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# Design and Development of DC-DC Resonant Converter for DC Power Systems

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**ABSTRACT:** The growing demand for higher power density and low profile in power converter designs has forced designers to increase switching frequencies. Operation at higher frequencies considerably reduces the size of passive components such as transformers and filters. However, switching losses have been an obstacle to high frequency operation. In order to reduce switching losses, allowing high frequency operation, resonant switching techniques have been developed. These techniques process power in a sinusoidal manner and the switching devices are softly commutated. Therefore, the switching losses and noise can be dramatically reduced.

The proposed converter is operated at a switching frequency from 15kHz to 30kHz using DSP controller. The converter is validated with an experimental setup which delivers the output voltage of 28V and output current of 200A with desired efficiency of 87%. Simulation is carried out with input of 300V and 400V DC input and DC output of 28V, 200A at full load and no load. The power rating is 6KW. The prototype of the proposed converter is built. Prototype was conducted for 400VDC with 28V,200A output.

**KEYWORDS:** LLC Resonant converter; ZVS; ZCS; high frequency operation; power stage design

## I. INTRODUCTION

DC-DC converters are power electronic circuits that convert a dc voltage to a different dc voltage level, often providing a regulated output. Imperfect switching is a major contributor to power loss in converters. Switching devices absorb power when they turn on or off if they go through a transition when both voltage and current are non-zero. As the switching frequency increases, these transitions occur more often and the average power loss in the device increases. High switching frequencies are otherwise desirable because of the reduced size of filter components and transformers, which reduces the size and weight of the converter.

There are many DC-DC converters such as Buck, Boost, Buck-Boost, CUK, SEPIC, Fly-back, Forward, Push-Pull converters in which switching is hard due to which power losses are more in the circuit. In resonant circuits, switching takes place when voltage and/or current is zero, thus avoiding simultaneous transitions of voltage and current and thereby eliminating switching losses. This type of switching is called soft switching, as opposed to hard switching in above mentioned circuits.

There are 2 types of conventional resonant converters. Series Resonant converter and Parallel resonant converter. These have got several limitations. Series resonant converter can achieve Zero Voltage Switching (ZVS) but fail to operate in Zero current switching (ZCS) due to frequency less than the resonant frequency. Also the output cannot be regulated for the no-load condition. As $R_L$ goes to infinity, Quality factor Q goes to zero. The output voltage is then independent of frequency. However, the parallel converter is able to regulated the output at no load. For the parallel converter Q becomes larger as the load resistor increases, and the output remains dependent on the switching frequency. A drawback of the parallel converter is that the current in the resonant components is relatively independent of load. The conduction losses are fixed, and efficiency of the converter is relatively poor for light loads.

In order to solve the limitations of these conventional resonant converters, the series-parallel LLC resonant

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converter has been proposed. This series-parallel converter combines the advantages of both the series and parallel converters. The LLC-type resonant converter has many advantages over conventional resonant converters. First, it can regulate the output voltage over wide line and load variations with a relatively small variation of switching frequency. Second, it can achieve Zero Voltage Switching (ZVS) over the entire operating range and the light-load efficiency is relatively high. The resonant switch converter with zero-current switching has theoretically zero switching losses.

The proposed resonant converter is a DC-DC switching converter that includes resonant tank circuit actively participating in determining input to output power flow. This Resonant DC-DC converter is preferred over other conventional topologies due to its features like soft switching namely Zero-Voltage Switching and Zero-Current Switching, high frequency operation, high efficiency, smaller size, light weight, low component stress and reduced EM interference.

## II. PROPOSED CONVERTER

### A. Circuit Description

The proposed LLC resonant converters consist of three reactive elements $C_r$, $L_s$ and $L_p$. One inductor is connected in parallel to the load. Rectifier block is coupled to resonant inverter through a transformer. To maximize the usage of energy, rectifier block is configured as full wave rectifier that needs a center tap arrangement of transformer's secondary winding. Full wave rectifier is preferred with a low voltage and high current output. In this converter power flow is controlled by the switch network by changing the switching frequency and phase shift control method is been used.

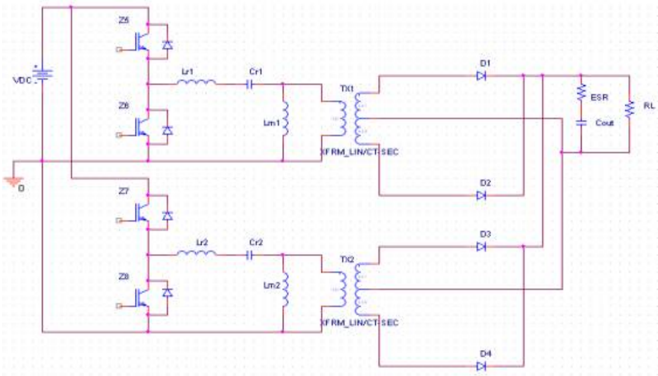


**Figure 1: Proposed LLC converter**

Since the resonant tank includes three reactive elements two resonant frequencies associated to this circuit. One is relating to condition of secondary winding conducting (constant voltage across it). Other is relating to secondary winding open ($L_s$ and $L_p$ are unified). LLC converter is normally operated in the region when input impedance of resonant tank has inductive nature which increases with frequency. Implies the power flow can be controlled by changing the operating frequency. Reduced power demand produces frequency rise and increased power demand causes frequency reduction.

### B. Operational Principle

The proposed converter topology is as shown in the figure 1. Switches $Z_1$ and $Z_2$ form one leg and connected to LC resonant tank other inductor is connected across secondary side which reflects on primary, then center-tapped transformer with diode bridge rectifier is connected. Filter capacitor connected at the load side helps filter the ripple current. Switches $Z_3$ and $Z_4$ form other stage with same components connected as above. Diodes across switches are connected for free-wheeling operation. Both the stages are phase shifted by 90 degrees. The dead-band between the top and bottom switches of same leg is maintained around 2usec. The input voltage is from $300V_{dc}$ to $400V_{dc}$. Frequency modulation is done from 15 kHz to 30 kHz. The transformer coupling is 1. The secondary winding of center-tapped transformer are equal so that voltage gets divided equally. The turns ratio of transformer is maintained 0.4.

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## III. DESIGN CONSIDERATIONS OF POWER STAGE

### A. LLC Converter

| Sl.No | Description | Specifications |
|---|---|---|
| 1 | Output power rating | 6KW |
| 2 | Input voltage range | 300-400Vdc |
| 3 | Switching frequency | 15kHz -30kHz |
| 4 | Output voltage range | 28V |
| 5 | Output current | 200A |

**TABLE 1: Input and output specifications for design**

The design of components depends on variation parameters including gain, resonant frequency, quality factor, and ratio of primary inductance to resonant inductance. Hence these factors have to be taken care while designing. These factors are calculated as follows.

$$Q = \frac{\sqrt{L_r/C_r}}{R_{ac}}$$ Quality factor

$$R_{ac} = \frac{8}{\pi^2} \cdot \frac{N_P^{\ 2}}{N_S^{\ 2}} \cdot R_o$$ Reflected load resistance

$$F_x = \frac{f_s}{f_r}$$ Normalized switching frequency

$$f_r = \frac{1}{2\pi\sqrt{L_r \cdot C_r}}$$ Resonant frequency

$$m = \frac{L_r + L_m}{L_r}$$ Ratio of total primary inductance to resonant inductance

### B. Transformer turns ratio for high switching frequency

| Sl. No | Description | Specifications |
|---|---|---|
| 1 | Primary turns ($NP_1$) | 12 |
| 2 | Secondary turns (NS1) | 15 |
| 3 | Secondary turns (NS2) | 15 |
| 6 | Transformer core | AMCC 100 |

**TABLE 2: Transformer specifications**

Table II Shows the centre-tapped Transformer parameters considered for the proposed converter circuit. The transformer design is carried out. During converter operation, when the top switch is on, input dc voltage appears across the transformer primary winding. When the switch is off reflection voltage can be seen across primary winding of the transformer.

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### C. Secondary Diode Rectification

An important step to achieve the best converter performance is to choose the right bridge and rectifier circuits. A full-wave rectifier requires diodes that are twice the voltage rating compared to a full-bridge rectifier. Since it has only two diodes it has half the total diode conduction losses compared to the full-bridge rectifier. A full-wave rectifier has two secondary windings, hence the resistance is doubled for the same winding area. In applications with low output voltages and high currents application, the full-wave is more common, because of lower total conduction losses and lower component count and cost.

**Rectifier Diode and Capacitor Selection**

Rectifier diode selection depends on the peak inverse voltage ($V_R$) across it and output current.

$$V_R \geq 1.25 \times PIV_S$$

Where $I_D$ is the diode rated DC current is the average output current which depends on the thermal rise in duration of peak load condition.

$$I_D \geq 3 \times I_O$$

$$I_O = \frac{P_O}{V_O}$$

Output capacitor selection depends on the ripple current.

$$I_{ripple} = \sqrt{\left(I_{rms}^2 - I_{av}^2\right)}$$

With low ESR an electrolytic capacitor is selected. Output ripple voltage is $I_{SP} \times ESR$ The capacitor rating is increased on the basis of measured capacitor temperature rise under worst case loading and ambient temperature. ESR of the capacitor is multiplied with the secondary peak current to give the switching ripple voltage. Therefore it is important to select the low ESR capacitor to reduce the ripple voltage. Usually, selecting a high ripple current rated capacitor results in a acceptable value of ESR.

## IV. SIMULATION

The proposed LLC DC-DC resonant converter topology is simulated using Orcad Pspice software. The simulation parameter is shown in the Table III. The simulation model includes $V_{DC}$ Source, Vpulse and IGBT switches with anti-parallel connected free-wheeling diodes, LLC resonant components, linear centre-tapped transformer and full-wave rectifier circuit with D1,D2,D3 and D4 diodes. Cout is the filter capacitor across the regulated output voltage for an DC input of 300V and 400V. The PWM pulse required for IGBT switches is given by the Vpulse with the required duty cycle for the given switching frequency. The simulation circuit is shown in Figure 4 and Simulation results are shown in Figure 5.

| Sl. No | Description | Specifications |
|---|---|---|
| 1 | $V_{DC}$ voltage | 300V-400V |
| 2 | Resonant Inductor (Lr1) | 119.7Uh |
| 3 | Resonant Inductor (Lr2) | 119.7uH |
| 4 | Resonant Capacitor (Cr1) | 940nF |
| 5 | Resonant Capacitor (Cr2) | 940nF |
| 6 | Magnetizing Inductance (Lm1) | 44uH |
| 6 | Magnetizing Inductance (Lm2) | 44uH |

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| | | |
|---|---|---|
| 7 | Output Capacitor with ESR | 10000uF, 9.4mE (5 no) |
| 8 | $R_{load}$ | 140mE |
| 9 | Switching Frequency ($f_{sw}$) | 15kHz-30kHz |

**TABLE 3: Simulation Parameters**

| Input | $R_L$ (Ohms) | $V_o$ (V) | $I_o$ (A) | $F_s$ (kHz) | $I_{ripple}$ (A) |
|---|---|---|---|---|---|
| 300V | 140m | 28 | 202 | 15.4 | 21A |
| 300V | 1.4 | 27.8 | 19.8 | 16.2 | 3.14A |
| 300V | 14 | 27.7 | 1.97 | 17.2 | 0.83A |
| 400V | 140m | 28 | 200.7 | 17.4 | 25.9A |
| 400V | 1.4 | 28.7 | 20.5 | 24.5 | 3.9A |
| 400V | 14 | 28.9 | 2.06 | 30.5 | 0.59A |

**TABLE 4: Simulation Result Tabulation**

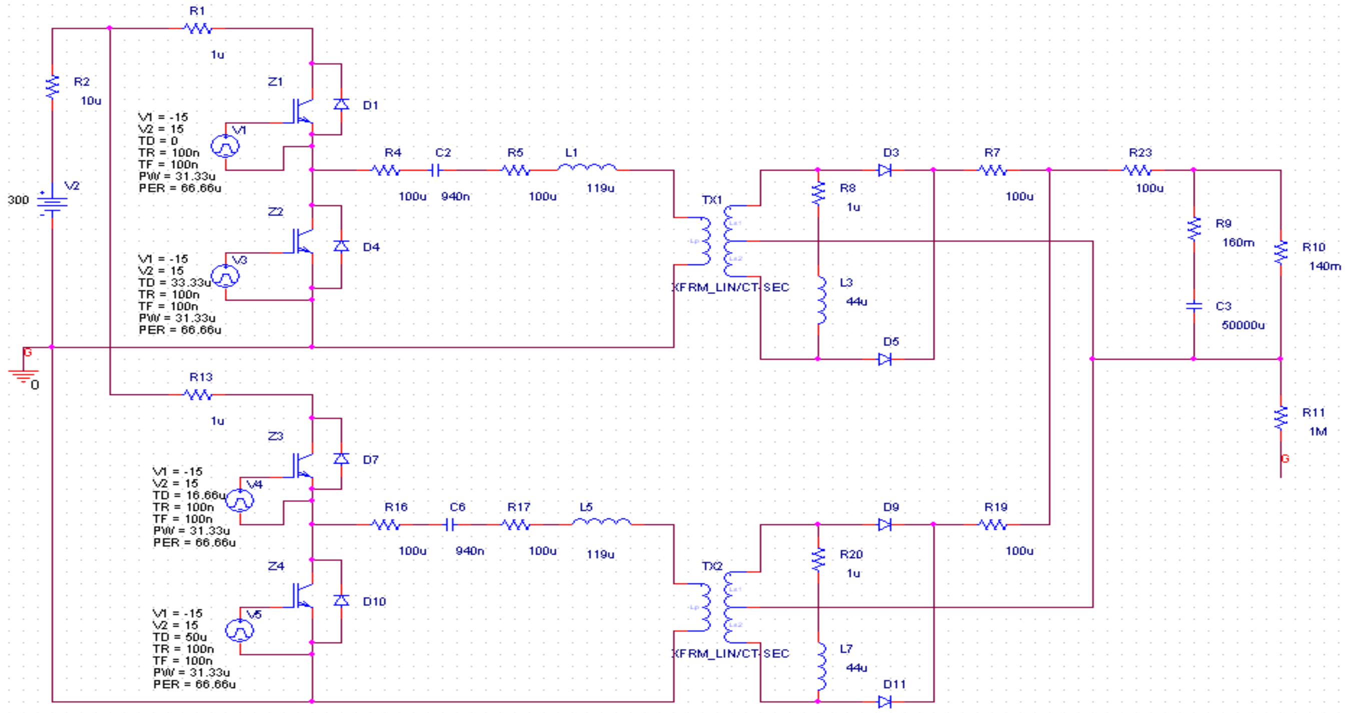


**Figure 4: Simulation Circuit**

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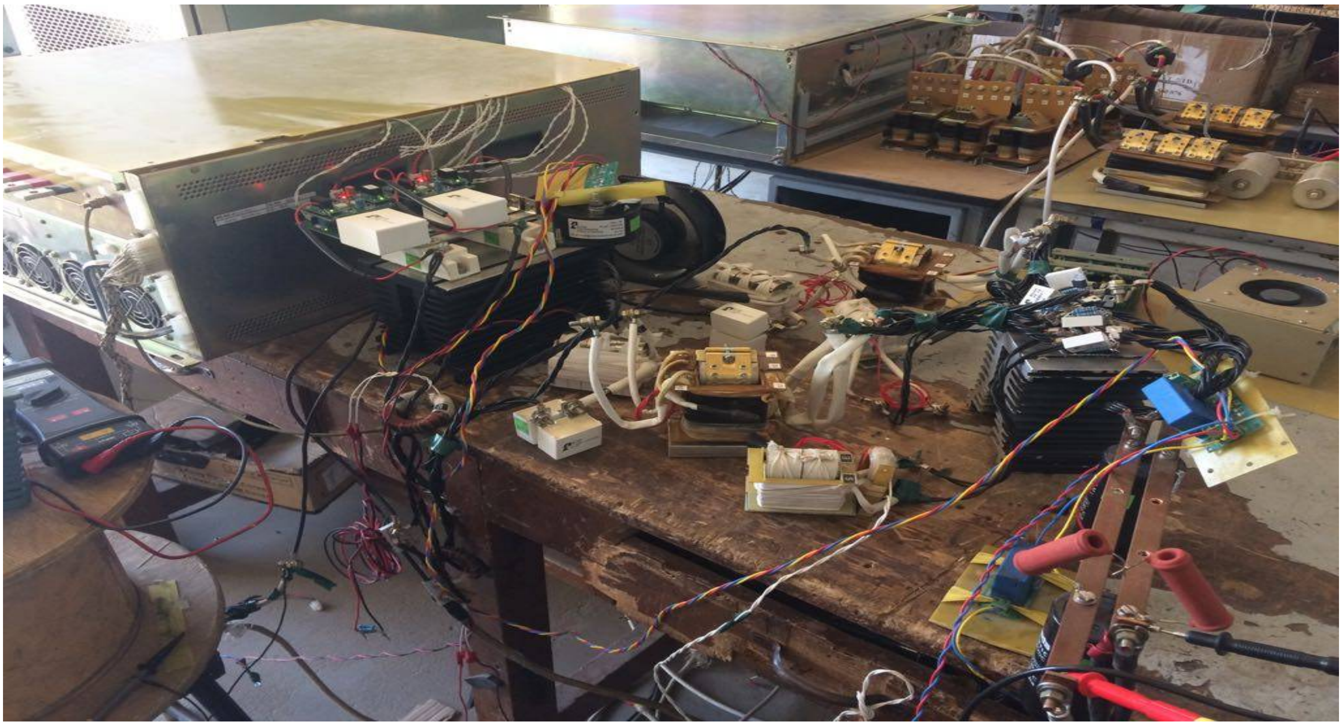

**Figure 9: Hardware setup**

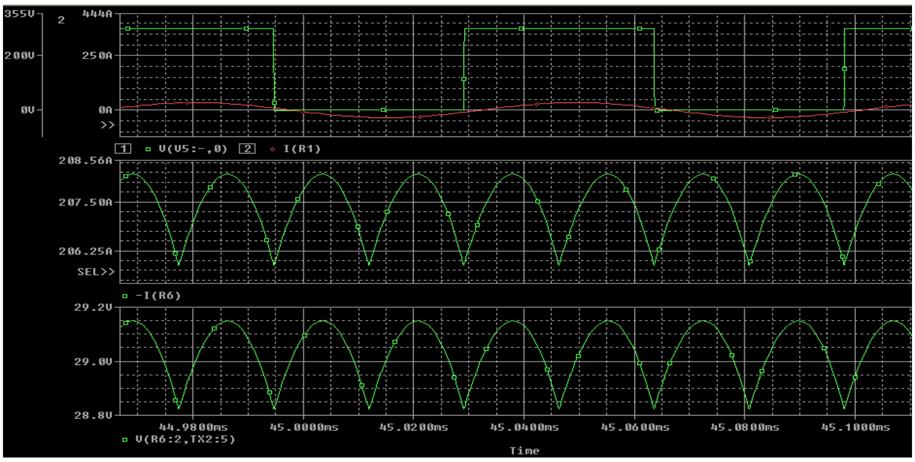


**Figure 5: Output Voltage & Current with soft switching waveforms**

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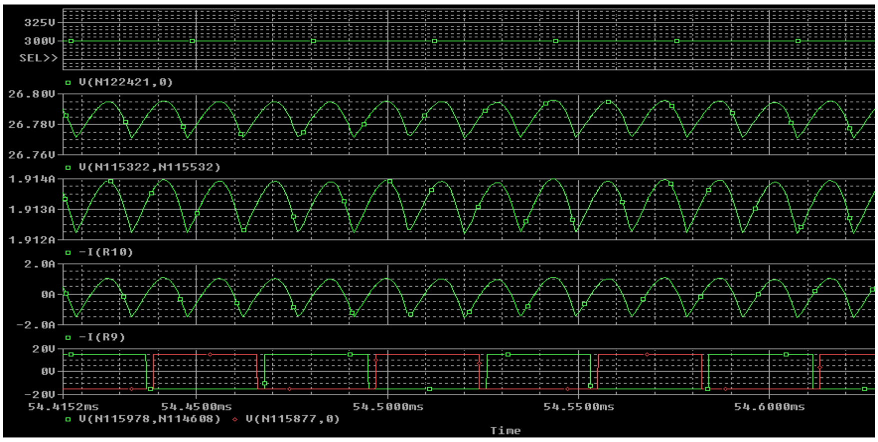


**Figure 6: Results with 300V input at Full-Load**

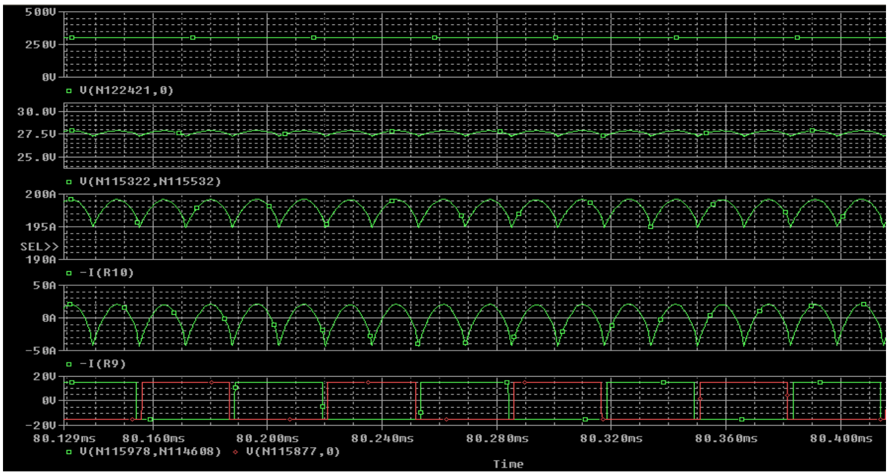


**Figure 7: Results with 300V input at no-Load**

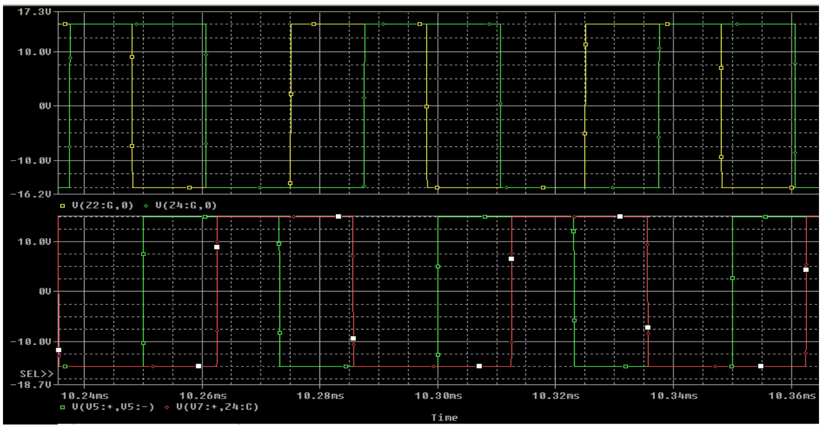


**Figure 8: Results with 300V input at no-Load**

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## V. RESULTS OF HARDWARE IMPLEMENTATION

The proposed resonant converter is implemented in the hardware as shown in Figure 9. As discussed in earlier section, PWM Controller generates initial PWM signal. Thus by switching action the converter provides 28V with 200A current for input voltage of 300V and 400V DC. The switching frequency is maintained from 15kHz to 30kHz. Output power rating is 6KW.


**Figure 10: output voltage and output current**


**Figure 11: Input voltage and Output voltage**

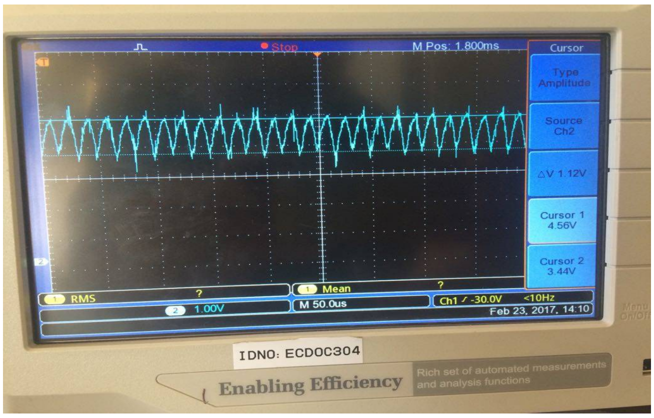


**Figure 12: Ripple current of 16.8A**

## VI. CONCLUSION

The proposed DC-DC resonant converter is designed to operate with 300V and 400V input. Simulation is carried out for the proposed topology. The hardware prototype is build and the results are captured. The converter is observed to have output ripple current quite less with good output voltage regulation. The efficiency achieved is 87%.

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