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Non-Isolated LLC Resonant Converter

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Abstract: The main objective of this paper is to simulate and implement Non-isolated LLC Resonant Converter to reduce transformer turns ratio and losses and to regulate output voltage. High power density and high efficiency are the motivation for both point-of-load and the voltage regulator for processors. Thus, high switching frequency is required for small passive components. A novel non-isolated LLC resonant converter can achieve most merits of isolated LLC resonant converter, like zero voltage switching and very low turn off loss for all MOSFETs. This converter combined the benefits of resonant converters and non-isolated structure. By non-isolated technique, the turns of transformer can be largely reduced. Meanwhile, the current through secondary windings is also reduced. Thus, the transformer loss is decreased. The non-isolated structure of PWM converters shows their benefits for low conduction loss and driven loss. The Non-isolated resonant converter is simulated using the software MATLAB and is implemented in a prototype model.

I. INTRODUCTION

DC-DC CONVERTER

A DC-to-DC converter is a device that accepts a DC input voltage and produces a DC output voltage.[1] Typically the output produced is at a different voltage level than the input. In addition, DC-to-DC converters are used to provide noise isolation, power bus regulation, etc. This is a summary of some of the popular DC-to-DC converter topologies.[2]

BUCK CONVERTER (STEP-DOWN CONVERTER)

In this circuit the transistor turning ON will put voltage Vin on one end of the inductor. [3]This voltage will tend to cause the inductor current to rise. When the transistor is OFF, the current will continue flowing through the inductor but now flowing through the diode. We initially assume that the current through the inductor does not reach zero, thus the voltage at Vx will now be only the voltage across the conducting diode during the full OFF time. The average voltage at Vx will depend on the average ON time of the transistor provided the inductor current is continuous.[4-6]

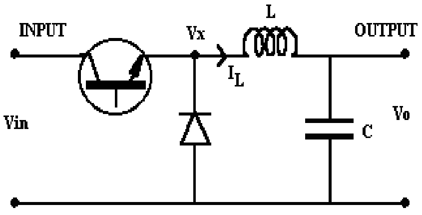

Fig 1.1 Buck converter

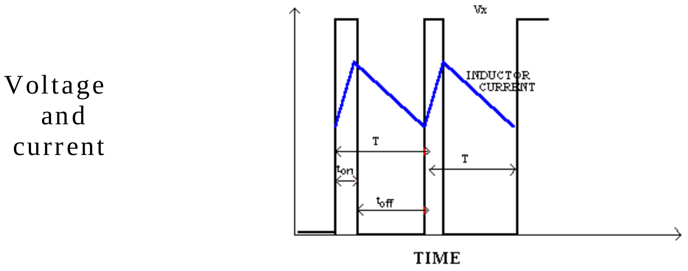

Fig 1.2 Voltage and current changes

To analyze the voltages of this circuit let us consider the changes in the inductor current over one cycle. From the relation

$$V_x - V_o = L\frac{di}{dt}$$

the change of current satisfies

$$di = \int_{ON}(V_x - V_o)dt + \int_{OFF}(V_x - V_o)dt$$

For steady state operation the current at the start and end of a period T will not change. To get a simple relation between voltages we assume no voltage drop across transistor or diode while ON and a perfect switch change. Thus during the ON time V_x=V_{in} and in the OFF V_x=0. Thus

$$0 = di = \int_0^{t_{on}}(Vin - Vo)dt + \int_{t_{on}}^{t_{on}+t_{off}}(-Vo)dt$$

which simplifies to

$$(Vin - Vo)t_{on} - Vo\ t_{off} = 0$$

and defining "duty ratio" as

$$D = \frac{t_{on}}{T}$$

the voltage relationship becomes Vo=D Vin Since the circuit is loss less and the input and output powers must match on the average V_o* I_o = V_{in}* I_{in}. Thus the average input and output current must satisfy I_{in} =D I_o These relations are based on the assumption that the inductor current does not reach zero.

BOOST CONVERTER (STEP-UP CONVERTER):

The schematic in Fig.1.1.2(a) shows the basic boost converter. This circuit is used when a higher output voltage than input is required.

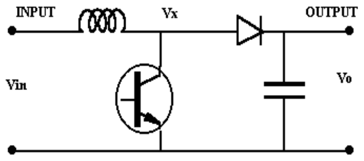

Fig 1.3Boost Converter Circuit

While the transistor is ON V_x =V_{in}, and the OFF state the inductor current flows through the diode giving V_x =V_o. For this analysis it is assumed that the inductor current always remains flowing (continuous conduction). The voltage across the inductor is shown in figure. and the average must be zero for the average current to remain in steady state

$$Vin\, t_{on} + (Vin - Vo)t_{off} = 0$$

This can be rearranged as

$$\frac{Vo}{Vin} = \frac{T}{t_{off}} = \frac{1}{(1-D)}$$

and for a loss less circuit the power balance ensures

$$\frac{Io}{Iin} = (1-D)$$

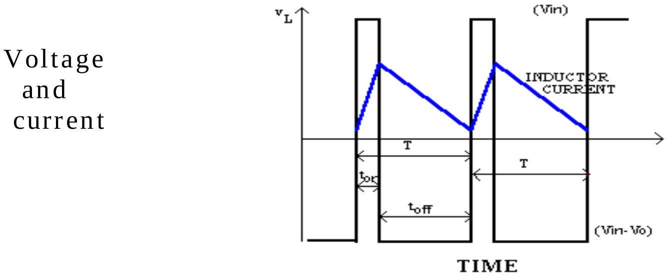

Fig 1.4 Voltage and current waveforms (Boost Converter)

Since the duty ratio "D" is between 0 and 1 the output voltage must always be higher than the input voltage in magnitude. The negative sign indicates a reversal of sense of the output voltage. [7-9]

BUCK-BOOST CONVERTER:

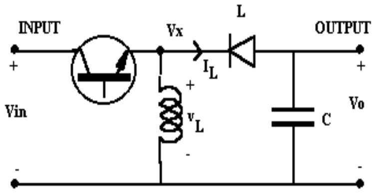

Fig 1.5 Schematic for buck-boost converter

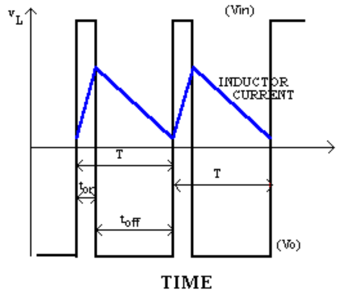

Fig 1.6 Waveforms for buck-boost converter

$$Vin\, t_{ON} + Vo\, t_{OFF} = 0$$

which gives the voltage ratio

$$\frac{Vo}{Vin} = -\frac{D}{(1-D)}$$

and the corresponding current

$$\frac{Io}{Iin} = -\frac{(1-D)}{D}$$

Since the duty ratio "D" is between 0 and 1 the output voltage can vary between lower or higher than the input voltage in magnitude. The negative sign indicates a reversal of sense of the output voltage.[11]

RESONANT CONVERTER:

LLC RESONANT CONVERTER:

Three traditional resonant topologies were analyzed in above part. From the results, we can see that all of them will see big penalty for wide input range design. High circulating energy and high switching loss will occur at high input voltage. They are not suitable for front end DC/DC application. Although above analysis give us negative results, still we could learn something from it.[12]

For a resonant tank, working at its resonant frequency is the most efficient way. This rule applies to SRC and PRC very well. For SPRC, it has two resonant frequencies. Normally, working at its highest resonant frequency will be more efficient. To achieve zero voltage switching, the converter has to work on the negative slope of DC characteristic. From above analysis, LCC resonant converter also could not be optimized for high input voltage.

The reason is same as for SRC and PRC; the converter will work at switching frequency far away from resonant frequency at high input voltage. Look at DC characteristic of LCC resonant converter, it can be seen that there are two resonant frequencies.

One low resonant frequency determined by series resonant tank Lr and Cs. One high resonant frequency determined by Lr and equivalent capacitance of Cs and Cp in series. For a resonant converter, it is normally true that the converter could reach high efficiency at resonant frequency. For LCC resonant converter, although it has two resonant frequencies, unfortunately, the lower resonant frequency is in ZCS region. For this application, we are not able to design the converter working at this resonant frequency. Although the lower frequency resonant frequency is not usable, the idea is how to get a resonant frequency at ZVS region. By change the LCC resonant tank to its dual resonant network, this is achievable.

By change L to C and C to L, a LLC resonant converter could be built. The DC characteristics of these two converters are shown in figure. The DC characteristic of LLC converter is like a flip of DC characteristic of LCC resonant converter. There are still two resonant frequencies. In this case, Lr and Cr determine the higher resonant frequency. The lower resonant frequency is determined by the series inductance of Lm and Lr. Now the higher resonant frequency is in the ZVS region, which means that the converter could be designed to operate around this frequency.

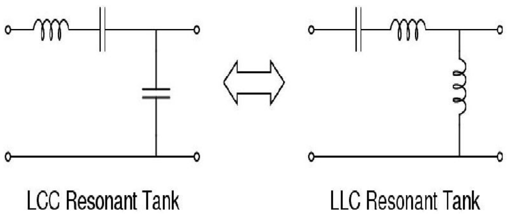

Fig 1.7 Resonant tank

ZERO VOLTAGE SWITCHING:

Resonant converters, on the other hand, use a different technique to reduce the switching losses. Returning to the turn-on loss equation (Eq. 1), if V_{DS} is set to zero, there will be no losses at all. This principle is known as zero-voltage switching (ZVS). It's used in resonant converters, in particular the LLC resonant converter.

Zero-voltage switching is achieved by forcing the current flowing through the switch to reverse. When the switch current reverses, the body (or external anti-parallel) diode clamps the voltage to a low value (for example, 1 volt). This is far lower than the 400 volts mentioned previously for the typical flyback converter.

A resonant circuit is required to achieve this objective. Two MOSFETs generate a square wave and apply it to the resonant circuit. If we choose the operating point to be above resonance, the current flowing into the resonant circuit will be approximately sinusoidal, as the higher-order components are generally well attenuated.

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The sinusoidal current waveform lags the voltage waveform. So when the voltage waveform reaches its zero crossing point, the current is still negative, allowing zero-voltage switching.

To catch up with and move ahead of the trend, higher switching frequency, higher efficiency and advanced packaging are the paths we are taking now. Within all these issues, a topology capable of higher switching frequency with higher efficiency is the key to achieve the goal.

With the techniques proposed the performance at normal operation could be improved. But none of these methods dealt with the switching loss problem of PWM converter. Even with Zero Voltage Switching technique, the turn on loss could be minimized; turn off loss still limits the capability of the converter to operate at higher switching frequency.

Resonant converter, which were been investigated intensively can achieve very low switching loss thus enable resonant topologies to operate at high switching frequency. In resonant topologies, Series Resonant Converter (SRC), Parallel Resonant Converter (PRC) and Series Parallel Resonant Converter (SPRC, also called LCC resonant converter) are the three most popular topologies. The analysis and design of these topologies have been studied thoroughly. In next part, these three topologies will be investigated for front-end application.

PARALLEL RESONANT CONVERTER:

The schematic of parallel resonant converter is shown in figure. Its DC characteristic is shown in figure. For parallel resonant converter, the resonant tank is still in series. It is called parallel resonant converter because in this case the load is in parallel with the resonant capacitor. More accurately, this converter should be called series resonant converter with parallel load. Since transformer primary side is a capacitor, an inductor is added on the secondary side to match the impedance.[13]

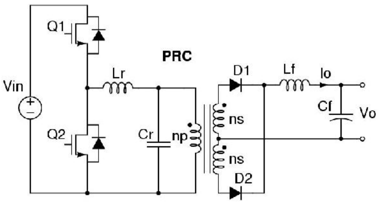

Fig 1.8 Parallel resonant converter

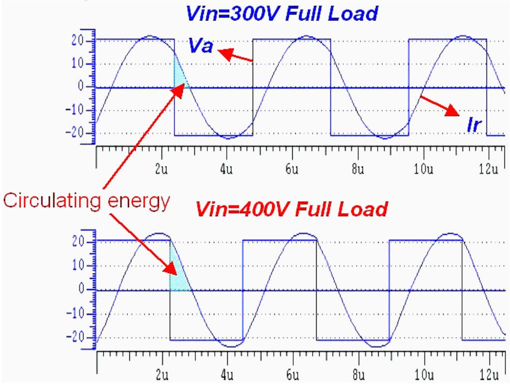

Fig 1.9 waveform for prc

Similar to SRC, the operating region is also designed on the right hand side of resonant frequency to achieve Zero Voltage Switching. Compared with SRC, the operating region is much smaller. At light load, the frequency doesn't need to change too much to keep output voltage regulated. So light load regulation problem doesn't exist in PRC. Same as SRC for PRC, the converter is working close to resonant frequency at 300V. At high input voltage, the converter is working at higher frequency far away from resonant frequency.

From simulation waveforms, at 300V input, the circulating energy is smaller than 400V input situation. Compare with SRC, it can be seen that for PRC, the circulating energy is much larger. Also from the MOSFET current we can see that the turn off current is much smaller in 300V input.

When input voltage increases to 400V, the turn off current is more than 15A, which is even higher than PWM converter.

For PRC, a big problem is the circulating energy is very high even at light load. For PRC, since the load is in parallel with the resonant capacitor, even at no load condition, the input still see a pretty small impedance of the series resonant tank. This will induce pretty high circulating energy even when the load is zero. With above analysis, we can see that PRC is not a good candidate for front end DC/DC converter too. The major problems are: high circulating energy, high turn off current at high input voltage condition.[14]

SERIES-PARALLEL RESONANT CONVERTER:

The schematic of parallel resonant converter is shown in figure. Its DC characteristic is shown in Figure 4.5. For parallel resonant converter, the resonant tank is still in series. It is called parallel resonant converter because in this case the load is in parallel with the resonant capacitor. More accurately, this converter should be called series resonant converter with parallel load. Since transformer primary side is a capacitor, an inductor is added on the secondary side to match the impedance.

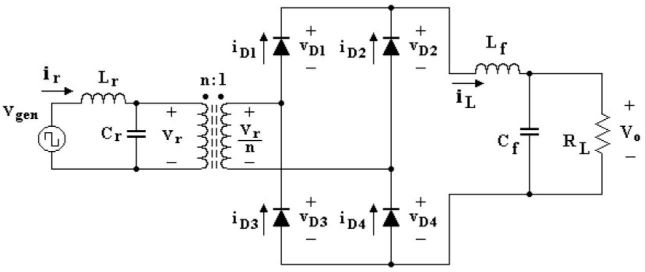

Fig 1.10 Series parallel resonant converter

LITERATURE REVIEW

FULL-BRIDGE INVERTER:

For the dc-to-dc conversion using the full-bridge converter, we pointed out that it can also be used to obtain time-varying voltages with a zero dc component when the duty cycle is 0.5. We now explore the capabilities of the full-bridge circuit as a dc-to-ac converter.

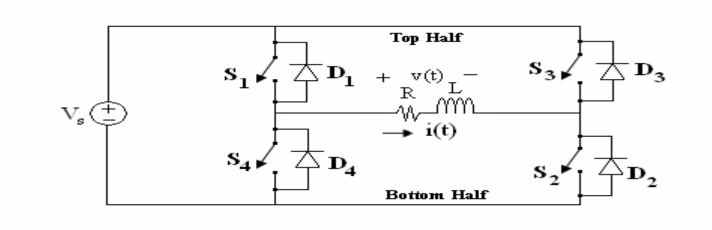

Fig 1.11 Full-bridge inverter feeding an RL load

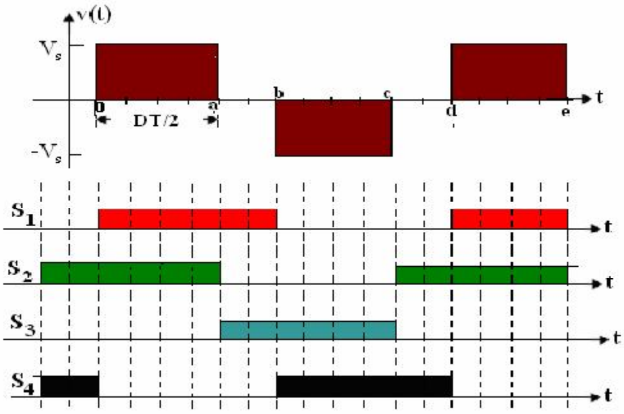

Fig 1.12 Output voltage and the gating scheme of the 4 switches

The full-bridge circuit feeding an inductive (RL) load is shown in Figure 1.11. Once again, we can use the pulse-width modulation (PWM) technique to obtain the required effective or maximum value of the time-varying output voltage. The output voltage, as shown in Figure 1.12, will undoubtedly have harmonic components in addition to the fundamental component. The harmonic components can be filtered out by including filter on the output side. The filter may not be necessary especially when the load is inductive such as an induction motor. A simple scheme of controlling the gating of the four switches is also shown. Although each switch is gated to be on for one-half the time period, each switch may not conduct for one-half the time period due to the constraints imposed by the load. The arrow-head shows the direction in which the current can flow through each switch. When a switch is gated on but the current is in the opposite direction, the freewheeling diode placed in antiparallel with the switch will provide the path for the current.[15]

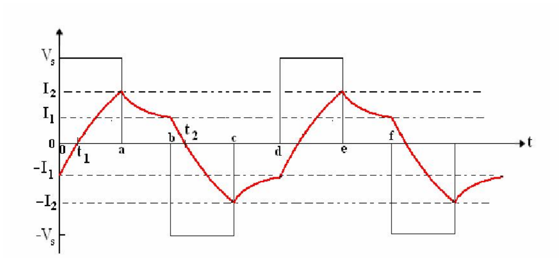

Fig 1.13 Output voltage and current waveforms for PWM operation

II. PROPOSED SYSTEM

This paper proposes a non-isolated LLC resonant converter, with reduced transformer turns ratio, wide input and output range and regulated output voltage. The high conduction loss of buck converter due to the high voltage ratio can be relieved by non-isolated techniques. This converter combined the benefits of resonant converters and non-isolated structure. This concept also can be extended to other resonant converters.

CIRCUIT DIAGRAM:

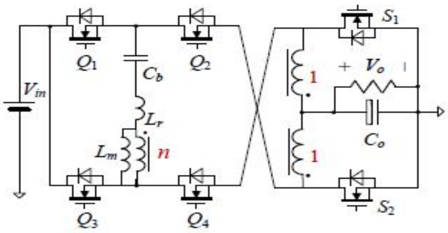

Fig 2.1Circuit diagram of non-isolated LLC resonant converter

MODES OF OPERATION
MODE 1

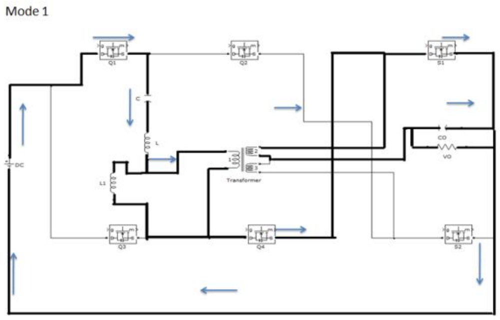

Fig 2.2 Mode 1

When mode 1 the switches Q1 and Q4 are turned ON and Q2,Q3 are turned OFF. The primary current helps to deliver the energy to the load. Thus the current through the secondary windings and the device S1 is turned ON.

MODE 2

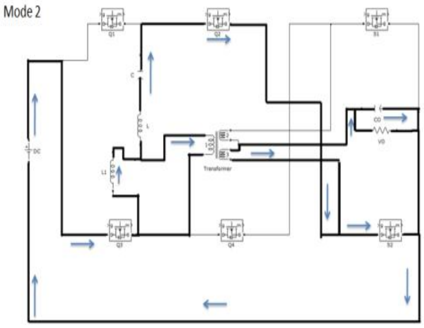

Fig 2.3 Mode 2

When mode 2 The switches Q3 and Q2 are turned ON and Q1,Q4 are turned OFF. The primary current helps to deliver the energy to the load. Thus the current through the secondary windings and the device S2 is turned ON.

WAVEFORMS:

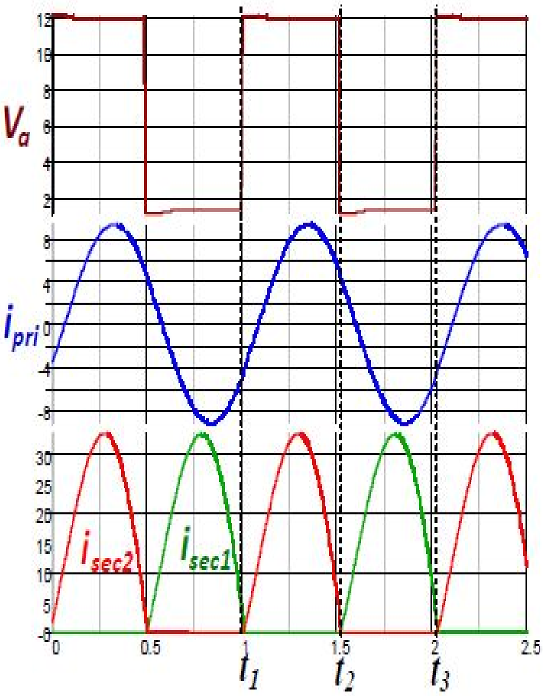

Fig 2.4 Operation waveforms of inverter voltage and current through transformer

LLC resonant converter is widely used in many applications for its high power density and high efficiency. LLC resonant converter can achieve zero-voltage switching (ZVS), low turn off loss for primary side switches and ZCS for output rectifier. Mostly LLC resonant converter is isolated by transformer. The non-isolated structure of PWM

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converters shows their benefits for low conduction loss and driven loss. Due to the same concept, non-isolated structure also can bring some benefits to resonant converters.

III. SIMULATION

SIMULATION CIRCUITS

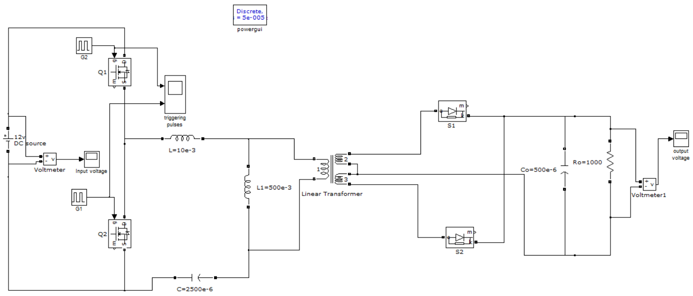

Fig 3.1 Isolated LLC resonant converter

The Fig 3.1 depicts the simulated circuit of isolated LLC resonant converter .

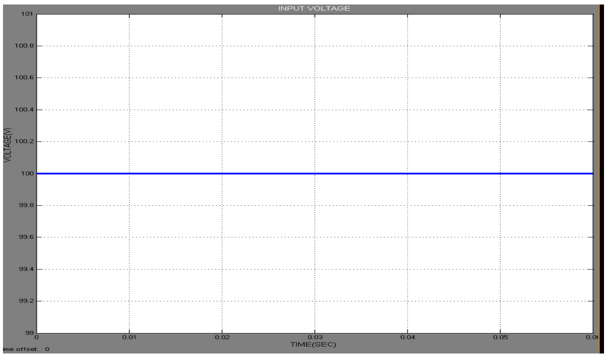

Fig 3.2 Input voltage

The Fig 3.2 depicts voltage supplied to the isolated LLC resonant converter i.e.12v.
X-axis-Time in seconds.
Y-axis-voltage in volts.

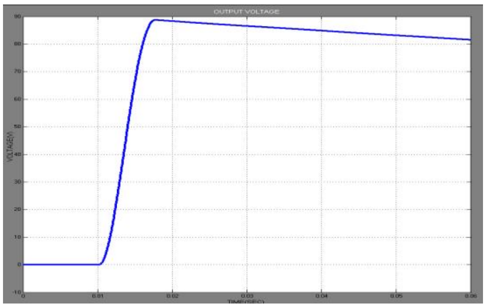

Fig 3.3 Output voltage

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The Fig 3.3 depicts the measurement of output voltage i.e. 8.9v.
X-axis-Time in seconds.
Y-axis-voltage in volts.

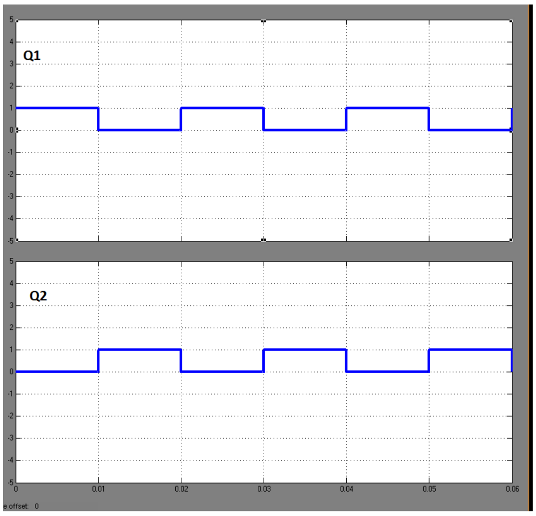

Fig 3.4 Triggering pulses

G1 triggers switch Q1 without any phase delay.
G2 triggers switch Q2 with phase delay of 0.01 seconds.

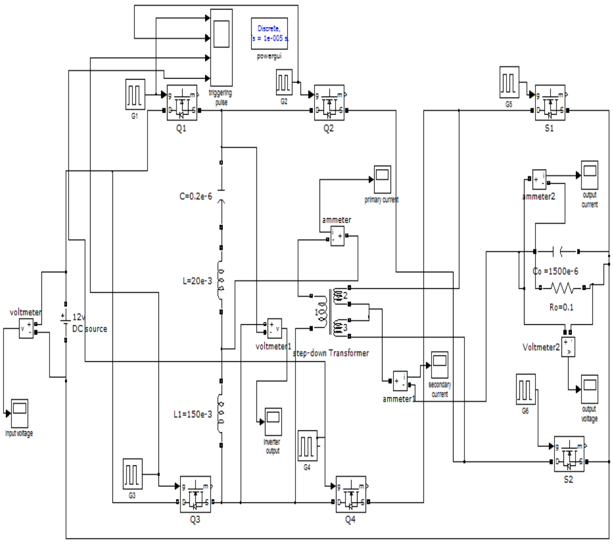

Fig 3.5 Non-isolated LLC resonant converter

Duty ratio:
D $=T_{ON}/T = 10/20 = 0.5$
Transformer turns ratio:
$N_1 = 4896.2$
$N_2 = 9792.4$
N2=N3
Ratio= 1:2:2.

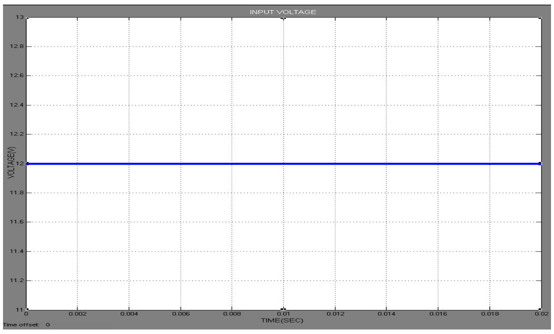

Fig 3.6 Input voltage

The Fig 3.6 depicts the voltage supplied to the non-isolated LLC resonant converter i.e.12v.
X-axis-Time in seconds.
Y-axis-Voltage in volts.

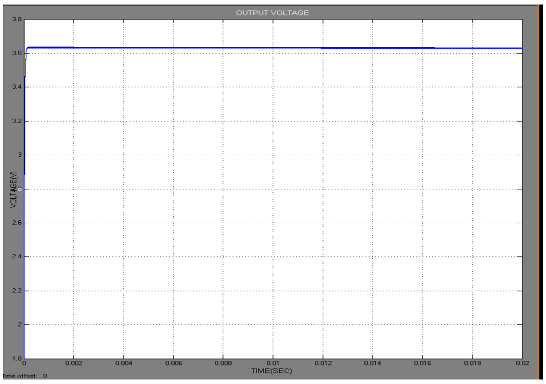

Fig 3.7 Output voltage

The Fig 3.7 depicts the measurement of the output voltage i.e.3.6v.
X-axis-Time in seconds.
Y-axis-Voltage in volts.

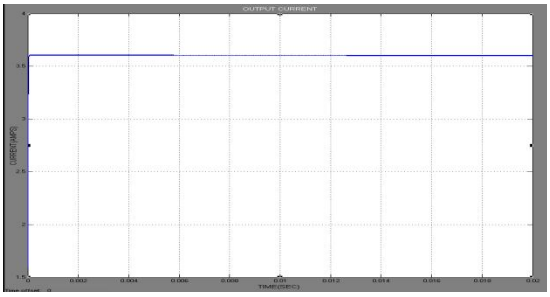

Fig 3.8 Output Current

The Fig 3.8 depicts the measurement of the output current i.e. 3.6A.
X-axis-Time in seconds.
Y-axis-Current in amps.

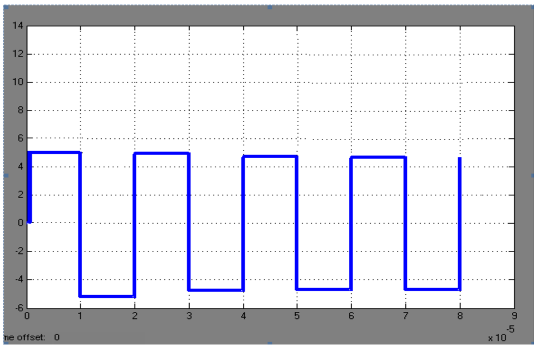

Fig 3.9 Inverter Output

The Fig 3.9 depicts the inverter output waveform which is taken across LLC resonant circuit.
X-axis-Time in seconds.
Y-axis-Voltage in volts

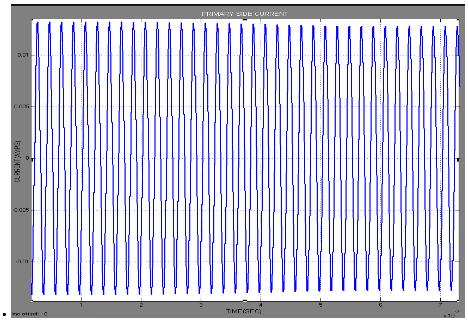

Fig 3.10 Primary side current

The Fig 3.10 depicts the current through primary side of the transformer.
X-axis-Time in seconds.
Y-axis-Current in amps.

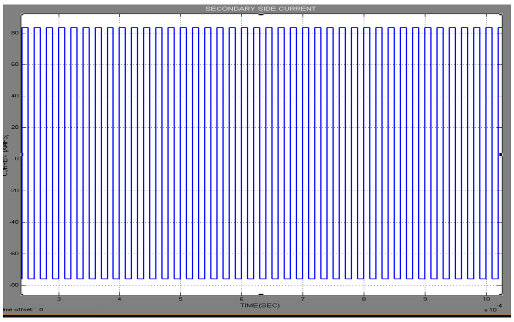

Fig 3.11 Secondary side current

The Fig 3.11 depicts the current through secondary side of the transformer.
X-axis-Time in seconds.
Y-axis-Current in amps.

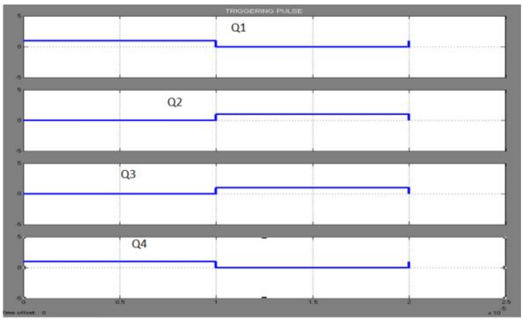

Fig 3.12 Triggering pulse

G1,G3 triggers the switches Q1,Q3 simultaneously without any phase delay.
G2,G4 triggers the switches Q2,Q4 simultaneously with phase delay of 0.01seconds.

IV. HARDWARE IMPLEMENTATION

BLOCK DIAGRAM :

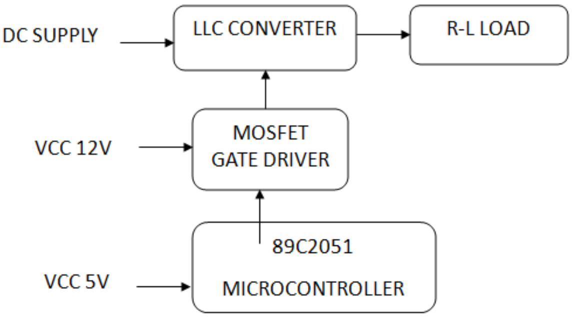

Fig 4.1 Block diagram

230V AC supply is given to the step-down transformer which steps down the voltage to 12V. The obtained 12v AC is rectified and supplied to the non-isolated LLC resonant converter. Another step down transformer provides a 5vAC supply to the microcontroller and buffer circuit, which in turn controls the gate drivers to trigger the switches.

V. RESULTS AND DISCUSSION

Hardware result obtained from CRO was compared with the simulation output both the output appears to be nearly same. In case of hardware while supplying 12 volt we get an output as 5 volt. In case of simulation while supplying 12 volt we get an output as 4 volt. The transformer ratio is reduced, the output voltage is regulated, zero voltage switching is achieved and the current stress on the switches is reduced due to the non-isolated structure. The overall efficiency is increased.

Table 1 Comparison of hardware and simulation results:

	INPUT VOLTAGE	OUTPUT VOLTAGE
HARDWARE RESULT	12V	5V
SIMULATION OUTPUT	12V	4V

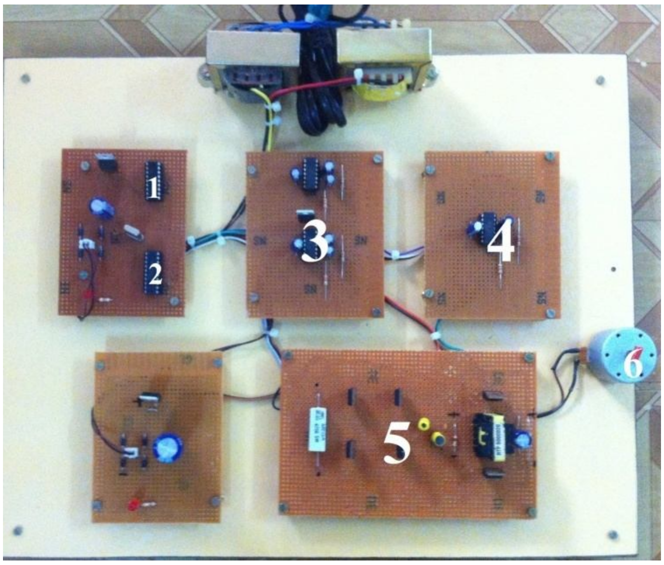

Fig 6.1 Screenshot of hardware

1. Micro controller
2. Buffer
3. Gate driver for switches 1,2,3 &4
4. Gate driver for switches 5 & 6
5. Non-isolated resonant converter
6. DC motor

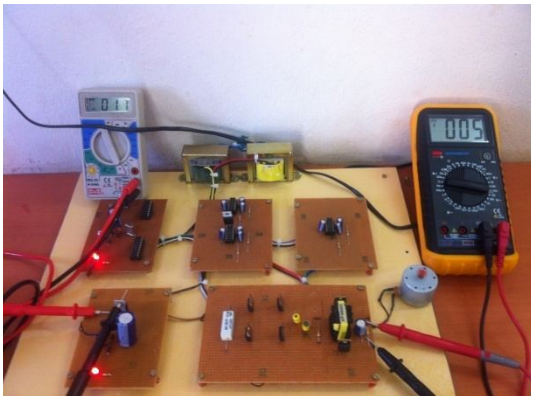

Fig 6.2 Screenshot of voltage measurements

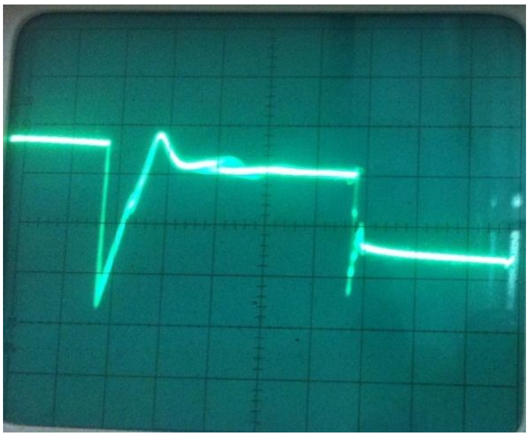

Fig 6.3 Screenshot of inverter outputwaveform

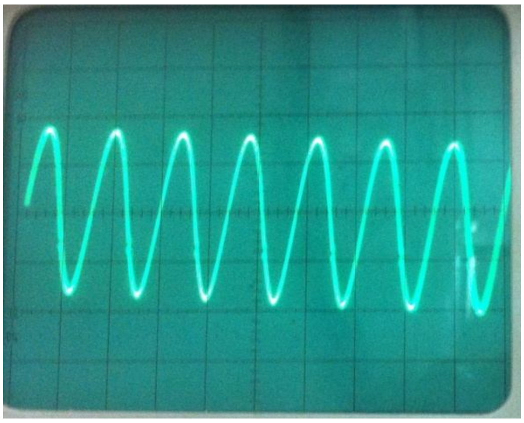

Fig 6.4 Screenshot of voltage across the primary side of the transformer

VI. CONCLUSION

VII. CONCLUSION

This work as a result, gives solution to unregulated voltage, therefore the system can be used in various applications for its high power density and high efficiency. This system seems to be more efficient when compared to converters using isolation techniques, because it can reduce the current stress on the switches. This converter has combined the benefits of resonant converters and non-isolated structure.

FUTURE SCOPE

Firstly, the results are obtained for LLC resonant coverters is verified through simulation and hardware implementation.

This system has four improved advantages simultaneously,including the reduced transformer's turns ratio,regulated output current,wide current gain and reduced switching losses.

- In future this non-isolated technique can be implemented in PWM converters so that conduction loss driven losses are reduced.
- This can be implemented in home appliances, street lamps, chargers and other electric devices – regulates the output voltage by adjusting the operating frequency.
- This can also be implemented in photovoltaic(PV)grid-connected power system in the residential applications where hig step-up,low cost and high-efficiency dc/dc conversion is achieved.

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