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DSP Based Interleaved Boost Converter for Fuel Cell Distributed Generation System

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Abstract— *Due to the high current and low voltage of fuel cells, a 2-phase interleaved boost converter is used to smooth out the current output. Eight comparable sub-circuits are given, each of which is analyzed in detail to reveal how the converter works. We create a uniform state-space averaged model of the converter in both continuous conducting mode (CCM) and discontinuous conducting mode (DCM) by categorizing its operating modes based on the waveforms of the inductor current. The transfer function is used to inform the controller design, and a DSP-320F28027-controlled 1.2kW converter prototype is built. Excellent electrical properties are shown by the hardware loop-in simulation results, proving the converter's viability for use in the Fuel Cell Distributed Generation system.*
Interleaved Boost Converter (fig. 1) is built to meet the need for low size, low weight, and high reliability.

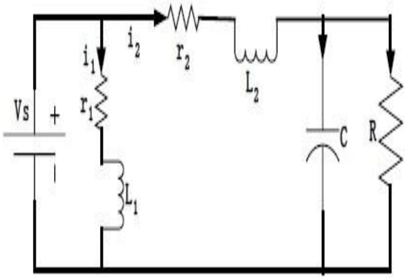
I. INTRODUCTION

Some consumers may find that distributed generation (DG) technologies provide superior solutions in terms of cost, environmental impact, power quality, and reliability when compared to more traditional options. The most promising development in terms of energy efficiency, conservation, and environmental protection is the use of fuel cell technology to DG. Rapid advancements are being made toward using proton exchange membrane fuel cells (PEMFC) as the major power source in portable power supplies and DG. PEMFC stack voltage drops significantly with increasing load current and rises with increasing temperature at constant current. So that other electrical devices may get a consistent voltage supply, a DC-DC converter is required. In addition, the Energy Management System relies heavily on the DC-DC converter.

In this study, we suggest the use of an interleaved boost converter for a fuel cell, analyze its operating principle in detail, and provide a CCM model of the converter's averaged state space. A prototype 1.2KW DC-DC converter is developed using DSP-320F28027 as the primary controller, and some of the experimental findings are reported.

THE PRINCIPLE OF INTERLEAVEDBOOST CONVERTER

The principle of Interleaved Boost Converter as follows: each phase is a BOOST/BUCK DC-DC Converter, whichis composed of a bridge of power switches and storage energy inductor. When S1u=S2u=OFF, S1d and S2d switch on and off, the system work in the BOOST mode.The power switched S1d and S2d have 180-degree phase difference of driving pulses in a cycle. The current fluctuation of input power supply is reduced greatly because the two 180-degree phase difference inductor currents minify the fluctuation of each other. In oneswitching cycle Ts, considering the commutation of powerswitched and diodes, there have eight kinds of running states.
The converter have eight equivalent sub-circuits ofstate 1-state 8, are shown below



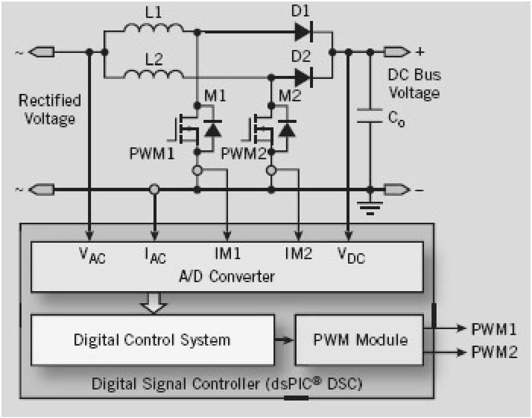


Fig 2a. The equivalent sub-circuits of state 1

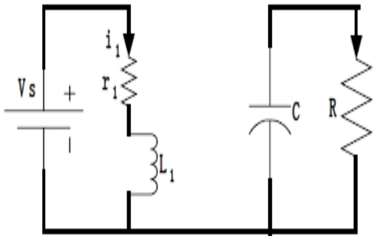


Fig 2b. The equivalent sub-circuits of state 2

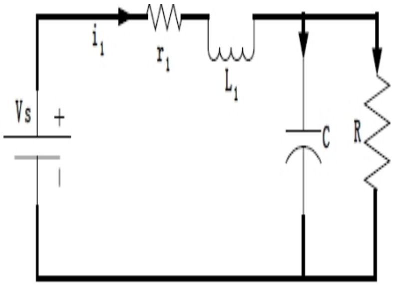


Fig 2c. The equivalent sub-circuits of state 3

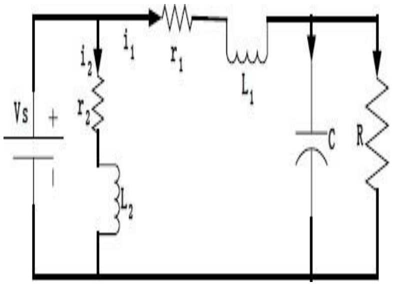


Fig 2d. The equivalent sub-circuits of state 4

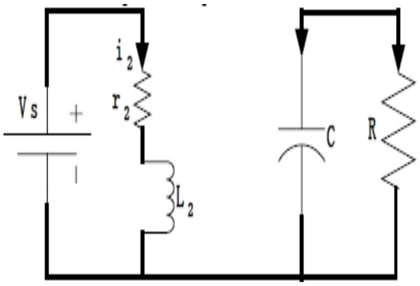
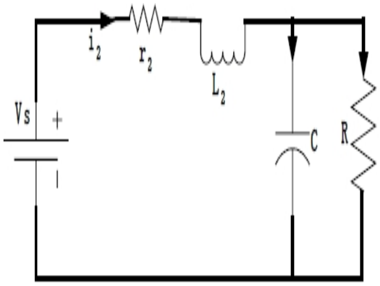


Fig 2e. The equivalent sub-circuits of state 5



r_1

0

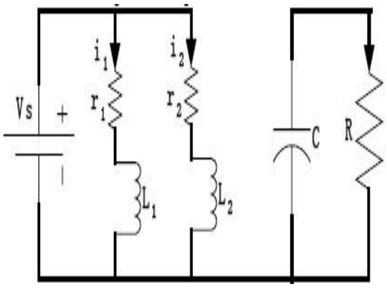


Fig 2g. The equivalent sub-circuits of state 7

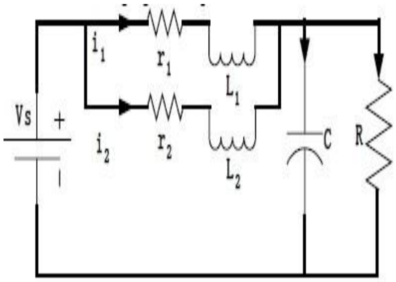


Fig 2h. The equivalent sub-circuits of state 8

II. STATE-SPACE AVERAGED SYSTEM MODEL

The state space equations are separately established according to the equivalent circuits in Fig 2. Supposing $\mathbf{i_1}$,$\mathbf{i}_2$,V_c as the state variables and V_s as the variable of theinput voltage and $V_\mathbf{0}$ as the variable of the output voltage. The state equation of the converter is :

$\dot{X}= A_n X+ B_n V_s$......................during d_{n*} T_s

$V_\mathbf{0} = C_n X$

n=1, 2,3,4,5,6,7,8....................................... (1)

$$A_{1=}\begin{bmatrix} \frac{-r_1}{L_1} & 0 & 0 \\ 0 & \frac{-r_2}{L_2} & \frac{-1}{L_2} \\ 0 & \frac{1}{C} & \frac{-1}{RC} \end{bmatrix};B_{1=}\begin{bmatrix} \frac{1}{L_1} \\ \frac{1}{L_2} \\ 0 \end{bmatrix};C_1=\begin{bmatrix}0 & 0 & 1\end{bmatrix}$$

$$A_2=\begin{bmatrix} \frac{-r_1}{L_1} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \frac{1}{\quad} \end{bmatrix};B_2=\begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \end{bmatrix}; C_2=\begin{bmatrix}0 & 0 & 1\end{bmatrix}$$

$-\frac{1}{\quad}\rceil$ $\lceil 1 \rceil$

$$A_3=\begin{bmatrix} -\frac{r_1}{L_1} & 0 & -\frac{1}{L_1} \\ 0 & 0 & 0 \\ \frac{1}{C} & 0 & -\frac{1}{RC} \end{bmatrix};B_3=\begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \end{bmatrix};$$

$$C_3=\begin{bmatrix} 0 & 0 & 1 \end{bmatrix}$$

$$A_4=\begin{bmatrix} -\frac{r_1}{L_1} & 0 & -\frac{1}{L_1} \\ 0 & -\frac{r_2}{L_2} & 0 \\ \frac{1}{C} & 0 & -\frac{1}{RC} \end{bmatrix};B_4=\begin{bmatrix} \frac{1}{L_1} \\ \frac{1}{L_2} \\ 0 \end{bmatrix};C_4=\begin{bmatrix} 0 & 0 & 1 \end{bmatrix}$$

$$A_5=\begin{bmatrix} 0 & 0 & 0 \\ 0 & -\frac{r_2}{L_2} & 0 \\ 0 & 0 & -\frac{1}{RC} \end{bmatrix};B_5=\begin{bmatrix} 0 \\ \frac{1}{L_2} \\ 0 \end{bmatrix};C_5=\begin{bmatrix} 0 & 0 & 1 \end{bmatrix}$$

$$A_6=\begin{bmatrix} 0 & 0 & 0 \\ 0 & -\frac{r_2}{L} & -\frac{1}{L} \end{bmatrix};B_6=\begin{bmatrix} 0 \\ \frac{1}{L} \end{bmatrix};C_6=$$

$$A_8=\begin{bmatrix} L_1 & & \frac{1}{L_1} \\ 0 & -\frac{r_2}{L_2} & -\frac{1}{L_2} \\ \frac{1}{C} & \frac{1}{C} & -\frac{1}{RC} \end{bmatrix};B_8=\begin{bmatrix} \frac{1}{L_1} \\ \frac{1}{L_2} \\ 0 \end{bmatrix};$$

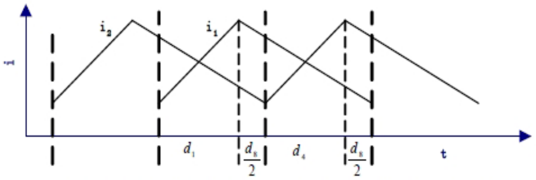
$$C_8=\begin{bmatrix} 0 & 0 & 1 \end{bmatrix}$$

AVERAGING: On the assumption that in one period T_s, the eight equivalent sub-circuits will run d_{n*} T_s respectively. The state-spaced equations of eight sub-circuits are time weighted and averaged over the switching period T_s. So the state-space averaged model of the whole system is:

$$\dot{X}=(A_1*d_1+A_2*d_{2+}A_3*d_3+A_4*d_4+A_5*d_5+A_6*d_{6+}+A_7*d_7+A_8*d_8)X+(B_1*d_1+B_2*d_{2+}B_3*d_3+B_4*d_4+B_5*d_5+B_6*d_{6+}+B_7*d_7+B_8*d_8)V_s$$

$$V_0=(C_1*d_1+C_2*d_{2+}C_3*d_3+C_4*d_4+C_5*d_5+C_6*d_{6+}+C_7*d_7+C_8*d_8)$$

The interleaved Boost Converter can operate in three kinds of CCM, and the inductor current waveforms of the converter according to the duty of the PWM pulse(D),as shown in Fig3.



| 2 2 |
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| 2 |
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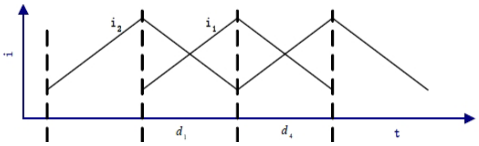
Fig 3a.The current of the two inductors,CCM(D<0.5)

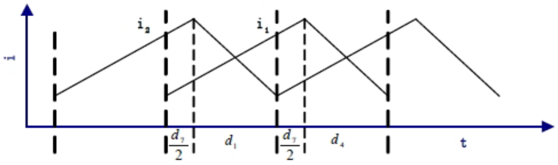


|⌊

[0 0 1] C RC |⌋

$$A_7 = \begin{bmatrix} -\frac{r_1}{L_1} & 0 & 0 \\ 0 & -\frac{r_2}{L_2} & 0 \\ 0 & 0 & -\frac{1}{RC} \end{bmatrix} ;B_7 = \begin{bmatrix} \frac{1}{L_1} \\ \frac{1}{L_2} \\ 0 \end{bmatrix};$$

Fig 3b.The current of the two inductors, CCM (D=0.5)



$C_7=[0 \quad 0 \quad 1]$

Define: D, rising time of the inductor current, D_p,Falling time of the inductor current.

1) **CCM(D<0.5):** The converter works in state1, state4and state 8. Because there are two times of state8 in one period, the running time of the each state 8 is ½*d_8, as shown in Fig 3a.

2) **CCM(D=0.5):** The converter works in state1, state4as shown in Fig 3b.

3) **CCM(D>0.5):** The converter works in state1, state4and state7. Because there are two times of state in one period, the running time of the each state 7 is ½ *d_7, as show in Fig 3c.

On the assumption that the two phase circuits is symmetrical, so $L_1= L_2$,$r_1= r_2$,$d_1=d_4$, $d_2=d_5$, $d_3=d_6$.

The uniform state-space averaged model of the whole system in CCM and DCM will be gained..THE CURRENT OF THE TWO INDUCTORS, CCM (D>0.5)

$$A=\begin{bmatrix} \frac{r_1}{L_1} & 0 & \frac{(1-D)}{L_1} \\ 0 & \frac{r_2}{L_2} & \frac{(1-D)}{L_2} \\ (1-D) & (1-D) & 1 \end{bmatrix}$$

$$B=\begin{bmatrix} \frac{1}{L_1} \\ \frac{1}{L_2} \\ 0 \end{bmatrix}$$

$$C=\begin{bmatrix} 0 & 0 & 1 \end{bmatrix}$$

STEADY-STATE:

$X=-A^{-1}BV_S$
$V_0=-CA^{-1}BV_S$

The steady state characteristics of the converter are as follows:

$$M=\frac{V_0}{V_S}=\frac{1}{1-D}$$

$$I_1=I_2=\frac{V_s}{} \quad \frac{V_s}{}$$

al

B

as
si
sp
T

$$A=\begin{bmatrix} \frac{r_1}{L} & 0 & \frac{(1-D)}{} \\ 0 & \frac{r_2}{L_2} & \frac{(1-D)}{L_2} \\ & & \end{bmatrix}$$

al

B

$$B=\begin{bmatrix} \frac{1}{L_1} \\ \frac{1}{L_2} \\ 0 \end{bmatrix}$$

$$C=\begin{bmatrix} 0 & 0 & 1 \end{bmatrix}$$

STEADY-STATE:

$$X=-A^{-1}BV_S$$

$$V_0=-CA^{-1}BV_S$$

The steady state characteristics of the converter are as follows:

$$M=\frac{V_0}{V_S}=\frac{1}{1-D}$$

$$I_1=I_2=\frac{V_s}{}\quad\frac{V_s}{}$$

a
si
s
T

$$A=\begin{bmatrix} -\frac{r_1}{L_1} & 0 & -\frac{(1-D)}{L_1} \\ 0 & -\frac{r_2}{L_2} & -\frac{(1-D)}{L_2} \\ \frac{(1-D)}{C} & \frac{(1-D)}{C} & -\frac{1}{RC} \end{bmatrix}$$

$$B=\begin{bmatrix} \frac{1}{L_1} \\ \frac{1}{L_2} \\ 0 \end{bmatrix}$$

$$C=\begin{bmatrix} 0 & 0 & 1 \end{bmatrix}$$

STEADY-STATE:

$$X=-A^{-1}BV_S$$
$$V_0=-CA^{-1}BV_S$$

The steady state characteristics of the converter are as follows:

III. THE DESIGN OF THE CONTROLLER

A. System Transfer function

The dynamic characteristics of the converter:

When $r_1= r2\approx 0$, the order of the state equation will be descend to two.

$$A=\begin{bmatrix} 0 & -\frac{(1-D)}{L} \\ \frac{(1-D)}{C} & -\frac{1}{RC} \end{bmatrix}$$

$$B=\begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix}$$

$$C=\frac{-LV_0 / D * s + V_0 RD}{RLC * s^2 + L * s + RD}$$

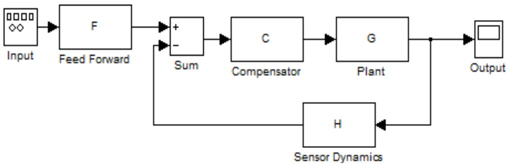
The transfer function of the converter derived from the above reduced state equation is

$$G_{vd}(s)=\frac{-LV_0 / D * s + V_0 RD}{RLC * s^2 + L * s + RD}$$

B. Design of the Controller

Based on the transfer function above the values of the variables, the BODE PLOT can be drawn and thedigital controller is designed. The control system of this converter is voltage controlled loop and is fully digitalized with DSP,

The voltage control loop is shown in below figure.



The voltage compensator is designed for the desired crossover frequency and phase margin and it is observed from the bode plot the loop is stable.

$$M=\frac{V_0}{V_S}=\frac{1}{1-D}$$

$$V_0=\frac{V_s}{(1-D)}$$

180-degree phase difference. Fig 4b is the waveforms of its output voltage, which shows that the voltage fluctuation is less than 1%. Figs 4c are the waveforms of the inductor current and its voltage of one phase. Fig 4d isthe step response for the transfer function of the converter.Figs 4e. are the Bode Plot of the converter model and it shows the converter is stable. Fig 4f. are the response without and with step change in load.

Fig 4a.Drive Signals of two phase IGBT switches

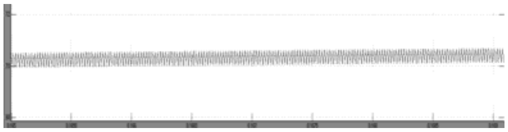


Fig 4b.Wave form of output Voltage

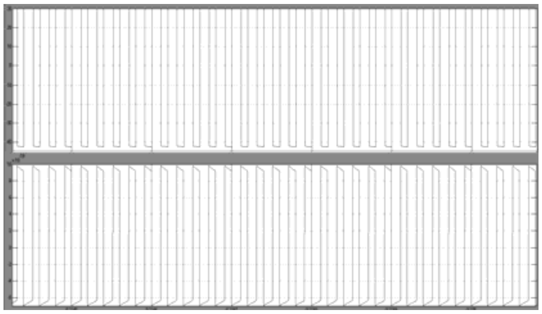


Fig 4c. Waveforms of the inductor current and itsvoltage of one phase

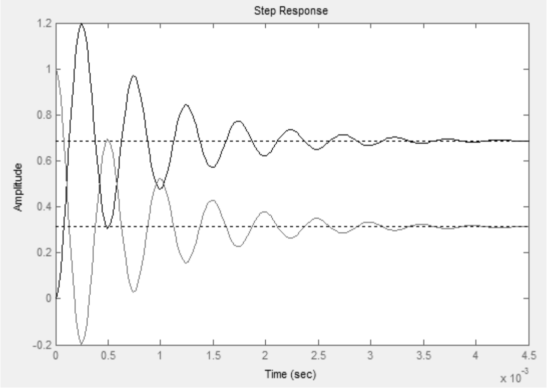


Fig 4d. Step Response for the transfer function of the converter

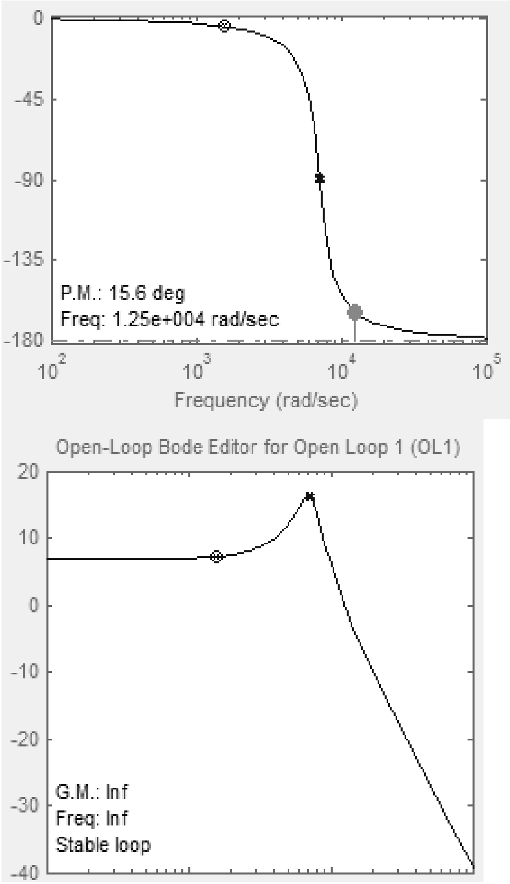
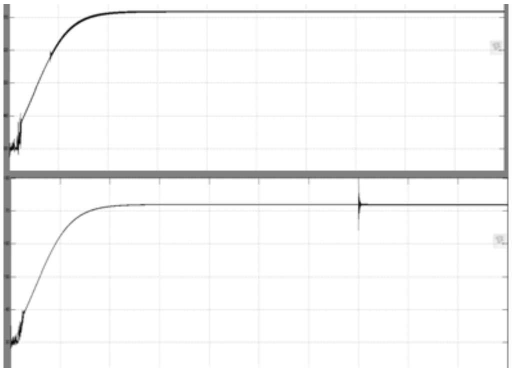


Fig 4e.Bode Plot of the converter model

Fig 4f. Response of the converter with step change inload



CONCLUSION

Hardware loop-in simulation using the ELVIS kit validates the MATLAB simulations of the Interleaved Boost Converter for Fuel Cell and the converter's state-space averaged model. Its dynamic and static qualities are top-notch because of the precision of the digital control. Therefore, the Fuel Cell Distributed Generation System may benefit from the Interleaved Boost Converter.

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