Implementation of Chaotic PWM method for Four phase Interleaved Boost Converter

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Abstract. Fuel cell is a rapidly developing electrical source, among the several types of renewable energy sources. The fundamental point of this paper is to implement chaotic PWM triggering Interleaved Boost Converter (IBC) for fuel cell. In chaotic PWM method, chaotic carrier signal has been generated. Then, it is compared with the input signal and the modulated signal has been applied to the switching devices of IBC. The simulations are carried out to highlight the benefits of chaotic compared to conventional PWM method. The simulations are validated with appropriate prototype. The ripples are analyzed between conventional and chaotic PWM based IBC. The power loss values of each component in four phase IBC have been calculated and it is proved that the chaotic PWM has less switching loss with improved efficiency compared to conventional PWM method. Also, the energy factors are calculated for chaotic PWM method.

1. Introduction
In recent scenario, fuel cell[1] shows much attraction among various types of renewable energy sources because it acts like a green energy source and has a property of high energy conversion. Proton Exchange Membrane Fuel Cell (PEMFC) is selected for this paper, due to its less temperature, less warm up time and high efficiency. For most of the applications, boost converters are utilized to step up the output voltage of fuel cell. In this work, interleaving concept is considered. Interleaving is paralleling of boost converters. Input current path is split up into n numbers, which improves modularity, reliability and high power capability. In IBC, each phase has same switching frequency and same phase shift angle. Based on the duty ratio, switching sequence [2-4] of each phase is overlapped, leading to reduction of the input current ripple. The input current ripple and output voltage ripple are inversely proportional to the number of phases. So, these ripples are reduced by connecting four stages of step up converter.

The converter performance has been improved by the interleaved topology[5-6] with the price of additional inductors and switching devices. The utilization of coupled inductor instead of multiple discrete inductor is preferred, since inductor is the largest and heaviest component in boost converter. The advantages of coupled inductor[7] are reduced core and winding losses and improves the electrical performance. Therefore, four phase directly coupled IBC acts as an appropriate interface for cell
The performance of the coupled IBC is further improved by chaotic PWM based IBC. In this work, the chaotic PWM signal is generated which is given to the switching devices of IBC. Due to chaotic carrier signal, the ripple of the output voltage is limited between the maximum and minimum limitations of the chaotic carrier signal[8]. A chaotic oscillator is the main part of the chaotic saw tooth signal generator which is constructed by a Chua’s diode. Simplicity and maturity action are the benefits of the chua’s diode. Simulations are performed with MATLAB environment to highlight the effectiveness of chaotic PWM method. The IBC characteristics and output are not altered by the chaotic carrier[9].

In the analysis part of this paper, the ripple of four-phase coupled IBC is analyzed. Conventional PWM based circuit and chaotic PWM based IBC circuit ripples[10-13] are analyzed by simulation manner and these ripple values are tabulated. By comparing these two PWM methods, chaotic PWM method produces less ripple values. So this method is selected as a better one. The power loss [14] values of each device of chaotic PWM based IBC circuit have been calculated, it is shown that chaotic PWM has less switching losses and high efficiency. At last the energy factor [15] also calculated for unperturbed and coupled IBC for fuel cell applications. Among these two methods, coupled IBC is selected due to high energy factor and less variation energy factor compared to uncoupled IBC.

2. Triggering technique employed for the proposed four phase IBC

2.1. Chaotic PWM method

In the traditional PWM method the concept of chaos is introduced. During this method an external PWM signal is added to the most DC-DC configuration to work in chaotic mode, which is shown by Figure.1. Therefore, the design of DC-DC converter becomes more flexible, because chaotic signal is produced by an external signal. The circuit of Figure.1 shows, four phase directly coupled IBC with chaotic PWM triggering method. The input current ripple, inductor current ripple and output voltage ripples are reduced effectively by chaotic PWM method.

![Figure 1. Chaotic PWM triggering for four-phase IBC](image)

2.2. Circuit Design

The circuit diagram for the chaotic carrier’s generator is shown in Figure.2. This circuit is in a position to get chaotic triangle waveform[16]. The resistor R1 and R2 decides the lower limit of the chaotic carrier Vlow. Vu and Vchaos signals decides upper limit of the chaotic carrier signal Vupp. Vupp is usually obtained from the chaotic oscillator’s output voltage V’chaos by a proportional modulation. Based on the characteristics table of RS flip flop of table 1 the chaotic carrier circuit operates. At first Vc=0 and
$V_C < V_{low} < V_{app}$. When $R=1$ and $S=0$, which produces $Q_{n+1}=1$. In this condition, switch $S_7$ turns ON and $C_6$ will be charged through $R_5$ and $R'_5$ by $V_{cc}$. Then $R=1$, $S=1$, $V_C > V_{low}$ and $V_C < V_{app}$, it produces $Q_{n+1}=Q_n$, which specifies the switch maintains ON until, $V_C$ arrives or exceeds $V_{app}$. The last condition of $S=1$, $R=0$ and $Q_{n+1}=0$, the switch turns OFF and $C_6$ begins to discharge until $V_C \leq V_{low}$, through the resistor $R'_5$. Again the new cycle starts. Figure 3. shows the generation of chaotic sawtooth carrier waveform.

| R  | S  | Q(n+1) |
|----|----|--------|
| 0  | 1  | 0      |
| 1  | 0  | 1      |
| 1  | 1  | $Q_n$  |
| 0  | 0  | Unstable |

When $R'_5$ is close to zero or very small, $C_6$ discharges at very fast and the output voltage of $C_6$ is close to a sawtooth waveform.
The frequency of chaotic carrier is

\[ f_{ch} = \frac{1}{t_{\text{charge}} + t_{\text{discharge}}} \]  

(1)

\[ t_{\text{charge}} = \frac{-(R_5 + R'_5)C_6\ln\left(1 - \frac{V_{\text{upp}} - V_{\text{low}}}{V_{\text{cc}} - V_{\text{low}}}\right)}{V_{\text{upp}} - V_{\text{cc}}} \]  

(2)

\[ t_{\text{discharge}} = \frac{-R'_5C_6\ln\left(\frac{V_{\text{low}}}{V_{\text{upp}}}\right)}{V_{\text{upp}} - V_{\text{cc}}} \]  

(3)

In practice, a reference frequency \( f_c \) is chosen and the passive components of the converter are designed based on this and when \( V_{\text{upp}} = V_u \), \( f_c \) is defined as the reference frequency. Generally \( V_{\text{chaos}} \in (-M, M) \), \( M \) is the positive real number. Frequency of chaotic carrier fluctuates around \( f_c \) and this fluctuation range dependent upon \( V'_{\text{chaos}} \), based on this condition, the circuit adjust oscillating signals amplitude proportionally. \( f_{ch} \) varies chaotically, due to the chaotic characteristics of \( V_{\text{upp}} \). So it is normally specified as chaotic carrier. The design values of the generator of a chaotic sawtooth carrier are \( R_1 = R_2 = R_3 = R_4 = 1K\Omega \), \( R_5 = 3.52 \times 10^{-3} \Omega \), \( R'_5 = 4.6 \times 10^{-5} \Omega \), \( C_6 = 0.1F \), \( V_{cc} = 12V \).

2.3. Oscillator Circuit
Among the various types of oscillator, chaotic oscillator[17] is selected for this research work, due to its simple circuit whose diagram is portrayed in Figure. 4. The main purpose of chaotic oscillator is to produce chaotic carrier signal. But the frequency of the existing chaotic oscillator does not follow the required switching frequency. So, this oscillator frequency should be increased by adjusting their circuit parameters. The output frequency such as \( V_{\text{chaos}} \), will be increased by \( N \) times when the parameters \( C_1, C_2 \) and \( L_1 \) are generally replaced by \( C_1/N \), \( C_2/N \) and \( L_1/N \). The parameters which transformed, are adjusted by trial and error, because of their non-ideal nature of the circuit components.
2.4. Chua’s Diode

Figure 5 shows chua’s diode. The main highlight of chua’s diode [18] is that it improves the switching to the required DC-DC converters frequency by the following way. \( V_{\text{chaos}} \) is proportionally modulated into \((-0.2, +0.2)\), then the upper signal \( V_{\text{upp}} \in (1.8, 2.2) \). So, the chaotic carrier signal [19-21] is generated based on this range. The design parameters of chua’s diode are \( R_{d1} = 2.4\, \Omega \), \( R_{d2} = 3.3\, \text{K}\, \Omega \), \( R_{d3} = 220\, \Omega \), \( R_{d4} = 220\, \Omega \), \( R_{d5} = 20\, \text{K}\, \Omega \), \( R_{d6} = 20\, \text{K}\, \Omega \), \( V_{\text{upp}} = 2\, \text{V} \), \( V_{\text{chaos}} = 12\, \text{V} \). Due to this special feature of chua’s diode, chaotic carrier does not change the DC-DC converters characteristic of output waveform.
Figure 6. Output voltage of IBC with chaotic PWM

Figure 7. Output voltage ripple with chaotic PWM
Figure 6. & 7. shows the output voltage and output voltage ripple of chaotic PWM based IBC. The chaotic carrier saw tooth waveform is shown in figure 8. The input current ripple of chaotic PWM based IBC is shown in figure 9. The inductor current ripple of chaotic PWM based IBC is shown in figure 10.

Table 2. Ripple calculation for chaotic PWM based IBC.

| Parameters                  | Conventional PWM based IBC | Chaotic PWM based IBC |
|-----------------------------|----------------------------|-----------------------|
| Output voltage ripple (%)   | 1.2                        | 0.0041                |
| Input current ripple (%)    | 0.03                       | 0.0076                |
| Inductor Current ripple(%)  | 9.23                       | 0.0005                |

Ripple calculation for chaotic PWM based IBC is tabulated in table 2. From this table, it is inferred that chaotic PWM based IBC gives less input current ripple, less inductor current ripple and less output voltage ripple compared to conventional PWM based IBC.
3. Hardware Implementation

A four phase directly coupled IBC with chaotic PWM triggering method is shown in Figure.11. The main parts of the hardware are power circuit, microcontroller board for producing the chaotic PWM signal and opto-coupler. The switching devices placed in the hardware circuit are MOSFET IRF840, diode 1N 4007 and microcontroller. In microcontroller part chaotic oscillator, comparator and SR flip flops are incorporated for producing chaotic carrier signal by using logistics map programming method. The logistics mapping is a polynomial mapping of degree 2. The main feature of this mapping is the chaotic behavior appears in simple, non linear and dynamic equations. The logistics map is generally written as,

\[ x_{n+1} = r x_n (1 - x_n) \]  

(3a)

\( x_n \) represents ratio of existing population to the maximum possible population. It takes the value between 0 and 1. \( r \) represents the behavior dependent.

Figure 11. Experimental setup of four-phase directly coupled IBC with chaotic PWM technique.
Figure 12. Output voltage waveform of chaotic PWM based IBC.

Figure 13. Output voltage ripple of chaotic PWM based IBC.

Figure 12 & 13 shows output voltage waveform and numerical value. From figure 13 the ripple values obtained in chaotic PWM method is 1.001%, which is very less against the conventional PWM method.
Figure 14 & 15 shows the input current waveform and input current ripple of chaotic PWM based IBC. The ripple value is less than the normal PWM method.
Figure 16 & 17 shows the inductor current waveform and inductor current ripple value. The ripple value is less than that of coupled IBC with normal PWM method. Table 3 shows the ripple analysis for chaotic PWM based IBC, comparing the simulation and experimental results.
Table 3. Ripple analysis for chaotic PWM based IBC.

| Parameter                | Simulation | Hardware |
|--------------------------|------------|----------|
| Output voltage ripple (%)| 0.0041     | 1.001    |
| Input current ripple (%)  | 0.0076     | 3.507    |
| Inductor Current ripple (%) | 0.0005     | 2.301    |

4. Four Phase IBC Analysis Part

The analysis of four-phase IBC is carried out in the following ways.
- Ripple Analysis
- Power loss calculations
- Energy factor calculations

4.1. Ripple Analysis

4.1.1 Ripple Analysis for various PWM technique. For coupled four-phase IBC, chaotic PWM triggering has been applied and the ripple values are calculated theoretically and obtained via simulation by considering the design parameters as $L_n=1.89H$, $R=33\Omega$, $C=0.049F$, $V_o=48V$, $I_{out}=0.2A$, $T=2.3ms$, $d=0.3$, $d'=0.1$, $N=4$. Figure 18 represents the output voltage ripple for different duty ratios for conventional and chaotic PWM based IBC. It is inferred that chaotic PWM based IBC gives less output voltage ripple compared to conventional PWM based IBC.

![Figure 18. Output voltage ripple analysis (simulation results).](image1)

![Figure 19. Input current ripple analysis (simulation results).](image2)

Figure 19 shows the input current ripple for various duty ratios of conventional and chaotic PWM based IBC. It is clearly depicts that chaotic gives less input current ripple than conventional PWM based IBC.
Figure 20. Output capacitor RMS current analysis (simulation results).

Figure 20 shows the output capacitor RMS current for different duty ratios of conventional and chaotic PWM based IBC. It is clearly noted that chaotic gives less output capacitor RMS current than conventional PWM based IBC. By comparing the conventional and chaotic PWM triggering for IBC, chaotic PWM shows reduced ripple and it is clearly depicted in table 4.

\textbf{Table 4.} Ripple analysis of four-phase IBC.

| Ripple/Duty Ratio | Methods          | 0.52 |
|-------------------|------------------|------|
| Output Voltage Ripple(%) | Chaotic PWM | 0.0041 |
|                   | Conventional PWM | 1.2  |
| Input Current Ripple(%) | Chaotic PWM | 0.0076 |
|                   | Conventional PWM | 0.03 |
| Output Capacitor RMS Current(A) | Chaotic PWM | 0.012 |
|                   | Conventional PWM | 0.07 |

4.2. Power Loss Calculations

The power loss values are calculated for chaotic PWM method and the loss values are tabulated in table 5. So the efficiency of the converter is calculated by using the above power losses as 93.88%.

4.3. Energy Factor Calculations

Table 6. shows the energy factor calculations of chaotic PWM technique for four phase coupled IBC, which is higher than the uncoupled four phase IBC because the coupling effect increases the energy storage values.
Table 5. Power loss values.

| S.No. | Components of Power loss | Types of Losses                | Power Loss Values (Watts) |
|-------|--------------------------|-------------------------------|---------------------------|
| 1.    | MOSFET                   | Switching Power Loss          | 20.31                     |
| 2.    | MOSFET                   | Conduction Power Loss         | 10                        |
| 3.    | Diode                    | Turn on Power dissipation     | 10.752                    |
| 4.    | Diode                    | Forward Power dissipation     | 4.14                      |
| 5.    | Diode                    | Turn off power dissipation    | 0.0384                    |
| 6.    | Diode                    | Core Power Loss               | 0.795                     |
| 7.    | Inductor                 | Copper Power loss             | 0.936                     |
| 8.    | Total Losses             |                               | 46.97                     |
| 9.    | Input power              |                               | 768                       |
| 10.   | Output power             |                               | 724                       |
| 11.   | Efficiency               |                               | 93.88%                    |

Table 6. Energy factor calculations for chaotic PWM technique.

| Parameter                                      | Uncoupled    | Coupled IBC  |
|------------------------------------------------|--------------|--------------|
| Pumping Energy (PE)                           | 0.0253 J     | 0.0253 J     |
| Stored Energy in the inductor                 | 0.0047 J     | 0.0115 J     |
| Stored Energy in the capacitor                | 0.0018 J     | 0.0018 J     |
| Total stored Energy (SE)                      | 0.0065 J     | 0.0133 J     |
| Capacitor-Inductor stored Energy Ratio (CIR)  | 0.38         | 0.15         |
| Time constant                                 | 1.08 µs      | 2.16 µs      |
| Damping time constant                         | 4.73µs       | 6.51 µs      |
| Time Constant Ratio                           | 4.37         | 3.01         |
| Variation in Stored energy in the Inductor    | 1.1718 J     | 0.8202 J     |
| Variation in Stored energy in the capacitor   | 0.2657 J     | 0.0705 J     |
| Total Variation in the stored energy(VE)      | 1.4375 J     | 0.8907 J     |
| Energy Factor (EF)                            | 0.2569       | 0.52         |
| Variation Energy Factor (EFv)                 | 56.8181      | 35.20        |

5. Conclusion
The chaotic PWM triggered IBC circuit is modeled, simulated and hardware prototype is developed. It produces less output voltage ripple within maximum and minimum limitations of chaotic carrier. The output voltage ripple, input current ripple and inductor current ripple are effectively reduced by chaotic PWM method compared to conventional PWM method. The reduction of output voltage ripple reduces the size of the filter. The reduction of input current ripple increases the lifetime of the fuel cell. The minimization of the inductor current ripple reduces the variation in energy factor of IBC. Therefore, chaotic PWM triggering proves to be better compared to conventional PWM triggering. The power losses
are calculated for chaotic PWM based IBC, which gives less losses and high efficiency as 93.88%. The energy factor and variation of energy factor are used to highlight the effective operation of coupled IBC compared to uncoupled IBC in terms of coupling co-efficient.

6. References

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