Analysis Of Uni-directional and Bi-directional LLC Resonant Converter For Battery Charger Application In Electric Vehicle

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Abstract. As the world is moving towards pollution free transportation, Electric vehicle is the prospective choice in this regard. Present paper limelights resonant converter which best suits for battery charger application in electric vehicle. A performance analysis between unidirectional and bi directional LLC resonant converter is described in this paper for battery charger application in electric vehicle.

1. Introduction

Besides being a big contributor to national economy the transportation sector also bears the name for polluting the environment. This certainly motivates to switch towards electric vehicles. Practically to implement the electric vehicles there are few technicalities that needs to be addressed like charging stations, charging mechanisms and most importantly battery. The battery should be of high efficiency, cost worthy and should have a compact charger. Charging architecture majorly relays on dc-dc converter. Maintaining good efficiency is the selection criteria of power converter, reducing the charging time is the main challenge in the electric vehicles. Currently research is underway to reduce the charging time by doubling the charging capacity\cite{1}.

The DC/DC converter topologies need to have-wide output voltage control, soft-switching in the primary switches under different loads and battery voltages, a low voltage in the secondary rectifiers, the reduction of circuit complexity by avoiding snubbers, the change in switching frequency must be low to decrease the switching loss and to avoid noise during wide load range and circulating current should be low\cite{2}. In this paper, a resonant DC/DC converter comprised of inverter, resonating tank and a rectifier associated with a filter. The converter has operational characteristics that best suits for an electrical vehicle battery charger. The block diagram of battery charger can be presented as below.
Figure 1 block diagram of LLC Resonant Converter

Switching Network: This network is particular in maintaining the frequency with 0.5 duty ratio individually to each switch. Zero voltage switching is made possible with the inclusion of dead times in between the switches. It converts input signal as square wave with previously mentioned duty ratio.

Resonating Tank and Transformer: Inductor $L_r$, capacitor $C_r$, constructs a resonant converter. The switching network combines with resonating tank to construct inverter. The resultant voltage of the resonant converter is sinusoidal and given as an input to transformer. Electric isolation and gain are determined from turns ratio of transformer.

Rectifier and Filter: The resultant outcome of the transformer is rectified by full wave rectifier. The diodes D1, D2 along with center tapped transformer constructs full wave rectifier[3].

2. LLC Resonant Converter

The proposed structure provides additional merits as high efficiency, wide output range, low EMI and low switching losses. ZVS operation of the switches can be accomplished by proper design of the resonant network. Since the design of the converter is related to various parameters - resonating tank, transformers turns ratio, magnetizing inductance, duty ratio. Based on this design procedure, the proposed converter is simulated and its characteristics are observed. The circuit diagram of LLC resonant converter can be presented as below.
Using LLC we can achieve buck and boost operations. Above series resonant frequency the gain of the converter is always below unity and the converter works as series resonant converter [5],[6]. Operating the converter at series resonant frequency $f_r$ is always preferred as it results in high efficiency and the circulating energy is very little. Gain characteristics of LLC resonant converter for different load condition are shown in the fig.3. $L_n$ is the ratio of magnetizing inductance $L_m$, to leakage inductance $L_r$, of the transformer. It can be seen that ZVS is possible only at that negative (inductive region). In the positive slope region ZCS is possible (capacitive region), but operating frequency of the converter is less. Under light–load condition the characteristics of parallel resonant converter dominate so regulation of output voltage is possible.

A LLC resonant converter is a transformer coupled dc/dc converter whose output voltage is controlled by the switching frequency [4]. The major benefit with a LLC resonant converter is that ZVS operation can be performed at light load also In backward operation mode ZVS is only possible at heavy load – like a traditional phase shifter and also it has the advantages of high efficiency and also its compact size. Though it has several drawbacks like complicated synchronous rectification And Large switching frequency change when it works as bi-directional converter. A new interleaved LLC-SRC without a complicated controller is proposed in [7]. LLC converter have a load independent peak gain, which makes ZVS possible with highest efficiency, which is not achieved in any of the resonant converter, and this projects LLC as peculiar among resonant converters. The DC characteristic of LLC resonant converter could be divided into ZVS region and ZCS region.

There exists two different frequencies as

$$f_{r1} = \frac{1}{2\pi L_r/C_r} \quad \ldots \ldots (1)$$

$$f_{r2} = \frac{1}{2\pi L_{eq}/C_r} \quad \ldots \ldots (2)$$

$$L_{eq} = L_m + L_r \quad \ldots \ldots (3)$$
3. Bi-directional LLC Resonant Converter

In new electric vehicles, two different voltage levels will be connected to ensure bidirectional power flow with high efficiency. In hybrid electric and pure electric vehicles, it is needed to connect the high voltage battery with the 14V supply.
Figure 5 bi-directional LLC Resonant Converter

The forward operation is from A to B as conventional LLC converters. The backward operation is from B to A where full bridge B is active but A is not. The full bridges produce a rectangular voltage waveform with variable frequency.

4. DESIGN PROCEDURE

DESIGN SPECIFICATIONS

Input Voltage 200V
Output Voltage 12-14V
Quality factor 0.42
Resonant frequency 108Khz
m=4.75

\[ n = \frac{V_{in}}{V_o} \]

\[ R_{ac} = \frac{8}{\pi^2} R_o \]

\[ C_r = \frac{1}{2\pi f_o R_{ac}} \]

\[ L_r = \frac{1}{2\pi f_o (2\pi f_o) C_r} \]

\[ L_m = m L_r \]

and the calculated values are given in table form as below
Table 1. Designed Values of circuit parameters

| Parameter               | Value   |
|-------------------------|---------|
| Input Voltage           | 200V    |
| Resonance Frequency     | 108kHz  |
| Transformer turns ratio | 16:1    |
| Resonant Capacitor \(C_r\) | 22\mu F|
| Resonant Inductor \(L_r\) | 99\mu H|
| Magnetizing inductance \(L_m\) | 475\mu H|
| Output Voltage          | 12-14V  |

The above designed values are incorporated in the simulation circuits and the output values are observed correspondingly to both uni- directional and bi-directional LLC resonant converter circuit.

5. SIMULATION AND RESULTS

The simulation Results of uni-directional LLC resonant converter with R load is shown below.

Figure 6 results of uni-directional LLC resonant converter

The general plot for the resonant converter is illustrated with the dc input and the output is happened to be incremental in the beginning and it ends to be a constant value.

The simulation result with R-load can be presented as below.
The plots illustrate that for a given R load, the output current wave form follows the output voltage and these are maintained constant which implies that the LLC resonant converter is best suitable for constant current applications.

The simulation result with L-load can be presented as below.

The plot illustrates that for the given inductive load, the output voltage is still maintained constant but according to the natural property of inductor, the current is not instantaneously affected and maintained.

Simulation results of LLC resonant converter for the given capacitive load can be displayed below.

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Simulation results of LLC resonant converter for the given capacitive load can be displayed below.
The plot illustrates that under capacitive load as it will not allow voltage to change voltage instantaneously, but the current is affected but voltage is maintained the same.

Simulation results of forward LLC resonant converter is displayed below.

![Simulation circuit of forward bi-directional LLC resonant converter.](image1)

**Figure 10** Simulation circuit of forward bi-directional LLC resonant converter.

Simulation results of backward LLC resonant converter is displayed below.

![Simulation circuit of backward bi-directional LLC resonant converter.](image2)

**Figure 11** Simulation circuit of backward bi-directional LLC resonant converter.

Advantages of LLC Resonant converter

1) Step-down and step-up characteristic.
2) Low-voltage high-current application.
3) Suitable for multiple outputs.

Disadvantages: These are uni-directional.

To avoid this disadvantage a bi-directional LLC resonant converter is designed and presented in this paper. This enables battery to function appropriately. Besides this, it is important for an electrical vehicle to be charged accordingly, there comes the necessity of a charging station.

Necessity of Charging Station Infrastructure
The responsibility of Electric vehicle charging station is to deploy the EVs. The Charging stations for electric vehicles require new infrastructure - IT security, encrypted information exchanging, and protection. The basic concern for a charging station is a multipurpose charger that serves different purposes - chargers for house, campus and commercial places. This obviously leads to a diversified tariff. The charging point speed should also be multiple types - fast, slow and normal. Fast chargers at public charging points save time. Residential charging will be mostly at night times. These will lead to good grid stability. So, the optimum design process must be made which suits to the Indian grid. But, contemporary distribution system does not meet the targets for huge EVs. Independent stations introduction may remarkably reduce time of charging. to been encouraged to reduce the time to find a public charging station.[8]

6. Conclusion
A DC/DC converter comprised of a resonant converter has been proposed for battery chargers. The proposed converter has the mixed operational characteristics of the two converters and all of them use soft switching, which reduces switching losses. ZVS operation of the switches can be accomplished by proper design of the resonance. In addition, the proposed structure provides merits such as no EMI, high efficiency, low switching losses, wide output range. Some analyses to explain the operation of the charger and select its design parameters has been performed.

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