatrix} -\frac{\Delta T}{L_f} & 0 \\ 0 & \frac{\Delta T}{C_f} \end{bmatrix}.$$

and for the bidirectional converter,

$$\Psi_{0-Half}=\begin{bmatrix} 1-\frac{r_f\Delta T}{L_f} & 0 \\ 0 & 1 \end{bmatrix},\ \Psi_{1-Half}=\begin{bmatrix} 1-\frac{r_f\Delta T}{L_f} & -\frac{\Delta T}{L_f} \\ \frac{\Delta T}{C_f} & 1 \end{bmatrix},$$

$$\Phi_{0-Half}=\Phi_{1-Half}=\begin{bmatrix} \frac{\Delta T}{L_f} & 0 \\ 0 & -\frac{\Delta T}{C_f} \end{bmatrix},\ \Gamma_{Half}=\begin{bmatrix} 0 \\ 1 \end{bmatrix}.$$

2.2 Decentralized control

Depending on the DC bus voltage levels, the DG operates in either the droop mode or the MPPT mode. The normal operation voltage range is between 360 V and 400 V. This converter operates in the droop mode when the voltage of the DC bus is

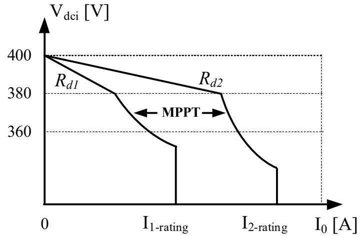

Fig. 3. *V-I* characteristics of distributed generators.

higher than 380 V. The references for the voltage controller are calculated as

$$V_{DCi}^{*} = 400 - R_{di} \cdot i_{oi} \tag{2}$$

where i_{oi} and R_{di} are the output current and the droop coefficient of i^{th} converter, respectively. Generally, the droop coefficient R_{di} is considered as a virtual resistor in the droop control, which is given as [3]

$$R_{di} = \Delta V_{dc} \cdot V_{dc\min} / P_i \tag{3}$$

where ΔV_{dc} is the voltage variation, $V_{dc\min}$ is the lower limit of the bus voltage and P_i is the rated power of i^{th} converter.

This converter operates as a constant power source if the MPPT mode is active. The *V-I* characteristic of the DG is shown in Fig. 3.

The charging and discharging modes of the DC-DC converter for battery are also determined by the DC bus voltage level. The hysteresis-based controller is employed. When the bus voltage decreases to 375 V, the operation of ESS converter is changed from charging mode to discharging mode. On the other hand, when the bus voltage increases to 385 V, it is changed from the discharging mode to the charging mode.

3. HIL Simulation Results

The standalone DC MGs power system is simulated in real-time on the NI PXI platform at a time step of 5 μs. Fig. 4 shows the HIL simulation platform. The parameters of the system are listed in Table I.

Fig. 5(a) shows the performance of the power management control when load is increasing. For $t<t_1$, two DG converters operate in droop control mode to supply power to the load. Due to the different droop coefficients, the current sharing between two DGs is different. After that, the bus voltage decreases as load power increases. When the voltage drops below 380 V, the operating mode of DGs is changed from droop control mode to MPPT mode. The discharging mode of ESS is activated at the bus voltage lower than 375 V. At t_3, the ESS supports power to the grid to maintain the bus voltage at 360 V.

At t_4, load power is decreased. The DG operating mode is changed from MPPT mode to droop control mode when the bus voltage reaches to 380 V at t_5. When the voltage is higher than 385 V, the charging mode of the ESS is activated. The ESS is controlled to charge at constant current mode. The performance of the power management control is illustrated in Fig. 5(b).

4. Conclusions

In this research, an application of real-time HIL simulation to microgrids has been investigated. The standalone DC microgid system has been built in HIL simulator. The decentralized power management based on DBS has been applied to achieve the stable operation of the system in different cases of load power.

Table I. Parameters of the system

Parameter	Value
Electrical parameters	
DG 1 power rating	4 kW
DG 2 power rating	2 kW
ESS power rating	1 kW
Maximum load power	7 kW
Nominal voltage	380 V
Line impedance #1	0.1 Ω, 1 mH
Line impedance #2	0.12 Ω, 1 mH
Line impedance #3	0.1 Ω, 1.2 mH
Droop coefficients	
R_{d1}	1.9 V/A
R_{d2}	3.8 V/A

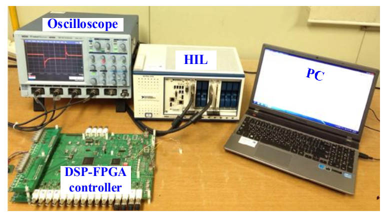

Fig. 4. HIL simulation platform.

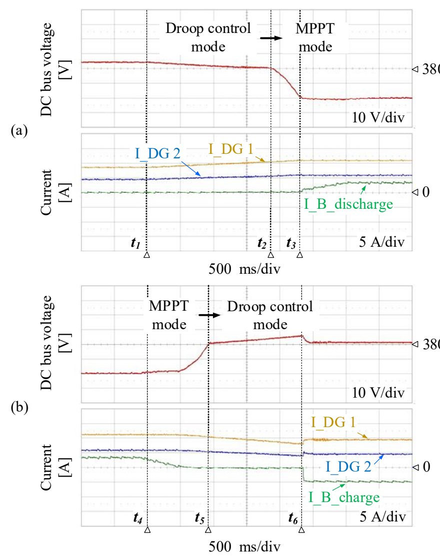

Fig. 5. System performances.

(a) Load power increases. (b) Load power decreases.

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