INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH
V. Rajini and A. Magdalene, Vol.11, No.2, June, 2021

# Investigations on Interleaved and Coupled Split-Pi DC-DC Converter for Hybrid Electric Vehicle Applications

V. Rajini*‡, A. Magdalene**

*Department of EEE, Sri Siva Subramaniya Nadar College of Engineering, Kalavakkam, Tamilnadu, India,603110

** Department of EEE, Sri Siva Subramaniya Nadar College of Engineering, Kalavakkam, Tamilnadu, India,603110

(rajiniv@ssn.edu.in, magdalene.anand.96@gmail.com)

‡ Corresponding Author; V.Rajini, Kalavakkam, Tamilnadu, India,

Tel: +91 9940684159, rajiniv@ssn.edu.in

*Received: 28.04.2021 Accepted:23.05.2021*

**Abstract-** With depleting fossil resources and increasing fuel demands, the need for an alternative source has become mandatory. Incorporation of Hybrid Electric Vehicles (HEVs) in place of conventional petrol and diesel guzzling vehicles has proved to be a promising solution for the above problem. In a HEV, bi-directional DC-DC power converter plays a major role as it acts as an interfacing unit between battery and load. Split-pi DC-DC Converter is one such converter which controls the power flow in both the directions and operates in both buck and boost modes of operation. In a conventional Split-pi Converter the ripple magnitude of input and output current is high and is quite undesirable. Thus, interleaving concept is introduced along with coupling in order to reduce the ripple content and the component size. The simulation of the circuit has been carried out using MATLAB/SIMULINK tool.

**Keywords** Coupling, interleaving, input current ripple, output current ripple, output voltage ripple, split-pi DC-DC converter, ripple content comparison.

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## 1. Introduction

Quick urbanization has drastically increased the number of internal combustion vehicles causing the depletion of non-renewable energy resources. The fuel emissions from these vehicles have greatly polluted our environment with harmful pollutants like CO, $CO_2$, NO and $NO_2$. In order to develop a pollution-free and sustainable environment, the automobile industry started manufacturing vehicles that can run on alternate energy resources. During the middle of the $19^{th}$ century Electric Vehicles (EVs) came into existence where the motor propulsion was done by the battery pack alone [1]. The main disadvantage of EV was that it required bulkier batteries and also had a short driving range. This has led to the development of Hybrid Electric Vehicle (HEV) where the propulsion power of Internal Combustion Engine (ICE) and the eco-friendly nature of EV were combined together to give a long driving range and a healthier environment. In a HEV, the DC-DC Converters form the integral part of the electric system which interfaces the battery with the load [ 2].

There are two types of DC-DC Converters namely uni-directional Converters and Bi-directional Converters. Uni-directional converters are those that convert power in only one direction. They are buck, boost, buck-boost, SEPIC and cuk converters. Bi-directional converters are those that convert power in both forward and reverse directions as shown in the Fig. 1. These converters either step up or step down the voltage which helps in discharging and charging the battery respectively. These bi- directional converters can function as non-isolated bi-directional converters or isolated bi-directional converters. Any basic non-isolated unidirectional DC-DC converter can be modified into a bidirectional converter by replacing the diodes with a controllable switch [3]. Examples of such non-isolated bi-directional transformer-less type converters are boost, buck, SEPIC and buck-boost converter.

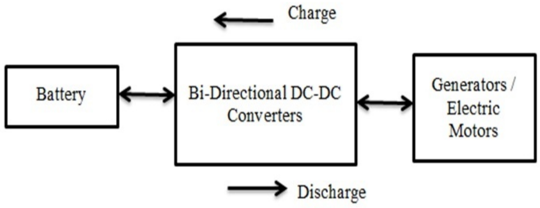


**Fig 1.** Bi-directional DC-DC Converters

Isolated bi-directional DC-DC Converters are those converters that have a galvanic isolation between its input and output terminals with the help of high frequency transformer as shown in Fig. 2. They block the noise signal interference. Examples of such converters are dual active bridge converter and dual half bridge converter [4].

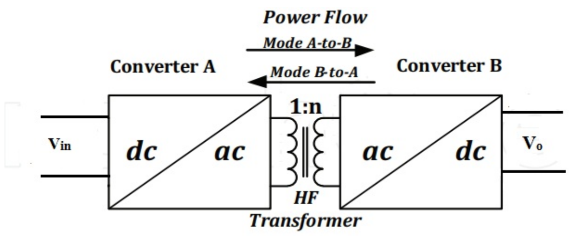


**Fig 2.** Isolated Bi-directional DC-DC Converters

They require more devices for the power converters, in addition to the snubber circuit which take care of the energy trapped in the leakage inductance of the transformer[5]Split-pi DC-DC Converter topology is one such non-isolated bi-directional DC-DC converter which was invented in the year 2004 by Timothy Richard Crocker.[6] By modifying the gate pulses to be given to the switches of this converter, the buck and boost modes of operation are exhibited [2]. This converter is used for a flywheel energy storage application [7] . The design of the controllers for this split pi converter was done [8].A passive ripple cancellation circuit was designed for this converter[9]. Many bidirectional converters for various power trains are investigated [10,11, 12].A ZVS based high gain converter[13] and ripple reduction through interleaving of inductors [14] and the control techniques of various converters are investigated.[15,16,17, 18,19]

This paper presents the modified version of the conventional Split-pi Converter by incorporating interleaving and coupling techniques. This is done in order to reduce the ripple content present in the current and voltage signals and to reduce the size and weight of components.

## 2. Split Pi DC-DC Converter

This converter topology consists of a boost converter followed by a buck converter as shown in the Fig. 3. It has four switches, two inductors and one input and one output filter capacitor [2]-[3]. The switching pattern is given in such a way that it can produce output voltage higher or lower than the input voltage as shown in the Table 1.

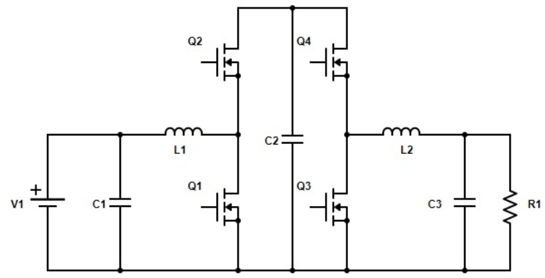


**Fig 3.** Split-pi DC-DC Converter

## 3. Interleaved Split-Pi DC-DC Converter

In a traditional split-pi Converter the magnitude of ripple level is quite high. Thus, interleaving concept is introduced where two or more legs are connected in parallel. The phase shift of (360°/n) is given to the switches in the converter where 'n' depends on the number of interleaving phases [2-4]. This causes current splitting as it goes out of phase leading to ripple cancellation at both the input and output side of the circuit.

The amount of allowable ripple current determines the size of an inductor. Lower the ripple content of current, lower will be the size of an inductor. Hence, interleaving plays a major role for reducing ripple content thereby decreasing the size of inductor. This document presents research about two phase, three phase and four phase interleaved Split-pi DC-DC Converter. Ripple content is minimum for two phase operation at 50% duty cycle, for three phase operation at 33% and 66% duty cycle and for four phase operation at 25%, 50%, 75% and 100% duty cycle.

The structure of two phase interleaved Split-pi Converter is shown along with 180° phase shifted pulses in the Fig. 4 and Fig.5 respectively. The structure of three phase interleaved Split-pi Converter is shown along with 120° phase shifted pulses in the Fig. 6 and Fig. 7 respectively. The structure of four phase interleaved Split-pi Converter is shown along with 90° phase shifted pulses in the Fig. 8 and Fig. 9 respectively.

## 4. Coupled and Interleaved Split-Pi DC-DC Converter

Coupling along with interleaving has been introduced for this converter where the inductors at the input and output side of the converter are coupled on the same core with a same coupling co-efficient 'k'. The two phase coupled and interleaved Split-pi DC-DC Converter is shown in the Fig. 10. Here the inductor size has been reduced to half of its original size and it has been coupled. This leads to reduction in bulkiness of the converter along with reduction in ripple content.

**Table1**. Modes of Operation

| **Modes of operation** | **$Q_1$** | **$Q_2$** | **$Q_3$** | **$Q_4$** |
|---|---|---|---|---|
| Buck | 0 | 1 | 1- α | α |
| Boost | α | 1- α | 0 | 1 |

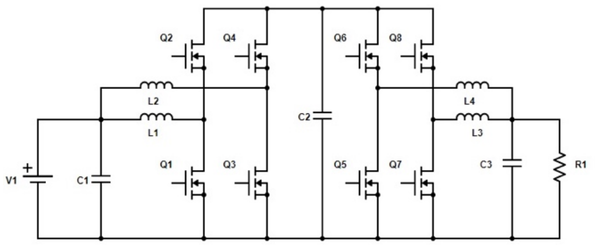

**Fig 4.** Two phase Interleaved Split-pi DC-DC Converter

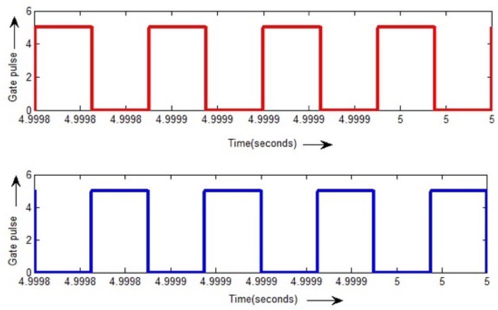


**Fig 5**. 180° phase shifted pulses

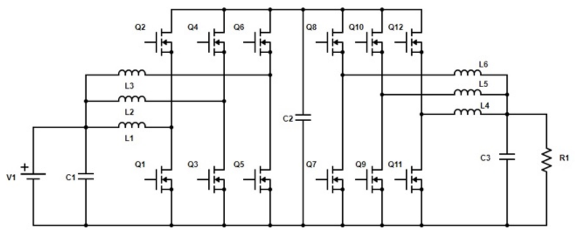

**Fig 6.** Three phase Interleaved Split-pi DC-DC Converter

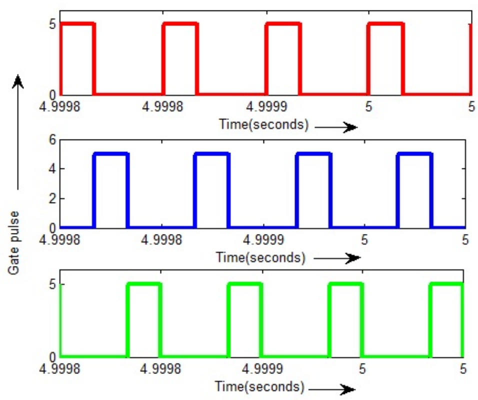


**Fig 7.** 120° phase shifted pulses

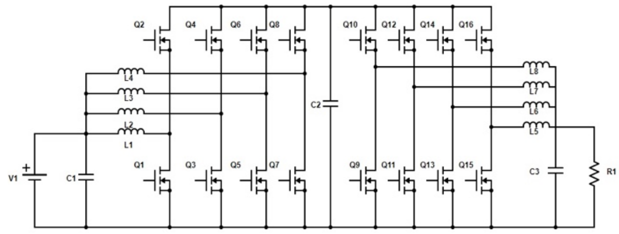

**Fig 8**. Four phase Interleaved Split-pi DC-DC Converter

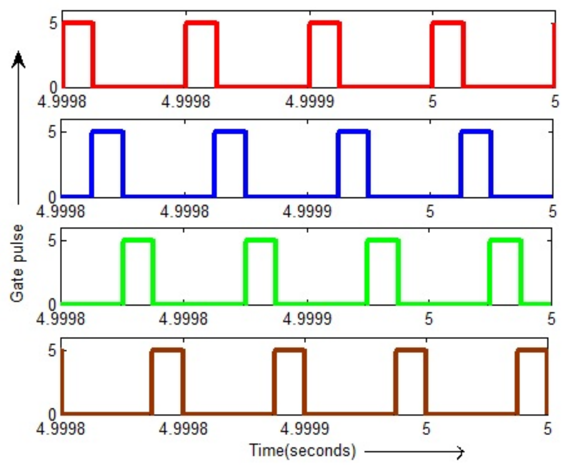


**Fig 9**. 90° phase shifted pulses

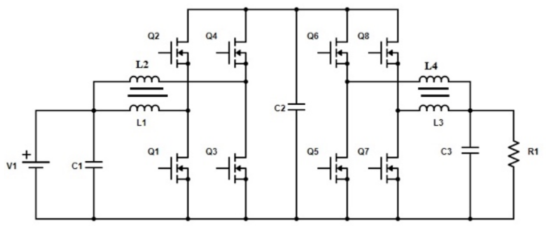

**Fig 10.** Two phase Coupled and Interleaved Split-pi DC-DC Converter

## 5. Simulation Results

The simulation is done using MATLAB software. The simulation parameters for the converter are given in the Table 2.

*5.1 Conventional Split-pi Converter*

The conventional Split-pi Converter is simulated for the two modes using the simulation parameters and the results are given.

**Table 2**. Simulation Parameters

| S.No. | Parameter | Value |
|---|---|---|
| 1 | Power rating($P_{rating}$) | 500W |
| 2 | Duty Ratio($\alpha$) | 0.5 |
| 3 | Input voltage ($V_{in}$) | 24-48V |
| 4 | Switching frequency($f_s$) | 20 kHz |
| 5 | Resistance | 4.609 Ω |
| 6 | Inductors(L1,L2) | 193 µH |
| 7 | Capacitors(C1,C3,C2) | 110 µF |

*Buck Mode:* The input current ripple, output current ripple and output voltage ripple for the buck mode of operation are shown in the Fig. 11.

*Boost Mode:* The input current ripple, output current ripple and output voltage ripple for the boost mode of operation are shown in the Fig. 12.

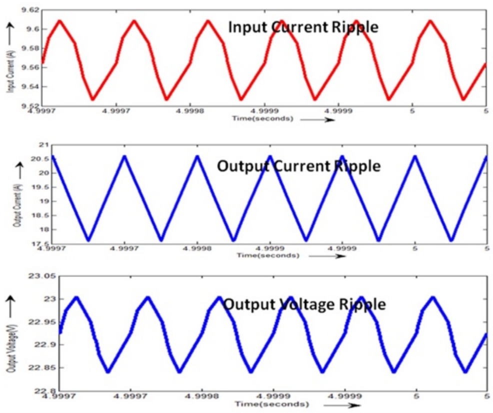


**Fig 11.** Input Current Ripple, output current ripple and output voltage ripple of a conventional split pi converter in buck mode

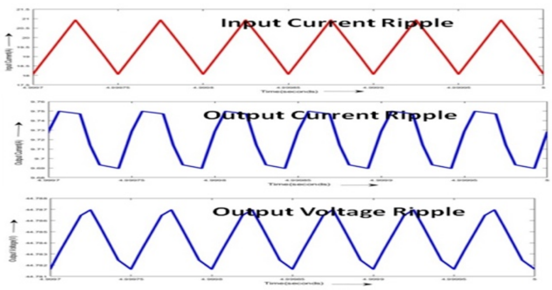


**Fig 12.** Input Current Ripple, output current ripple and output voltage ripple of a conventional split pi converter in boost mode

*5.2 2-phase Interleaved Split-pi Converter*

The two phase Interleaved Split-pi Converter is simulated for the two modes using the same simulation parameters and the results are presented.

*Buck Mode:* The input current ripple, total output current ripple and output voltage ripple for the buck mode of operation are shown in the Fig. 13.

*Boost Mode:* The total input current ripple, output current ripple and output voltage ripple for the boost mode of operation are shown in the Fig. 14.

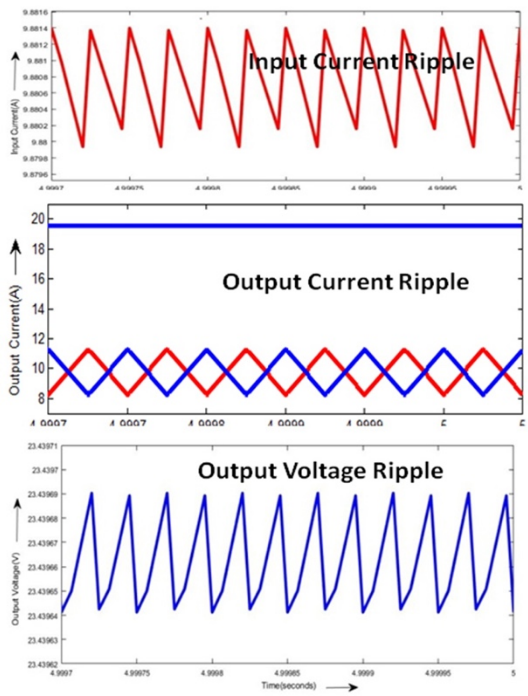

**Fig 13.** Input Current Ripple, output current ripple and output voltage ripple of a two phase interleaved split pi converter in buck mode

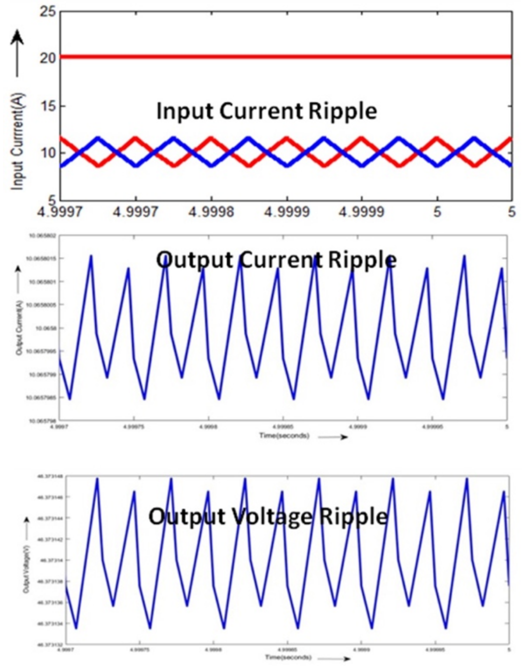


**Fig 14.** Input Current Ripple, output current ripple and output voltage ripple of a two phase interleaved split pi converter in boost mode

*5.3. 3-phase Interleaved Split-pi Converter*

The three phase Interleaved Split-pi Converter is simulated for the two modes using the simulation parameters from the Fig. 15 and Fig.16.

*Buck Mode:* The input current ripple, total output current ripple and output voltage ripple for the buck mode of operation are shown in the Fig. 15.

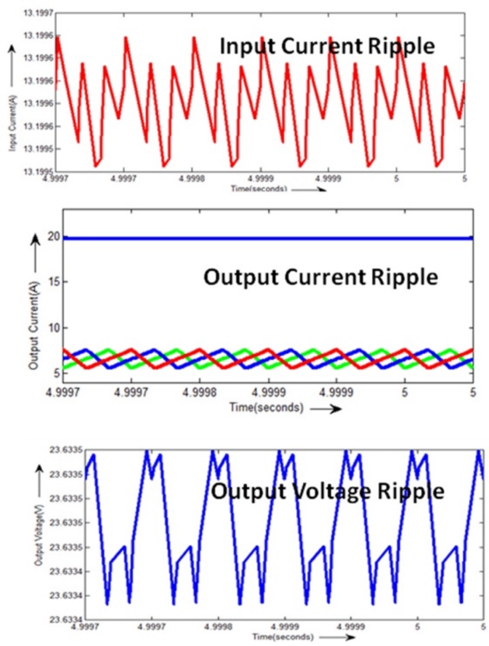


**Fig 15.** Input Current Ripple, output current ripple and output voltage ripple of a three phase interleaved split pi converter in buck mode

*Boost Mode:* The total input current ripple, output current ripple and output voltage ripple for the boost mode of operation are shown in the Fig. 16

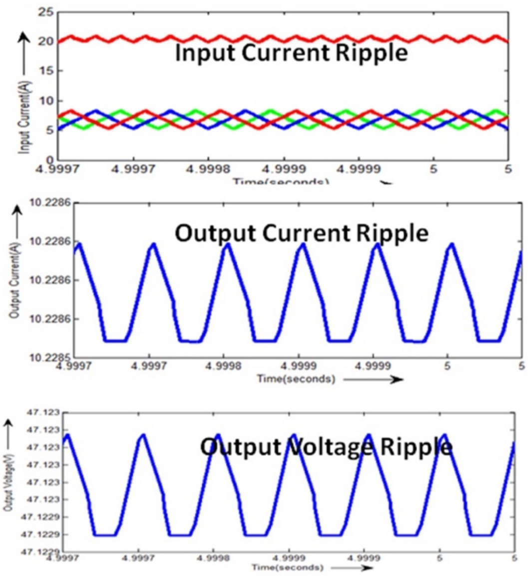


**Fig 16.** Input Current Ripple, output current ripple and output voltage ripple of a three phase interleaved split pi converter in boost mode

*5.4 4-phase Interleaved Split-pi Converter*

The four phase Interleaved Split-pi Converter is simulated for the two modes using the simulation parameters from the Fig. 17 and Fig18.

*Buck Mode:* The input current ripple, output current cancellation, output current ripple and output voltage ripple for the buck mode of operation are shown in the Fig. 17.

*Boost Mode:* The input current ripple cancellation, input current ripple, output current ripple and output voltage ripple for the boost mode of operation are shown in the Fig. 18.

The ripple content of conventional Split-pi Converter has been compared with the two phase, three phase and four phase of the Interleaved Split-pi Converter for both the boost and buck modes of operation and the results are shown in the Table 3.From the comparison, it is inferred that the ripple content of interleaved converter is quite less than that of traditional converter. As the number of interleaving phases increase, the ripple magnitude decreases drastically.

*5.5 2-phase Interleaved and Coupled Split-pi Converter*

The two phase interleaved and coupled Split-pi DC-DC Converter is simulated for the two modes based on the same simulation parameters from the Fig. 19 and Fig.20.

*Buck Mode:* The input current ripple, total output current ripple and output voltage ripple for the buck mode of operation are shown in the Fig. 19.

*Boost Mode:* The total input current ripple, output current ripple and output voltage ripple for the boost mode of operation are shown in the Fig. 20.

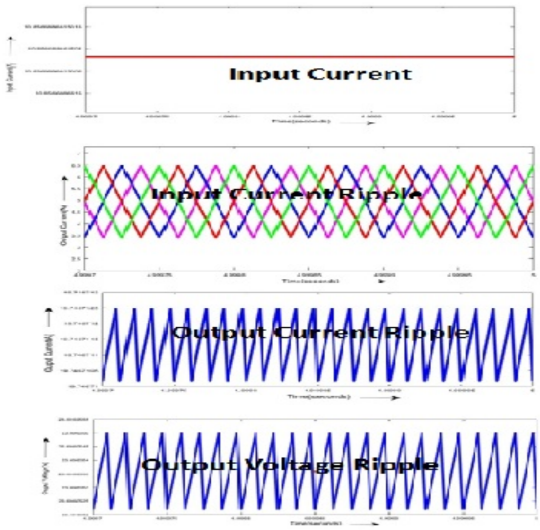


**Fig 17.** Input Current Ripple, output current ripple and output voltage ripple of a four phase interleaved split piconverter in buck mode

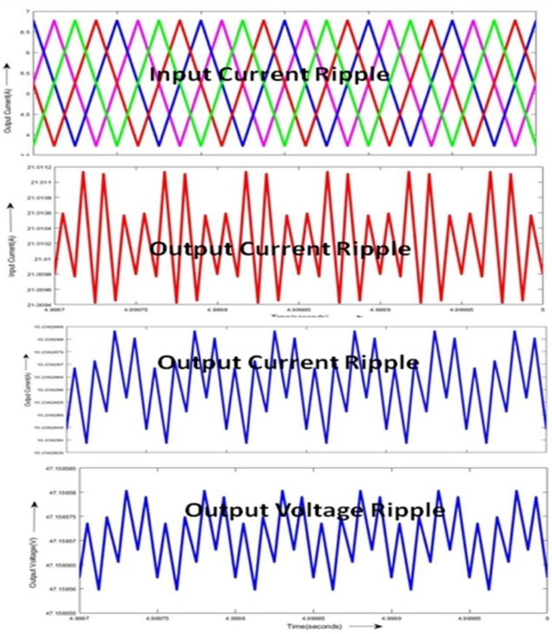


**Fig 18.** Input Current Ripple, output current ripple and output voltage ripple of a four phase interleaved split pi converter in boost mode

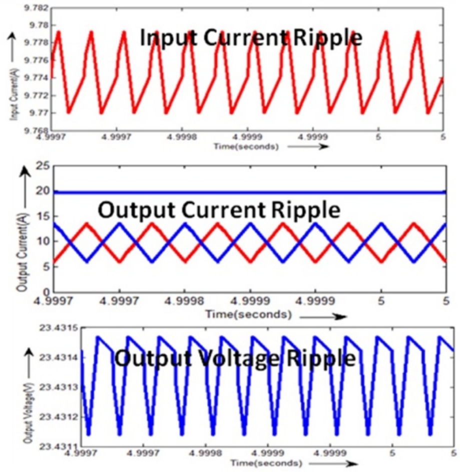


**Fig 19.** Input Current Ripple, output current ripple and output voltage ripple of a two phase interleaved and coupled split pi converter in buck mode

The ripple content of two phase Interleaved and coupled Split-pi Converter has been compared with the two phase Interleaved Split-pi Converter for the boost and buck modes of operation in the Table 4. Thus, it can be inferred that the ripple content of two phase interleaved and coupled converter is less than that of two phase interleaved converter and the size of inductor also is reduced to half of its designed value.

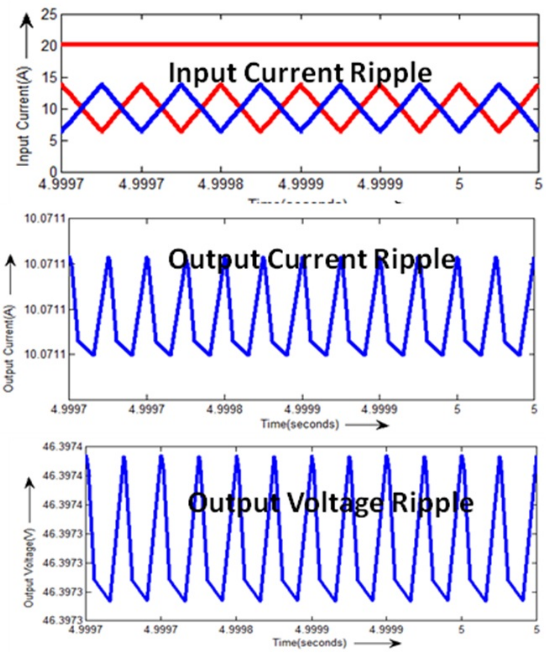


**Fig 20.** Input Current Ripple, output current ripple and output voltage ripple of a two phase interleaved and coupled split pi converter in boost mode

**Table 4**. Ripple Content Comparison for Buck and Boost Mode of Operation in two phase interleaving and coupling

| | **Buck mode of operation** | | **Boost mode of operation** | |
|---|---|---|---|---|
| | **With 2phase Interleaving** | **With 2 phase Inter leaving and coupling** | **With 2phase Interleaving** | **With 2 phase Interleaving and coupling** |
| Input Current Ripple (%) | 0.012 | 0.009207 | 1.0975 | 0.0794 |
| Output Current Ripple (%) | 2.093*10^-3 | 1.638*10^-3 | 0.0307 | 1.987*10^-3 |
| Output Voltage Ripple (%) | 2.093*10^-3 | 1.32*10^-3 | 0.0014 | 5.39*10^-4 |

## 6. Hardware Implementation and Results

The hardware implementation of a single phase split pi converter is done with the same specifications as that of simulation and the results are presented. STM32F103C8T6 is used to generate the desired gate signals for the Split-pi converter. Experimentation on two phase interleaving is also done and the results are also presented. The PCB layout and the fabricated converter are shown in Fig 21. The experimental setup used is shown in Fig 22.The control pulses for boost and buck mode are given in Fig 23.The input voltage and current waveforms for the boost and buck modes are shown in Fig 24. Figure 25 shows the inductor voltage and current waveforms for boost and buck modes of operation. The output voltage and current waveforms of both the modes are given in Fig 26.

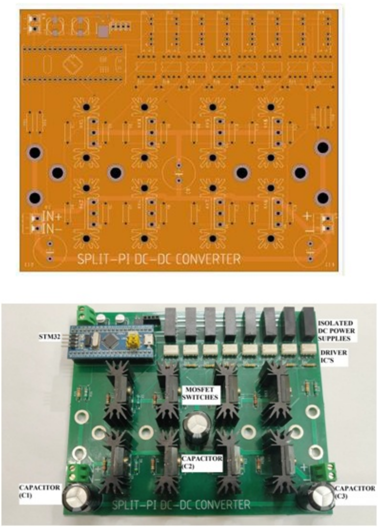


**Fig 21**. PCB layout of conventional split pi converter

The two phase interleaving is done on either side of the converter and the boost and buck modes were tested. The inductor currents in boost and buck modes are shown in Fig. 26 and Fig.27 respectively. The input voltage and current in boost and buck modes are given in figures 28 and 29 respectively. The percentage ripple for the input current in boost mode has decreased to 1.001 from 1.08 obtained from split pi converter without interleaving. Similarly, for the buck mode, the percentage ripple for the input current has decreased to 0.01 from 0.04 obtained without interleaving.

**Fig 22**. Photograph of the hardware

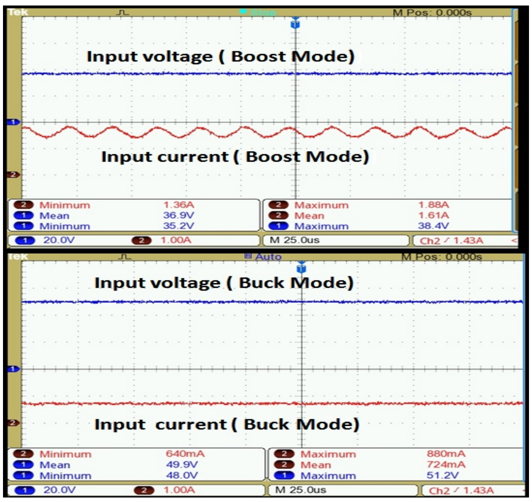

**Fig 23.** Input voltage and current of split pi converter in Buck and boost modes

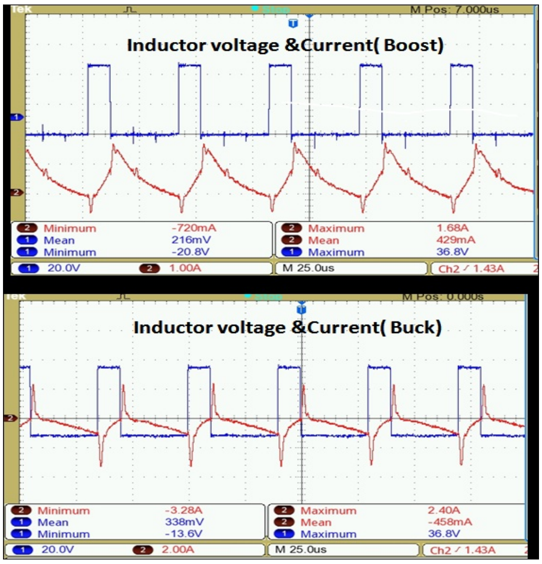


**Fig 24.** Inductor voltage and current of split pi converter in Buck and boost modes

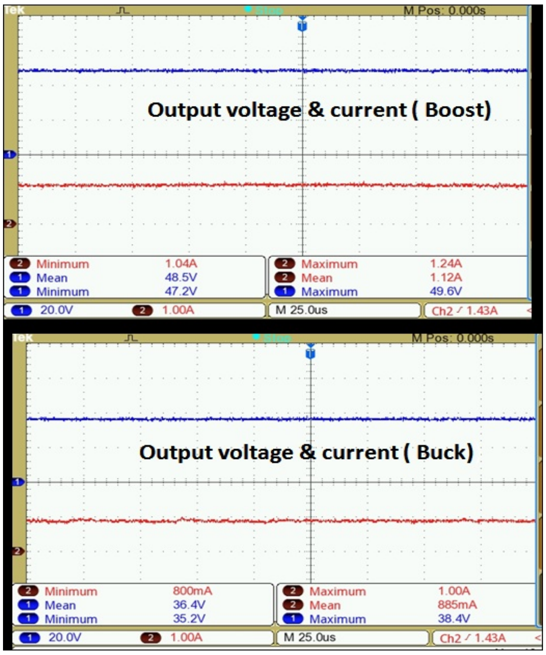


**Fig 25.** Output voltage and current of split pi in buck and boost modes

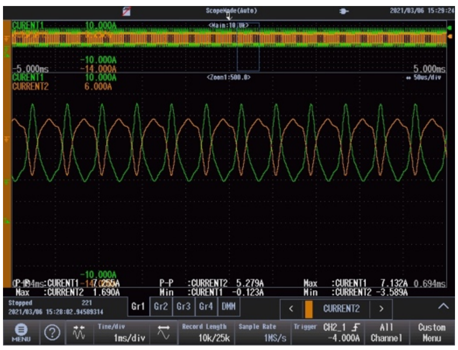

**Fig 26.** Inductor currents of the two phase interleaved converter in boost mode

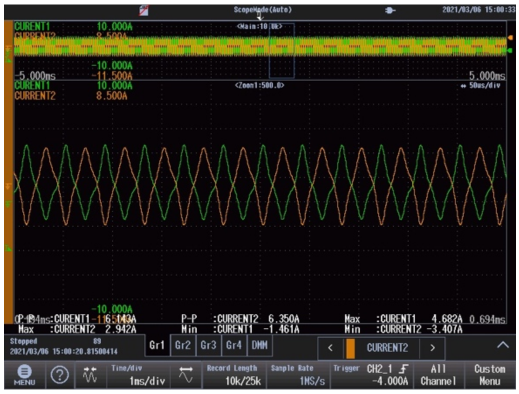

**Fig 27.** Inductor currents of the two phase interleaved converter in buck mode

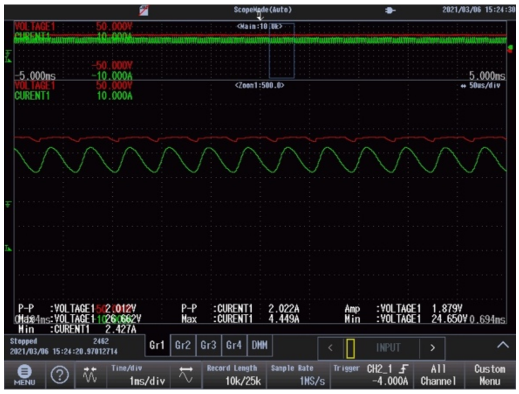

**Fig 28.** Output voltage and current of the two phase interleaved converter in boost mode

**Fig 29.** Output voltage and currents of the two phase interleaved converter in buck mode

## 7. Conclusion

Split-pi DC-DC Converter is simulated for buck and boost modes of operation with various interleaving technique and coupling between them.

- Without interleaving higher ripple content has been observed in input current, output current and output voltage
- With two phase of interleaving the ripple content has decreased compared to that of without interleaving.
- With three phase of interleaving the ripple content has been drastically reduced.
- With four phase of interleaving the ripple content has been ideally made zero.

Thus, with four phases of interleaving ,the ripple content is completely eliminated. This helps in improving the power density of the converter as all the four inductors can be wound on the same core.

It is interesting to note that due to the mutual coupling between the inductors, the size of inductor is reduced to half. This also gives very less ripple content compared to that of two phase interleaved converter.Thus, two phase interleaving and coupling technique for Split-pi Converter is a promising feature which can reduce the ripple content as well as the bulkiness of the converter. The experimental investigations are made for a conventional split pi converter and two phase interleaved converter and the results match with that of the simulation. Experimental Investigations with the coupled inductors have to be done and it becomes the future scope of this work.

**Acknowledgements**

The authors would like to thank SSN College of Engineering for providing the financial support for this work.

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