Half Bridge LLC DC-DC Converter for EV Battery Charger

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Abstract:- The battery charger is essential to the development of PHEVs (plug-in hybrid electric vehicles) and electric automobiles (EVs). This thesis focuses on the DC-DC converter utilized in high-voltage battery chargers. The background of EV battery chargers is discussed, as well as the topologies of isolated DC- DC converters that could be used in battery charging due to the high voltage and high power of the EV battery charger, LLC and half-bridge converters are frequently utilized in high power applications. They are often believed to have high power density, exceptional dependability, and high efficiency; yet, their most remarkable features are limited to specific working ranges. To fully exploit the benefits of Half-bridge and LLC converters while avoiding their limitations.

Keywords: Battery charger, Electric vehicle, Half bridge converter, LLC resonant Converter.

1. Introduction

Electric vehicles have several advantages over gas-powered vehicles, including higher energy conversion efficiency, motor- regenerative braking, reduced local exhaust emissions, and reduced vibration and noise levels. In the development of electric vehicle (EVs), the battery is essential. Compared with the present conventional cars on the road, electric cars use a lot more fossil fuels[1-2]. This energy can be produced externally to the car and kept in a battery, or it can be generated onboard using fuel cells (FCs). The progress of EVs stagnated due to their impracticality and inefficiency resulting from their heavy weight and extended recharging times. Additionally, starting from 1910, they became more expensive

2. Charger Classifications

Many various charging schemes have been presented since the first EVs were introduced. Due to the wide array of charger configurations available, it is essential to categorize them according to common design and application characteristics. Table 1 outlines five distinct approaches for classifying chargers[3-4].

Chargers are categorized according to their circuit topologies. A separate circuit is used just to charge the battery. In comparison, while the vehicle is not in use and is hooked into the grid for charging, the traction inverter drive may also function as the charger. These are frequently referred to as integral/integrated chargers [5]. A secondary categorization pertains to the placement of the charger. Incorporating the charger within the vehicle significantly enhances charging accessibility. Conversely, off-board chargers have the capability to utilize higher amperage circuits, allowing for faster charging times for vehicles [6].

The charger functions as an external component rather than being integrated within the vehicle itself.

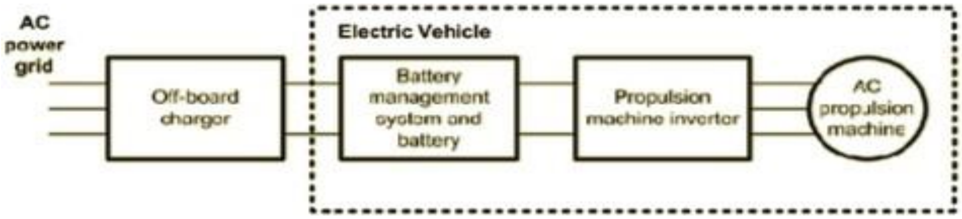

Fig. 1. Off-board charger

TABLE I Classification of rectifier parameters

Classification type	Options
Topology	Dedicated, Integrated
Location	On-board, Off-board
Connection type	Conductive, Inductive, Mechanical
Electrical Waveform	AC, DC
Direction of power flow	Unidirectional, Bidirectional
Power level	Level 1, Level 2, Level 3

As a result, charging an EV's battery without an adequate charger that produces the required high DC voltage on-site is difficult.

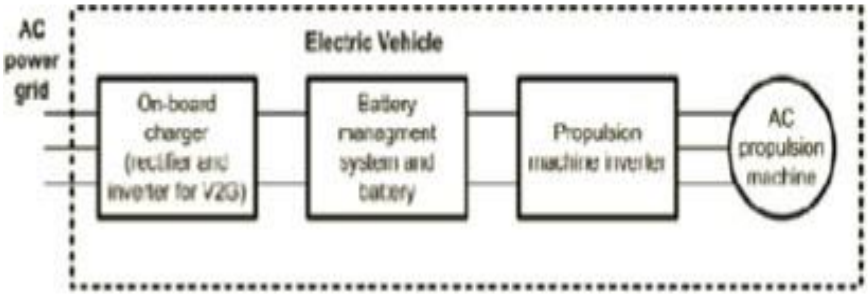

Fig. 2. On-board charger

When it comes to the onboard charger shown in Fig.2, the charger is part of the electric vehicle. A single-phase or three-phase source may be used to charge the EV practically anywhere [7-10]. The main disadvantage of this architecture is that it necessitates the use of a separate DC/AC converter. The vehicle-to-grid (V2G) capability is enabled by one inverter, while the AC propulsion machine is driven by the other.

The connecting method is the third. Conductive charging involves direct metal-to-metal contact, while inductive charging employs a mountable high-frequency transformer to connect the AC grid to the vehicle. Mechanical charging entails swapping a depleted battery pack with a fully charged one at battery switch stations[11].

Fourth, the electrical waveform at the vehicle's grid connection port may be either direct current (DC) or alternating current (AC).

TABLE II Battery charging levels

Level	AC Voltage (V)	Max. Current (A)	Max. Power (kW)
Level 1	120	16	1.92
Level 2	240	80	19.2
Level 3	300-600	400	240

Currently, most electric cars (EVs) utilize an AC connection. However, future changes in the availability and prevalence of DC sources could lead to a shift in the connection type.

Fifth, by just charging the battery, the charger may transmit electricity in a unidirectional manner. Bidirectional power transmission is used in more sophisticated designs. Unidirectional chargers are used in all of the chargers on the market

3. Conventional isolated DC-DC converter

There are two topologies known on-isolated and isolated converters which is shown in table 2. These topologies are classified based on galvanic isolation. Depending on how the B-H curve is used, isolated power converter topologies can also be divided into single- ended and double-ended categories[1-2]. When in operation, a single-ended topology swings flux in only one quadrant of the B-H curve, while a double-ended topology swings flux in two quadrants of the B-H curve. A double-ended topology requires a smaller core than a single-ended topology for a given set of requirements and does not require an additional reset winding [12-13]. The first and most crucial choice to be made in an independent dc-dc power converter is its topology. Topology selection used to be dependent on the intended output power level. , , , half- bridge, full-bridge, flyback and push-pull were traditionally the order of lower power to greater power for the fundamental topologies.

The flyback is maybe the most popular isolated topology. It's mostly used in low-cost, low-power applications. In addition to the transformer, the flyback architecture eliminates the need for an additional output inductor and just requires one active switch. As a result, the topology is simple to utilize and affordable in cost. Because it is a single-ended topology, the flyback topology has a low transformer usage rate, and the high input and output ripple currents need the installation of capacitors at both the input and output. During steady- state operation, the active clamp forward converter operates in two quadrants, although peak flux can reach significant levels during initiation and transitional situations. In both the forward and active clamp forward topologies, the maximum duty cycle is regulated in order to reset the transformer [14].

The next two topologies, half-bridge, and full-bridge, are actual double-ended topologies in which power is transferred in two quadrants of the BH curve without the need for extra transformer reset arrangements [15].

These topologies are the perfect choice for applications that demand the highest energy density, as the transformer core can be fully utilized. Because of the higher duty cycle range accessible with double-ended topologies, the transformer may be further improved. Double-ended topologies may function at approximately 50.

3.1 Basic Isolated PWM Converters

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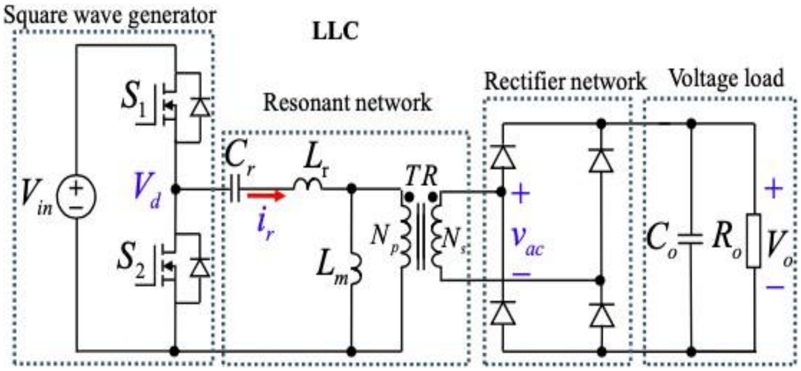


Fig. 3. Half Bridge LLC Resonant Converter

The circuit architecture of a Half bridge LLC resonant converter is shown in Fig.2. The voltage gain of an LLC tank converter may be regulated in buck and boost mode using adjustable frequency control. The LLC tank converter can operate in boost mode during the holdup interval. As a result, substantial voltage gain is achieved, allowing for the reduction of bulky capacitors. Meanwhile, the converter works extremely near to the resonant Frequency in nominal conditions, the most effective operating point for obtaining high efficiency is the point at which the highest level of efficiency is obtained. Moreover, at the moment of serial resonance, the gain voltage of different Q values come together. One may adjust the characteristics of the LLC resonant tank to achieve high efficiency across a broad range of loads. This converter is a preferred topology for a wide input voltage range. The switching loss of the converter is minimal. In an LLC tank converter, the magnetizing inductor current is employed to create Zero Voltage Switching, and it may be obtained with a minimal turnoff current from zero to full load circumstances. As a result, it is possible to achieve zero turn-on loss and a tiny turnoff loss. Furthermore, when the di/dt of an LLC resonant converter is low, the secondary side diode shuts off. As a result, on the secondary side, reverse recovery loss may be minimal. The LLC tank converter efficiency is not subject to dynamic (switching) loss due to reduced switching losses on the elementary and secondary levels, as well as the circuit can reach wide switching frequency operation.

Let's assume that the ratio of Np to Ns is equal to 1[7]. By using the same methodology previously mentioned, the corresponding circuit for LLC in Figure 3 can be acquired, and the voltage gain, denoted as M, may be determined.

By using the equivalent load resistance, the LLC AC equivalent circuit is obtained, as illustrated in Fig.4

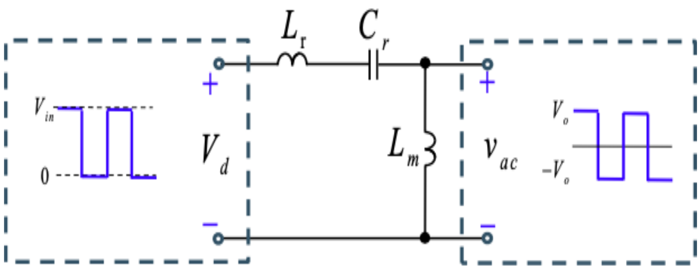
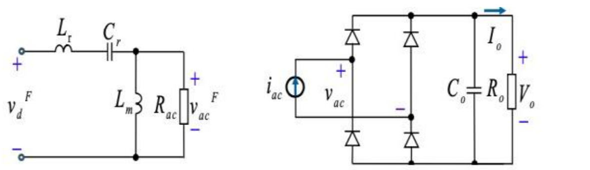


Fig. 4. Equivalent Circuit for Half Bridge LLC Resonant Converter



(a) Primary side AC equivalent circuit (b) Secondary side AC equivalent circuit

Fig. 5. Equivalent Circuit

By using the same approach as used in SRC, the formula for calculating the equivalent load resistance (R) is

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$$M = \frac{\omega^2 (l_p - l_\tau)}{\omega^2 L_p - 1 + j\omega\left(\omega^2 - \frac{1}{L_r C_r}\right)(L_p - L_r)\frac{\sqrt{L_r C_r}}{R_{ac}}} \quad (1)$$

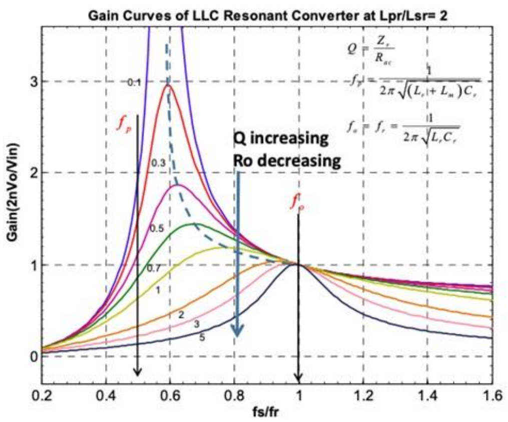

Fig. 6. Gain Curves of Half Bridge LLC

This converter has two resonance frequencies. The resonant components Cr and Lr determine a certain value or character istic. The variables Lm, Cr, and the load condition determine the remaining factors. The resonance frequency will change to a higher frequency as the load becomes heavier. The two resonant frequencies are:

$$f = \frac{1}{2\pi\sqrt{L_r C_r}} \quad (2)$$

$$f = \frac{1}{2\pi\sqrt{(L_r + L_m) C_r}} \quad (3)$$

As seen in Fig.6, converter gain might be more than or less than one. When the switching frequency, fs, is close to the resonant frequency, fo, the gain characteristics of the LLC resonant converter are practically load independent. LLC resonant converters provide a notable advantage over series resonant converters. In order to minimize fluctuations in switching frequency [9].

LLC converter characteristic can be separated into two parts as shown in Fig 6: Zero Voltage Switching and Zero Current Switching (a). This feature enables it to be placed precisely at the resonant frequency of fo when subjected to a high input. This frequency corresponds to the resonant frequency of the series resonant tank formed by Cr and Lr. With a reduced switching frequency, a higher gain may be gained as the input voltage declines. The converter might function within the ZVS area for load and line variation if the resonant tank was chosen correctly [14]. This DC characteristic has a few intriguing features. The SRC on the right side of fo has the same characteristics as this converter. The images of SRC and PRC are competing for dominance on the left side of fo. Equation 1 represents the frequency when there is no load. Equation 2 represents the frequency under load circumstances. The LLC converters, however, are designed in a manner that. The frequency is governed by the gain of the transformer. The switching frequency regulates the transfer of electricity from the input to the load side.

There are three modes of operation for the LLC Converter, depending on the frequency range. They fall into 3 categories.

(i) Below resonance, (ii) at resonance, and (iii) above resonance.

Resonant Frequency = Switching Frequency To enhance the circuit efficiency of typical tank converters, Operating the converter at the resonance frequency is preferable.. However, these circuits exhibit zero current switching when they run below the resonance frequency. Enough design margins must be considered at the design stage to assure ZVS operation. As a result, the circuit would be unable to operate at its best efficiency. ZVS switching can be achieved for LLC resonant converters with switching frequencies that are either above or below than the resonance frequency [16]. As a result, there is no requirement for a design margin, and the circuit may function at its resonant frequency whereas still achieving optimal efficiency

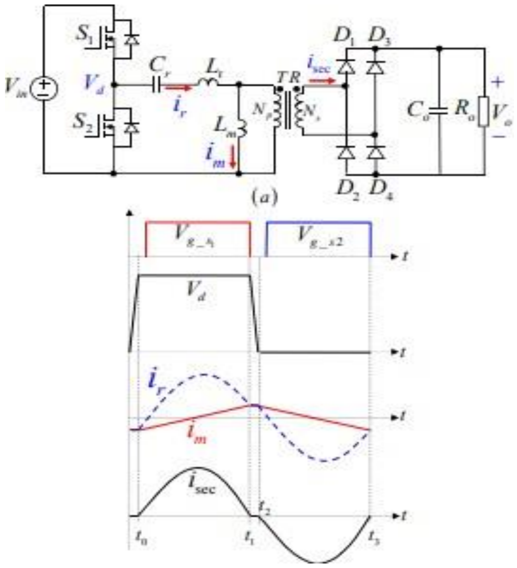

Fig. 7. Operating principle at resonant Frequency

3.2 Lower Resonant switching Frequency

When the switching frequency of an LLC converter is below the frequency of resonance, the circuit operates with a magnetizing inductor, which changes the voltage gain characteristics of the converter. Figure 4 shows the corresponding circuit and crucial waveform, whereas Figure 4.1 shows the topological modes.

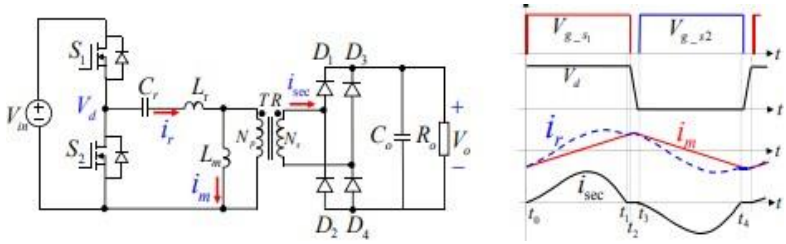

Fig.8. Gain curve of half bridge LLC

Switching S1 and diodes D1 and D4 are conducting between t0 and t1, and the converter delivers energy to the load [7]. The tank current resonates back with the exact amplitude as the magnetizing current at time t2. Subsequently, the magnetizing inductor contributes to the resonance. The secondary diodes are deactivated due to the resonance current being equal to the magnetizing inductor current. The magnetizing inductor transfers its stored energy to the resonance capacitor. When S1 shuts off between t2 and t3. As a result, the converter can raise the gain in this mode of operation. Before t3, the switches' junction capacitors Cs1, Cs2 are fully charged and drained. The resonant tank is then sent to S2's body diode. As a result, S2 is able to turn on ZVS. The circuit enters the other half cycle between t3 and t4.

3.3 Lower Resonant switching Frequency

LLC resonant converter is considered an SRC circuit when its switching frequency exceeds the resonant frequency. The analogous circuit and Switch S1 is conducting between t0 and t1, and the circuit is delivering energy to the load via diodes D1 and D4. S1 is turned off at time t1. The tank current is higher than the magnetizing current because of the switching frequency is higher than the resonant frequency .Both S1 and S2 are off between t1 and t2 , and the tank current (I) is alternating between charging and discharging the junction capacitors of the main side switches. At time t2, the voltage on switch S2's junction capacitor is discharged to zero. When the diode of switch S2 is turned on between t2 and t3, the resonant tank current rapidly falls. The resonant tank current equals the magnetizing current at time t3, and the diodes D1 and D4 turn off. S2 can be turned on to ZVS at time intervals t3 and t4 and diodes D2 and D3 switches on, and the circuit initiates the transmission of energy to the load [4].

Due to the significant turn off current, ZVS switching on primary side switches may be ensured in this operation mode. The high turnoff current, on the other hand, causes excessive turnoff loss on the primary diode switches off, resulting in a more reverse recovery on the diodes. Furthermore , the fast rate of change of current (di/dt) in the diodes causes additional voltage stress during switch off, making the circuit less dependable. From the above research, it can be observed that the LLC resonance converter can obtain a higher gain below resonance, a lower gain above resonance or a gain of 1 at resonance. The converter voltage gain is equal to one when the circuit works at resonant Frequency, and the circuit performs ideally [13].

As the operation frequency falls below the resonance frequency, the circulating current increases. Due to the confinement of the frequency below the resonant frequency, even in the absence of a load, the operation below resonance has a limited frequency range in relation to load fluctuations. Operating above the resonance frequency may decrease the circulating current, but it may result in severe reverse recovery loss due to the non-gentle commutation of the rectifier diodes. The conduction loss is lower in the above resonance operation than in the below resonance operation. However, operating at a frequency higher than the resonance frequency may result in an excessive increase in Frequency when the load is light.

4. Design Procedure

The following steps explain the design procedure for the proposed converter.

STEP 1: Complete the system specification

The system’s efficiency must be known before the input power can be calculated. If no efficiency data is available, assume a low voltage efficiency of 0. 880.092 and a high voltage efficiency of 0. 920.096. The power source is

$$P_{in} = \frac{P_o}{E_{ff}} \tag{4}$$

STEP 2: Determining the resonant converter’s maximum and minimum voltages. The gain value is specified to be between 25 and 35. The minimum resonant voltage is now equal to,

$$M_{min} = \frac{k}{k+1} M_{max} = \frac{V_{in}(\max)}{V_{in}(\min)} \tag{5}$$

STEP 3: Determine the proportion of transformer turns. The turns ratio of the full-wave rectifier is calculated by consider- ing its connection to the secondary side of the transformer:

$$n = \frac{v_{in}}{(V_o+V_f)^2} \tag{6}$$

STEP 4: Load Resistance Calculation: The load resistance is computed by,

$$R_{ac} = \frac{8n^2 v_0^2 E_{ff}}{n^2 V_0} \tag{7}$$

Where, n is the turns ratio of the transformer

V_o is the output voltage, Eff is the efficiency

STEP 5: Calculation of resonant parameters: The selection of resonant parameters is critical for achieving soft switching in the proposed converter. Implemented Hardware Prototype

$$C_r = \frac{1}{2\pi Q f_O R_{ac}} \tag{8}$$

$$L_r = \frac{1}{4\pi^2 f_O^2 C_r} \tag{9}$$

$$L_m = kL_r \tag{10}$$

5. Hardware Prototype

The prototype has gone through various stages of testing, and we have obtained the different outputs at three different resonance frequencies.

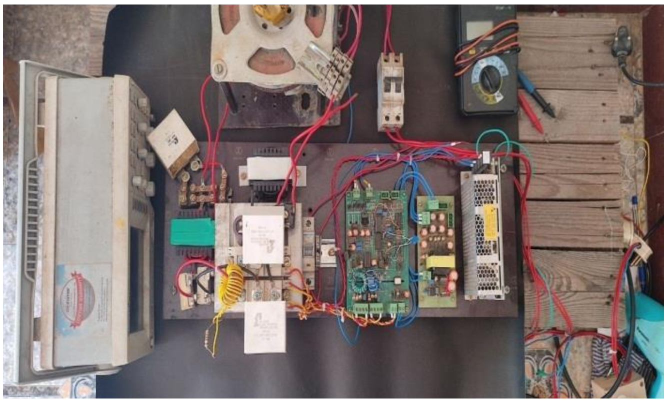

Fig. 9. Prototype

Table.3. Output at different resonance

Frequency	44kHz (Above Resonance)	38kHz (Below Resonance)	41kHz (At Resonance)
Input Voltage	31.5 V	31.5 V	31.5 V
Rectified Output	40.2 V	40.2 V	40.2 V
Inverter Input	4.1 V	4.2 V	4.1 V
Tank Current	2.4 A	2.4 A	2.4 A
Tank Circuit (Primary End)	2 V	2.1 V	2 V
Tank Circuit (Secondary End)	26.7 V	10.3 V	150 V
Inverter Output	3.56 V	1.4 V	22 V
Output	5.3 V	1.9 V	30 V

5.1 Duty cycle at 10 percent

In this work, using digital oscilloscope the chopper voltage at different duty cycles has been tested and the tank voltage and current is been recorded at resonant frequency to ensure the efficiency of the system.

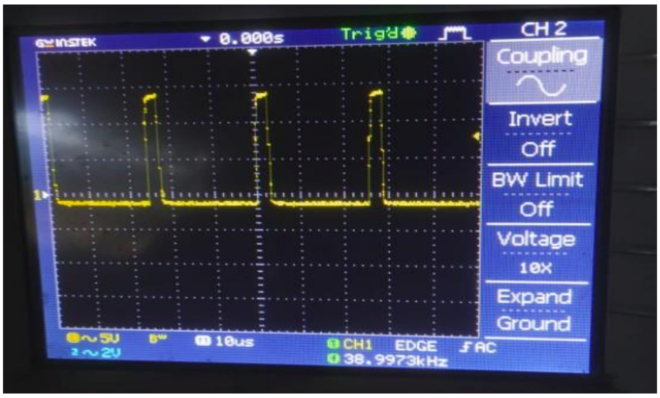

Fig. 10. Chopper circuit voltage

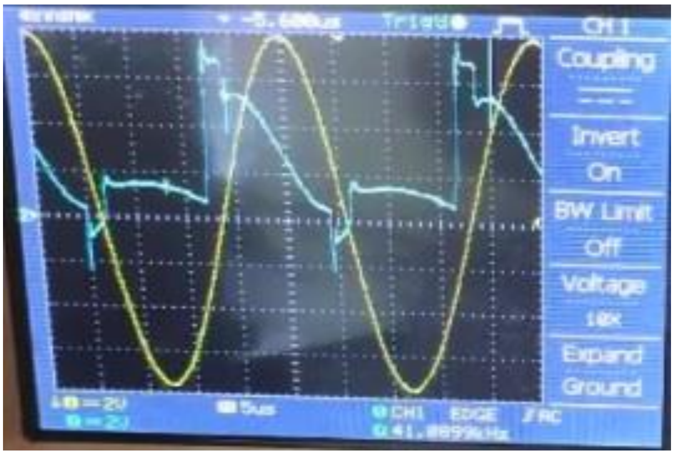

Fig.11 Resonant voltage &current

6. Conclusion

In this work, an LLC resonant converter is proposed, and a hardware prototype employing the indicated components is implemented, with the results described. Because of the filter capacitor employed across the load, the waveforms indicate that a constant output voltage is achieved with no distortion. In a closed loop system, the steady state error is decreased. As a result of its consistent output voltage and low switching losses, resonant converters can be employed in battery applications.

Conflicts of interest

There is no conflicts of interest to declare.

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