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# Analysis of power loss calculation for interleaved converter using switched capacitors

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ABSTRACT

Interleaved Boost Converter (IBC) topologies have received increasing attention in recent years for high power applications. It serves as a suitable interface for fuel cells to convert low voltage high current input into a high voltage low current output. The advantages of interleaved boost converter compared to the classical boost converter are low input current ripple, high efficiency, faster transient response, reduced electromagnetic emission and improved reliability. This paper focuses on power loss analysis of the interleaved converter with winding –cross-coupled inductors and switched-capacitors. The performance parameter of interleaved converter such as switching losses, conduction losses and efficiency has been studied. Simulations of IBC interfaced with fuel cells have been performed using MATLAB/SIMULINK.

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# Introduction

Keywords

Efficiency.

IBC,

A distributed energy source consisting of a fuel cell [1] normally requires a high power boost converter for energy management to assist the slow responding fuel cell. Comparison with the other types of fuel cells, Proton Exchange Membrane (PEM) fuel cell [2,3] shows charming attraction with its advantage such as low temperature, high power density, fast response and zero emission. In this paper, an interleaved boost converter using switched capacitors has been proposed as a suitable interface for PEM fuel cells to improve its efficiency[4]. IBC for fuel cell application reduces the ripple amplitude of the high frequency input current, avoids high frequency interaction inside the fuel cell stack and prolongs the fuel cell lifetime. Also, the steady-state voltage ripples at the output capacitors of IBC are reduced.

Compared to the conventional boost converter, IBC [8] has more inductors increasing the complexity of the converter. In order to reduce this complexity and to increase the voltage gain of the converter, cross- coupled inductors and switched capacitors are used. For the proposed converter, the conduction losses, inductance losses and switching losses has been analysed and the efficiency curve has been plotted.

Section II discusses about the operation of interleaved converter. Section III focuses on the power loss analysis. Section IV presents the efficiency curve. Section V deals with conclusions.

# Interleaved boost converter with winding cross coupled inductors and switched capacitors

The proposed isolated ZVT interleaved converter [9] with winding-cross-coupled inductors (WCCIs) and switched capacitors (SCs) is shown in Fig.1. The coupling method of the coupled inductors is marked by "o" and "\*" as shown in Fig. 1. The second winding couples to the inductor in its phase ( $L_{1b}$  versus  $L_{1a}$  and  $L_{2b}$  versus  $L_{2a}$ ) and the third winding couples to the inductors in another phase ( $L_{1c}$  versus  $L_{1a}$  and  $L_{2b}$ . The voltage gain extension circuit, which is composed of the third winding of the coupled inductor, a

Tele: E-mail addresses: seyezhair@ssn.edu.in © 2012 Elixir All rights reserved switched capacitor and a diode, has the advantages of the voltage gain extension and the reduction of the switch voltage stress. The active clamp circuit, which is composed of a power MOSFET and a small capacitor, is inserted to the primary side of each phase to recycle the leakage energy and to absorb the voltage spikes when the main switches turn off. The equivalent circuit model of the proposed converter is demonstrated in Fig. 2. where  $L_{m1}$  and  $L_{m2}$  are the magnetizing inductors;  $L_{Lk1}$  and  $L_{Lk2}$  are the leakage inductances;  $C_{s1}$  and  $C_{s2}$  are the parallel capacitors of the main switches;  $S_{c1}$  and  $S_{c2}$  are the active-clamp switches;  $C_{c1}$  and  $C_{c2}$  are the clamp capacitors;  $S_1$  and  $S_2$  are the main switches;  $C_{o1}$  and  $D_{o2}$  are the output diodes;  $C_{o}$  is the output capacitor;  $C_{sc1}$  and  $C_{sc2}$  are the switched capacitors;  $D_{sc1}$  and  $D_{sc2}$  are the switched diodes.

Based on the PWM gate signals of the main switches  $S_1$ ,  $S_2$  and the clamp switches  $S_{c1}$ ,  $S_{c2}$ , there are 16 stages in a switching period. Due to the symmetry of the converter, only 8 stages are described here. The key steady waveforms are given in Fig.3.



Fig1. Proposed converter with WCCIs and SCs

Stage 1 [t<sub>0</sub>, t1]: At t<sub>0</sub>, S<sub>1</sub>, S<sub>2</sub> are in turn-on stage, S<sub>c1</sub>, S<sub>c2</sub> are in turn-off state, D<sub>o1</sub>, D<sub>o2</sub> and D<sub>sc1</sub>, D<sub>sc2</sub> are all turned-off. L<sub>m1</sub>,L<sub>m2</sub> and L<sub>Lk1</sub>, L<sub>Lk2</sub> are charged by the input voltage.

Stage 2  $[t_1, t_2]$ : At  $t_1$ ,  $S_2$  turns off.  $C_{s2}$  is charged by the magnetizing current linearly.  $S_2$  realizes ZVS turn-off operation.

(1)

Stage 3 [ $t_2$ ,  $t_3$ ]: At  $t_2$ , the voltage across  $C_{s2}$  reaches a value that makes the anti-parallel diode of  $S_{c2}$  forward-biased.

Stage 4 [t<sub>3</sub>, t<sub>4</sub>]: At t<sub>3</sub>, the voltage  $v_{ds2}$  reaches the point that  $D_{sc2}$  and  $D_{o2}$  start to conduct. The energy stored in  $L_{m2}$  is transferred to the load and  $C_{sc1}$ ,  $L_{Lk2}$ ,  $C_{c2}$  and  $C_{sc2}$  begin to resonate.



Fig 2.Equivalent circuit

The current through  $L_{1c}$  is reflected to its primary winding in phase 1 and goes into  $S_1$ . That is given by

$$i_{s1}(t) = i_{Lm1}(t) + i_{Do2}(t).N$$

Stage 5 [t<sub>4</sub>, t<sub>5</sub>]: Before t<sub>4</sub>, the anti-parallel diode of  $S_{c2}$  is still in turn-on state and the current through  $C_{c2}$  does not change its direction. At t<sub>4</sub>,  $S_{c2}$  turns on with ZVS condition.

Stage 6 [t<sub>5</sub>, t<sub>6</sub>]: At t<sub>5</sub>, S<sub>c2</sub> turns off, which removes C<sub>c2</sub> from the circuit. A new resonant circuit between L<sub>Lk2</sub> and C<sub>s2</sub> is formed. The energy stored in C<sub>s2</sub> starts to transfer to L<sub>Lk2</sub>.

Stage 7 [t<sub>6</sub>, t<sub>7</sub>]: At t<sub>6</sub>, the voltage across  $C_{s2}$  reaches zero and the anti-parallel diode of  $S_2$  starts to conduct.  $L_{Lk2}$  is charged linearly by the voltage of  $V_{out/N}$ . This also controls the current falling slew rate of  $D_{o2}$ . During this stage,  $S_2$  is turned on with ZVS condition.

$$i_{Lk2}(t) = I_{Lk2}(t6) + \frac{V_{out} * t}{N * L_{Lk2}}$$
(2)  
$$\frac{di_{Do2}(t)}{dt} = -\frac{V_{out}}{N^2 \cdot L_{Lk2}}$$
(3)

Stage 8 [t<sub>7</sub>, t<sub>8</sub>]: The currents through  $D_{sc2}$  and  $D_{o2}$  decreases as the leakage inductance current increases. At t<sub>8</sub>, the current through  $L_{Lk2}$  is equal to the current through  $L_{Lm2}$ . The currents through  $D_{sc2}$  and  $D_{o2}$  reach zero and these two diodes are reverse-biased.  $L_{m2}$  and  $L_{Lk2}$  are charged by the input voltage again. A similar operation works in the rest stages of a switching cycle.



Time(s)

Fig.3. Inductor current, switch current and diode current of IBC

#### Power loss analysis of the interleaved boost converter

The power loss analysis of the converter includes power loss of the MOSFETs, diodes and main inductor used in the converter circuit[10]. The switching losses ,conduction losses and induction losses are calculated and the results are tabulated. The specifications used in the power loss analysis are given in Table I

#### **Power Loss of Mosfet**

The power loss of MOSFET consists of the switching loss  $(P_{SW(MOSFET)})$  and the conduction loss  $(P_{COND(MOSFET)})$ .  $P_{MOSFET} = P_{SW(MOSFET)} + P_{COND(MOSFET)}$  (4)

The drain current waveform of MOSFET when it is turned on is considered for calculating conduction loss [11,12]. The MOSFET current during each time interval as shown in fig.4 is used in calculating the rms value of drain current.



Fig.4 MOSFET drain current waveform

The  $P_{COND(MOSFET)}$  is as follows:

 $P_{\text{COND(MOSFET)}} = I^2_{\text{Drain(rms)}} \times R_{\text{DS(on)}}$ (5) where  $R_{\text{DS(ON)}}$  is the on state drain-source resistance.

The rms value of the drain current is calculated using the formula,  $r^2$ 

$$= \frac{I_{0}^{2} + I_{1}^{2} + I_{0}I_{1}}{3} \frac{t_{a1}}{T} + \frac{I_{1}^{2} + I_{2}^{2} + I_{1}I_{2}}{3} \frac{t_{a2}}{T} + \frac{I_{2}^{2} + I_{3}^{2} + I_{2}I_{3}}{3} \frac{t_{a3}}{T} + \frac{I_{3}^{2} + I_{4}I_{3}I_{4}}{3} \frac{t_{a4}}{T} + \frac{I_{4}^{2} + I_{5}^{2} + I_{4}I_{5}}{3} \frac{t_{a5}}{T} + \frac{I_{5}^{2} + I_{6}^{2} + I_{5}I_{6}}{3} \frac{t_{a6}}{T}$$
(6)

where, the  $I_{\text{Drain}(\text{rms})}$  is the root-mean-square (rms) value of the  $I_{\text{Drain}}.$ 

The P  $_{SW(MOSFET)}$  is calculated on the basis of the overlap area of the drain-source voltage (V<sub>DS</sub>) and drain current (I<sub>Drain</sub>) as shown in Fig.5. The switching frequency used is 20kHz. P  $_{SW(MOSFET)} = 0.5V_{DS}*I_{Drain}*f_{sw}*(t_{on}+t_{off})$  (7)



Fig.5 Switching characteristics of MOSFET

The power curve is drawn for MOSFET as shown in fig.6 during turn on and turn off .The maximum power is estimated to be 20W during turn on and turn off.



#### **Fig.6 Power curve of MOSFET**

The estimation of power loss of four MOSFETs used in the proposed circuit is shown in TABLE II.

# Power Loss of The Diode

A FR-diode was used as the main diode. The reverse recovery current is almost zero. Thus, although the fCsw is increased, the switching loss is not increased. The power loss of the diode (PDIODE) consists of the reverse recovery loss (Ptrr(DIODE)) and the conduction loss (PCOND(DIODE)).

 $P_{\text{DIODE}} = P_{\text{trr}(\text{DIODE})} + P_{\text{COND}(\text{DIODE})} + P_{\text{SW}(\text{DIODE})}$ 

The switching loss of a diode is calculated from the equation (9) with the help of the switching characteristics of the diode as shown in Fig.7



Fig.7 Switching characteristics of diode

The PCOND(DIODE) consists of the equivalent resistance loss (PRD) and the forward voltage drop loss (PVF).

$P_{\text{COND(DIODE)}} = P_{\text{RD}} + P_{\text{VF}}$	(10)
$P_{RD} = R_D * I_{rms}^2$	(11)
$P_{VF(DIODE)} = VF^* I_{avg}$	(12)

where  $R_D$  is the equivalent resistance of the diode, VF is the forward voltage drop, Irms is the rms value of the diode current and Iavg is the average value of the diode current.

The main diode current waveform during each time interval as shown in Fig.8 can be used to calculate rms value of diode current  $I_M DIODE_{(RMS)}$  and average value of diode current  $I_M DIODE_{(AVG)}$ .

The  $I_{M}^2$ DIODE(rms) and  $I_M$  DIODE(avg) are as follows:

$$I_{M}^{2} \text{DIODE(rms)} = \frac{I_{0}^{2} + I_{1}^{2} + I_{0}I_{1}}{3} \frac{t_{b1}}{T} + \frac{I_{1}^{2} + I_{2}^{2} + I_{1}I_{2}}{3} \frac{t_{b2}}{T}$$
(13)  
$$I_{M} \text{DIODE(avg)} = \frac{I_{0} + I_{1}t_{b1}}{2} \frac{t_{1}}{T} + \frac{I_{1} + I_{2}}{2} \frac{t_{b2}}{T}$$
(14)

where  $I_{M_{DIODE(rms)}}$  is the rms value of the main diode current and  $I_{M_{DIODE(avg)}}$  is the average value of the main diode current.



Fig. 8. Diode current waveform Power loss of the main inductor

The power losses of the main inductor  $(P_{ML})$  consist of the core losses  $(P_{Mfe})$  and the copper losses  $(P_{Mcu})[14]$ .

 $P_{ML} = P_{Mfe} + P_{Mcu}$  (15) Magnetics 0F-42515EC ferrite EE core [17]is used for the main inductor.

The core loss per unit volume Pv of this type of material is given by

$$P_v = a f^c (10 \times B_m)^d \tag{16}$$

where f is in kHz,  $B_m$  is in Tesla, and  $P_v$  is in mW/cm<sup>3</sup>. The core power loss per unit volume at f = 20 kHz is

$$P_{v} = 0.0717 \times f^{1.72} \times (10 \times B_{m})^{2.66}$$

$$= 0.0717 \times 20^{1.72} \times (10 \times 0.2)^{2.66}$$

$$= 9.901 \text{ Mw/cm}^{3}$$
(17)

The total core loss is

$$P_{Mfe} = P_v V_c$$

$$=9.901 \times 10^{-3} \times 2.95 =0.029 \text{ W}$$

The  $P_{Mcu}$  can be written as follows:

$$P_{Mcu} = I_{L(rms)}^2 \times (R_{ML} \times 1.3 @80 \circ C)$$

The calculated power losses of the main inductor such as core loss and copper loss are shown in TABLE V.

(18)

(19)

Therefore, the total loss of inductor is found to be

 $P_{ML} = 6.1734 \text{ W}.$ 

# Total power loss of the interleaved boost converter

Detailed values of the different power losses of IBC are given in Table VI. The total power loss of the interleaved converter with respect to the switch, diode, inductor is observed to be approximately 76 W.

# **Efficiency Curve**

The efficiency of the proposed converter under different loads is sketched in Fig.9.Based on power loss analysis it can be inferred that the conduction losses are minimised by the use of interleaved converter using switched capacitors by means of distribution of the input current. As fast recovery diode has been used, the reverse recovery loss is zero. The total calculated power loss of the converter is estimated to be 76W. Hence it can be seen that the proposed converter gives high efficiency. The maximum efficiency is found to be 98.6% at an input voltage of 20.83V. By interfacing low voltage fuel cells with interleaved converter using switched capacitors ,the efficiency of the fuel cells can be improved.

# Conclusion

This paper has presented the power loss analysis of the high efficiency Interleaved boost converter using switched capacitors for fuel cells. The proposed strategy has been verified through MATLAB simulation. The power losses of the proposed boost converter in detail taking into account the power loss of the

# **Table I Specifications of IBC**

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Parameter	Value	Unit
Input voltage(V <sub>in</sub> )	20.83	[V]
Output voltage(V <sub>o</sub> )	88	[V]
Switching frequency(fsw)	20	[KHz]
Boost inductor(L)	15	[µH]
Switched capacitors(C <sub>sc1</sub> ,C <sub>sc2</sub> )	2.2	[µF]

#### **Table II Power loss of mosfet**

MOSFET Power Loss Parameter	Value	Unit
$P_{sw(MOSFET)} \times 4$	15.947	[W]
$P_{COND(MOSFET)} \times 4$	40.89	[W]
P <sub>MOSFET</sub> ×4	56.837	[W]

#### Table III Power loss of the diodes

Main Diode (FR-Diode) Power Loss Parameter	Value
(Ptrr) *4	0 W
(P <sub>RD</sub> )*4	84.8 mW
(P <sub>VF</sub> )*4	5.735 W
$(P_{SW(DIODE)})*4$	1.08 W
$(P_{\text{COND(DIODE)}}) *4$	5.82 W
P <sub>M DIODE</sub>	12.71W

#### **Table IV Specifications of inductor**

Main Inductor Core Parameter	Value	Unit
Inductance (L <sub>M</sub> )	15	[µH]
Cross section (A <sub>Me</sub> )	1.833	[cm <sup>2</sup> ]
Volume (V <sub>Me</sub> )	26.48	[cm <sup>3</sup> ]
Turn (N)	17	
Resistance (R <sub>ML</sub> )	0.27	[Ω]

#### Table V Power loss of main inductor

Main Inductor Power Loss 0F-42515EC ferrite EE core	Value	Unit
(P <sub>Mfe</sub> )×3	0.0594	[W]
(P <sub>Mcu</sub> )×3	6.114	[W]

### Table VI Total power loss of proposed converter

Power Loss Parameter	Value	Unit
P <sub>MOSFET</sub>	56.837	[W]
P <sub>M DIODE</sub>	12.71	[W]
P <sub>ML</sub>	6.1734	[W]

switch, diode, main inductor has been analyzed and the results were tabulated. The total power loss of the proposed converter is estimated and then the efficiency curve has been plotted. The maximum efficiency of the proposed interleaved converter is found to be 98.6%. With this improved efficiency this converter can be interfaced with fuel cell systems.



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