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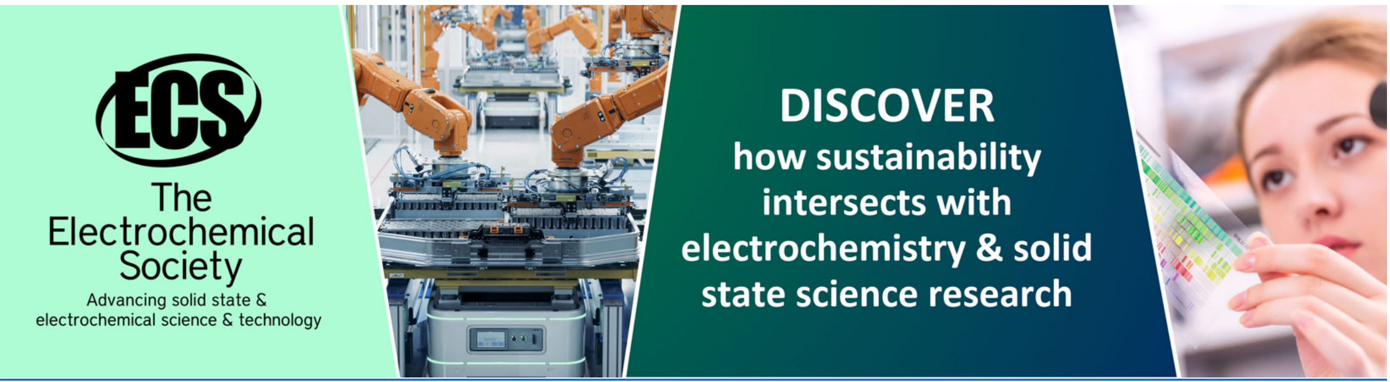

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Sliding mode control of direct coupled interleaved boost converter for fuel cell

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Abstract A three phase direct coupled interleaved boost converter (TP-DIBC) was recommended in this paper. This converter has a small unbalance current sharing among the branches of TP-DIBC. An adaptive control law sliding mode control (SMC) is designed for the TP-DIBC. The aim is to 1) reduce ripple output voltage, inductor current and regulate output voltage tightly 2) The total current carried by direct coupled interleaved boost converter (DIBC) must be equally shared between different parallel branches. The efficacy and robustness of the proposed TP-DIBC and adaptive SMC is confirmed via computer simulations using Matlab SimPower System Tools. The simulation result is in line with the expectation.

1. Introduction

It is known that fuel cells (FCs) are good energy sources to provide reliable power at steady state[1]. But a fatal disadvantage of FCs systems are slow to transient and instantaneous peak power demand, typically requested by the load. Therefore, fuel cells generally need a DC-DC power converter to boost the voltage to the required level. DC-DC converters can be used to interface the elements in the electric power train by boosting or chopping the voltage levels[2]. However, a classical boost DC-DC converter adds output current ripple. The disadvantages caused by the ripple current, include fuel consumption increasing and life time shortening, etc[3]. The various topologies and control algorithms of interleaved converter were proposed. Po-Wa Lee et al. studied two interleaved and coupled boost converter, which has good current sharing and small input current ripple[4]. Shin, H. B, et al. studied steady-state analysis of the multi-phase interleaved and coupled boost converter[5]. Seyezhai, R., and Mathur, B. L. studied a three-phase direct coupled interleaved boost converter, which has better current sharing and smaller overall current ripple compared to the uncoupled inductor [6].

A three phase direct coupled interleaved boost converter has been proposed in this paper whose advantages are reducing part count, volume, weight, and output inductor current ripple. A sliding mode controller is designed for the DIBC to ensure load voltage be tightly regulated to a given reference value. The proposed direct coupled interleaved boost converter (IBC) for FCs applications has excellent current sharing performance and property of reducing current ripple. Overall system has excellent robustness and high tracking accuracy under time-varying resistance load. Simulation results show that the proposed TP-DIBC has a low ripple and good robustness.

2. System model of Direct Coupled Three Phase Interleaved Boost Converter

There is the Simulink model of three phases IBC with direct coupled inductors in this paper, as shown in Figure 1. Each transistor is switched at the same period (Ts), at a phase difference of Ts/3. Since the output current is divided by the number of phases, which in each transistor is reduced to 1/3. The output current ripple of DIBC can be considerably reduced comparing with decoupled IBC. The coupled inductor designed with each leg of converter obtains a phase shift of 120°.

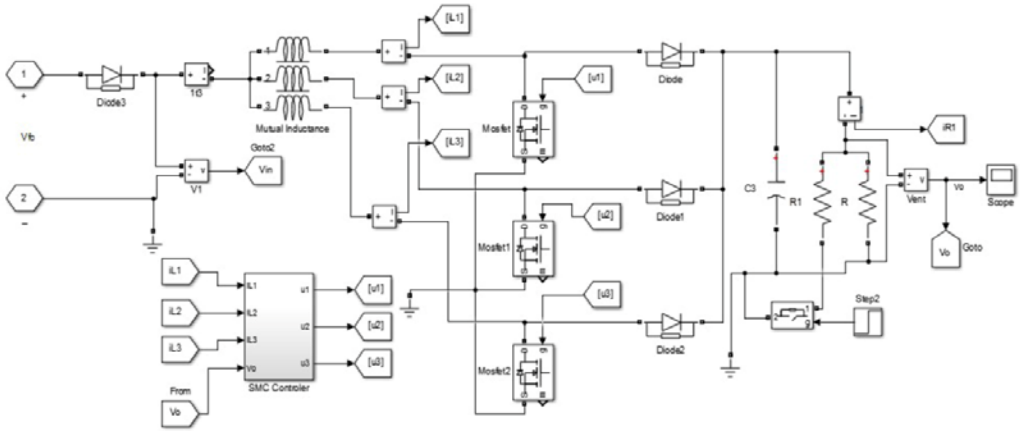


Figure 1. Simulink model for FC interface with TP-DIBC

The state space averaging model describing the operation of the converter can be written as:

$$\begin{cases} \mathrm{di_{Lk}/dt} = \dfrac{\mathrm{V_{fc}}}{\mathrm{L_k}} - (1-\mathrm{u_k})\dfrac{\mathrm{V_O}}{\mathrm{L_k}} \\ \dfrac{\mathrm{dVo}}{\mathrm{dt}} = -\dfrac{\mathrm{Vo}}{\mathrm{RC}} + (1-\mathrm{u_k})\dfrac{\mathrm{i_{Lk}}}{\mathrm{C}} \end{cases} \tag{1}$$

where $\mathrm{i_{Lk}}$ is input current; L_k is equivalent inductor of each branches[7].

3. The Design of Sliding Mode Controller

For the interleaved boost converter and fuel cell have very high nonlinear characteristics, many of nonlinear control methods for IBC topology have been proposed, especially sliding mode control method[8]. Sliding mode is a phenomenon that may appear in a dynamic system governed by ordinary differential equations with discontinuous right-hand sides. It may happen that the control as a function of the system state switches at high frequency, and this motion is called sliding mode [9-10].

A branch of the sliding mode control module is shown in (Figure 2).

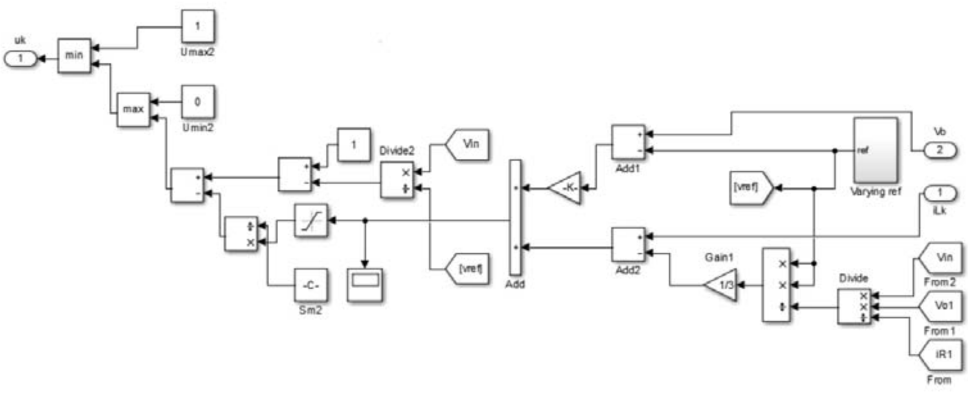


Figure 2. Simulink model of sliding mode control for DIBC

Sliding mode state variable ($\xi_k \to 0$) is composed of the voltage error and current error:

$$x_{1k} = V_o - V_{ref} \quad (2)$$

$$x_{2k} = i_{Lk} - I_{refk} \quad (3)$$

$$\xi_k(x,t) = x_{1k} + \beta_k x_{2k} \quad (4)$$

$$\dot{\xi}_k = \frac{d\xi_k}{dt} \quad (5)$$

where ξ_k is sliding variable, β_k is control gains. We define the sliding surface as:

$$S_k = \{x_k | \xi_k(x,t) = 0\} \quad (6)$$

Supposing system is lossless, we can get input power equal to output power and we find:

$$i_L = \frac{V_o^2}{V_{fc}R} \quad (7)$$

$$i_L = i_{L1} + i_{L2} + i_{L3} \quad (8)$$

From (7) and (8), i_{refk} can be given by:

$$i_{refk} = \frac{1}{3} \times i_{ref} = \frac{V_{ref}^2}{3V_{fc}R} \quad (9)$$

Comparing equations (1), (4), (5) and (7), $\dot{\xi}_k$ is derived as follows:

$$\dot{\xi}_k = \left(1 - \frac{(1-u_k)V_o}{V_{fc}}\right)\left(\frac{V_{fc}}{L_k} - \frac{\beta_k V_o}{RC}\right) \quad (10)$$

Then $$\dot{\xi}_k(u_{eqk}) = 0 \quad (11)$$

Comparing equations (7), (9) and (10) is derived as follows:

$$u_{eqk} = 1 - \frac{V_{fc}}{V_o} \quad (12)$$

The sliding mode control law can be defined as the following rules, which include two part equivalence control u_{eqk} and discontinuous control u_{disk}:

$$u_k = u_{eqk} + u_{disk} \quad (13)$$

$$u_k(t) = sat(u_k) = \begin{cases} 1 & u_k > 1 \\ 0 & u_k < 0 \\ u_k & \text{else} \end{cases} \quad (14)$$

High frequency component is actually a discontinuous trajectory that alternates between the ξ_{mink} and ξ_{maxk} which is called u_{disk}

$$u_{disk} = -\frac{\xi_k}{M_k} \quad (15)$$

M_k is a positive number. In order to guarantee the sliding mode variable is functional only in the sliding mode surface ($\xi_{mink} \le \xi_k \le \xi_{maxk}$), the value of M should meet this condition:

$$M_k \le \lfloor \xi_{mink} \rfloor + \lfloor \xi_{maxk} \rfloor \quad (16)$$

To ensure the finite time convergence, this condition should be achieved:

$$\xi_k \dot{\xi}_k < 0 \quad (17)$$

Verifying the existence of the sliding mode and attraction of the chosen sliding variable by substitution of (10), (12), (14) and (17), we can obtain:

$$.\dot{\xi} = \left(\frac{U_s}{L} - \frac{kV_{ref}}{RC}\right) < 0 \qquad \xi \to 0^+ \quad (18)$$

$$\dot{\xi} = -\frac{u_{eq}}{(1-u_{eq})} \times \left(\frac{U_s}{L} - \frac{kV_{ref}}{RC}\right) > 0 \quad \xi \to 0^- \quad (19)$$

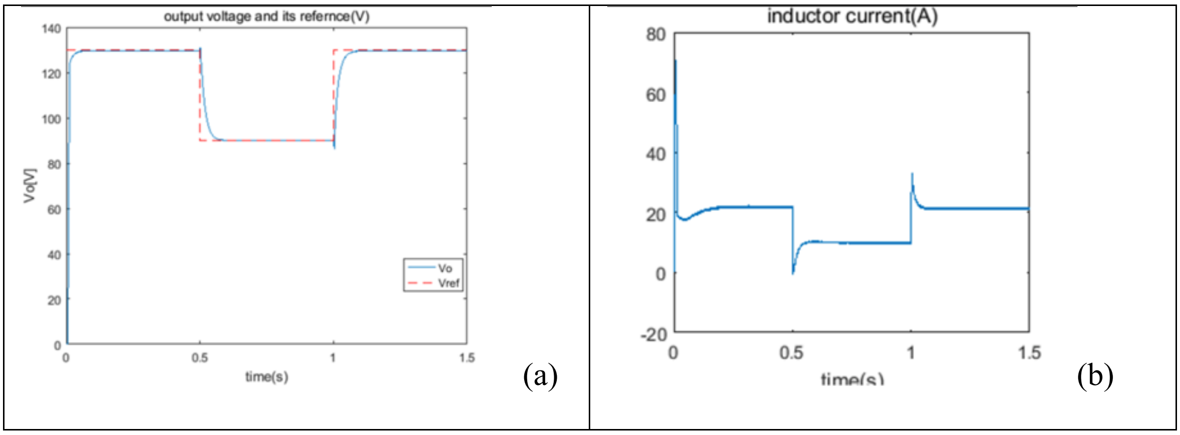
By the analysis of the above formulas (16), (18) and (19), reaching the sliding surface within a limited time as well, the targets are:

$$\begin{cases} \beta_k < \frac{U_{fc} \times R \times C}{L \times Uref} \\ u^- < u_{eq} < u^+ \\ M_k \le \lfloor \xi_{mink} \rfloor + \lfloor \xi_{maxk} \rfloor \end{cases} \quad (20)$$

4. Simulation and results

The simulation parameters are summarized as follows: self-inductance L is 5mH, coupling coefficient A is 0.7, output capacitor is 3000uF, switching frequency f_s is 25kHz, load resistance R is 50 to 100Ω, PEMFC voltage V_{fc} is 39 to 44V, control gain β1=β2=β3=1.2.

The capability of the proposed adaptive sliding mode control to ensure a perfect output voltage tracking, which illustrates a considering square reference signal switching between 90 and 130V. Meanwhile, the unknown load keeps constant, which equals to 50 Ω. The obtained controller performances are shown in Figure 3. Fig.3(a) illustrates the good tracking quality of the controller for the output voltage tracks its reference voltage well, and the output voltage ripple is 0.015V. Fig.3 (b) shows the output current with the changed reference voltage, while the current ripple is 0.3A.

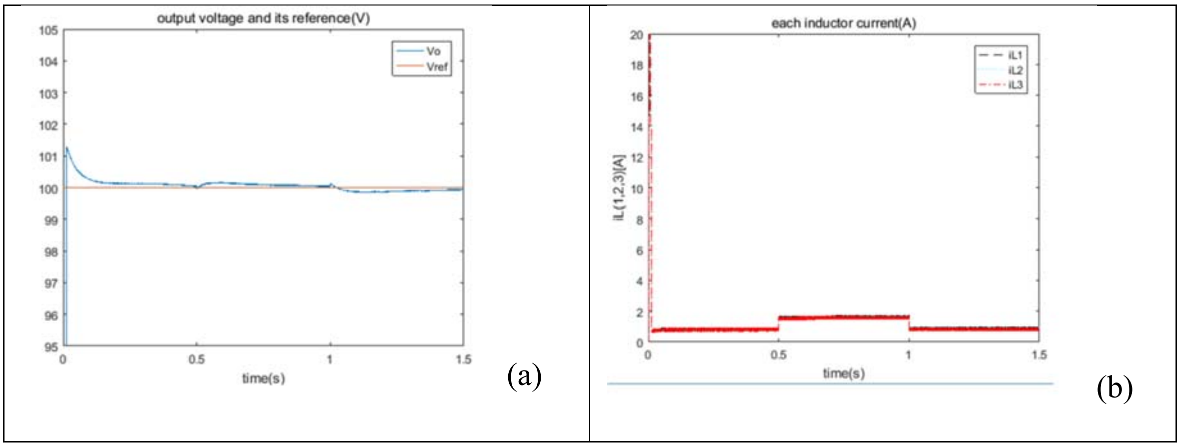


(a) Output voltage V_o and reference Vref (b) Input current in the presence voltage of reference voltage step change

Figure 3. Simulink results obtained controller performances

4.1. Output Voltage Regulation in Presence of Varying Load

The voltage reference maintains constant, $V_{ref} = 100V$, whereas the unknown load changes with time going on. Specifically, the load value is switching between 50 and 100Ω (the step at times 0.5 and 1 sec, respectively). In Figure 4, (a) illustrates the good tracking quality of the controller, and the (b) shows measured currents iL1, iL2, and iL3 in case of changeable loads and constant reference voltage.

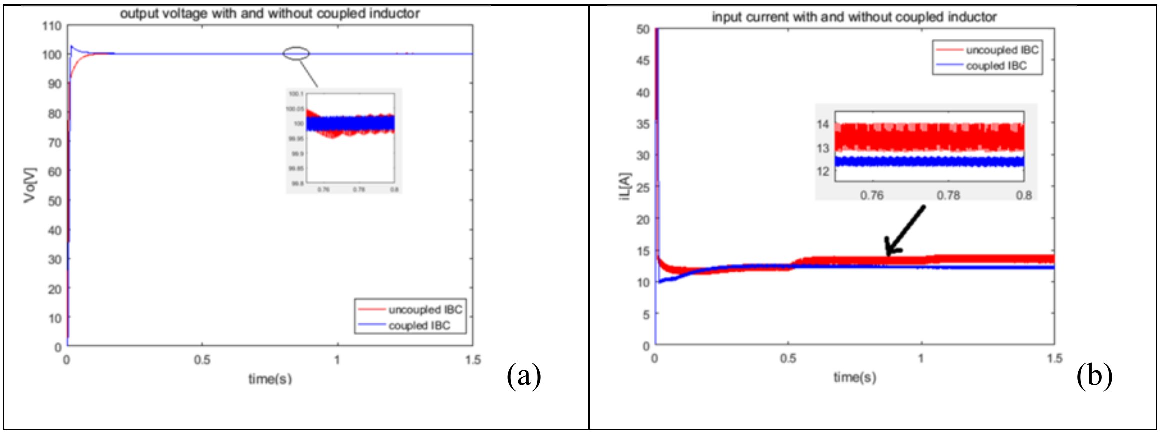


(a) Output voltage Vo and voltage reference Vref (b) Currents iL1, iL2, and iL3 in the presence of load varying

Figure 4. The voltage and current varying with the load

4.2. Simulation results of uncoupled and direct coupled IBC

Comparing the uncoupled and direct coupled IBC from Figure 5 with same control method, the coupled IBC shows the lesser voltage and current ripple, the faster response speed. Fig5(a) shows output voltage of uncoupled IBC and direct coupled IBC. Fig5(b) illustrates output current of uncoupled IBC and direct coupled IBC.



(a) Output voltage with and without coupled IBC (b) Input current with and without coupled IBC

Figure 5. the uncoupled and direct coupled IBC

5. Conclusions

Based on the adaptive control law method, a sliding mode control reduces the discontinuous component near the sliding surface is designed. The analysis demonstrates that the proposed system meet the expectations: the perfect output voltage reference tracking and equal current sharing. It also shows that the controller tracks the varying loads well. In contrast to uncoupled inductors, coupled inductors more effectively reduces the overall current ripple and enhances the response speed.

Acknowledgements

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