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Comparative Analysis of Four Phase Interleaved Boost converter with Coupled Inductor, Battery Charging Application

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***Abstract*: This article analyzes the different controller with coupled and uncoupled inductors are compared. Battery charging with constant voltage (CV) and constant current (CC). IBC is highly efficient and reliable as it uses coupled inductors and the size of power converter is also reduced. Interleaving technique is uses the PID controller. The comparative analysis of the converter circuits is simulated in MATLAB Simulink and the outcome to improve performance of the converter.**

***Keywords*: IBC Interleaved Boost converter, Coupled inductors, Battery Charging, Constant Current (CC), Constant Voltage (CV), PID Controller.**

1. Introduction

In recent years advancement in technology led to the increase in electronic devices or equipment's Using in industries, homes and domestic purposes generating electricity from the renewable energies like solar, wind, fuel cell and etc. for this power converters are required. This will give power conversion from low power to high power applications.

Now-a-day interleaving topology is using widely in large scale industries and small-scale industries. Switch mode power supply (SMPS) are playing most important role in this type of topologies. The most frequently used that is single step-up dc to dc converter. By using this non isolated dc to dc converter it can achieve low voltage to high voltage in this power converter have high ripple input current and output voltage and high stress on the power semiconductor switch to overcome this by using Four Phase Interleaved Boost Converter. This dc-to-dc converter has equal current share in each leg and multiple boost converters are connected in parallel, each phase shifted 90° by interleaving technique. The power converter are works with highly efficient and more reliability compare to conventional boost converter and also reduces the input current ripple and output voltage ripple.

The interleaved boost converter it has uncoupled inductor size is large compare to conventional boost converter because of high power application, to overcome this by using coupled inductor that is directly and inversely coupled inductor. by coupling of the inductors, it reduces the size and winding losses of the inductor and current sharing is equal in circuit the coupling co-efficient is $M = K\sqrt{L1*L2}$.

In this Four Phase Interleaved Boost Converter are analyze the different control techniques those are P, PI, PID controllers are used and also open loop with coupled inductors, closed loop with coupled inductors. The load is taken as Battery. The battery is charging method is constant current (CC) and constant voltage (CV). And the circuit was compared by simulation using MATLAB/Simulink.

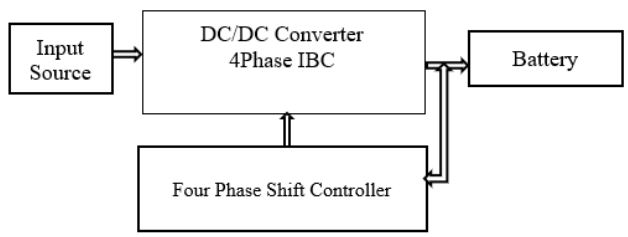

Fig. 1. Block diagram of 4PIBC

2. Four Phase Interleaved Boost Converter

A. Open Loop Four Phase Interleaved Boost Converter

In this open loop four phase interleaved boost converter are operated in parallel and 90° out of phase. it includes power semiconductor switches that is MOSFET, power diodes, output filter capacitance and battery is a load. Those are S1, S2, S3, S4 and D1, D2, D3, D4 and Co Respectively. the switching of the converter is same. The parameters of four converters are assumed to be same.

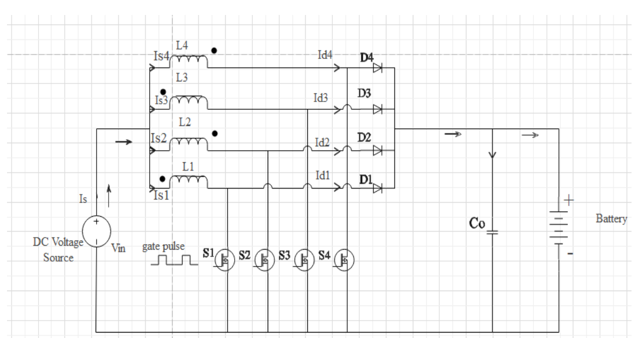

Fig. 2. Open loop 4 phase interleaved boost converter

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The input current ripple is reduced by converters are connected in parallel, therefore the current is equally sharing in all the four branches and the efficiency is increased and also coupled inductors are used it will reduce the losses of inductor and it has smaller input current ripple than the uncoupled inductors.

B. Closed Loop Four Phase Interleaved Boost Converter

In this FPIBC dc-dc converter is operated in closed loop manner. Which is have different control techniques like voltage control, current control, P controller, PI controller that is Proportional Integral controller, PID that is controller, PD controller that is Proportional Derivative controllers are designed with ‘Ziegler Nichols Second Method’ of Tuning Rules for controller designed for the DC-DC Converter that is step up dc-dc converter. It will operate on the same switching frequency F_s.

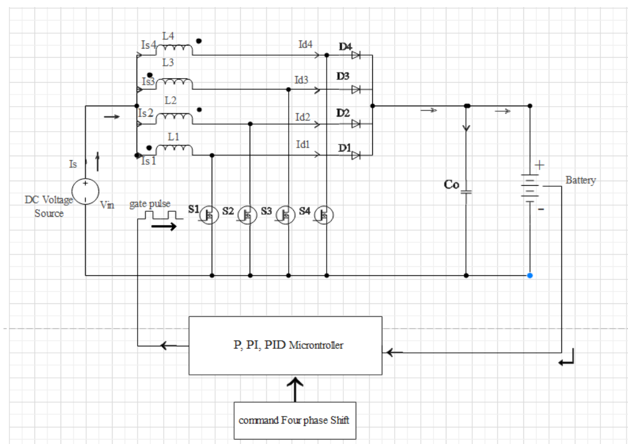

Fig. 3. Closed loop 4 4 phase interleaved boost converter

3. The Working of FPIBC is Different Modes of Operations with Waveforms

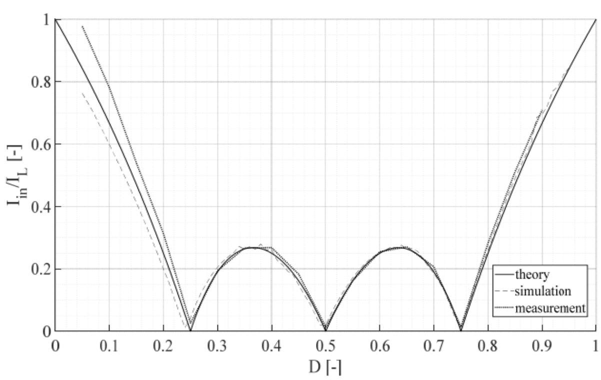

Fig. 4. Duty cycle of 4 phase interleaved boost converter

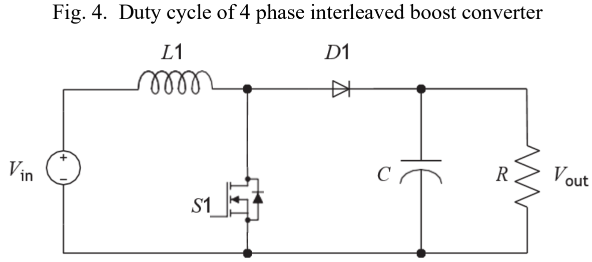

Fig. 5. Conventional boost converter

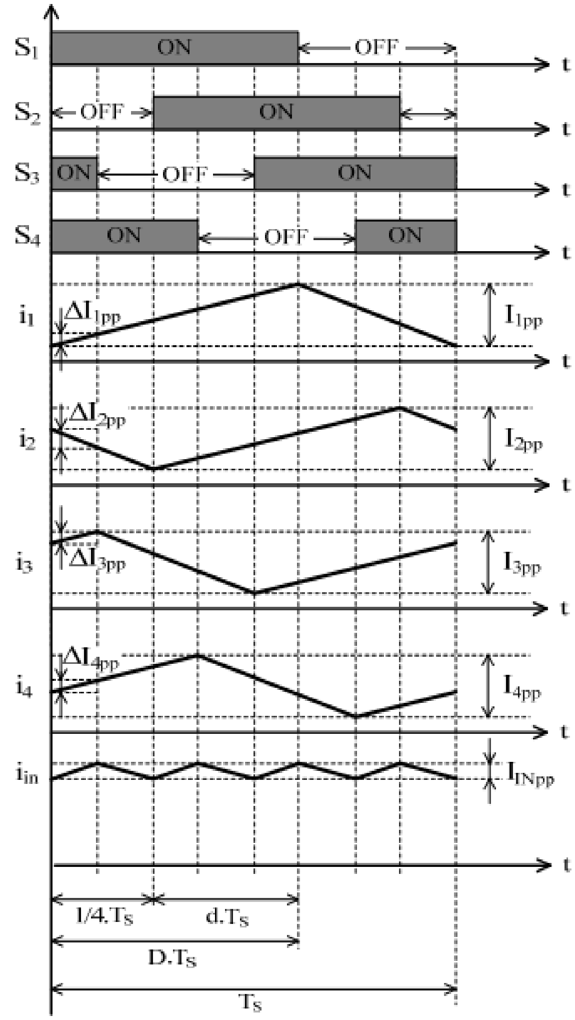

Fig. 6. Inductor current waveforms in range of duty ratio ½ ≤ D ≤ ¾

4. Design Methodology

A. PID Controller Design

PI controller improves the transient response and eliminates the steady state error. The proportional and integral gain constant was derived by trial & error method.

P-I-D controller has the optimum control dynamics including zero steady state error, fast response (short rise time), no oscillations and higher stability. The necessity of using a derivative gain component in addition to the PI controller is to eliminate the overshoot and the oscillations occurring in the output response of the system. One of the major advantages of the P-I-D controller is that it can be used with higher order processes including more than single energy storage.

It can be calculated by Ziegler-Nichol’s step response method also.

K_p, K_i, K_d is set to zero

K_p is rises gradually from 0 to critical value, when oscillation is stable and sustain.

Simplified Equation of PID

$$K_p = K_p \quad (1)$$

$$K_i = \frac{K_p}{T_i} \quad (2)$$

$$K_d = K_p * T_d \quad (3)$$

K_p = Proportional gain
K_i = Integral gain
K_d = Derivative gain
K_{cr} = Critical gain
P_{cr} = Critical Period
T_i = Integral time period
T_d = Derivative time period

From the Equations (1), (2) & (3)

$K_p = 0.01$; $K_i = 10$; $K_d = 0.01$

1) Design of FPIBC

$$\text{Duty Cycle D} = 1 - \frac{12}{28} = 0.57 \quad (4)$$

$D \approx 0.6$

$$\text{Input Voltage Vin} = L \frac{\Delta i}{(1-D)T} \quad (5)$$

Let ΔI = 1 % of 40A

$$\Delta I = 0.4A \quad (6)$$

Switching Frequency F_S = 30k

$$T = \frac{1}{30k} = 3.333e^{-5} \text{ sec} \quad (7)$$

Inductor design

$$L = \frac{Vin(1-D)}{Fs * \Delta I} = \frac{12(1-0.6)}{30K*0.4} = 470\mu f$$

$$\text{Mutual Inductance } M = K\sqrt{L1*L2} \quad (8)$$

$$M = 0.9 \sqrt{(470 * \mu)^2}$$
$$M = 420\mu H$$

Output Capacitance

$$Co = \frac{i * \Delta t}{\Delta y} =$$
$$\frac{i}{Fout*\Delta v} = \frac{40}{120k*0.4} = 937\mu F \approx 1000\mu F \quad (9)$$

$$Co = 1000\mu F$$

$$\text{Gate Pulse } \theta = \frac{360}{N} = \frac{360}{4} = 90^0 \quad (10)$$

N = No. of Phases
V_0 = Output voltage
K = Coupling Coefficient

The table 1 shows the Four Phase Interleaved Boost Converter with coupled inductors and battery is taken as load and simulation design parameter.

B. Simulation Design Parameters

Table1
FPIBC simulation design parameters

Parameters	Design values
Input Voltage, Vin	12V
Output Voltage, Vo	24-28V
Inductor, L1=L2=L3=L4	470μH
Ripple Voltage Δv	0.4V
Output Capacitor, Co	1000μF
Battery Load	24v,100Ah
Switching Frequency, F_S	30KHz
Duty Cycle, D	60%
Ripple Voltage ΔI	0.4A

5. Simulation Circuit and Results

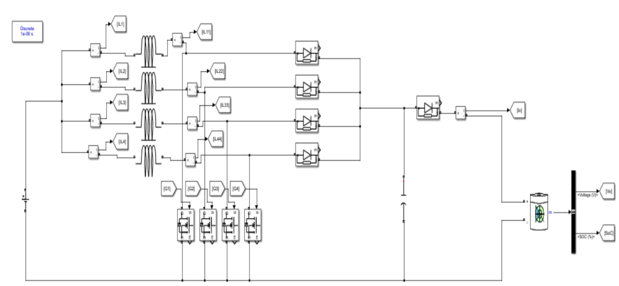

Fig. 7. Four phase interleaved boost converter with coupled inductor, closed loop

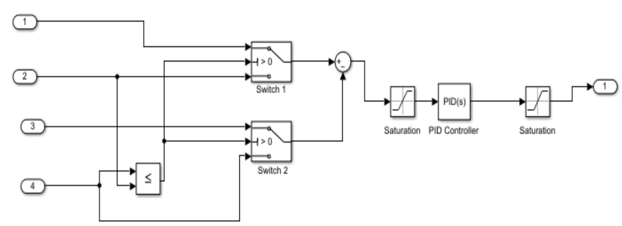

Fig. 8. PID controller for closed loop

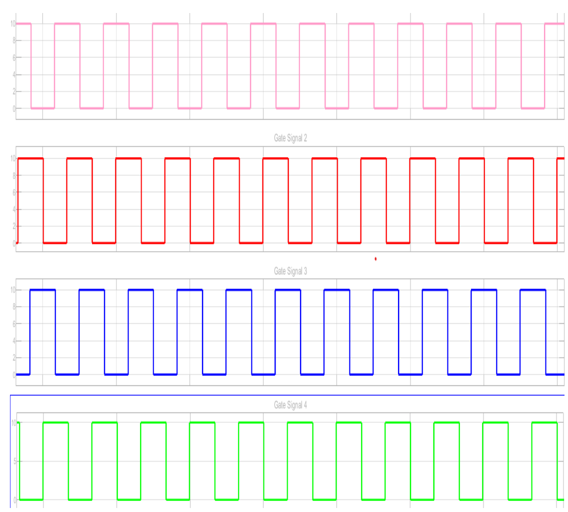

Fig. 9. Gate pulse of FPIBC

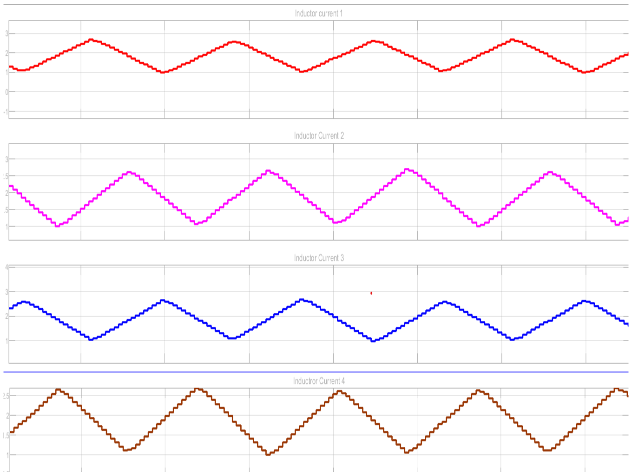
Fig. 10. Inductor current IL1, IL2, IL3, IL4

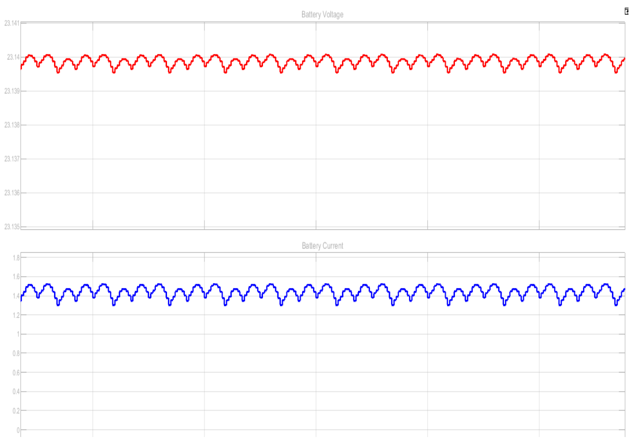
Fig. 11. Battery voltage and current of FPIBC closed loop

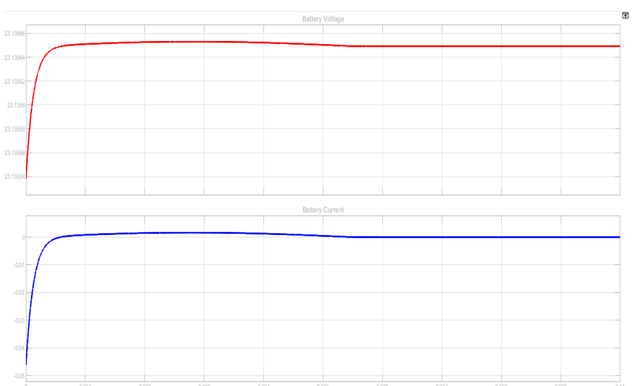
Fig. 12. Battery voltage and battery current in FPIBC Close loop

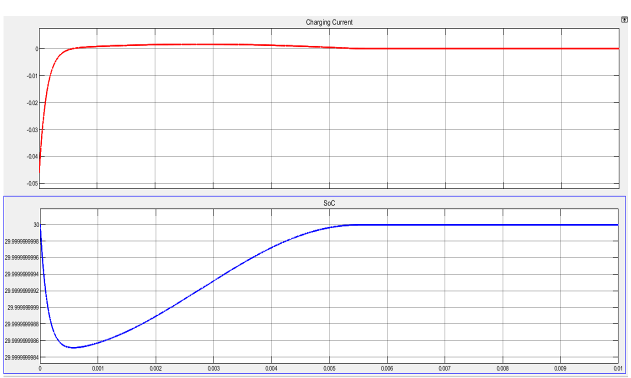
Fig. 13. Battery current and SOC

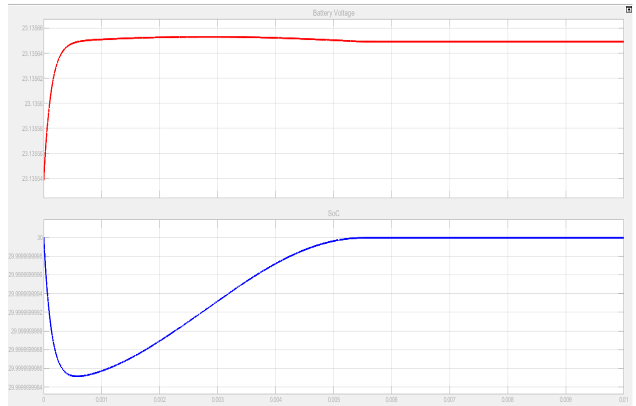
Fig. 14. Battery voltage and S

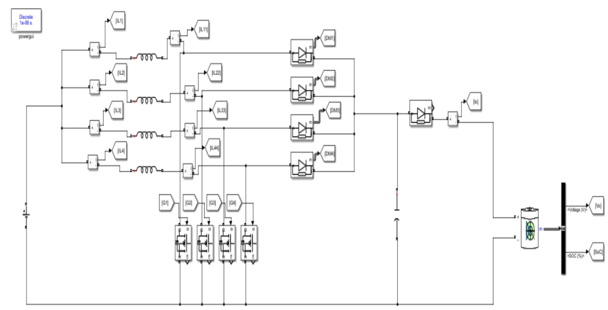
Fig. 15. Four phase interleaved boost converter with uncoupled inductor, closed loop

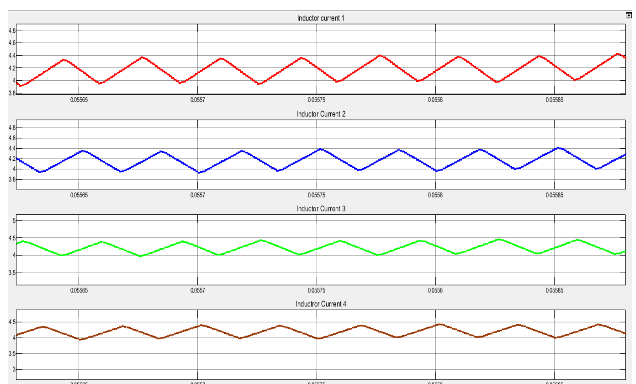
Fig. 16. Input uncoupled inductor current closed loop

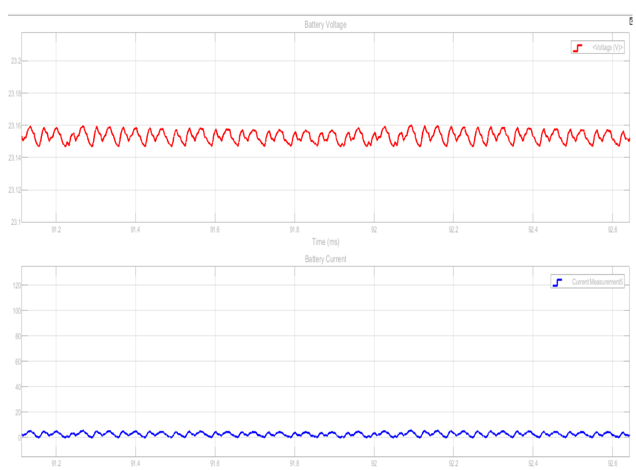
Fig. 17. Battery voltage and current of FPIBC closed loop with uncoupled inductor

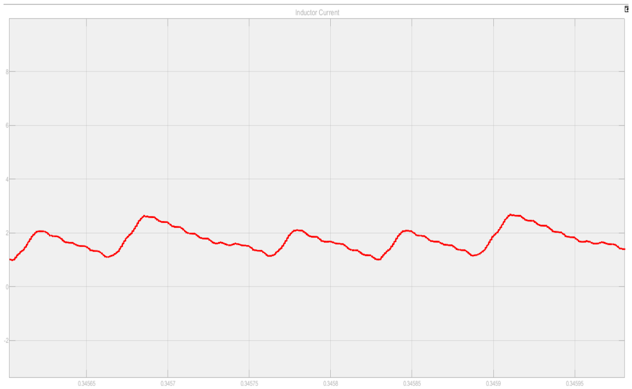

Fig. 18. Total input uncoupled inductor current closed loop

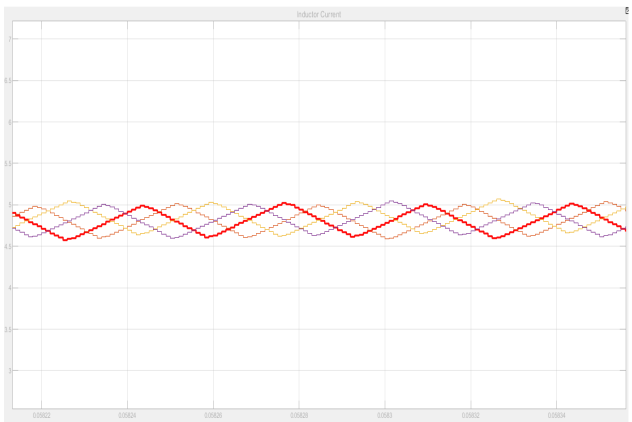

Fig. 19. Uncoupled inductor current closed loop

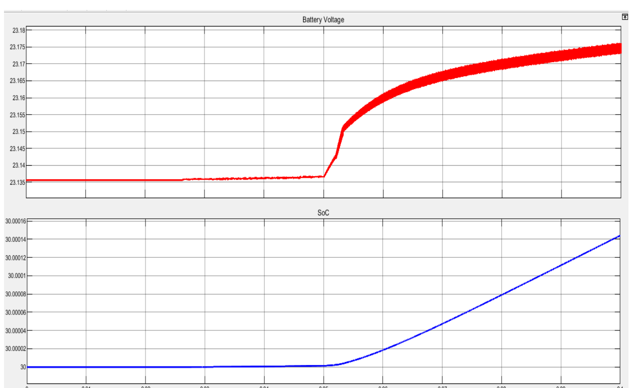

Fig. 20. Uncoupled inductor battery SOC and voltage closed loop

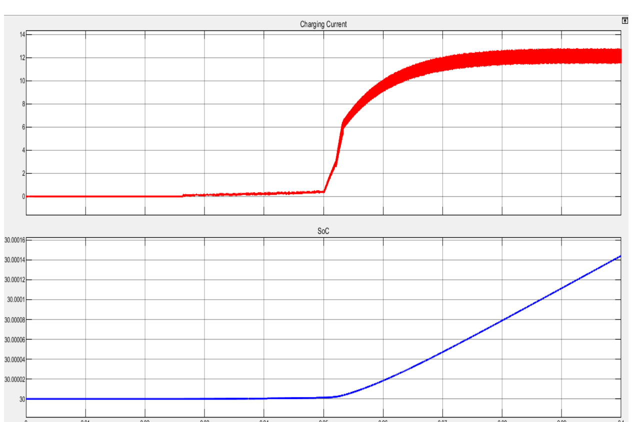

Fig. 21. Uncoupled inductor battery SOC and current closed loop

The comparative analysis done on closed loop coupled inductor and uncoupled inductor. Input Ripple current is reduced to 0.3A from 5.45A and ripple voltage is 0.003 by constant voltage battery charging method. And conversion efficiency is 98% this is for coupled inductor, for uncoupled inductor 92% and the both coupled and uncoupled inductor are operated in closed loop.

In this Four Phase Interleaved Boost Converter with Coupled inductor with open loop and closed loop system was analyzed and Battery charging application taken as load.

Transient response of the system was improved by using closed loop controller with effects of coupled inductor.

The Peak over shoot of the coupled inductor of Four Phase Interleaved Boost Converter was lesser than uncoupled inductor.

6. Conclusion

The comparative analysis of Four Phase Interleaved Boost converter done by MATLAB/Simulink. The circuit was simulated in open loop and closed loop and with using coupled inductor. For this reduces input current ripple as well as output ripple voltage and load are battery which 24V, 100Ah which is charging in constant current (CC) and constant voltage (CV). Also analyzed that conversion efficiency higher in closed loop and less in open loop.

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