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Original Article

Basic Design and Review of Two Phase and Three Phase Interleaved Boost Converter for Renewable Energy Systems

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ABSTRACT

This paper investigates the performance of two-phase and three-phase Interleaved Boost Converter (IBC) for renewable energy applications. By employing three-stage IBC, the overall current ripple can be effectively reduced which increases the lifetime of renewable sources [1-3]. In this paper, a three phase interleaved boost converter has been discussed and it is compared to the conventional two-phase IBC presented in the literature. The advantage of three Phase IBC compared to the two Phase is low input current ripple [4,5]. The output voltage, input current and inductor current ripples of the two types of converters are compared for various duty cycles. Simulation is carried out in MATLAB/SIMULINK. The results are discussed and verified with the theoretical values.

INTRODUCTION

The depletion of fossil fuels and global warming, caused largely by greenhouse gas emissions led to the development of non-conventional energy sources. These sources of energy are also called Renewable energy. Renewable sources are continuously replenished by natural processes. Renewable energy comes from many commonly known sources such as solar power, wind, running water and geothermal energy. Also another great benefit from using renewable energy is that many of them do not pollute our air and water, the way burning fossil fuels does. Any such renewable energy system requires a suitable converter to make it efficient. Interleaved boost converter is one such converter that can be used for these applications. Interleaved boost converter is a promising interface between renewable energy sources such as fuel cells, PV and the DC bus of inverters. Due to interleaving operation, IBC exhibits both lower current ripple at the input side and lower voltage ripple at the output side.[6] Here two IBC topologies are discussed namely: Two and Three Phase. The frequency of the current ripple is twice for two phase IBC than the conventional boost converter. Due to a phase shift of 180 degrees ripple cancellation takes place. In this paper the operation of both two phase and three phase IBCs are discussed. The waveforms of input, inductor current ripple and output voltage ripple are obtained using MATLAB/SIMULINK. The design equations for two phase as well as three phase IBCs have been presented. Output RMS currents are calculated.

TWO PHASE IBC

Circuit Operation

The circuit of two phase interleaved boost converter is shown in Fig.1. When the device M is turned ON, the current in the inductor L increases linearly. During this period energy is stored in the inductor L. When M is turned OFF, diode D conducts and the stored energy in the inductor ramps down with a slope based on the difference between the input and the output voltage. The inductor starts to discharge and transfer the current to the load through the diode. After a half switching cycle of M, M1 is also turned ON completing the same cycle of events. Since both the power channels are combined at the output capacitor, the effective ripple frequency is twice that of a single phase boost converter. The amplitude of the input current ripple is small. This advantage makes this topology very attractive for the renewable energy sources. The gating pulses of the two devices are shifted by a phase difference of 360/n, where n is the number of parallel boost converters connected in parallel. For a two phase interleaved boost converter n=2, the phase shift is 180 degrees and it is shown in Fig.2. It can be seen that the input current, for two phase interleaved boost converter is the sum of each channel inductors currents. As the two devices are phase shifted by 180 degrees, the input current ripple is minimum.[7-12]

When the duty ratio is less than 0.5 the ideal waveforms are shown in Fig.2. Here the duty ratio is 0.2.

When the duty ratio is greater than 0.5 the waveforms are shown in Fig.3. Here the duty ratio is 0.75.

Design Equations

1. Boost ratio

The boosting ratio of the IBC is a function of the duty ratio. It is same as in conventional boost converter. It is defined as

$$\frac{V_o}{V_{in}} = \frac{1}{1-D} \tag{1}$$

Where V_o is the output voltage, is the V_{in} input voltage and D is the duty ratio.

2. Input current

The input current can be calculated by the input power and the input voltage.

$$I_{in} = \frac{P_{in}}{V_{in}} \tag{2}$$

Where I_{in} is the input current, P_{in} is the input power and V_{in} the input voltage.

3. Inductor current ripple peak-to-peak amplitude

The inductor current ripple peak-peak amplitude is given by

$$\Delta I_{l1,l2} = \frac{V_{in} D}{F_S L} \tag{3}$$

Where V_{in} represents the input voltage, D represents the duty ratio, F_S represents the switching frequency and L represents the value of the inductor.

4. Selection of inductor and capacitor

In the power electronic systems the magnetic components play a major role for energy storage and filtering. As discussed in the operation of IBC the inductor is used to transform the energy from the input voltage to the inductor current and to convert it back from the inductor current to the output voltage. As per the principle the two inductors shown in the Fig. 1. are identical in order to balance the current in the two boost converters. The value of the inductor can be found out by the following formula

$$L \geq \frac{V_{in} D T_S}{2 \Delta I_o} \quad (4)$$

Where, T_S -Switching period, ΔI_o -Output current ripple,

The value of the capacitor is given by the formula

$$C \geq \frac{D V_o}{R \Delta V_o F_S} \quad (5)$$

Where, R- Load resistor, ΔV_o -Output voltage ripple and V_o - Output voltage

5. Output RMS Current

i. For $\delta < 0.5$**:**

$$I_{CoRMS} = \frac{I_{out}}{2(1-\delta)} \sqrt{\delta(1-\delta)} \quad (6)$$

Where I_{out}=Output current

ii. For $\delta > 0.5$**:**

$$I_{CoRMS} = \frac{I_{out}}{2(1-\delta)} \sqrt{\frac{1}{2}(2\delta-1)(2-2\delta)} \quad (7)$$

Simulation Parameters

Simulation Parameters are shown in Table.1.

Simulation Results

i) For $\delta < 0.5$

The switching patterns of two MOSFETs (M and M1) used in the two phase IBC is shown in Fig.4.The pulse of second switch is phase shifted by 180 degrees from the first device.

The input current and the current through the parallel inductors are shown in Fig.5.They can be obtained as 6.1 A and 3.1A respectively. It can be inferred from the figure that the inductor currents are same. Using these waveforms the input current ripple is obtained as 0.008A and inductor current ripple is obtained as 0.023A.

The output current waveform is shown in Fig.6.It is obtained as 4.8 A.

The output voltage waveform is shown in Fig.7.It is obtained as 24 V.

Output current ripple waveform is shown in Fig.8.Ripple current of 0.0003A is also calculated using this waveform.

Output Voltage Ripple waveform is shown in Fig.9. Voltage Ripple of 0.0003V is also calculated using this waveform.

ii) For $\delta > 0.5$

The switching patterns of two MOSFETs (M and M1) used in the two phase IBC is shown in Fig.10.The pulse of second switch is phase shifted by 180 degrees from the first device.

The input and inductor currents are shown in Fig.11.They can be obtained as 41 A and 21A respectively. Using these waveforms the input current ripple is obtained as 0.009A and inductor current ripple is obtained as 0.003A.

The output current waveform is shown in Fig.12.It is obtained as 12.2 A.

The output voltage waveform is shown in Fig.13.It is obtained as 71 V.

Output current ripple waveform is shown in Fig.14.Ripple current of 0.00007A is also calculated using this waveform.

Output Voltage Ripple waveform is shown in Fig.15. Voltage Ripple of 0.00006 V is also calculated using this waveform.

THREE PHASE IBC

Circuit Operation

The circuit diagram for three phase Interleaved Boost Converter is shown in Fig.16. The number of inductors and switches are the same as the number of phases. However, a single capacitor is used as a filter in IBC. Because the output current of the source 1 is divided by 1/N times separately, the current stress in IBC can be reduced. Each phase switching frequency of 3-phase IBC can be identical and each switch has same phase shift angle as 360°/N. According to the duty ratio, switching sequences of each phase can be overlapped or not. While IBC is operated at non-overlapped condition, the input current ripple is decreased. However, it is linearly increased after switching sequence is totally overlapped.[13,14]

Ideal Waveforms for $\delta < 0.5$

When the duty ratio is less than 0.5 the waveforms are obtained as shown in Fig.17. Here the duty ratio is 0.2.

Ideal Waveforms for $\delta = 0.5$

When the duty ratio is at 0.5 the waveforms are obtained as shown in Fig.18.

Ideal Waveforms for $\delta > 0.5$

When the duty ratio is greater than 0.5 the waveforms are obtained as shown in Fig.19. Here the duty ratio is 0.75.

Design Equations

1. Duty ratio

Duty ratio is defined as

$$\frac{V_o}{V_{in}} = \frac{1}{1-D} \tag{8}$$

Where V_o is the output voltage, V_{in} is the input voltage and D is the duty ratio.

2. Input current

The input current can be calculated by the formula,

$$I_{in} = \frac{P_{in}}{V_{in}} \tag{9}$$

Where I_{in} is the input current, P_{in} is the input power and V_{in} the input voltage.

3. Inductor current ripple peak-to-peak amplitude

The inductor current ripple peak-peak amplitude is given by

$$\Delta I_{l1,l2} = \frac{V_{in} D}{F_S L} \tag{10}$$

Where V_{in} represents the input voltage, D represents the duty ratio, F_S represents the switching frequency and L represents the value of the inductor.

4. Selection of inductor and capacitor

The value of the inductor can be found out by the following formula

$$L \geq \frac{V_{in} D T_S}{2\Delta I_o} \tag{11}$$

Where, T_S -Switching period and ΔI_o -Output current ripple

The value of the capacitor is given by the formula

$$C \geq \frac{D V_o}{R \Delta V_o F_S} \tag{12}$$

Where, R- Load resistor, ΔV_o -Output voltage ripple and V_o - Output voltage

5. Output RMS Current

i) For $\delta < 0.5$

$$I_{CoRMS} = \frac{I_{out}}{3(1-\delta)} \sqrt{\delta(1-3\delta)} \tag{13}$$

ii) For $\delta = 0.5$

$$I_{CoRMS} = \frac{I_{out}}{3(1-\delta)} \sqrt{\frac{1}{3}(3\delta-1)(2-3\delta)} \tag{14}$$

iii) For $\delta > 0.5$

$$I_{CoRMS} = \frac{I_{out}}{3(1-\delta)} \sqrt{\frac{1}{3}(3\delta-2)(3-3\delta)} \tag{15}$$

Simulation Parameters

Simulation Parameters are shown in Table.2.

i) For $\delta < 0.5$

Simulation Results

i) For $\delta < 0.5$

The switching patterns of three MOSFETs (M, M1and M2) used in the three phase IBC is shown in Fig.20.The phase shift is 120(360/n) degrees.

The input and inductor currents are shown in Fig.21.They can be obtained as 6 A and 2.9A respectively. Using these waveforms the input current ripple is obtained as 0.0033A and inductor current ripple is obtained as 0.0086A.

The output current waveform is shown in Fig.22.It is obtained as 4.3 A.

The output voltage waveform is shown in Fig.23.It is obtained as 24 V.

Output current ripple waveform is shown in Fig.24.Ripple current of 0.00025 is also calculated using this waveform.

Output Voltage Ripple waveform is shown in Fig.25. Voltage Ripple of 0.00025V is also calculated using this waveform.

ii) For $\delta = 0.5$

The switching patterns of three MOSFETs (M, M1and M2) used in the three phase IBC is shown in Fig.26.The phase shift is 120(360/n) degrees.

The input and inductor currents are shown in Fig.27.They can be obtained as 15.5 A and 4.9A respectively. Using these waveforms the input current ripple is obtained as 0.0032A and inductor current ripple is obtained as 0.015A.

The output current waveform is shown in Fig.28.It is obtained as 7.7 A.

The output voltage waveform is shown in Fig.29.It is obtained as 38.6 V.

Output current ripple waveform is shown in Fig.30.Ripple current of 0.00014A is also calculated using this waveform.

Output Voltage Ripple waveform is shown in Fig.31. Voltage Ripple of 0.00016V is also calculated using this waveform.

iii) For $\delta > 0.5$

The switching patterns of three MOSFETs (M, M1and M2) used in the three phase IBC is shown in Fig.32. The phase shift is 120(360/n) degrees.

The input and inductor currents are shown in Fig.33. They can be obtained as 16 A and 5.3A respectively. Using these waveforms the input current ripple is obtained as 0.00019A and inductor current ripple is obtained as 0.005A.

The output current waveform is shown in Fig.34.It is obtained as 14.6 A.

The output voltage waveform is shown in Fig.35.It is obtained as 73.2 V.

Output current ripple waveform is shown in Fig.36.Ripple current of 0.000024A is also calculated using this waveform.

Output Voltage Ripple waveform is shown in Fig.37. Voltage Ripple of 0.000024V is also calculated using this waveform.

COMPARISON BETWEEN TWO PHASE AND THREE PHASE IBC

Current ripple and voltage ripples are minimum for a three phase IBC when compared with two phase IBC ripple.

The values of the ripple contents are summarized as follows:

Two Phase IBC

Table.3.gives the values of ripples of Two Phase IBC

It can be inferred from the above table that the ripples are reduced with the increased duty ratio.

Three Phase IBC

Table.4.gives the values of ripples of Three Phase IBC

It is clear from the above table that the ripples are reduced for three phase IBC compared with two phase IBC. In three phase IBC itself, it has low ripples for higher duty ratios. By observing output voltage and output current ripples, are also same for all the cases of duty ratio.

Output RMS currents are calculated for both two phase and three phase IBC. They are listed in Table.5.

It is obvious from the above table that the Output RMS Currents are maximum in case of two phase IBC.

CONCLUSION

This paper has discussed the basic design aspects of two phase and three phase interleaved boost converters. The feature and performance of both the IBCs under various duty cycle conditions have been investigated. It is found that the three-phase interleaved boost converter provides a reduced input current and output voltage ripple compared to the classical two-phase IBC. Also, the output RMS current in three-phase IBC is less which results in the reduction of the size of the output capacitor filter. Therefore, a three-phase IBC proves to be a suitable candidate for renewable energy sources.

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Table 1. Simulation Parameters

Parameter	Designator	Value $\delta < 0.5$	Value $\delta > 0.5$
Input Voltage	V_{in}	20 V	20 V
Inductor	L	11 mH	42 mH
Capacitor	C	10 mF	120 mF
Switching Frequency	F_s	5KHz	5KHz

Table 2. Simulation Parameters

Parameter	Designator	Value $\delta < 0.5$	Value $\delta = 0.5$	Value $\delta > 0.5$
Input Voltage	V_{in}	20 V	20 V	20 V
Inductor	L	11 mH	28 mH	42 mH
Capacitor	C	10 mF	40 mF	120 mF
Switching Frequen	F_S	5KHz	5KHz	5KHz

Table 3. Parameters of Two Phase IBC

Type of Ripple	$\delta < 0.5$ ($\delta = 0.2$)	$\delta > 0.5$ ($\delta = 0.75$)
Input current ripple	0.008	0.009
Inductor current ripple	0.023	0.003
Output current ripple	0.0003	0.00007
Output voltage ripple	0.0003	0.00006

Table 4. Parameters of Three Phase IBC

Type of Ripple	$\delta < 0.5$ ($\delta = 0.2$)	$\delta = 0.5$	$\delta > 0.5$ ($\delta = 0.75$)
Input current ripple	0.0033	0.0032	0.00019
Inductor current ripple	0.0086	0.015	0.005
Output current ripple	0.00025	0.00014	0.000024
Output voltage ripple	0.00025	0.00016	0.000024

Table 5. Output RMS Currents

Value of δ /Type of IBC	Two Phase IBC	Three Phase IBC
$\delta < 0.5$ ($\delta = 0.2$)	1.25A	0.589A
$\delta > 0.5$ ($\delta = 0.75$)	11.3A	5.33A

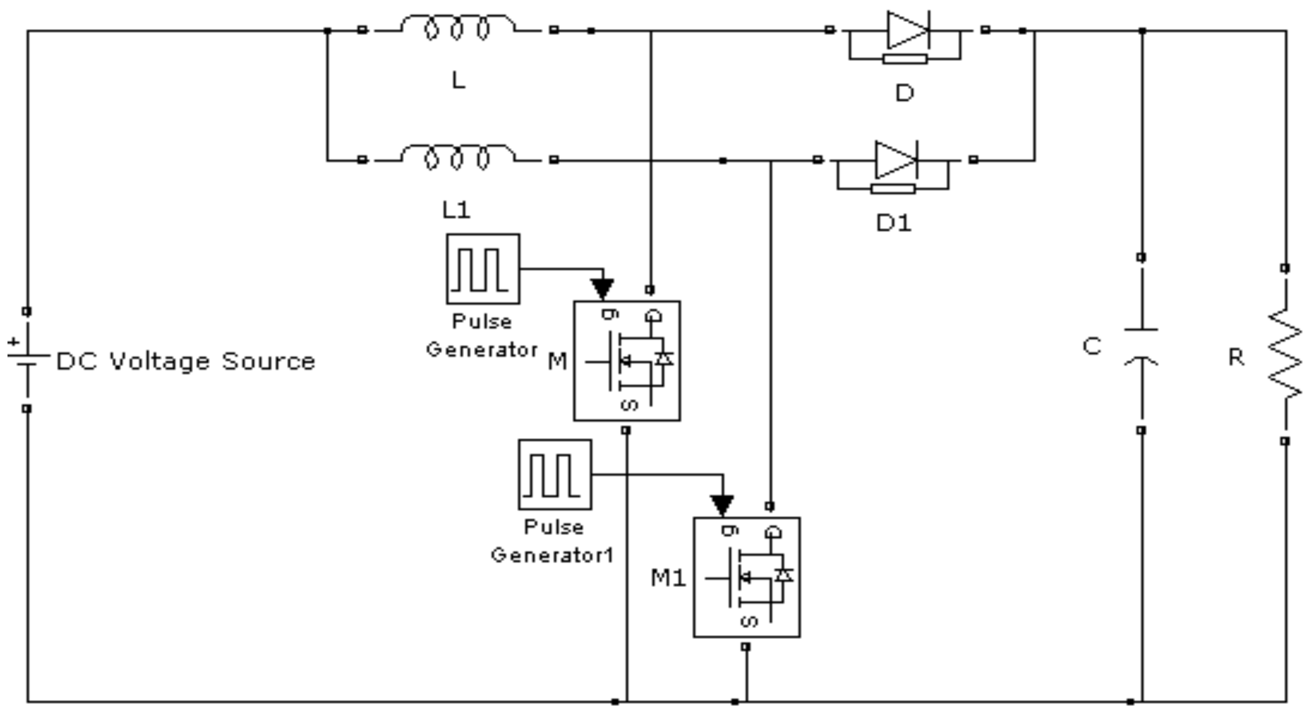

Figure 1. Circuit Diagram of Two Phase IBC

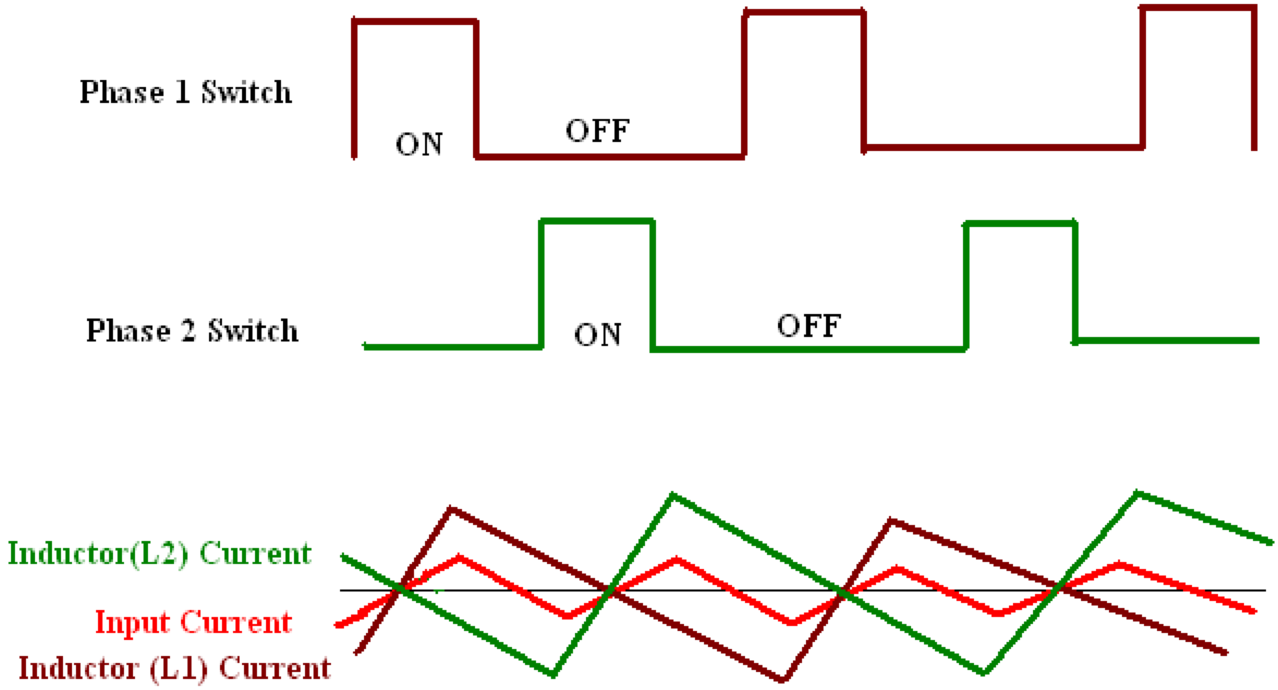

Figure 2. Ideal Waveforms for $\delta < 0.5$ of Two Phase IBC

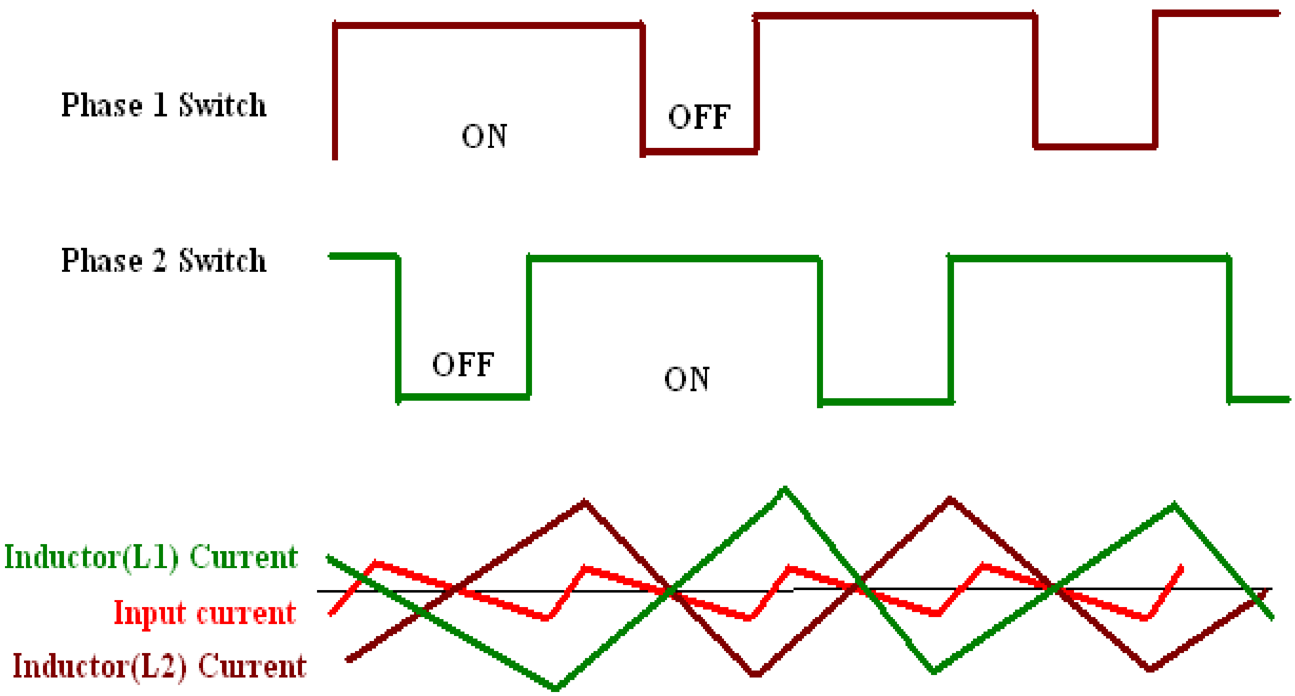

Figure 3. Ideal waveforms for $\delta > 0.5$ for two phase IBC

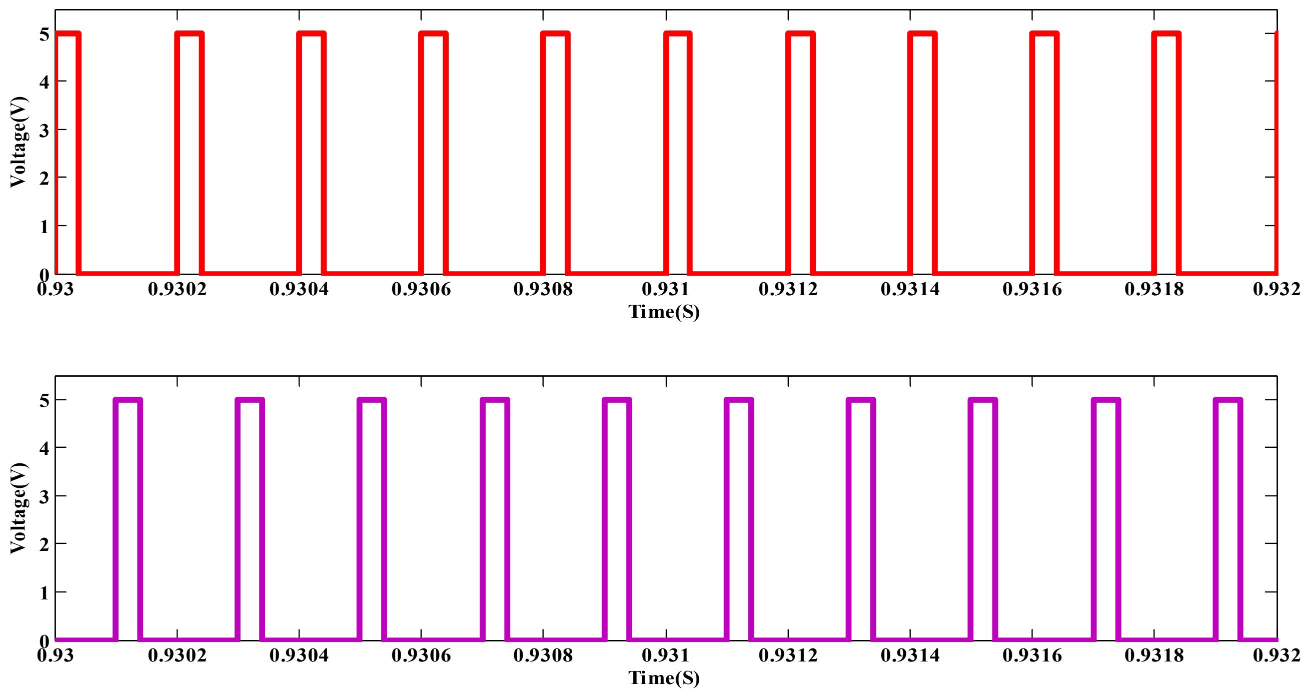

Figure 4. Gating Patterns of Two MOSFETs (M and M1)

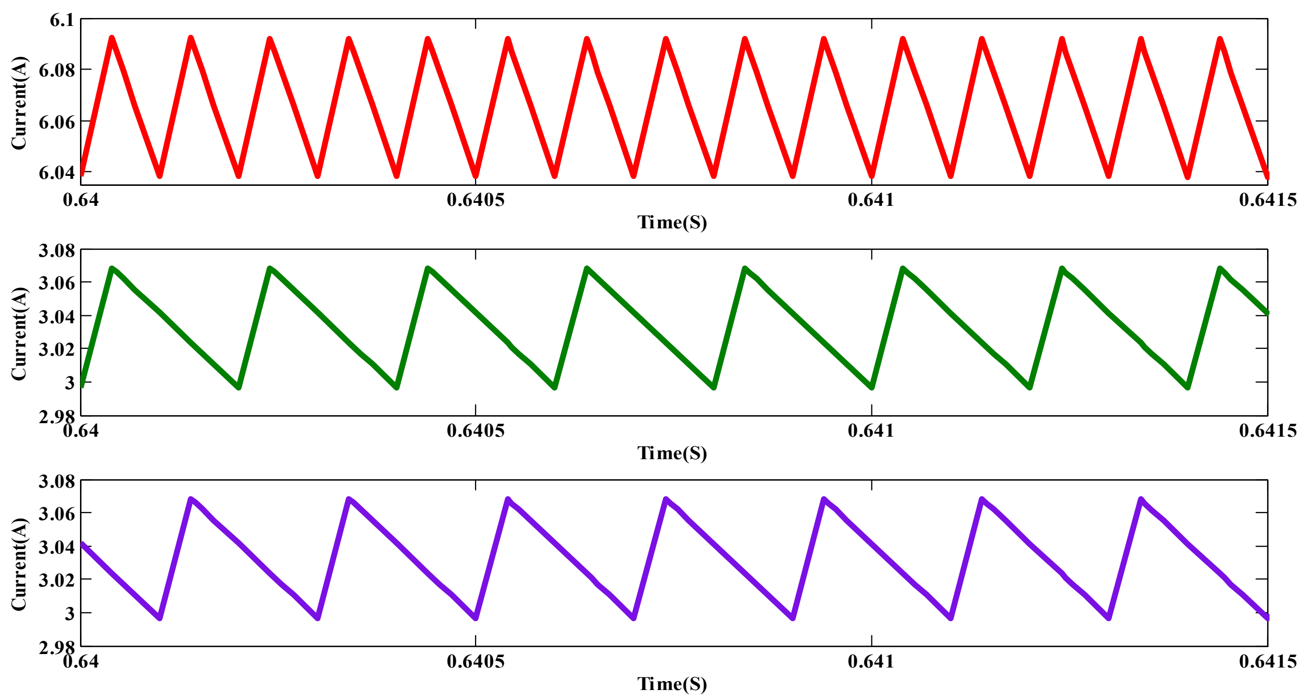

Figure 5. Input current and Inductors (L_1 and L_2) Currents

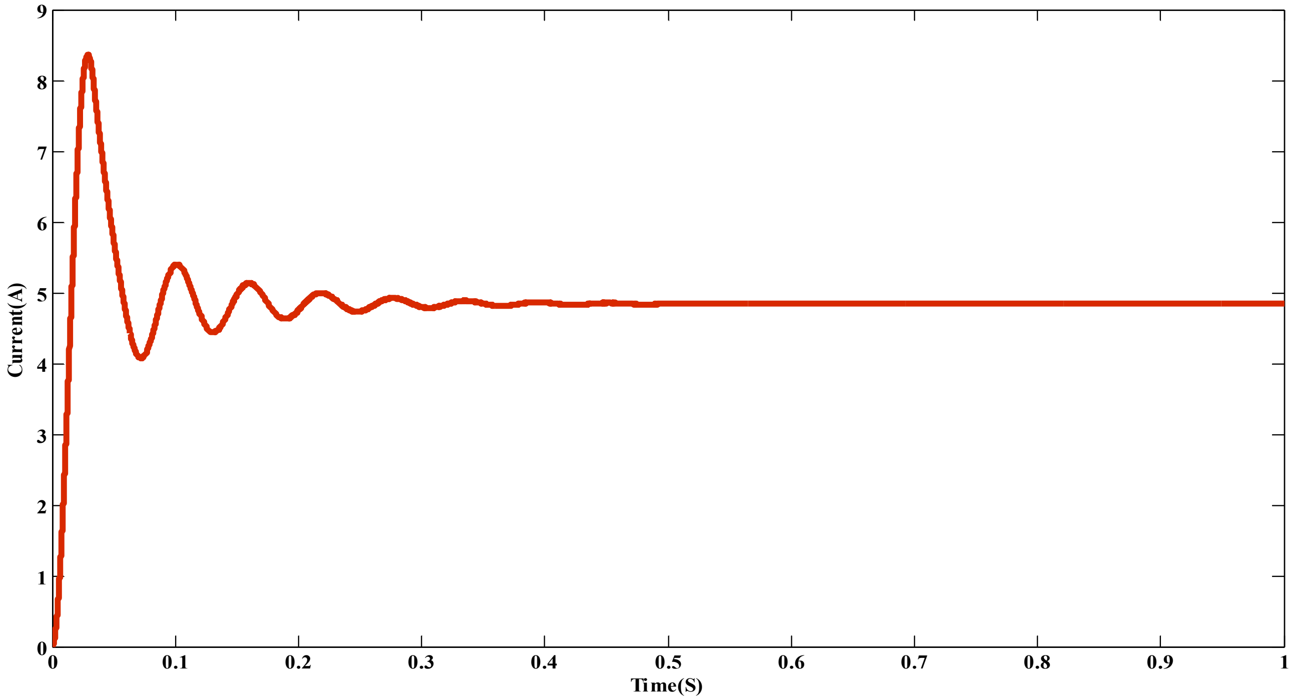

Figure 6. Output Current waveform

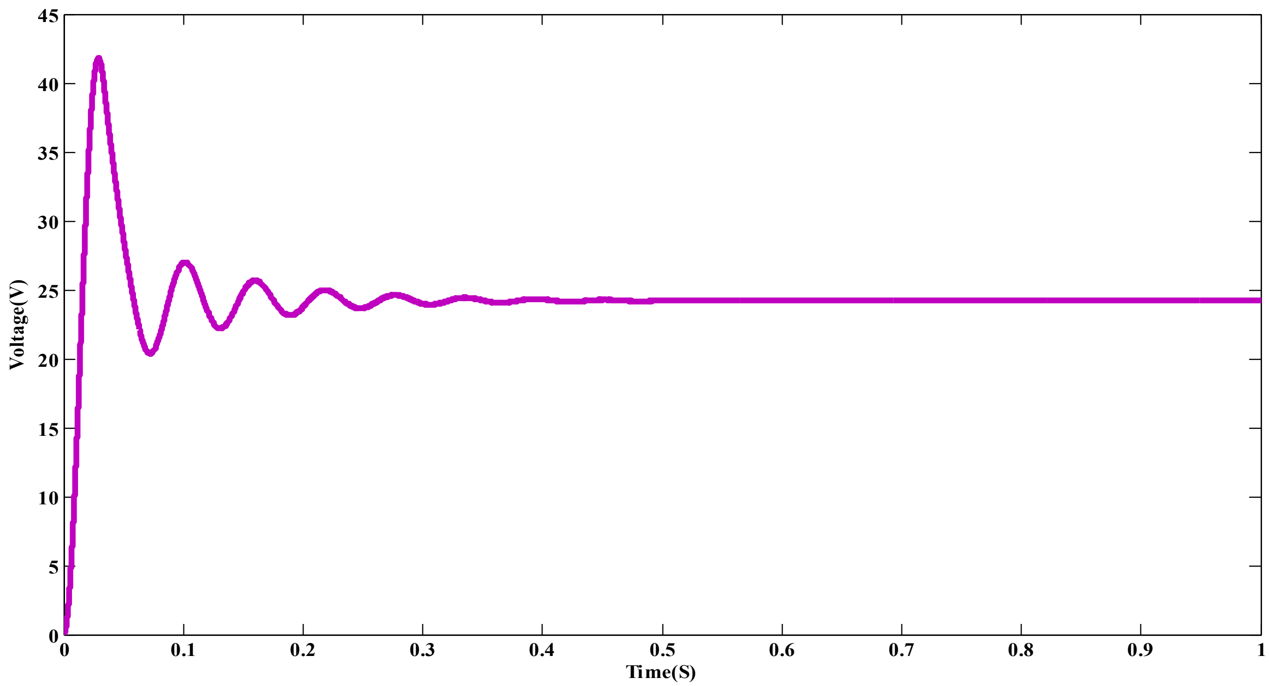

Figure 7. Output voltage waveform

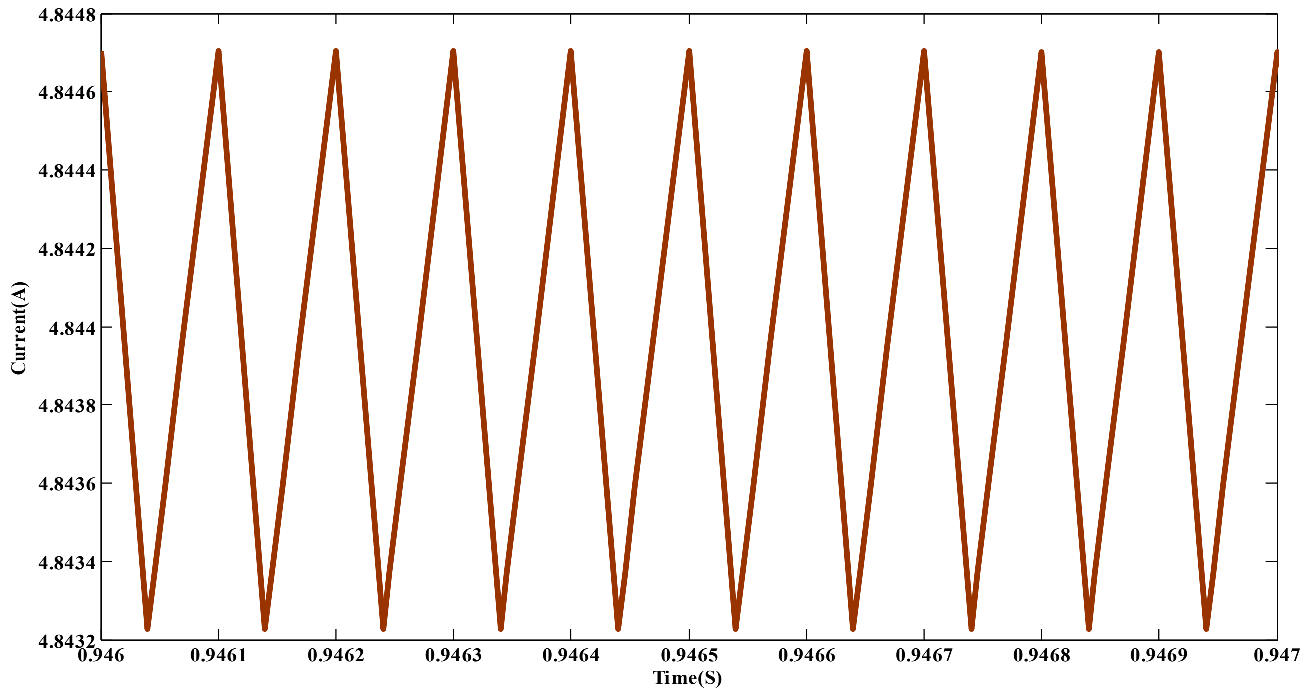

Figure 8. Output Current Ripple Waveform

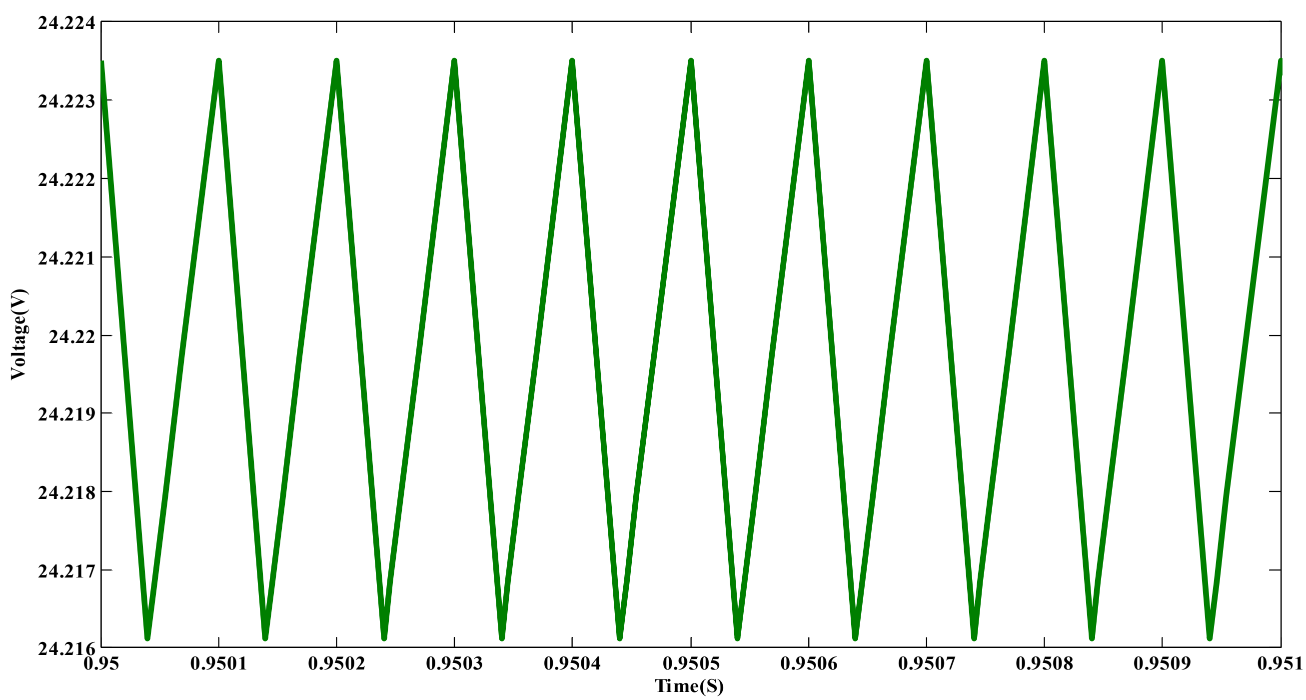

Figure 9. Voltage Ripple Waveform

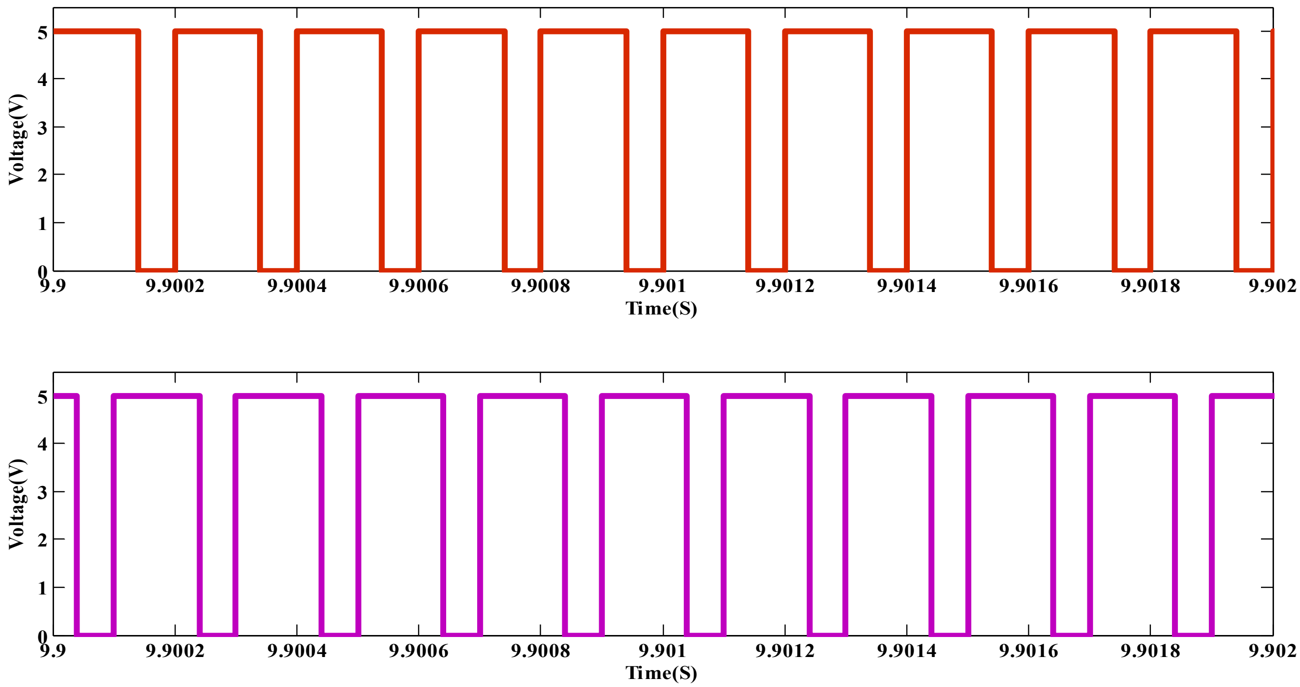

Figure 10. Gating Patterns of MOSFTs (M and M1)

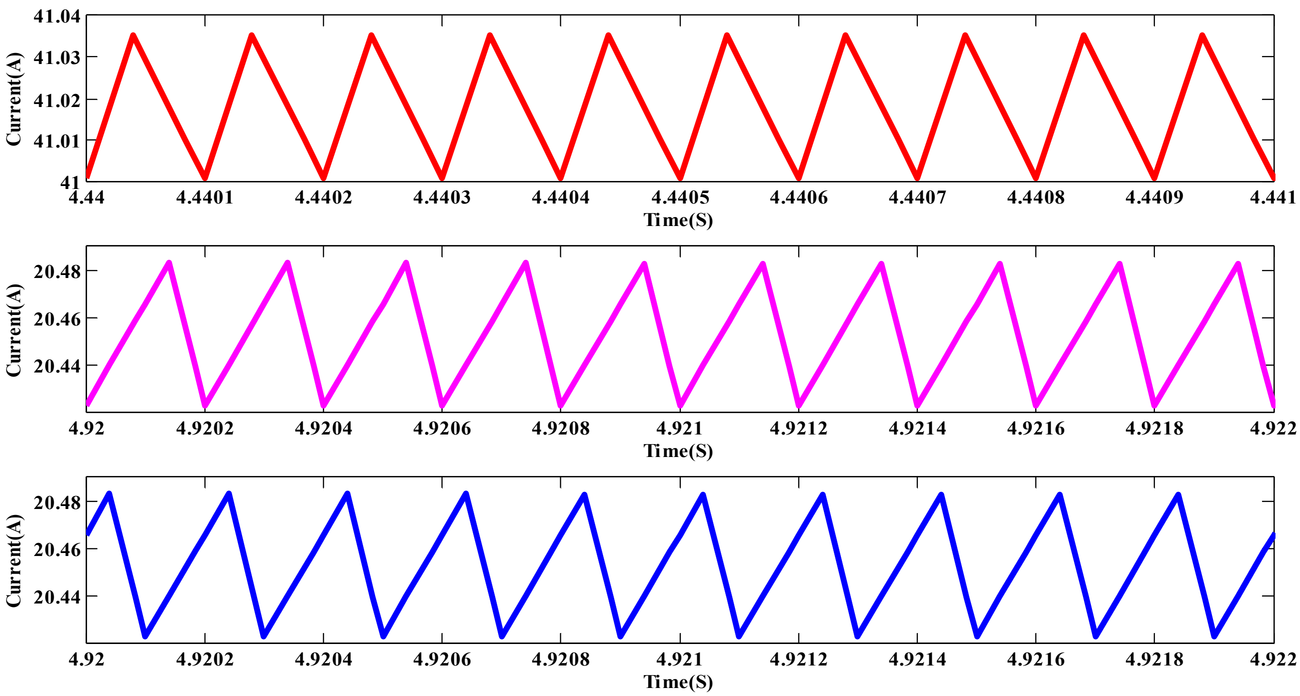

Figure 11. Input Current and Inductors (L_1 and L_2) Currents

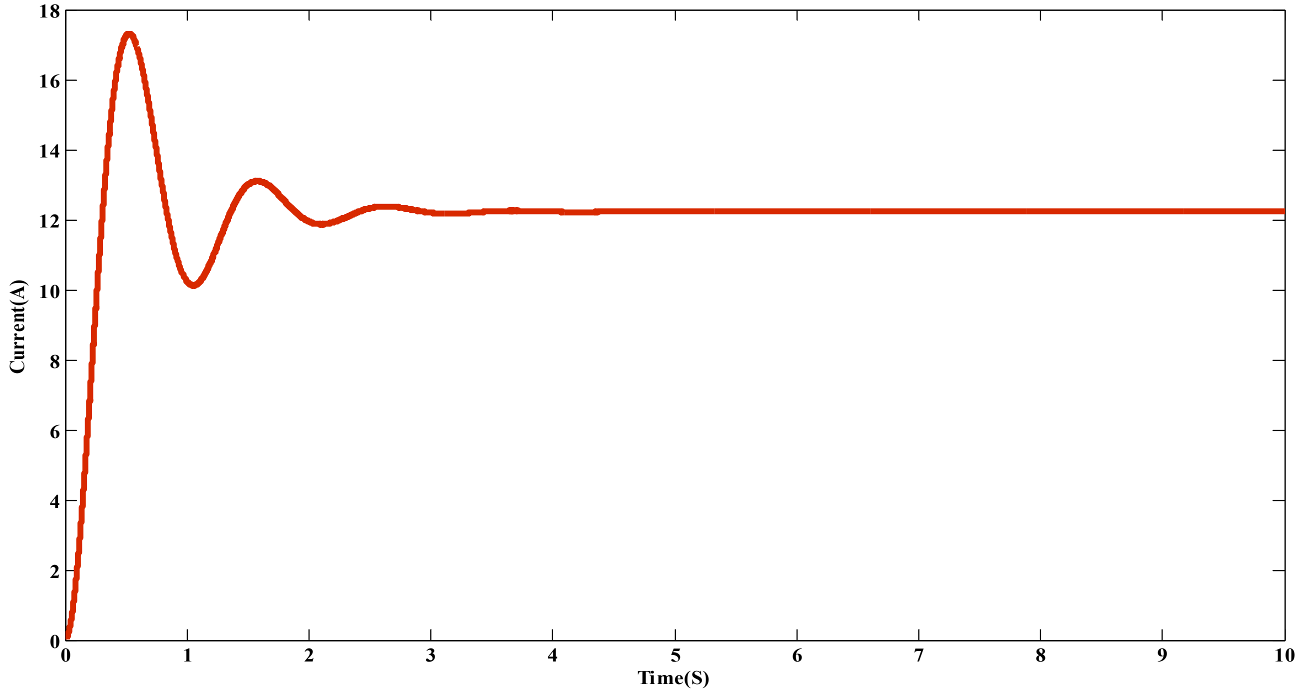

Figure 12. Output Current

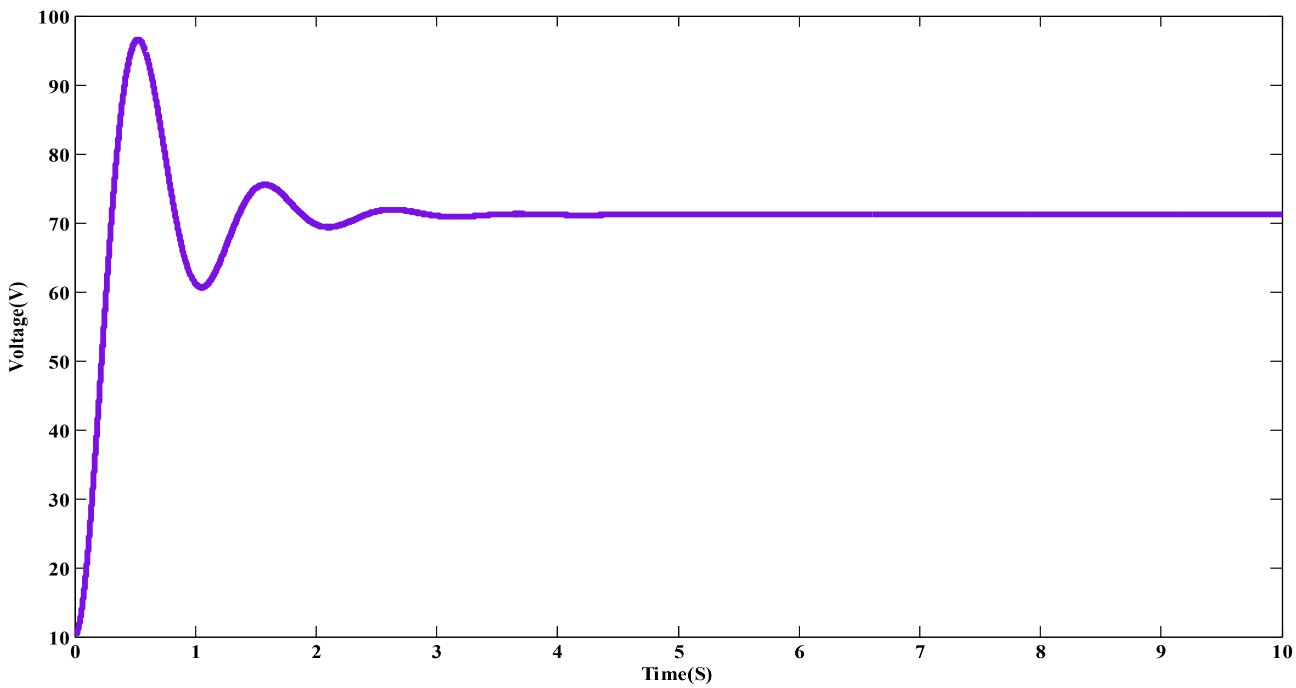

Figure 13. Output Voltage

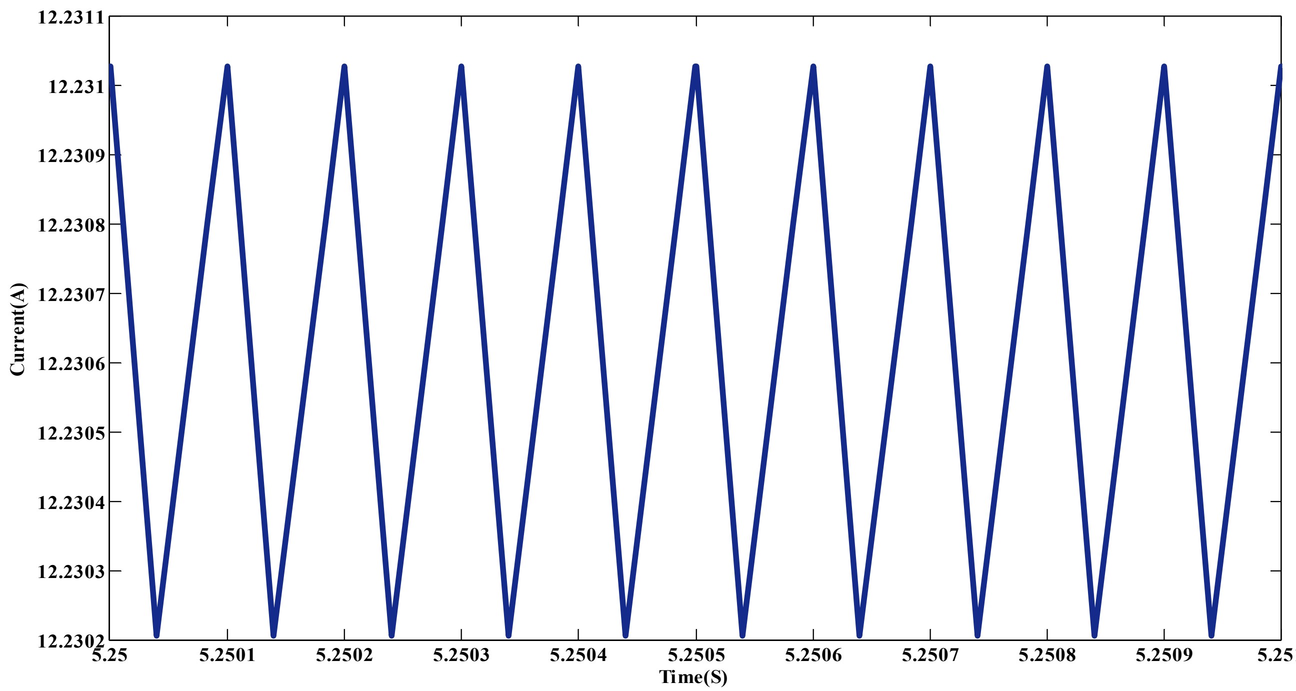

Figure 14. Current Ripple Waveform

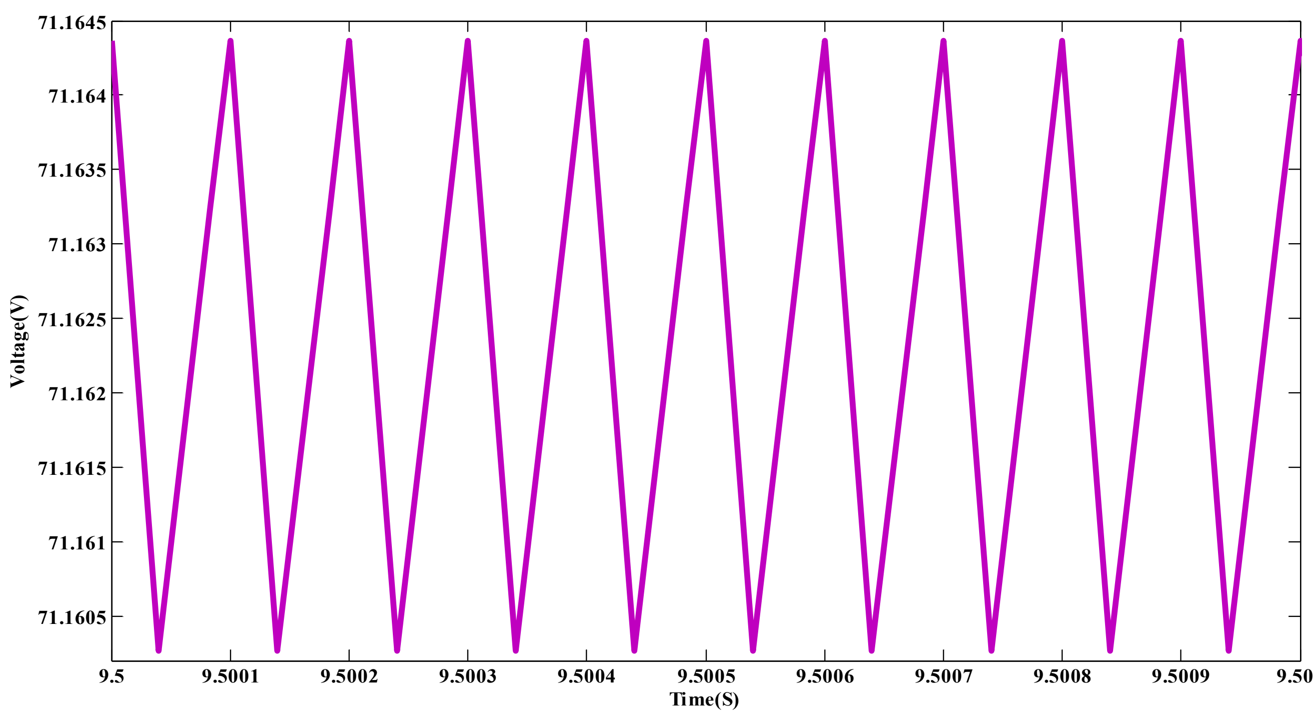

Figure 15. Voltage Ripple Waveform

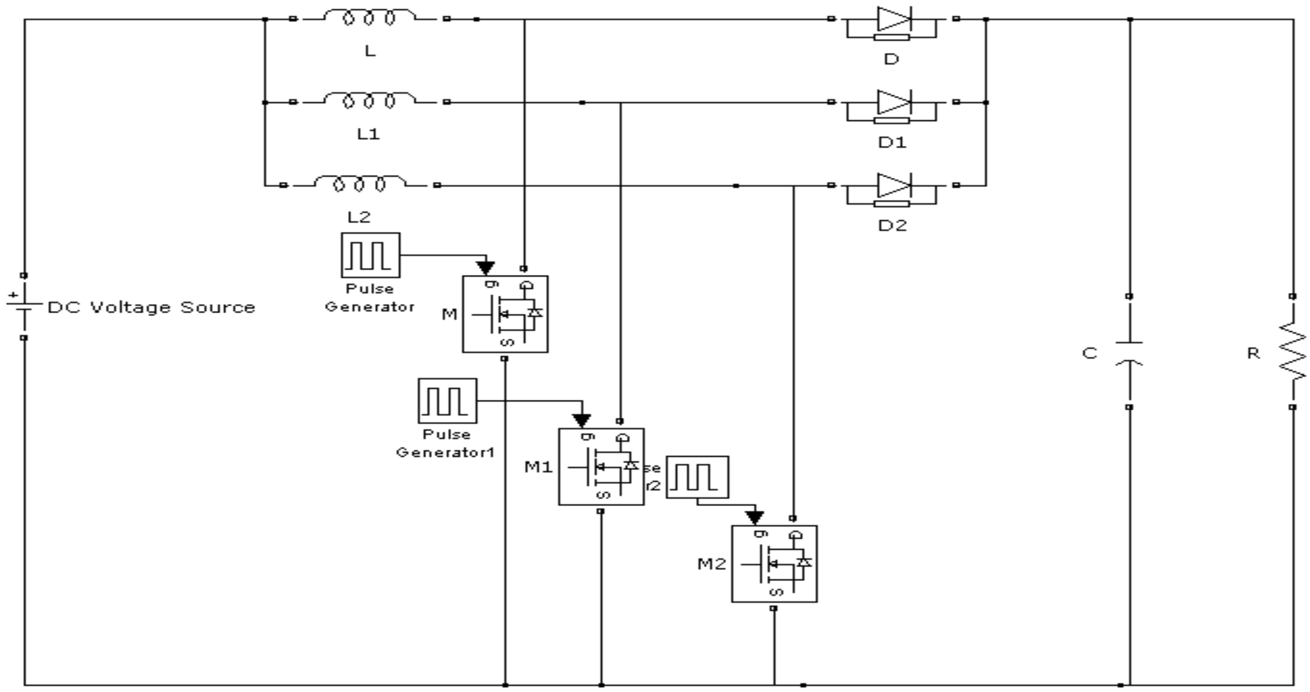

Figure 16. Circuit Diagram of Three Phase IBC

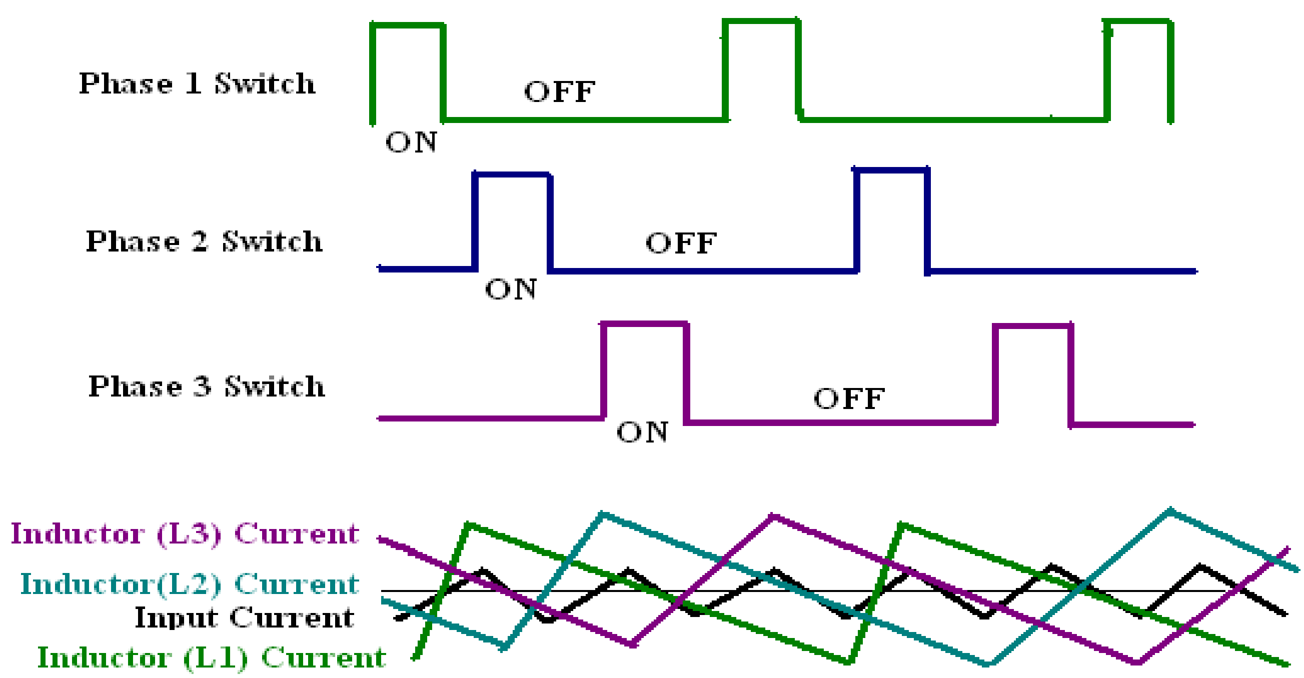

Figure 17. Ideal waveforms for three phase IBC when $\delta < 0.5$

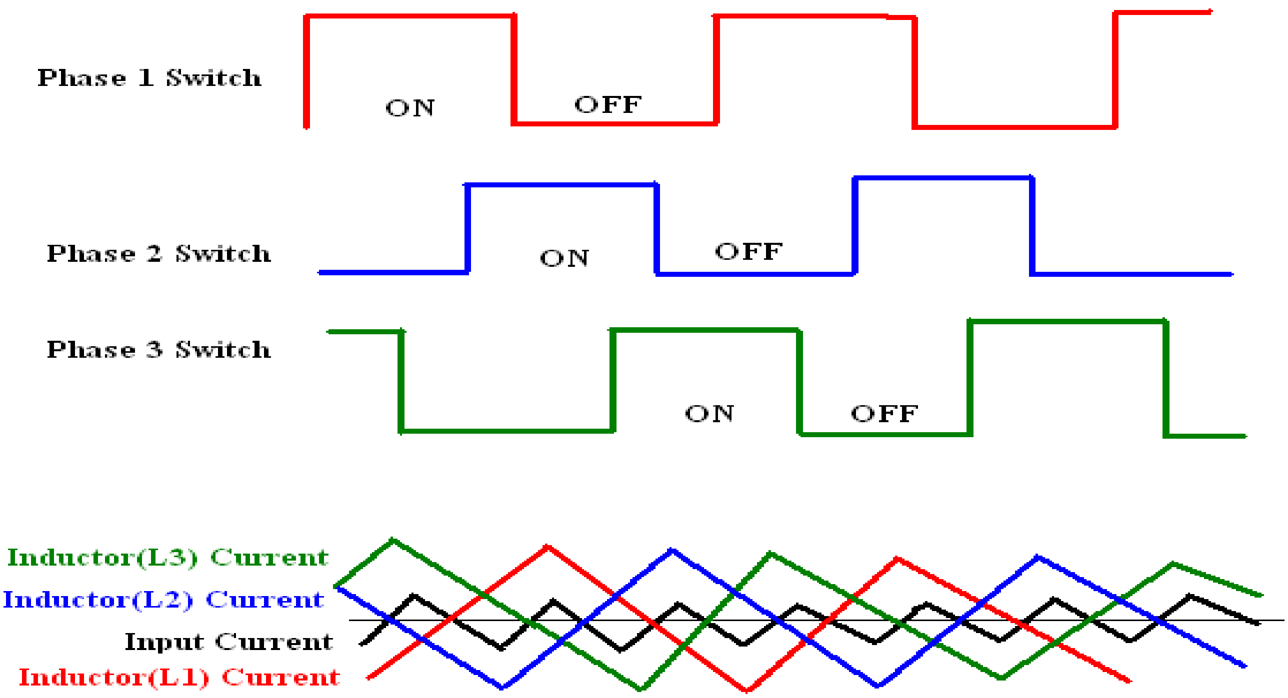

Figure 18. Ideal waveforms for three phase IBC when $\delta = 0.5$

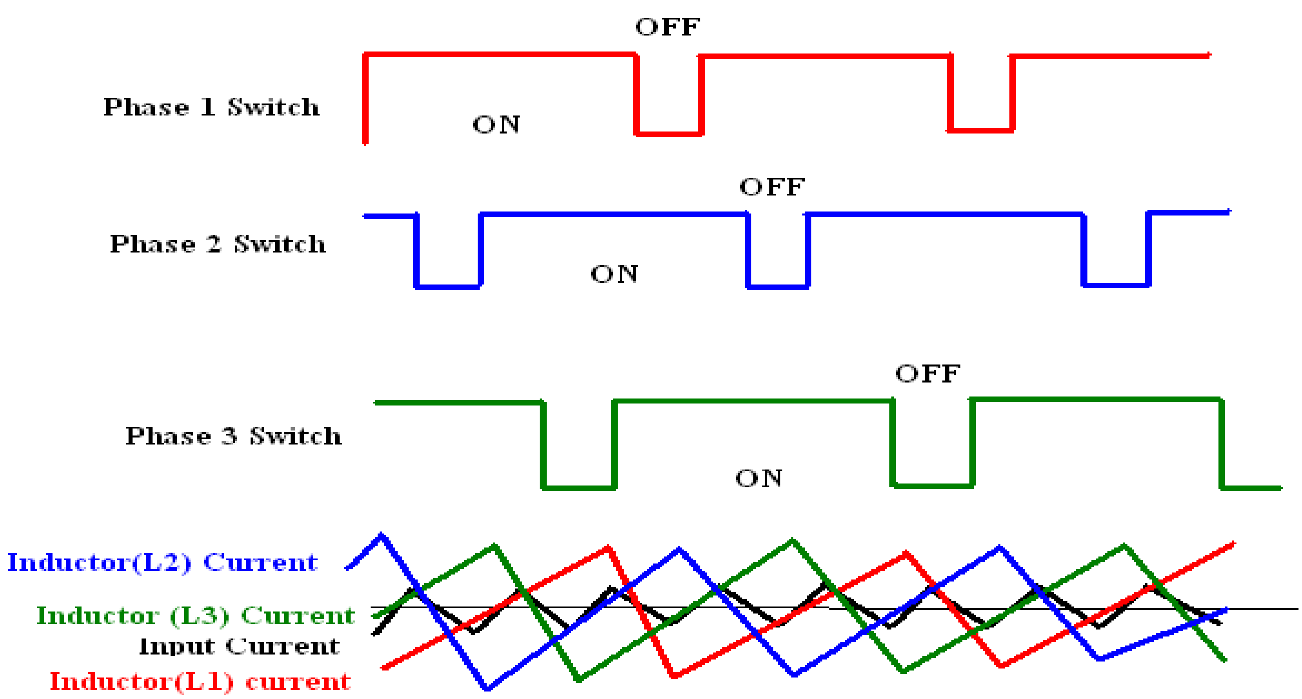

Figure 19. Ideal waveforms for three phase IBC when $\delta > 0.5$

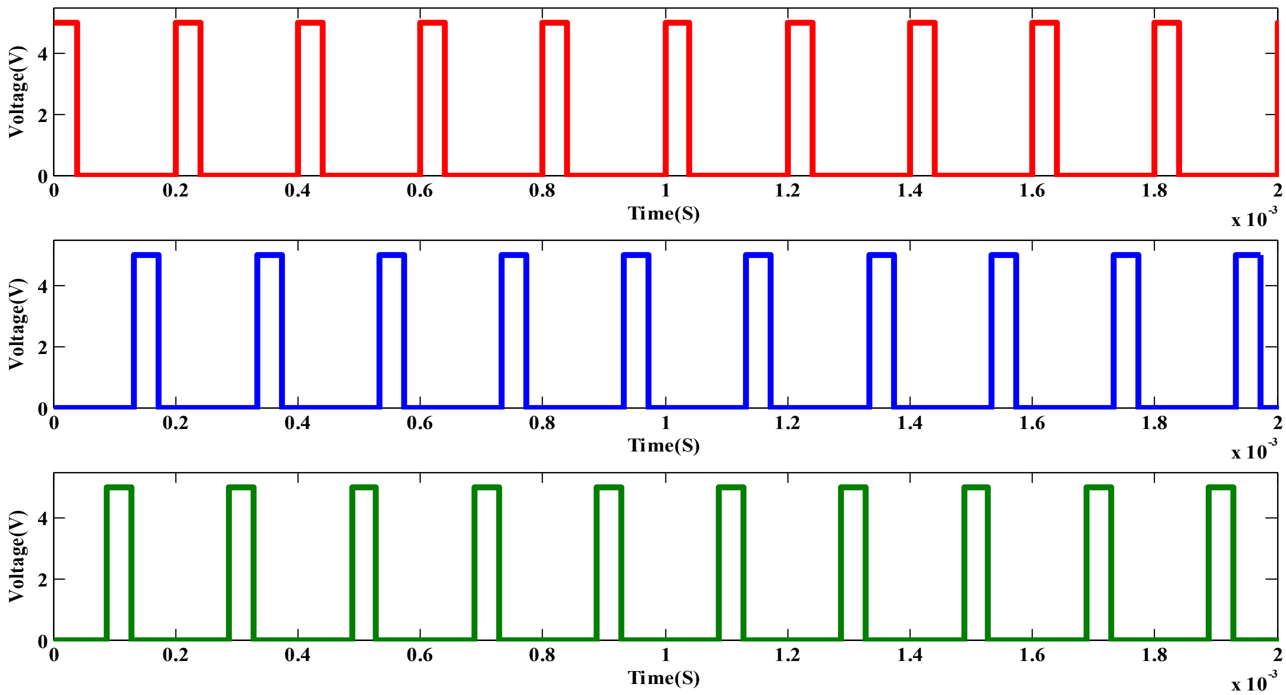

Figure 20. Gating Patterns of three(M,M1,M2) MOSFETs

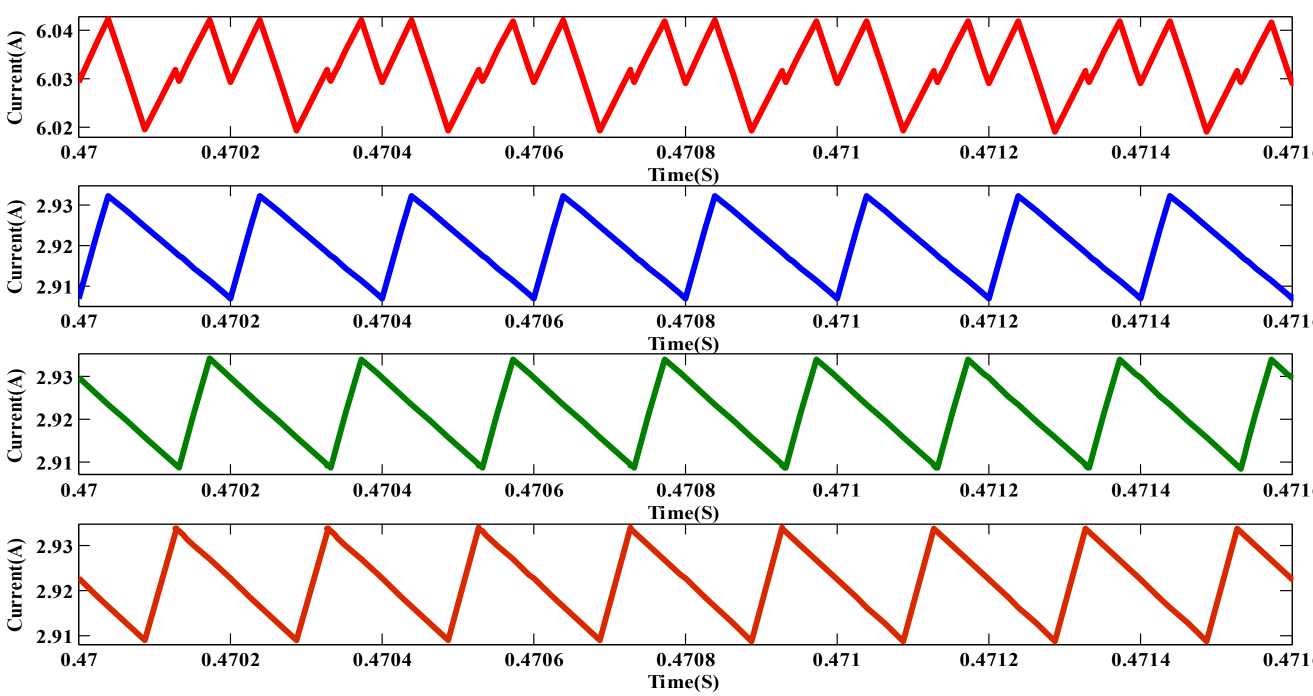

Figure 21. Input current and Inductors (L, L_1 and L_2) Currents

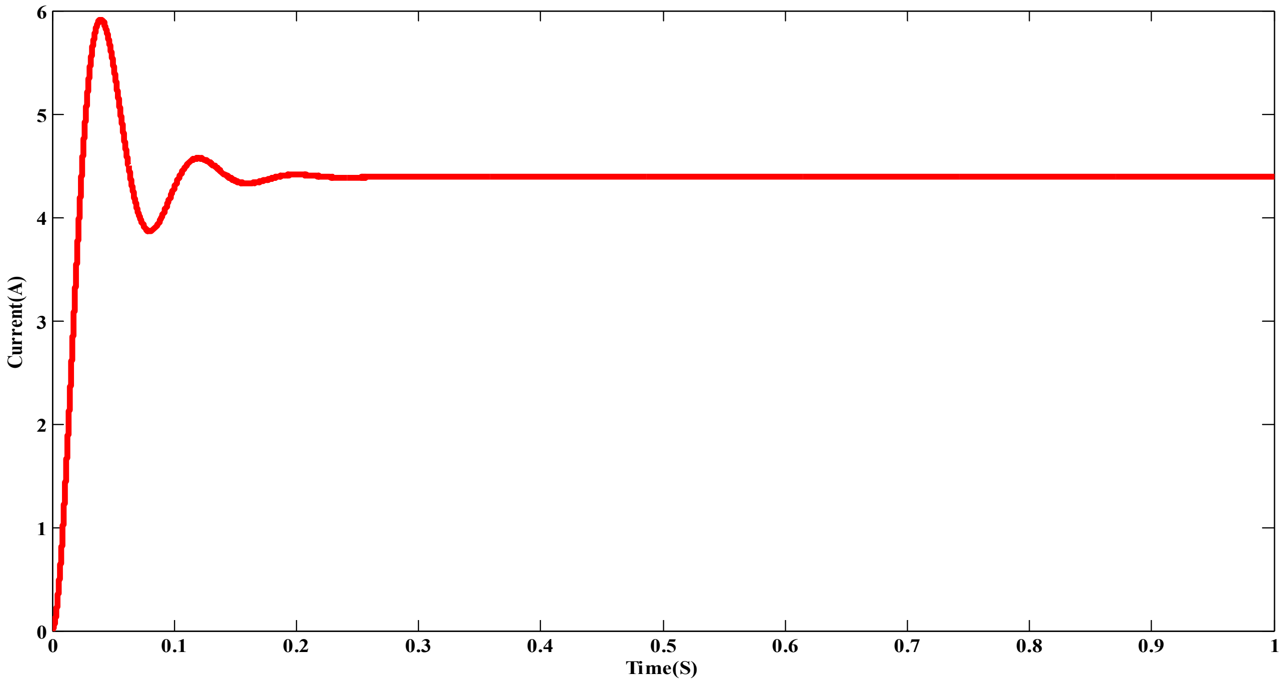

Figure 22. Output Current waveform

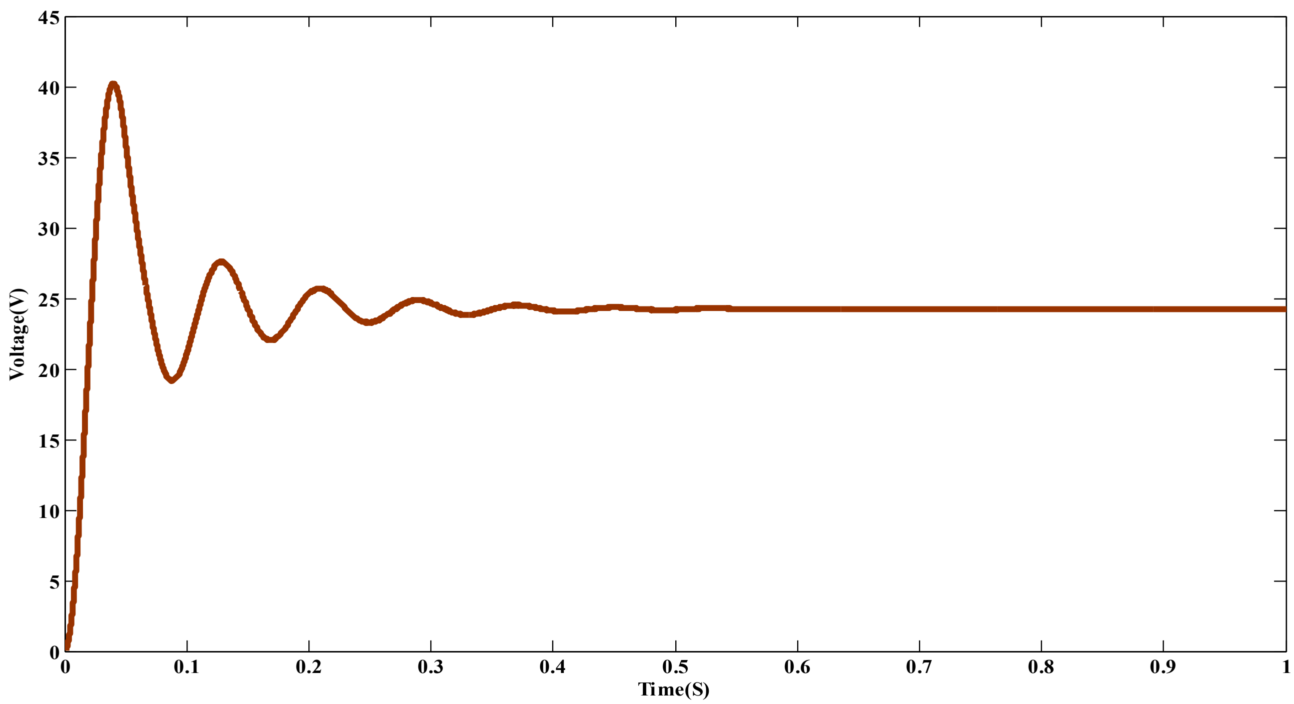

Figure 23. Output voltage waveform

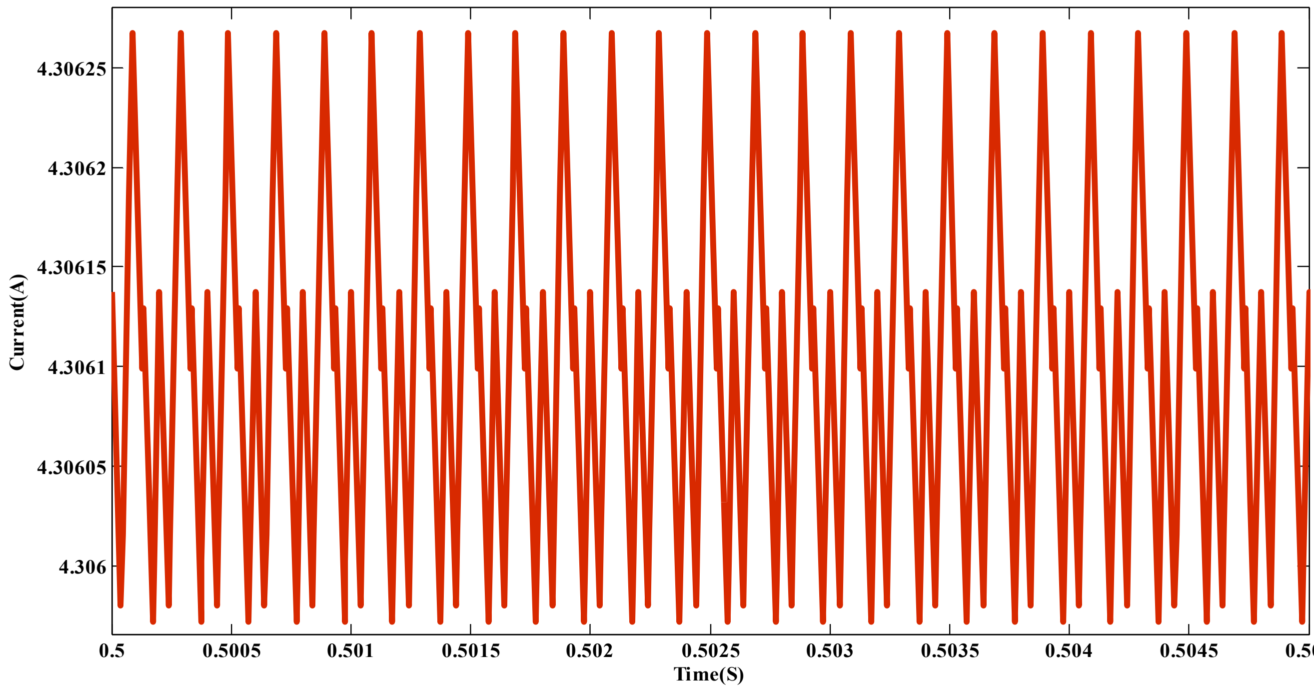

Figure 24. Output Current Ripple Waveform

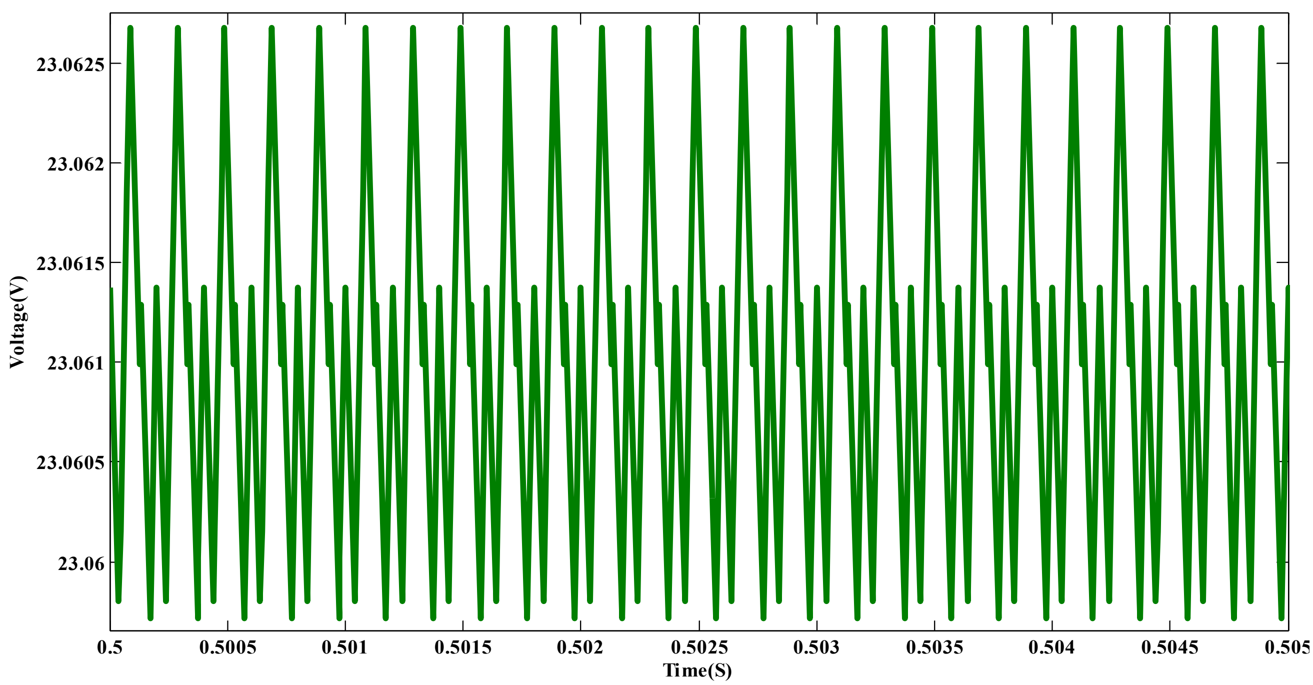

Figure 25. Output Voltage Ripple Waveform

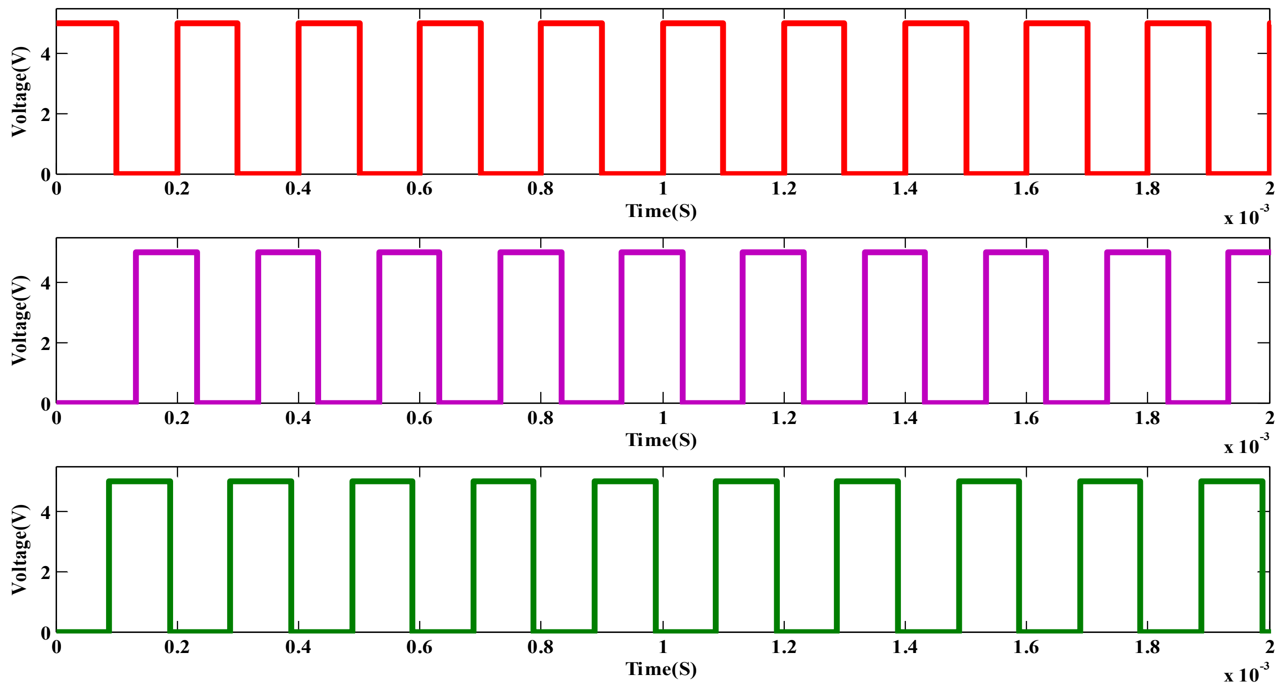

Figure 26. Gating Patterns of MOSFETs (M, M1, M2)

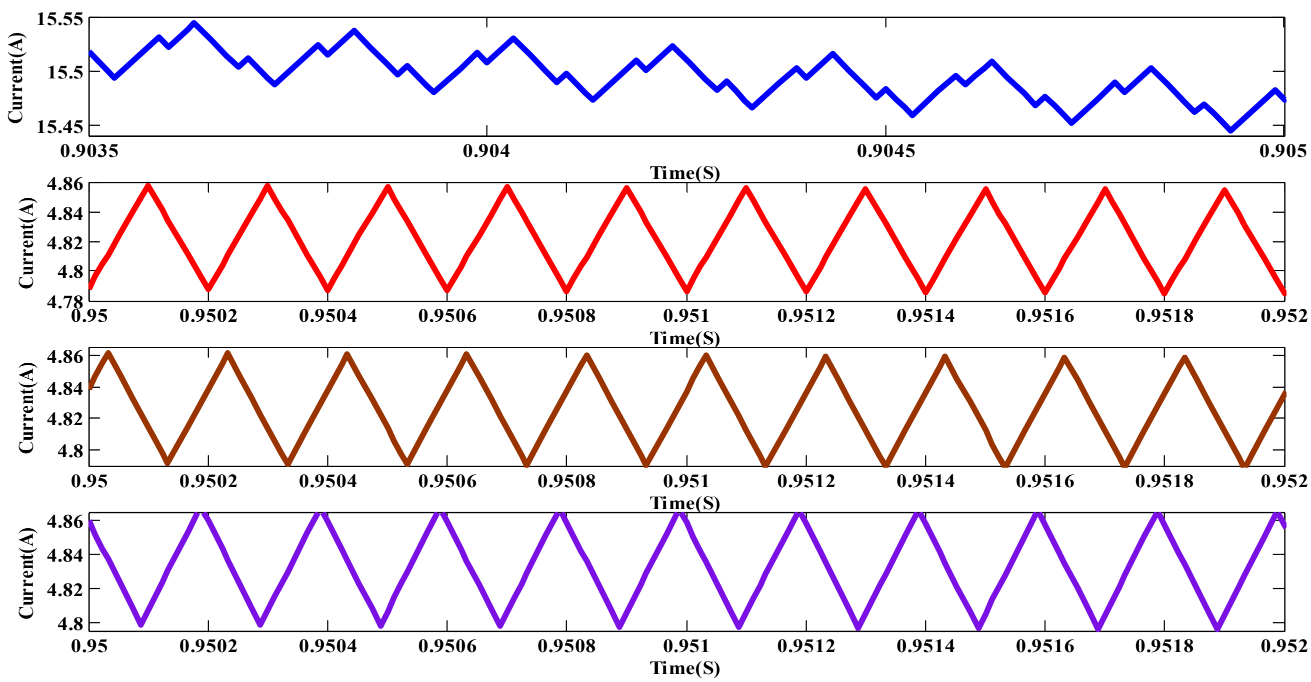

Figure 27. Input Current and Inductors (L, L_1 and L_2) Currents

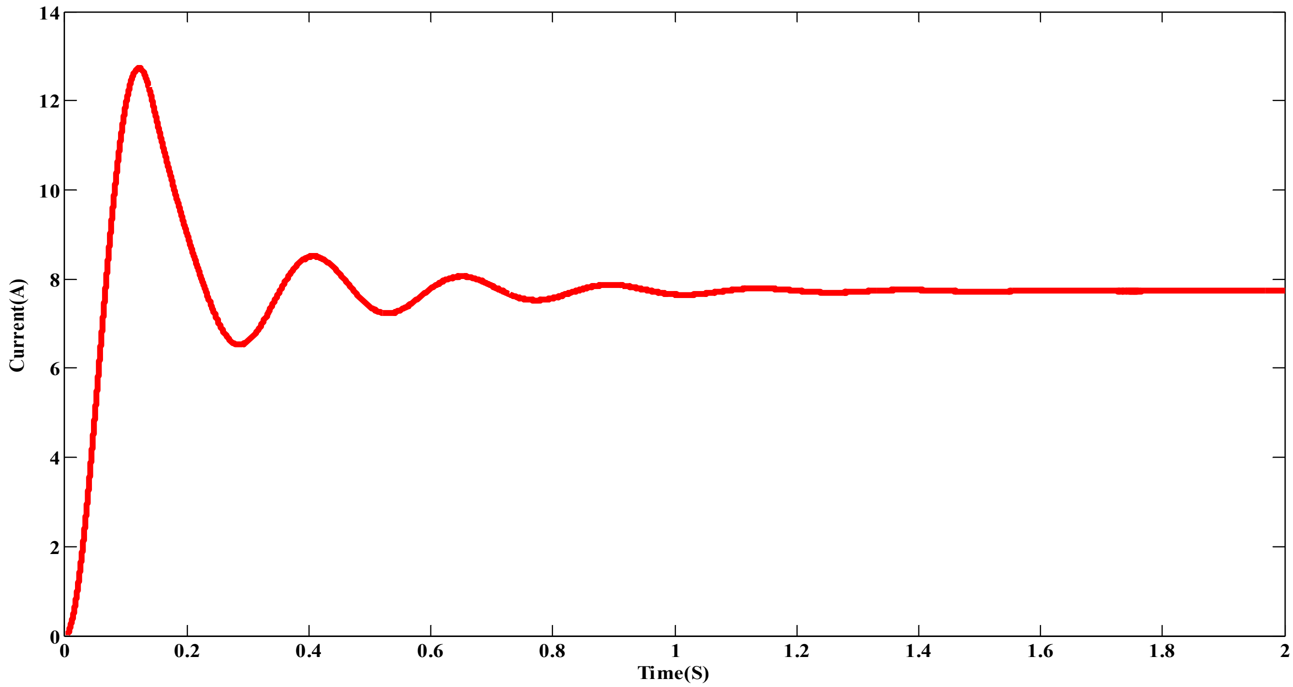

Figure 28. Output Current

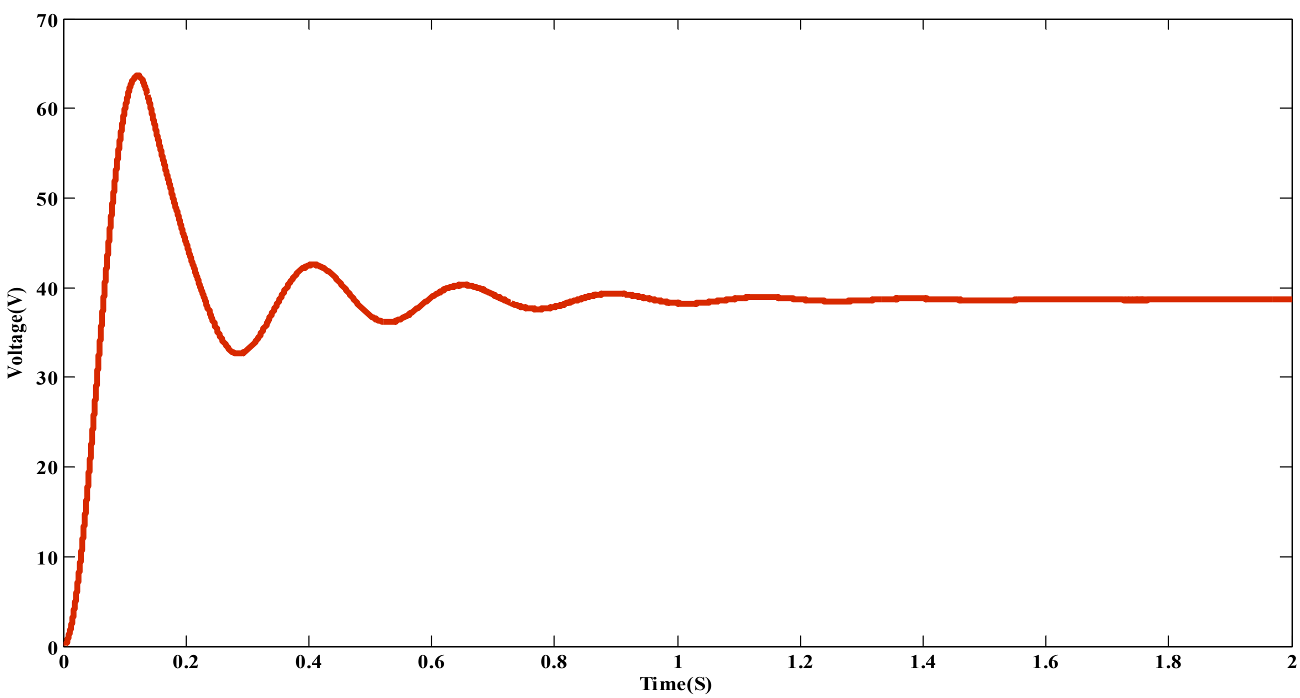

Figure 29. Output Voltage

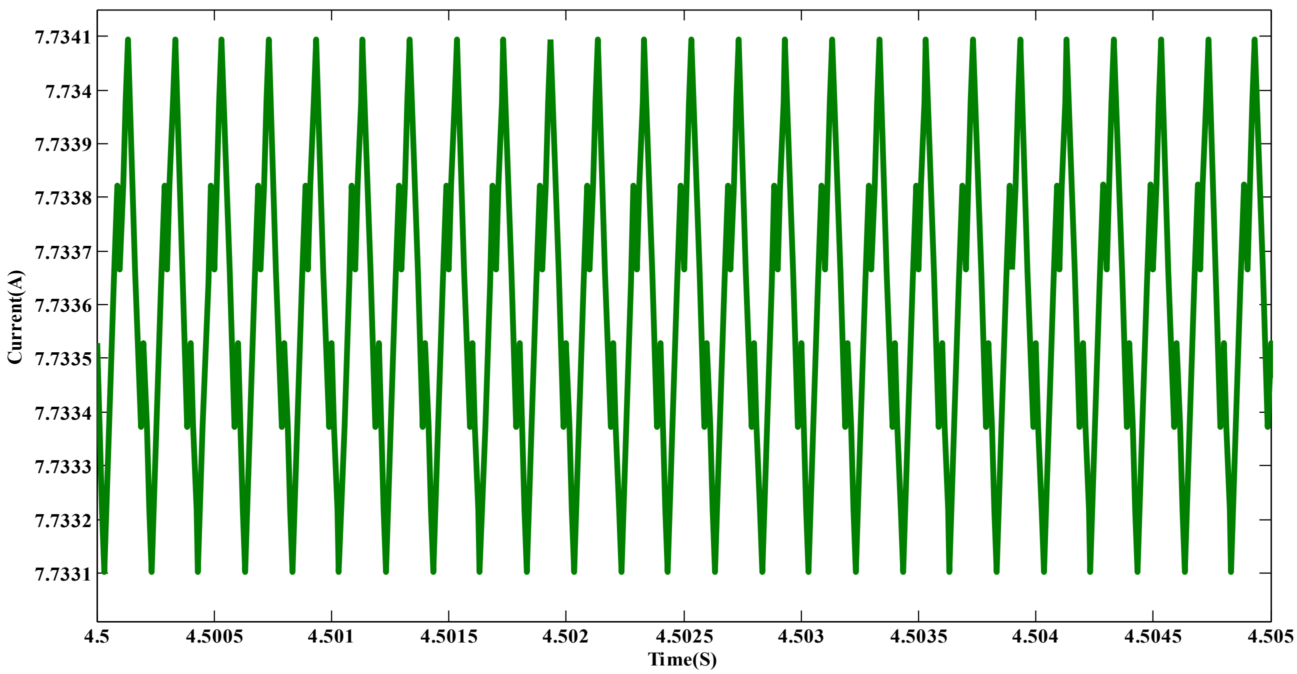

Figure 30. Current Ripple Waveform

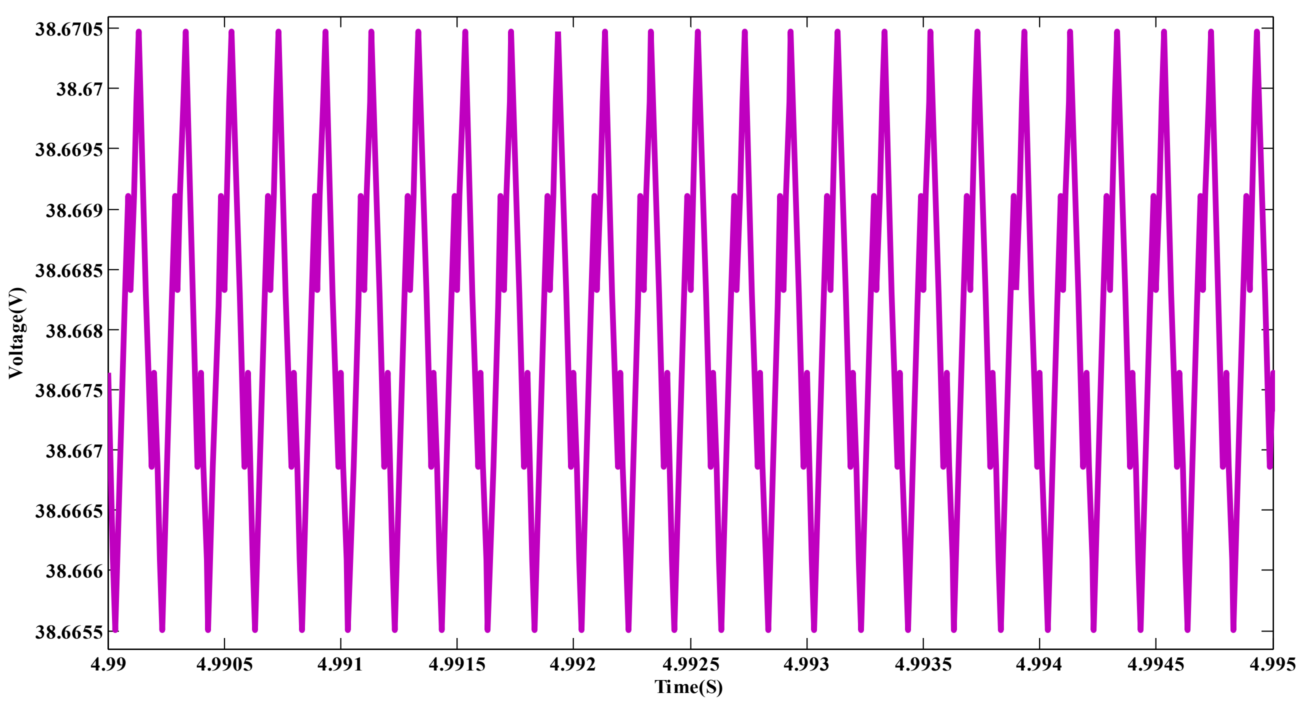

Figure 31. Voltage Ripple Waveform

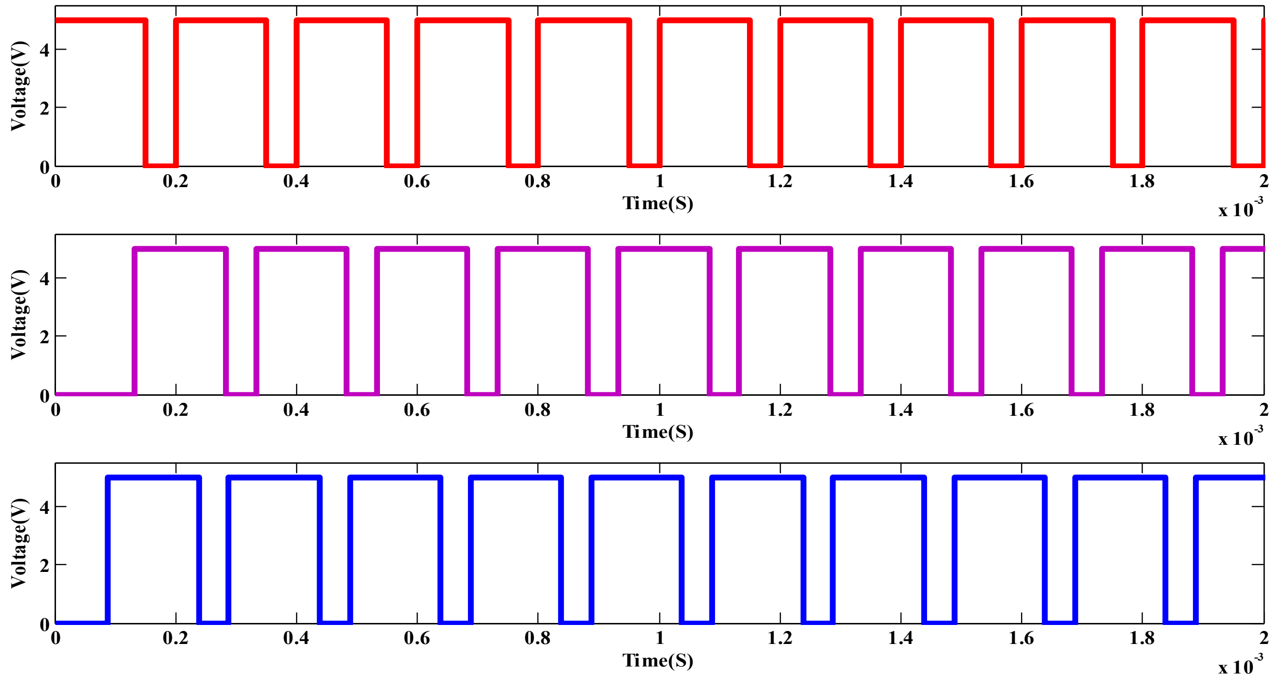

Figure 32. Gating Patterns of MOSFTs (M, M1, M2)

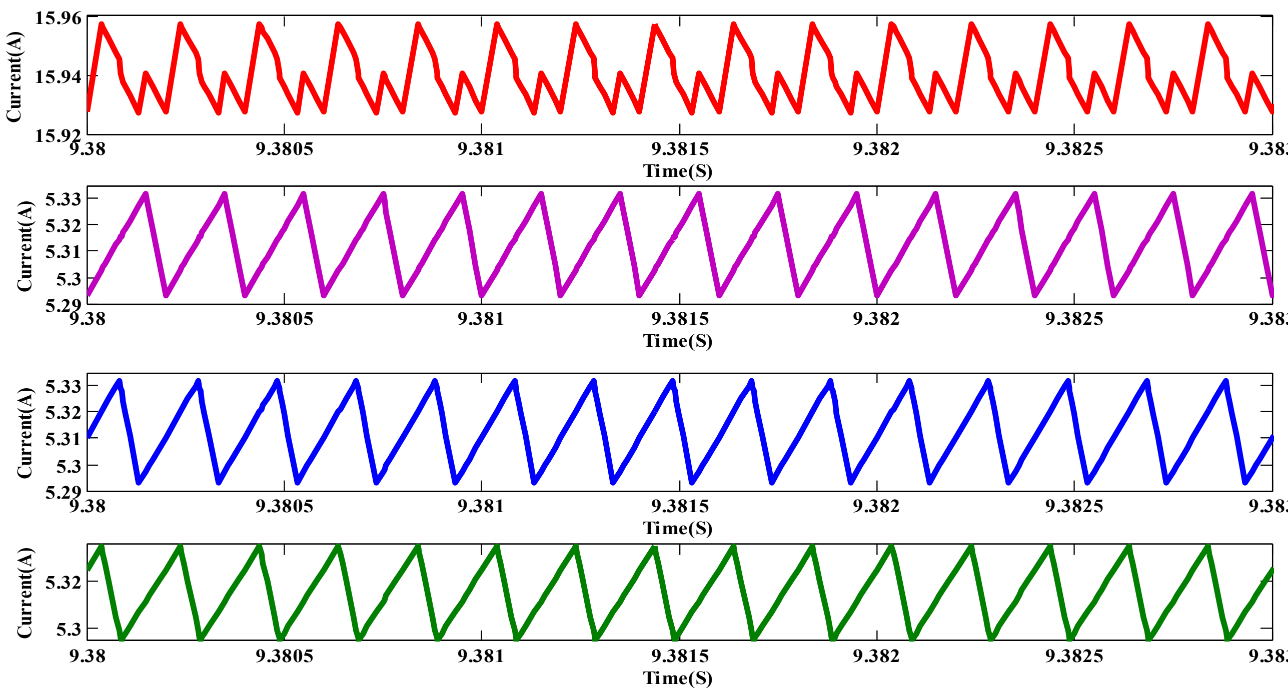

Figure 33. Input Current and Inductors (L, L^1 and L^2) Currents

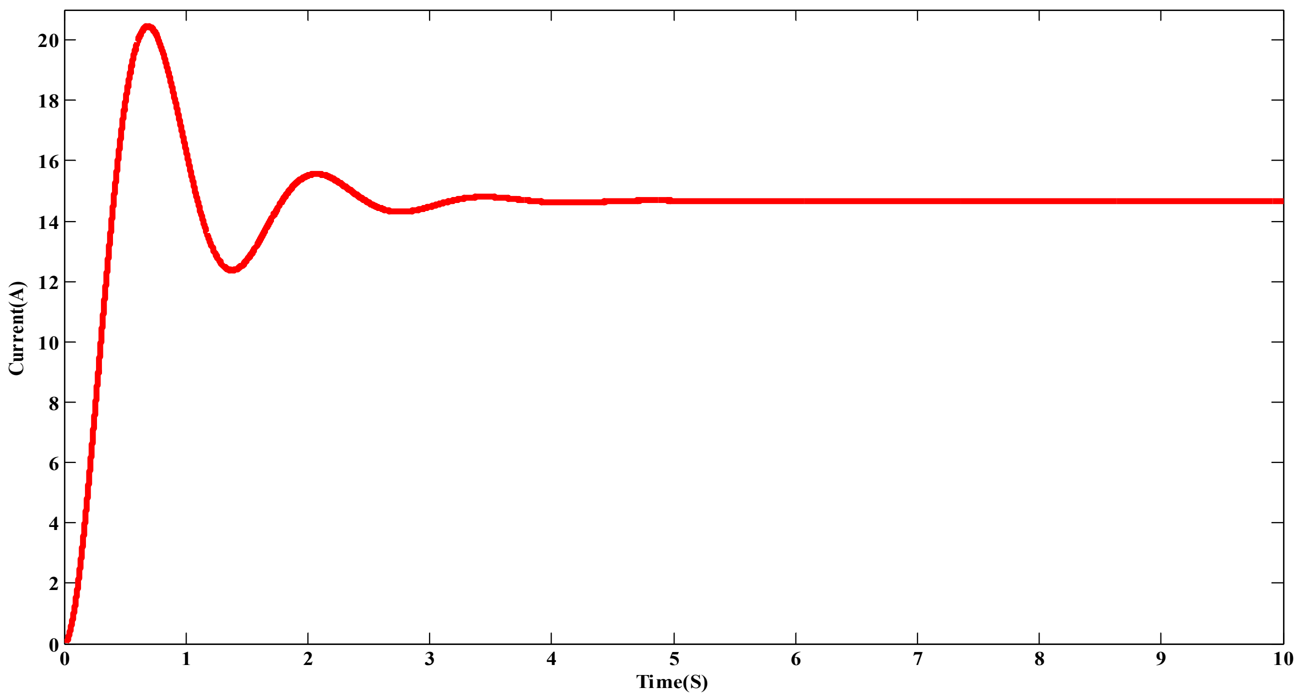

Figure 34. Output Current

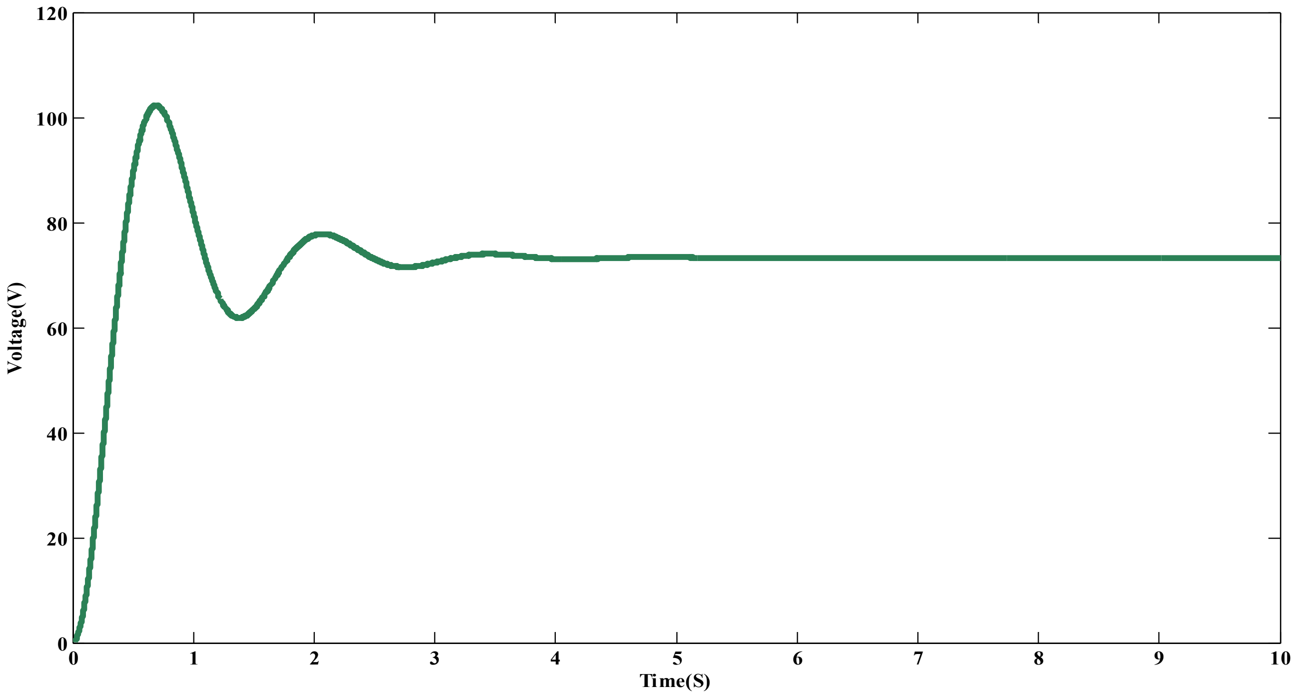

Figure 35. Output Voltage

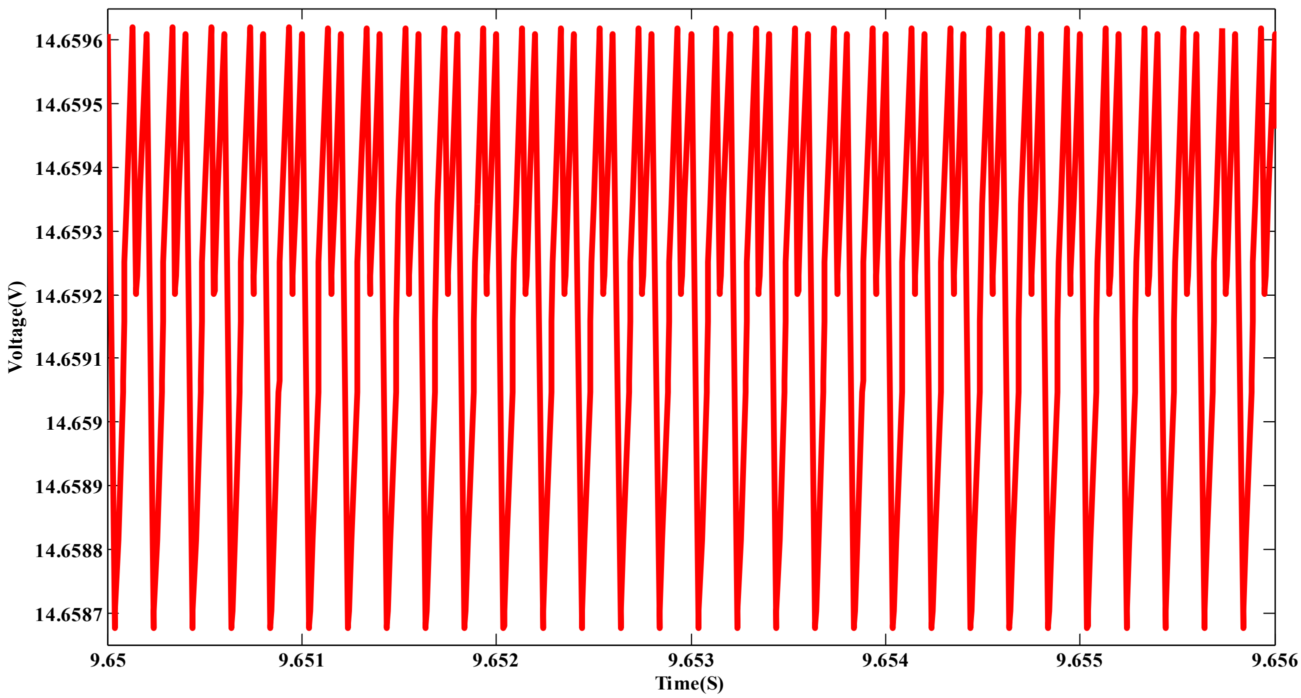

Figure 36. Current Ripple Waveform

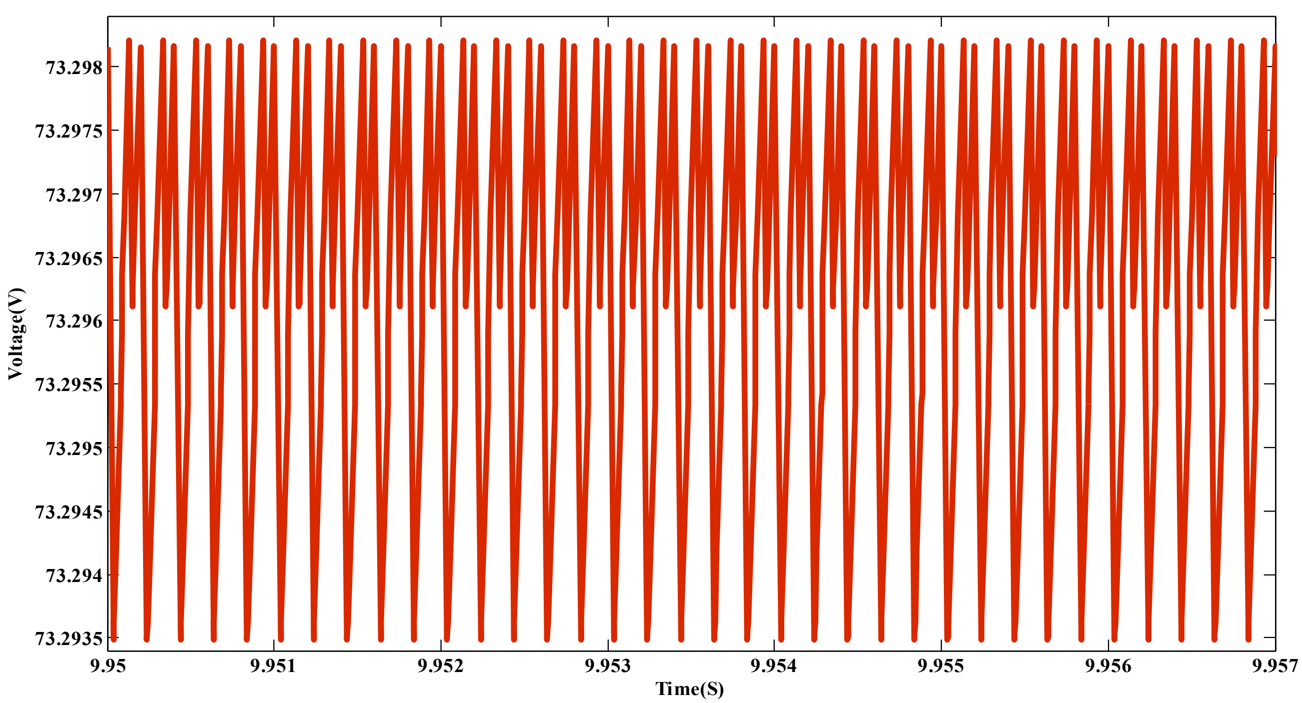

Figure 37. Voltage Ripple Waveform