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Study of Bidirectional DC-DC Converter Interfacing Energy Storage for Vehicle Power Management Using Real Time Digital Simulator (RTDS)

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Abstract

The bidirectional dc-dc converter, being the interface between Energy Storage Element (ESE) and DC bus, is an essential component of the power management system for vehicle applications including electric vehicle (EV), hybrid electric vehicle (HEV), and fuel cell vehicle (FCV). In this paper, a novel multiphase bidirectional dc-dc converter interfacing with battery to supply and absorb the electric energy in the FCV system was studied with the help of real time digital simulator (RTDS). The mathematical models of fuel cell, battery and dc-dc converter were derived. A power management strategy was developed and first simulated in RTDS. A Power Hardware-In-the-Loop (PHIL) simulation using RTDS is then presented. The main challenge of this PHIL is the requirement for a highly dynamic bidirectional Simulation-Stimulation (Sim-Stim) interface. This paper describes three different interface algorithms. The closed-loop stability of the resulting PHIL system is analyzed in terms of time delay and sampling rate. A prototype bidirectional Sim-Stim interface is designed to implement the PHIL simulation.

Key Words: Bidirectional dc-dc converter, Energy management, Fuel cell vehicle, Real time digital simulator

I. Introduction

Due to high prices and short supply of fossil fuels coupled with the more stringent regulations on emissions and fuel economy, electric vehicle (EV), hybrid electric vehicle (HEV), and fuel cell vehicle (FCV) have attracted the attention of automakers, governments and customers. The energy storage element plays an important role in the above green vehicles [1]–[3]. For example, fuel cell (FC) has slow response time (time constants range from 10 to 200s) and is inertia less, energy storage elements (ESE) such as battery or ultra-capacitor are usually combined with fuel cells in order to compensate for their slow dynamics and to meet the load requirements [4]–[6].

A typical FCV power train configuration was selected to study in this paper and illustrated in Fig.1. The power train is composed of several components: a Proton Exchange Membrane (PEM) fuel cell, an ESE, a bidirectional dc-dc converter, a propulsion inverter and a propulsion motor. In the FCV power train, a bidirectional dc-dc converter is connected to ESE to boost the low voltage level from the ESE to a high DC bus voltage, and to control the bidirectional power flow between ESE and the DC bus. The fuel cell stack is connected to a unidirectional dc-dc converter to boost the voltage.

Fig. 1. FCV power train configuration.

In such a FCV system, the advantages of using bidirectional dc-dc converter to interface with ESE are: 1) boost the lower voltage of ESE to the higher voltage of DC bus, 2) keep the DC bus voltage constant consistent with State of Charge (SOC) control of ESE, 3) isolate the low voltage ESE side and high voltage DC bus side, and 4) achieve optimal and more flexible power management strategy between ESE, FC and load.

There are two traditional approaches to study a bidirectional dc-dc converter topology and control performance in vehicle applications. The first approach is software approach. The vehicle power train including the dc-dc converter can be implemented in software simulation. This approach is

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economic, safe and flexible. However, the simulation time will increase significantly if the system becomes complicated and the power management control becomes delicate. For example, it will take Matlab/Simulink more than 3 hours to simulate 200 seconds of ECE R40 driving cycle to study the dc-dc converter dynamic performance under applied power management strategy in FCV application.

The second approach is hardware approach. The hardware of bidirectional dc-dc converter is either connected to a resistor load [7] or connected to a real FCV test bed [8]. The former implementation is easy and cost-effective but limit for dc-dc converter dynamics study since the bidirectional power flow and state of charge (SOC) control of ESE cannot be implemented. Moreover, the linear load resistor cannot emulate the real vehicle conditions very well. The FCV hardware test bed provides a most accurate way to investigate the dc-dc converter performance under proposed power management strategy in the real vehicle conditions. However, it is costly and time-consuming. In addition, after the hardware test bed is built, it is not flexible to test the system operation if the configuration of a power train is required to change and so does power management strategy.

This paper presents a new solution to study a bidirectional dc-dc converter interfacing with ESE for FCV using real time digital simulator (RTDS). RTDS can provide benefits in both software and hardware approach. Firstly, FCV subsystem models including the PEM fuel cell, the ESE and the proposed multiphase bidirectional dc-dc converter are developed and simulated in RTDS. With the fast computation through distributed parallel processing of the RTDS, the complete FCV power train with its power management can be simulated in RTDS in real time. Therefore the time-consuming demerit of traditional software-based approach can be avoided in RTDS software simulation.

Secondly, a hardware prototype of a bidirectional dc-dc converter was built in the laboratory and connected to the rest of the FCV system simulated in RTDS using Power Hardware-In-the-Loop (PHIL) simulation method. PHIL simulations have been reported in [9]–[11]. This paper provides a RTDS based PHIL simulation to study dc-dc converter with proposed power management strategy in a virtual FCV system under a wide range of realistic conditions repeatedly, safely and economically.

The key to an effective PHIL is the interface called Simulation-Stimulation (Sim-Stim) interface between the simulated system and the real hardware. The characteristics of the interface (i.e., from time delay, sampling rate, etc.) can result in instability. In order to avoid equipment damage and to acquire reliable experimental results, a stability investigation is required before performing the PHIL simulation. This paper describes three different interface algorithms (Current-Voltage amplification, Voltage-Current amplification and Voltage-Voltage amplification). The closed-loop stability of the resulting PHIL system is studied analytically in terms of time delay and sampling rate.

Fig. 2. Power management strategy for the FCV power train.

II. Fuel Cell Vehicle Subsystem Models And RTDS Simulation

The interfacing of bidirectional dc-dc converter with ESE is an essential component of FCV power management, which is illustrated in the developed power management strategy of Fig. 2. In this strategy, fuel cell is controlled to supply the average power of the load power and the system loss. The fuel cell power flow control is achieved by regulating the fuel cell current to be the desired value. The ESE will supply power or absorb power by controlling the phase shift angle of the proposed three-phase bidirectional dc-dc converter. To study how the bidirectional dc-dc converter interfacing with ESE to assist the power management strategy, the complete FCV power train is firstly to be modeled and simulated.

A. PEM Fuel Cell System Dynamic Model

In [13], El-Sharkh introduced a model of PEM fuel cell. The model has been modified for this application by adding complexity due to the electrode phenomenon called the charge double layer. A detailed PEM fuel cell dynamic model developed in this study. The V-I curve and P-I curve of PEM fuel cell is also shown in Fig. 3. The model parameters are shown in Table II in the Appendix A. The slow dynamics of the fuel flow causes the voltage drops or rises before reaching a new steady state value. This voltage drops or rises could be compensated by a secondary ESE such as battery or ultra-capacitor, and will determine its capacity.

B. Energy Storage Element Dynamic Model

A 12 V battery is selected as the ESE in the simulation. The circuit proposed in [14] can accurately model the dynamic behavior of the battery. The battery model is listed in Fig. 4 where the parameters were derived from the measurements in the laboratory using a 12V lithium ion battery (U24-12RT by Valence Technology). The validation of the battery dynamic model is approved by simulated and the experimental analysis in [14].

C. Bidirectional DC-DC Converter Model

A number of topologies are proposed to interface with ESE [15]–[18]. A soft-switching 50KHz three-phase isolated

Fig. 3. The adopted dynamic PEM fuel cell with reformer model with V-I and P-I characteristic.

Fig. 4. The battery transmission-line dynamic model.

bidirectional dc-dc converter is selected in this study because of (1) reduction of current ripple due to three-phase, (2) reduction of dc capacitance due to smaller current ripple, (3) higher dynamics due to smaller inductors, and (4) higher efficiency due to smaller current stress and soft-switching. The topology is dual three-phase bidirectional dc-dc converter (DTHB) shown in Fig.5. The power flow is bidirectional and controlled by the phase shift angle ϕ between active bridges at low voltage side and high voltage side. The commutation inductor L_S is acting as the intermediate element to store and transfer the power. Let $C_1 = C_2 = C_P$, $C_3 = C_4 = C_S$. As duty ratio $D = 0.5$, $V_1 = V_2 = 0.5V_d$ and $V_3 = V_4 = 0.5V_o$ will be established. The key operating waveforms in boost mode and buck mode of a DTHB converter are illustrated in Fig. 6.

An average model of the DTHB converter was modeled and simulated. I_{in}, V_d and V_o are chosen to be state variables; V_b, V_s and ϕ are chosen to be control inputs and V_o is chosen to be output in boost mode; V_{in} is chosen to be output in buck mode. The average model of the DTHB converter in either direction can be expressed as follows in (1). The power flow can be calculated as equation (2). Based on equation (1), the average circuit model is derived and shown in Fig. 7 where $g = \frac{3\phi(\pi-|\phi|)}{2\pi\omega L_s}$. The small signal model of the DTHB converter is developed in Appendix B to design the controller to allow the converter to meet load regulation and transient response specifications.

$$\begin{cases} <\dot{I}_{in}> = -\dfrac{3R_b}{L_{dc}} <I_{in}> - \dfrac{3}{2L_{dc}} <V_d> + \dfrac{3}{L_{dc}} <V_b> \\ <\dot{V}_d> = \dfrac{1}{C_P} <I_{in}> - \dfrac{3\phi(\pi-|\phi|)}{2\pi\omega L_S C_P} <V_O> \\ <\dot{V}_O> = \dfrac{3\phi(\pi-|\phi|)}{2\pi\omega L_S C_S} <V_d> - \dfrac{2}{R_s \cdot C_S} <V_O> + \dfrac{2}{R_s C_s} <V_s> \end{cases} \quad (1)$$

$$P_o = \frac{3\phi(\pi-|\phi|)}{4\pi\omega L_s} <V_d><V_o>. \quad (2)$$

Fig. 5. Dual three-phase half-bridge bidirectional dc-dc converter (DTHB).

Fig. 6. (a) The operating waveforms when DTHB works in boost mode, (b) the operating waveforms when DTHB works in buck mode, D=0.5.

Fig. 7. Average circuit model of the DTHB converter.

Fig. 8. Block diagram of FCV power train on RTDS.

(a) (b) (c)

Fig. 9. Simulation results of FCV power train. (a) Fuel cell current, DC bus voltage and Fuel cell power, (b) battery current, battery voltage and battery power, (c) load profile.

Fig. 10. Structure of the PHIL system showing the Sim-Stim interface, VES and HUT.

This paper is focused on developing and verifying the power management strategy between dc-dc converter and energy storage element for fuel cell vehicle application. Therefore the dynamic model of dc-dc converter is studied in this paper since it will affect the power train control system design. The topology, including the transformer design, as well as the bidirectional control loop of dc-dc converter can be found in [22], [23].

D. Introduction of Simulation Environment RTDS

Real Time Digital Simulator (RTDS) is a fully digital electromagnetic transient power system simulator that operates in real time [12]. The simulator is generally designed to simulate systems in real time with time-step size about 50μs. It

Fig. 11. Equivalent circuit of the PHIL simulation (Current-Voltage amplification interface algorithm).

Fig. 12. Block diagram of the PHIL system.

Fig. 13. Voltage-Current amplification interface algorithm.

Fig. 14. Voltage-Voltage amplification interface algorithm.

has the capability of simulating sub-networks modeling power electronic converters in real time, which can be interfaced to the main network solution with a small time-step of $\sim 2\mu$s. The system makes use of a number of digital signal processors (DSPs) operated in parallel, and provides a number of digital and analog I/O ports for interfacing hardware to the simulation. Its real time capability allows the user to incorporate real devices into the simulation in a closed loop environment. The simulation cases are constructed, downloaded to the simulator, and monitored and controlled using a custom software suite, RSCAD.

E. FCV Power Train Simulation on RTDS

With a 5HP dynamic induction machine model, the FCV system with battery is simulated under the Economic Commission for Europe Regulation 40 (ECE R40) driving cycle on RTDS [19]. A complete FCV system model of power train is implemented on RTDS as illustrated in Fig.8. The PEM fuel cell system dynamic model, the battery dynamic model and the proposed DTHB converter model were simulated with time step of 50μs. The three-phase propulsion inverter and the induction machine for propulsion application were simulated with smaller time step $\sim 2\mu$s

Fig. 9 gives the simulation results of FCV power train. The value of fuel cell output power corresponds to the averaged load power plus system loss during one driving cycle. The battery power curve P_{Bat} shows that the battery compensates for the difference between the electric drive requirements and the power provided by the fuel cell system. During the accelerating, the energy flowing from the battery provides the

the peak load power, while during the regenerative braking, when the motor operates as generator, the battery power drops to negative values, which indicate a recovery of braking energy.

Fig. 15. Discrete control representation of the PHIL system.

Fig. 16. Simplified dc power system with constant power load.

III. Power Hardware-In-the-Loop (PHIL) Simulation

Section II enables the study of bidirectional dc-dc converter interfacing with ESE in FCV power management strategy using software simulation environment. However, due to the limitations of software simulation, some important information of the dc-dc converter operation, especially in small time step will be lost therefore some potential issues of dc-dc converter switching operation and control under wide system dynamic environment may not be able to be identified in the simulation. The most accurate way to evaluate the dc-dc converter and control in the system environment is to operate the whole system including the converter in real hardware conditions. This section provides an alternation solution, a PHIL simulation to achieve the advantages of both hardware and software approaches.

A. Simulation-Stimulation Inteface

The key to an effective PHIL is the interface called Simulation-Stimulation (Sim-Stim) interface (shown in Fig.10) that connects the Hardware-Under-Test (HUT) with the Virtual Electrical System (VES). The Sim-Stim interface translates the computed VES power information output (e.g. voltage, current, frequency, phase, harmonics, etc.) via the DAC and power source/sink into real energy which powers to the HUT (feedforward). Moreover, the Sim-Stim interface also monitors HUT and supplies information on its operating states to the VES via the sensors and ADC (feedback), thus allowing closed-loop, real-time interaction between the HUT and the VES as if the HUT were connected to a real system.

The stability of a PHIL system will be affected by the newly introduced Sim-Stim interface parameters since the presence of the Sim-Stim interface in the PHIL system will introduce additional dynamics into the system both in the feedforward and feedback paths. To analyze the stability effect caused by additional dynamics of interface, an equivalent circuit of the PHIL was used, which was shown in Fig. 11. Z_1 is the simulated impedances and Z_2 is the real impedance. The

Fig. 17. Bode diagrams of a PHIL system in terms of sampling.

Sim-Stim interface is Current-Voltage amplification interface algorithm.

A PHIL system can be represented by its transfer function blocks as shown in Fig. 12. In the diagram, u_1, u_2 are the internal stimulus in the simulated system and the hardware, respectively, and y_1, y_2, r_1, r_2 are the interface signals transmitted between the two subsystems. Applying this analysis to the system in Fig.11, we derive: $u_1 = V_S$, $T_{11} = 1$, $T_{12} = Z_1$, $y_1 = V_1$, $y_2 = V_2$, $T_F = e^{-T_{d1}s}$,$u_2 = 0$, $T_{21} = 0$, $T_{22} = 1/Z_2$,$r_1 = I_1$, $r_2 = I_2$,$T_B = e^{-T_{d2}s}$. Then the open loop transfer function for the PHIL simulation can be presented by equation (3):

$$G_o(s) = \frac{Z_1(s)}{Z_2(s)} e^{-T_d s} \tag{3}$$

where $T_d = T_{d1} + T_{d2}$. If $T_d = 0$, and then:

$$G_o(s) = \frac{Z_1(s)}{Z_2(s)}. \tag{4}$$

T_d is the whole time delay introduced in the PHIL simulation, which is mainly caused by the computational time of the numerical model and A/D, D/A converters, etc. T_{d1} and T_{d2} represent the delay time in the forward and feedback circuits, respectively. The open loop transfer function or the virtual system which has no time delay is presented by equation (4). Since the factor of $e^{-T_d s}$, which is a pure time delay element, cause linear phase lag in the bode diagram. Therefore, comparing equation (3) with (4), it can be deduced that even the virtual system in equation (4) were stable, the PHIL simulation may lose stability due to the factor of $e^{-T_d s}$.

Using the Nyquist stability criteria, if there are no poles of open loop transfer function $G_o(s)$ in the right-half s plane, the system is stable when there is no encirclement of the $-1 + j0$ point.

A PHIL simulation can be implemented in different ways. Taking the system in Fig. 11 as an example, a Voltage-Current amplification interface implementation is shown in Fig. 13. Note that instead of amplifying the voltage, V_1, now the current, I_1, is amplified and the voltage across the load impedance is measured and fed back to the simulator.

Applying the analysis of block diagram of PHIL system in Fig. 11 to the Voltage-Current amplification interface algorithm in Fig. 13, we derive: $u_1 = V_S$, $T_{11} = 1/Z_1$, $T_{12} = 1/Z_1$, $y_1 = I_1$, $y_2 = I_2$, $T_F = e^{-T_{d1}s}$, $u_2 = 0$, $T_{21} = 0$, $T_{22} = Z_2$, $r_1 = V_1$, $r_2 = V_2$, $T_B = e^{-T_{d2}s}$. Then the open loop transfer function for the PHIL simulation can be presented by equation (5):

$$G_o(s) = \frac{Z_2(s)}{Z_1(s)} e^{-T_d s}. \tag{5}$$

Again, using the Nyquist stability criteria, if there are no poles of open loop transfer function $G_o(s)$ in the right-half s plane, the system is stable when there is no encirclement of the $-1 + j0$ point. Comparing equation (3) with (5), a PHIL system not stable with Current-Voltage amplification interface algorithm can be stable with Voltage-Current amplification interface implementation. In conclusion, the interface algorithm can affect the PHIL simulation system instability issue. Therefore, a proper interface algorithm should be applied in a PHIL system.

Another interface method utilizes the commutating bus as shown in Fig. 14, which is the Voltage-Voltage interfacing at the commutating bus. Using this technique, the voltage V_2' measured from the HUT was read by the simulator using A/D converters. The simulator then transforms V_2' to a voltage V_1 in series of a resistance Z_{ab} to allow incorporation into the VES. The resistance was kept small so as not to significantly affect the solution. After incorporating the V_1 into the VES, V_1' was calculated. That value of V_1' was in turn applied to the HUT via D/A converters in combination with voltage amplifiers V_2, thus closing the loop.

Furthermore, applying the analysis of block diagram of PHIL system to Voltage-Voltage interface algorithm in Fig. 14: $u_1 = V_S$, $T_{11} = Z_{ab}/(Z_1 + Z_{ab})$, $T_{12} = -Z_1/(Z_1 + Z_{ab})$, $y_1 = V_1'$, $y_2 = V_2$, $T_F = e^{-T_{d1}s}$, $u_2 = 0$, $T_{21} = 0$, $T_{22} = Z_2/(Z_2 + Z_{ab})$, $r_1 = V_1$, $r_2 = V_2'$, $T_B = e^{-T_{d2}s}$. Then the open loop transfer function for the PHIL simulation can be presented by equation (6):

$$G_o(s) = -\frac{Z_1 Z_2}{(Z_1 + Z_{ab})(Z_2 + Z_{ab})} e^{-T_d s}. \tag{6}$$

From the above equation we conclude that at least for resistive systems the Voltage-Voltage interface method has higher stability than the Voltage-Current and Current-Voltage interface methods because it is easier to keep the magnitude of $G_0(s)$ below unity. This method is also used in large circuit simulation software such as SPICE, which is the method 2 in [20]. It separates the original circuit into multiple sub-circuits and utilizes iteration methods for the solution. A detailed discussion about this algorithm can be found in [21]. The dynamics, stability and implementation of three interfaces are analyzed and illustrated in Table I. More asterisks mean higher stability and easier implementation in Table I.

B. *Discussion of Sampling Rate and Time-Delay Effect*

Both the time-delay element introduced by the Sim-Stim interface and the sampling rate between simulation and hardware will affect the stability of performance of the PHIL system.

A discrete-time (DT) model of the PHIL system is first determined to investigate the system stability by obtaining

Fig. 18. Block diagram of the PHIL simulation for FCV with bidirectional interface.

Fig. 19. PHIL simulation system for FCV test bed.

TABLE I
STABILITY AND IMPLEMENTATION COMPARISON BETWEEN THREE INTERFACES

Interface	Open loop transfer function	Stability	Imple-mentation
Current-Voltage interface	$G_o(s) = \frac{Z_1(s)}{Z_2(s)} e^{-T_d s}$	*	**
Voltage-Current interface	$G_o(s) = \frac{Z_2(s)}{Z_1(s)} e^{-T_d s}$	**	***
Voltage-Voltage interface	$G_o(s) = -\frac{Z_1 Z_2}{(Z_1+Z_{ab})(Z_2+Z_{ab})} e^{-T_d s}$	***	*

region of stable operation in terms of Sim–Stim interface parameters with the impedance parameters fixed. The stability of the PHIL system is guaranteed if all the eigenvalues of the system matrix lie inside the unit circle. Note that the eigenvalues of the PHIL system, thus stability, are function of not only the system parameters but also of the Sim–Stim interface parameters. Furthermore, even though the original system (without the Sim–Stim interface) is only a first-order continuous system, the order of the DT model of the PHIL system would be increased at least by one degree due to the introduction of the Sim–Stim interface. The effects of sampling period and time delay on stability performance of the PHIL system can be analyzed using the region of stable operation. Such a region of stable operation would be helpful in determining how much delay the system can tolerate before it becomes unstable, indicating the trade-off between the sampling period and delay. It is generally well known that increasing the sampling rate at the input would enhance the stability of the closed-loop system. However, it should also be

(a) (b)

Fig. 20. (a) PHIL simulation waveforms on RTDS. (b) PHIL waveforms on hardware.

noted that to enlarge sampling periods may also cause closed loop instability. Hence, it is important to determine the limit of the sampling period that guarantees closed loop stability, which would be the topic of our next paper.

Based on the above analysis, the capability of the PHIL to represent the physical all-hardware system is a function of the sampling rate between simulation and hardware. The stability of overall system will be decreased, when the sampling frequency is decreased.

To verify this, the dynamics of a PHIL system are represented in block diagram form in Fig. 15. From this diagram, the output voltage of the PHIL system V_{dc} is calculated in terms of source voltage in the Z-domain as

$$V_{dc}(z) = \frac{G_1(z)G_2(z)}{1+G_1(z)G_2(z)} V_S(z) \tag{7}$$

where $G_1(z) = Z(G_1(s)H_{zoh}(s))$ and

$$G_2(z) = Z(G_2(s)H_{zoh}(s)). \tag{8}$$

The open-loop transfer function in Fig.15 is

$$G(z) = G_1(z)G_2(z). \tag{9}$$

When the PHIL is introduced, equation (7) represents the overall system dynamics. To analyze differences due to sampling and its influence on system stability, the system shown in Fig.16 was developed using Matlab. In this typical system, the source impedance is a resistor $R = 4.2\Omega$ in series with an inductor L=5mH. Shown in the figure, a capacitor $C = 150\mu$F in parallel with a converter is the load working as a constant power load. There is a command voltage 150V and power 1118W at the load side. The values of series resistance, inductance, and bus capacitance were selected to make sure that the system was stable in the steady-state, which provided a means to ensure that respective instabilities were caused by the low sampling, and not the interaction between source and load.

The bode diagram of this PHIL system represented using both continuous and discrete analysis is shown in Fig. 17. It can be seen that a system is stable in continuous time. But it is predicted to be unstable as the sampling frequency of PHIL is reduced. In this figure, at the sampling rate of 1μs, the PHIL and continuous system results are almost identical. But when the sampling period is increased to 0.4ms, the phase margin becomes negative, which would predict an unstable system. It is verified that as the sampling frequency is decreased, the stability of overall PHIL system is decreased.

C. Power Hardware-In-the-Loop Simulation Setup

The PHIL simulation of a FCV system block diagram is proposed in Fig. 18. The FCV power train is modeled and simulated on RTDS in real time, which including the PEM FC model, the unidirectional dc-dc converter model, the three-phase propulsion inverter model and the induction motor model. The ESE and the bidirectional dc-dc converter are built as hardware. By Sim-Stim interface, the ESE should perform the same when connecting to the PHIL system as when it is a part of an all hardware system. ESE is required to absorb the regenerative electric energy during deceleration and provide peak power during acceleration transients respectively. Therefore, a bidirectional Sim-Stim interface is the key part in the PHIL simulation of the FCV system.

Based on the above interface analysis, a voltage-current amplification interface algorithm is applied to the PHIL simulation of the FCV system. The bidirectional Sim-Stim interface is implemented by a voltage amplifier and an electronic load

in the experiment shown in Fig. 18. The voltage amplifier is LV3622 made by AETechron. The output voltage is 305Vpk maximum, no load condition. Output current is 7.25Apk maximum. Output power is 630W maximum continuous (into 24ohm). Therefore, it is possible that the voltage amplifier generates 250V, 1∼2A output. The electronic load is PLA3K-400-300 made by AMREL. The voltage range is 0∼400Vdc rating. The current range is 0∼30Adc rating. The power range is 0∼3KW rating. In Fig.18, I_1 is the current signal derived by the virtual FCV system simulated on RTDS and amplified by the hardware to the corresponding I_2. The I_1 information in a driving cycle is derived from the simulated ECE R40 driving cycle. The V_2 is the DC bus voltage controlled to be constant in the hardware and then fed back to the virtual FCV system simulated on RTDS to the corresponding V_1. When ESE provides power during the motor acceleration, $I_1 > 0$ and $I_2 > 0$. While ESE absorbs the regenerative power during the motor deceleration, $I_1 < 0$ and $I_2 < 0$. But during the whole driving cycle, the DC bus voltage V_2(corresponding V_1 on RTDS) is kept constant.

In the regenerative power flow mode, ESE absorbs the regenerative power and $I_2 < 0$. Only the voltage amplifier works in this mode. $|I_{2amp}|$ is controlled to be equal to $|I_2|$ by regulating the voltage V_{2amp}. The voltage signal V_{2amp} is derived from RTDS and amplified by the voltage amplifier. The electronic load does not work in this mode and $I_{2eL} = 0$. While in the motor acceleration stage, ESE provides power to the motor and $I_2 > 0$. Only the electronic load works in this stage. The current signal I_{2eL} is amplified by the electronic load and $I_{2eL} = I_2$. The voltage amplifier does not work in this stage and $V_{2amp} = V_2$, $I_{2amp} = 0$. Therefore, a bidirectional power flow PHIL system is achieved. The ESE should perform the same when connecting to the PHIL system as when it is a part of an all hardware system.

In Fig. 19, the PHIL simulation system test bed is developed in the lab. The FCV power train VES is modeled and simulated on RTDS in real time. The bidirectional dc-dc converter and the bidirectional Sim-Stim interface composed by the voltage amplifier and the electronic load are both developed as hardware shown in the figure. Lithium ion battery is used as the ESE in the test bed.

D. Power Hardware-In-the-Loop Simulation Results

Based on the above system setup, the PHIL simulation results are shown in Fig. 20. In Fig. 20(a), real-time simulation waveforms on RTDS of some signals are illustrated. During the whole period, FC power is controlled to be constant and $P_{FC} = 687.4W$. The DC bus voltage V_1 on RTDS is controlled to be constant and $V_1 = 200V$. The first stage and second stage are in Buck mode. In the Buck mode, power flow from the motor load to charge the ESE and $I_1 < 0$. In the first stage, ESE absorbs power 427.4W. In the second stage, ESE absorbs power 587.4W. Only the voltage amplifier works in the Sim-Stim interface and $I_{2amp} > 0$, $V_{2amp} > V_1$. The third stage and fourth stage are in Boost mode, where power is provided by the ESE to the motor load and $I_1 > 0$. ESE supplies power 651.6W in the third stage and 751.6W in the fourth stage. According to the Sim-Stim interface analysis, only the electronic load works in the Boost mode and $I_{2eL} > 0$, $I_{2amp} = 0$. In Fig.20(b), PHIL waveforms on hardware are present. During the whole period, the DC bus voltage V_2 matches the corresponding voltage signal V_1 on RTDS, which has a constant value of 200V. The battery is charged during the Buck mode in the first and second stage and $I_{Bat} < 0$. During Boost mode in the third and fourth stage, the battery is discharged and $I_{Bat} > 0$. During the whole period, the battery voltage V_{Bat} varies within a small range. I_{2eL} waveform on hardware in Fig. 20(b) follows the same value and curve of that in Fig. 20(a) on RTDS.

Although the PHIL simulation results of Fig. 20 are similar to the pure simulation results of Fig.9, the controller parameters of bidirectional dc-dc converters were designed differently in PHIL simulation and pure simulation. The controller design of dc-dc converter derived from PHIL simulation is more accurate, since in the PHIL simulation the bidirectional dc-dc converter interfacing with ESE and its power management controller are all implemented in hardware, therefore eliminates the unpredictable error from the modeling of the converter, ESE and the controller, which increases the realism of the design based on the PHIL simulation.

IV. Conclusion

This paper presents a study of a bidirectional dc-dc converter interfacing with ESE under a delicate power management strategy using RTDS in the fuel cell vehicle application. The software simulation of FCV in RTDS provides an efficient real-time simulation environment to investigate the dc-dc converter and ESE dynamic performance. Moreover, the Power Hardware-In-the-Loop capability of RTDS offers a more accurate method compared to traditional software simulation method, as well as a more flexible and safe method compared to hardware vehicle test bed method.

The key to an effective PHIL is the interface called Simulation-Stimulation interface between the simulated system and the real hardware. The effect of additional dynamics introduced by the Simulation-Stimulation interface on the system stability has been analyzed in detail. The stability effect cause by time delay and sampling rate of the interface was presented and can be analyzed using the region of stable operation. Such a region of stable operation would be helpful in determining how much delay the system can tolerate before it becomes unstable, indicating the trade-off between the sampling period and delay, which would be the topic of a future extension of this paper. Based on the interface analysis, a voltage-current amplification interface algorithm is applied to the PHIL simulation of the FCV system in this paper. The bidirectional Simulation-Stimulation interface is implemented by a voltage amplifier and an electronic load. The PHIL simulation results demonstrate the effectiveness of this approach in studying the bidirectional dc-dc converter interfacing with ESE for vehicle applications.

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APPENDIX A

TABLE II
PEM FC DYNAMIC MODEL PARAMETERS

Stack Temperature, (K)	343
Faraday's constant, F (C/kmol)	96484600
Universal gas constant, R [J/(kmolK)]	3814.47
No load voltage, E_0 (V)	1.096
Number of cells, N_0	40
Kr constant = N_0/4F [kmol/(sA)]	1.036e-7
Utilization factor, U	0.8
Hydrogen valve constant, K_{H2} [kmol/(s atm)]	4.22e-6
Water valve constant, K_{H2O} [kmol/(s atm)]	7.716e-6
Oxygen valve constant K_{O2} [kmol/(s atm)]	2.11e-5
Hydrogen time constant, τ_{H2} (s)	3.37
Water time constant, τ_{H2O} (s)	18.418
Oxygen time constant, τ_{O2} (s)	6.74
Reformer time constant, τ_1 (s)	2
Reformer time constant, τ_2 (s)	2
Conversion Factor, CV	2
Hydrogen-oxygen flow ratio, r_{H-O}	1.168
Charge double layer capacitor, C_d (F)	0.27
Ohmic loss of the stack $\mathrm{R^{int}} = \mathrm{R_r} + \mathrm{R_a}[\Omega]$	0.78

APPENDIX B

The small signal model of the DTHB converter is developed as in equation (10), the transfer function matrix from input to output can be derived, as $T_1(s) = \frac{\tilde{V}_o(s)}{\tilde{\phi}(s)}$ in equation (11), $T_2(s) = \frac{\tilde{V}_o(s)}{\tilde{V}_b(s)}$ in equation (12) and $T_3(s) = \frac{\tilde{V}_o(s)}{\tilde{V}_s(s)}$ in equation (13). The transfer functions are used to design the controller to allow the converter to meet load regulation and transient response specifications, especially the control-to-output transfer function $T_1(s)$.

$$\begin{bmatrix} \dot{\tilde{i}}_{in} \\ \dot{\tilde{V}}_d \\ \dot{\tilde{V}}_o \end{bmatrix} = \begin{bmatrix} -\frac{3R_b}{L_{dc}} & -\frac{3}{2L_{dc}} & 0 \\ \frac{1}{C_p} & 0 & -\frac{3\phi(\pi-|\phi|)}{2\pi\omega L_s C_p} \\ 0 & \frac{3\phi(\pi-|\phi|)}{2\pi\omega L_s C_s} & -\frac{2}{R_s C_s} \end{bmatrix} \begin{bmatrix} \tilde{i}_{in} \\ \tilde{V}_d \\ \tilde{V}_o \end{bmatrix} + \begin{bmatrix} \frac{3}{L_{dc}} & 0 & 0 \\ 0 & 0 & -\frac{3V_o(\pi-2|\phi|)}{2\pi\omega L_s C_p} \\ 0 & \frac{2}{R_s C_s} & \frac{3V_d(\pi-2|\phi|)}{2\pi\omega L_s C_s} \end{bmatrix} \begin{bmatrix} \tilde{V}_b \\ \tilde{V}_s \\ \tilde{\phi} \end{bmatrix} \tag{10}$$

$$T_1(s) = \frac{(\pi-2\phi)(as^2+bs+c)}{\frac{24\pi^2\omega^2 L_s^2}{R_s}(\frac{R_s C_s}{2}s+1)(\frac{1}{3}C_p L_{dc}s^2 + R_b C_p s + 1)}$$

$$\begin{cases} a = 6\pi\omega L_s V_d C_p L_{dc} \\ b = 18\pi\omega L_s V_d R_b C_p - 9\phi V_o L_{dc}(\pi-\phi) \\ c = 18\pi\omega L_s V_d - 27\phi V_o R_b(\pi-\phi) \end{cases} \tag{11}$$

$$T_2(s) = \frac{3\phi(\pi-\phi)}{\frac{4\pi\omega L_s}{R_s}(\frac{R_s C_s}{2}s+1)(\frac{1}{3}C_p L_{dc}s^2 + R_b C_p s + 1)} \tag{12}$$

$$T_3(s) = \frac{1}{\frac{R_s C_s}{2}s+1}. \tag{13}$$

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