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SIMULATION AND EVALUATION OF PERFORMANCE PARAMETERS FOR PWM BASED INTERLEAVED BOOST CONVERTER FOR FUEL CELL APPLICATIONS

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ABSTRACT

In the present scenario, renewable energy sources are playing an important role to satisfy the requirements of customer's demand. Among these sources, fuel cell is an attractive technology as it provides a clean and efficient source of electricity. But a suitable power conditioner is required to convert the DC power of fuel into useful AC power. This paper focuses on a four-phase directly coupled Interleaved Boost Converter (IBC) as a suitable interface for fuel cell applications based on pulse width modulation technique. The proposed converter is simulated in MATLAB/SIMULINK. Input current, inductor current and output voltage ripple is studied. Various energy factors have been computed and the results are verified.

Keywords: interleaved boost converter, PWM, energy factor and ripple.

1. INTRODUCTION

Among the renewable energies, fuel cell is a rapidly developing technology and it is preferred because of its high conversion efficiency. The output of a single fuel cell is about 0.6 -0.7V, therefore a series connection of fuel cells (stack) is required to get a higher output. But a bigger stack will increase the cost of the system and hence to overcome this, a suitable DC-DC converter is preferred. Different configurations of DC-DC converters have been discussed by many researchers [1, 2, 3], but this paper focuses on the four-phase IBC[5] employing PWM technique to reduce the ripples both at the input and output side. IBC has number of benefits such as harmonic cancellation, better efficiency, better thermal performance and high power density. The concept of PWM generation for IBC is discussed. Design equations and ripple calculations are carried out for the proposed converter. The performance of the converter is analyzed by computing the energy factor parameters and the theoretical results are verified through MATLAB/SIMULINK.

2. FOUR-PHASE INTERLEAVED BOOST CONVERTER

The circuit diagram for the 4-phase directly coupled IBC with PWM generator is shown in Figure-1. In the proposed IBC, coupled inductors[14,15] are used to improve the performance of the converter. Also, coupled inductors results in reduced core and winding losses, improved input and inductor current ripple[6,7]. The gating signals are generated by using PWM technique. PWM uses a rectangular pulse whose pulse width is modulated resulting in the variation of the average values of the waveform.

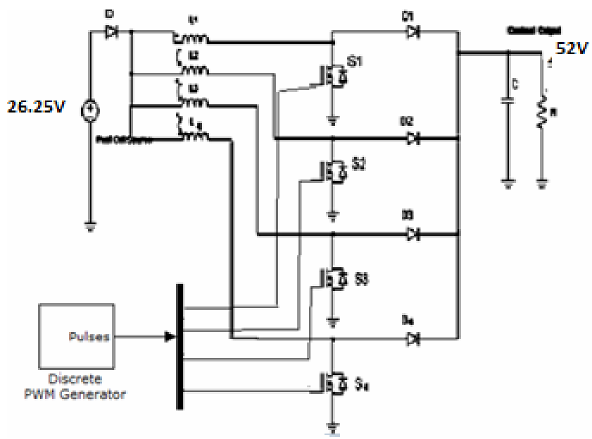

Figure-1. Circuit diagram for 4_phase direct coupled IBC with PWM generator.

3. PWM GENERATION METHOD

Consider a pulse waveform f (t) as shown in Figure-2 with a low value y_{min}, a high value of the waveform is given by,

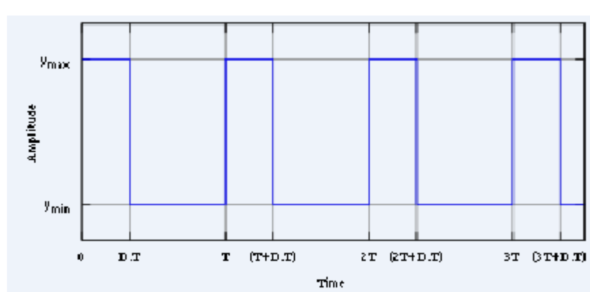

Figure-2. Average value of PWM waveform.

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$$y = \frac{1}{T}\int_0^T f(t)dt \tag{1}$$

As f (t) is a pulse wave, its value is

y_{max} for 0<t<D.T 2(a)

y_{min} for D.T<t<T 2(b)

The expression for 'y' is given by

$$y = \frac{1}{T\left[\int_0^{DT} y_{max\,dt} + \int_{DT}^{T} y_{min\,dt}\right]} = \frac{DT y_{max} + T(1-D) y_{min}}{T}$$

$$y = D * y_{max} + (1-D) * y_{min} \tag{3}$$

The equation (3) can be simplified in many cases where y_{min}= 0 as y = D.y_{max}. It's evident that the average value of the signal y is directly dependent on the duty cycle D.

The PWM generator block generates pulses for carrier based pulse width modulation converters using two level topology. The block can be used to fire the forced commutated devices. The pulses are generated by comparing a triangular carrier waveform to a reference modulating signal. The modulating signal can be generated Bv the PWM generator itself, or they may be a vector of external signals connected at the input of the block. One reference signal is needed to generate the pulses for a single or two arm bridges three reference signals are needed to generate the pulses for a three phase single or double bridge. The amplitude, phase and frequency of the reference signals are set to control the output voltage of the bridge connected to the PWM generator block.

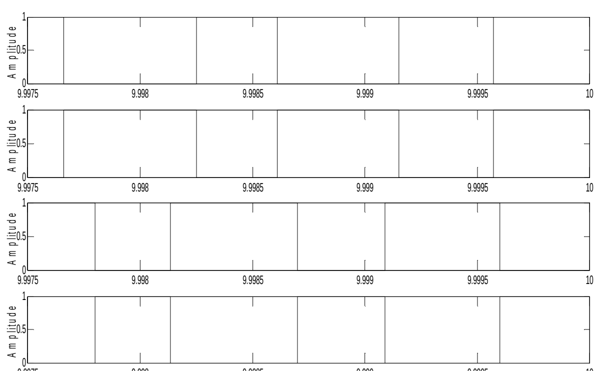

Figure-3. Gating pattern for the switches of IBC.

4. DESIGN EQUATIONS FOR THE PROPOSED IBC

The steps for designing IBC are as follows[8]:

a) Design of inductor[16]
b) Design of capacitor[16]
c) Choice of devices[16]
d) Selection of duty ratio and number of phases [16]

(i) Design of coupled inductors [12,13]

The phase shift of 90° can be achieved between each phase leg. The equivalent inductance expression for the direct coupled IBC is [1].

$$L_{eq} = \frac{V_{in} DT}{\Delta I_{phase}} \tag{4}$$

Where

V_{in} = Input voltage
D = Duty ratio
ΔI_{phase} = Phase ripple current

$$\Delta I_{phase} = \frac{V_{in} DT}{L} \cdot \frac{1 + \alpha + 2\alpha \frac{D}{1-D}}{1 + \alpha - 2\alpha^2} \tag{5}$$

The self inductance of the coupled inductor is found as [1],

$$L = \frac{1 + \alpha \frac{D}{1-D}}{1 + \alpha - 2\alpha^2} L_{eq} \tag{6}$$

The value of L_m and L_k is calculated as [1],

$$L_m = \alpha . L \tag{7}$$

$$L_k = (1-\alpha). L \tag{8}$$

Overall input current ripple is [1]

$$\Delta I_{in} = \frac{V_{in} DT}{L} \cdot \left[\frac{(1-\alpha)\left(1 - \frac{2D}{1-D}\right)}{1 + \alpha - 2\alpha^2}\right] \tag{9}$$

To reduce the input current ripple and to keep the phase current ripple within limits the coupling co-efficient can be carefully chosen as 0.61.

(ii) Design of capacitor

A capacitor filter is needed at the output to limit the peak to peak ripple. The capacitance value is[13],

$$C = \frac{V_o DT}{R \Delta V_o} \tag{10}$$

V_o = Output voltage
D = Duty ratio
T = Switching period
R = Load resistance
ΔV_o = Output voltage ripple

(iii) Choice of devices

To improve the electrical performance of the converter, the proper choice of semiconductor materials is important.

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(iv) Choice of phase and duty ratio

For any particular input, output voltages and power ratings of the converter is given as,

$$D = \frac{V_o - V_{in}}{V_o} \quad (11)$$

Using the above equations, the proposed IBC is designed.

5. SIMULATION RESULTS

The simulation of the four-phase direct coupled IBC[9,10] with PWM generator is carried out using MATLAB/SIMULINK. The parameters of the circuit are shown in Table-1.

Table-1. Simulation parameters for 4-phase direct coupled IBC.

Input voltage	26.25V
Output voltage	52V
R	1.6Kohm
C	0.049F
f_s	30KHz
L_m	1.1529H
$L_{k1} = L_{k2}$	0.737H
D	0.52
A	0.61
I_1	76.19A
I_2	33.33A
I_L	6.25A
Voltage transfer gain	2.08

The output voltage waveform for 4 phase direct coupled IBC with PWM generator is shown in Figure-4.

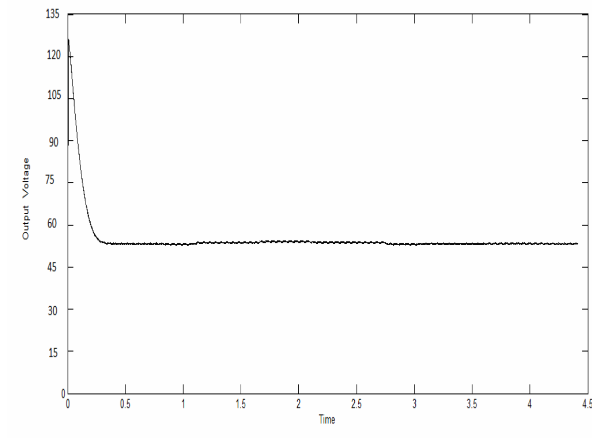

Figure-4. Output voltage for 4-phase direct coupled IBC with PWM generator.

The input current ripple waveform for 4 phase direct coupled IBC with PWM generator is shown in Figure-5.

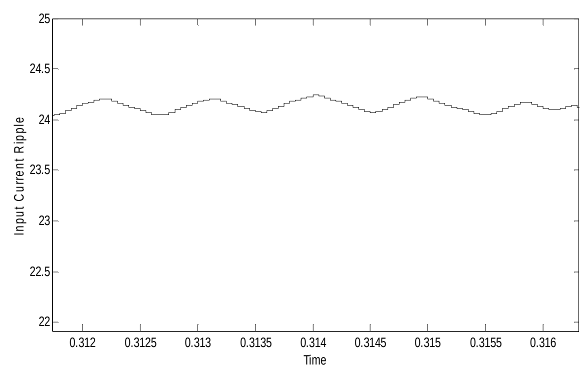

Figure-5. Input current ripple for 4 phase direct coupled IBC with PWM generator.

Figure-6 depicts that the output voltage ripple waveform for 4 phase direct coupled IBC with PWM generator.

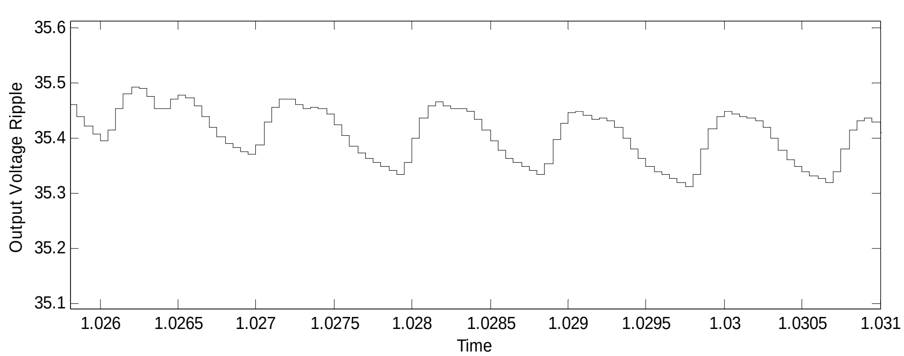

Figure-6. Output voltage ripple waveform for 4-phase direct coupled IBC with PWM generator.

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Table-2 shows the ripples for PWM based IBC.

Table-2. Ripple calculation for PWM based IBC.

Performance parameter	PWM generator
Input current ripple	0.012A
Output voltage ripple	0.0056V

6. ENERGY FACTOR CALCULATIONS FOR IBC

The energy factor and sub-sequential parameters are calculated in this section. The instantaneous and average values of input voltage and current are assumed as V_1, I_1, v_1 (t), i_1 (t). Similarly the instantaneous output voltage, current and the average values are assumed as V_2, I_2, v_2 (t), i_2 (t). The various energy factor parameters are given by the following equations.

(a) Pumping energy (PE)

Pumping energy is the transfer of energy from source to energy storage elements like inductor and capacitor in a switching period T[4].

$$PE = \int_0^T P_{in}(t)dt = \int_0^T v_1(t) i_1(t) dt = V_1 I_1 T \quad (12)$$

(b) Stored energy (SE)

Stored energy is the amount of energy which is stored in the inductors and capacito[4]r.

$$W_L = 0.5 L I_L{}^2 \quad (13)$$

$$W_C = 0.5 C V_C{}^2 \quad (14)$$

If the number of inductors and capacitors are assumed as n1 and n2, the total stored energy is, [4].

$$SE = \sum_{j=1}^{n1} W_{Lj} + \sum_{j=1}^{n2} W_{Cj} \quad (15)$$

(c) Capacitor-inductor stored energy ratio (CIR)

It's the ratio between capacitor stored energy to the inductor stored energy.

$$CIR = \frac{\sum_{j=1}^{n2} W_{Cj}}{\sum_{j=1}^{n1} W_{Lj}} \quad (16)$$

(d) Stored energy variation on inductors and capacitor (VE)

The variation of stored energy on the inductor is given by,

$$\Delta W_L = L I_L \Delta i_L \quad (17)$$

Δi_L = Ripple in the inductor current

The variation of stored energy on the capacitor is given as,

$$\Delta W_C = L V_C \Delta v_C \quad (18)$$

Δv_C = Variation of voltage across capacitor (ripple).
Hence the total variation,

$$= \sum_{j=1}^{n1} \Delta W_{Lj} + \sum_{j=1}^{n2} \Delta W_{Cj} \quad (19)$$

(e) Energy factor (EF)

Energy factor is the ratio between stored energy to the pumping energy. It's inversely proportional to the switching frequency,

$$EF = \frac{\sum_{j=1}^{n1} W_{Lj} + \sum_{j=1}^{n2} W_{Cj}}{V_1 I_1 T} \quad (20)$$

(f) Variation energy factor (EF_V)

Variation energy factor is the ratio between variations of stored energy to the variation of the pumping energy [4].

$$EF_V = \frac{VE}{PE} = \frac{\sum_{j=1}^{n1} \Delta W_{Lj} + \sum_{j=1}^{n2} \Delta W_{Cj}}{V_1 I_1 T} \quad (21)$$

(g) Time constant (τ)

Time constant is used to describe the transient process of the converter.

$$\tau = \frac{2T * EF}{1 + CIR\left[1 + CIR * \frac{(1-\eta)}{\eta}\right]} \quad (22)$$

If there is no power loss in converter means η =1.

(h) Damping time constant (τ_d)

This parameter is used to estimate, the oscillation response for unit step or impulse interference. It's also used to describe the transient process of the converter.

$$\tau d = \frac{2T * EF}{1 + CIR\left[\frac{CIR}{\eta + CIR(1-\eta)}\right]} \quad (23)$$

(i) Time constant ratio (ξ)

It's also used to analyze the transient process of the converter. [4].

$$\xi = \frac{\tau d}{\tau} = \frac{CIR}{\left(1 + CIR * \frac{(1-\eta)}{\eta}\right)^2} \quad (24)$$

Using the above equations, the energy factor and the sub-sequential parameters were computed for the proposed 4- phase directly coupled IBC with PWM generator and the values are tabulated in Table-3.

Table-3. Energy factor parameters for IBC.

Parameter	Values
Pumping energy (PE)	0.0659 J
Stored energy in the inductor	0.0410 J
Stored energy in the capacitor	88.2 J
Total stored energy (SE)	88.36 J
Capacitor-inductor stored energy ratio (CIR)	537.8
Time constant	0.1064 sec
Damping time constant	0.0016 sec
Time constant ratio	0.015
Variation in stored energy in the Inductor	0.0086 J
Variation in stored energy in the capacitor	0.0338 J
Total variation in the stored energy (VE)	0.0682 J
Energy factor (EF)	1340.8
Variation energy (EFv)	1.03

7. CONCLUSIONS

In this paper, a four- phase directly coupled IBC with PWM generator has been designed. Employing coupled inductor in the proposed converter resulted in reduced ripples at the input side which is found from the simulation results. Also, PWM based IBC gave a reduced voltage ripple at the output side. From the energy factor calculation, it is obvious how effectively the converter operates and these values are useful in designing a digital controller for the converter.

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