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Improving Battery Charging Efficiency with Soft Switching Technique

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Abstract: Battery is an essential component of energy systems, especially in renewable applications, where power imbalance between supply side and load side exists. Chargers are used to store redundant energy when generated power (from renewable sources) is larger than the load consumption, with an expectation for high conversion efficiency. This paper presents an implementation of the DC/DC converter for battery charging applications, aiming at improving energy conversion efficiency. This converter is controlled with soft switching methods with respect to variations in input voltages and load conditions. It has zero voltage turn on for its primary switches thus reducing losses and increasing energy efficiency. The results obtained using this design along with synchronous rectifier can lead to an efficiency in the range of 95% or higher, which is difficult to achieve using hard switching converters. Soft switching techniques also help increase the operating frequency of the converter, which in turn reduces the volume/size of passive components, leading to lighter and smaller chargers. This paper proposes a new approach where frequency control is combined with synchronous rectification in a DC/DC resonant converter. The resulting system consists of a high efficiency DC/DC converter and has been simulated in LTSpice and designed to be controlled by an ARM Cortex-M4 microcontroller. The performance of the proposed system has been experimentally verified on a 120 W prototype of battery charger, supplied by two PV panels connected in series, confirming the feasibility of the proposed converter design and control method.

Keywords: *Battery Charging, Efficiency, Soft Switching, Zero Voltage Switching, Frequency Control, Synchronous Rectification*

Introduction:

Nowadays, power electronic systems can be found in almost every electronic product and power electronics is continuously expanding its applications through newly developing and innovative industries, such as electrical vehicles, lighting, renewable energy and wireless power transfer [1].

Among all power electronic applications, the DC/DC converter is one group of electronic circuits in which a DC input voltage is converted into a DC output voltage having a larger or smaller magnitude, possibly with opposite polarity or with isolation between input and ouput ground references [2].

They are normally employed in distributed power system for computers and servers, and in telecommunication systems, adapters for laptops and chargers for consumer electronics.

In the DC/DC converter, higher switching frequency is always the persistent pursuit because of the smaller volume of passive components, for example inductors, capacitors, and transformers. Higher power density, on account of smaller components, means lower cost of the converter and allows more units to be accommodated in the infrastructure where the space is limited. However, the switching loss of semiconductor devices is directly related to the switching frequency and the permissible temperature rise of switching components will limit the operation frequency. In an effort to reduce the switching loss, soft-switching technology was introduced and a number of main topologies have been proposed to approach higher operation frequency, such as phase–shift converters and resonant converters. Among these converters, resonant converter is very popular [3,4]. Among the resonant converters, the series resonant converter (SRC) has good efficiency but poor voltage regulation at light load [5,6,7]. The parallel resonant converter (PRC) does not have light load regulation issue but it has high circulating energy [8]. While the series parallel resonant converter (SPRC) overcomes the disadvantage of both SRC and PRC; it is not sensitive to load changes [9]. The inductor-inductor-capacitor (LLC) resonant converter combines the advantages of SRC, PRC and SPRC but it is still sensitive to load changes [10]. The LLC resonant topology allows for zero voltage switching (ZVS) of the main switches, therefore dramatically lowering switching losses and boosting efficiency. Moreover, this converter can operate at a wide output voltage range with a comparatively small variation of switching frequency.

The LLC resonant converter has been successfully employed in many power applications. Exact analysis of LLC resonant converters [10] ensures accuracy but cannot be easily used to get a handy design procedure due to the complexity of the model. The first harmonic approximation (FHA) analysis [4],[12-15] gives quite accurate results for operating points at and above the resonance frequency of the resonant tank. LLC resonant topology is widely utilized in the isolated dc/dc converter [16]. Another challenge is the high current at the low-voltage side, which results in the utilization of the synchronous rectification control (SRC) to avoid the conduction loss [17-19]. An 1 MHz 120 W LLC resonant converter based on a DSP-driven silicon-on-insulator power MOS module with maximum efficiency of 95% has been reported in [20]. However, in most of these applications, converters are designed for operating at a constant output and input voltage or at a narrow input voltage range [21].

Among all DC/DC converter applications, battery charging is a growing interest because of increasing portable devices, i.e. laptops, mobile phones, electric bicycles, … and stand-alone photovoltaic systems. The cost of photovoltaic systems is still high, therefore a high efficiency battery charger is desirable for stand-alone photovoltaic systems.

In this paper, an LLC resonant converter is proposed for PV-powered battery charger, with its block diagram shown in Figure 1. The simulated average charging efficiency of the battery charger is 98%.

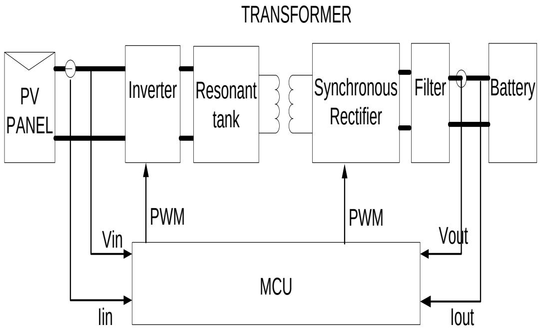


Figure 1: The proposed PV-based battery charger using LLC resonant converter

Analysis and Design Parameters of DC/DC LLC Resonant Converters:

The LLC topology can be implemented by a half-bridge or a full bridge. In this paper, the half-bridge configuration is preferable in battery charging due to low power (around 120 W). A typical schematic of a half-bridge LLC resonant DC/DC converter [1,3,4,10-21] is shown in Figure 2, where synchronous rectifier is used.

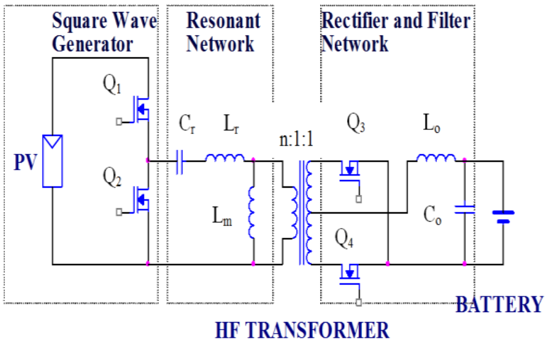


Figure 2: Schematic of half-bridge LLC resonant converter

In the diagram, Lr is the series resonant inductor, Cr is the resonant capacitor and Lm represents the magnetizing inductance. In general, the LLC resonant converter consists of three stages: a square wave generator, a resonant tank and rectifier circuits in secondary. The square wave generator produces a square wave voltage at phase node between switches Q1 and Q2 with 50% duty cycle [5]. Then, the resonant tank filters the higher harmonic currents, so that only fundamental current is allowed to go through the resonant tank and the current lags the voltage applied to the resonant tank, which allows the switches to be turned on at zero voltage, hence the name zero voltage switching (ZVS). Therefore, turn on loss is reduced. Finally, DC voltage is produced by the center-tapped synchronous rectifier.

A simplified method applicable in general to any resonant circuit topology can now be exploited. It is based on the assumption that input to output power transfer is due essentially to the fundamental fourier series components of current and voltage. This approach is called “First Harmonic Approximation” technique (FHA) [2]. The equivalent circuit of the LLC topology is shown in Figure 3 and the analysis is performed using FHA technique [3,4,25].

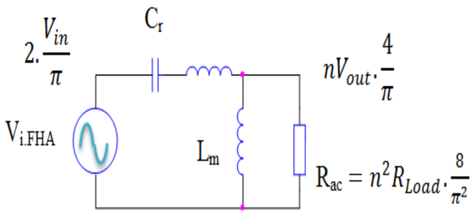


Figure 3: The FHA equivalent circuit

Because the battery behaves like a resister in very small time intervals (in the order of microseconds), we may replace it with a resistive load to simplify calculations. Using the equivalent circuit of Figure 3, the voltage gain is obtained as [Ax-Ay]:

$$M(f_n, L_n, Q) = \frac{1}{\sqrt{[1+\frac{1}{L_n}(1-\frac{1}{f_n^2})]^2 + Q^2(f_n - \frac{1}{f_n})^2}} \qquad (1)$$

Definitions of main parameters, namely quality factor Q, inductance ratio L_n, and normalized frequency f_n are given below, in terms of characteristic impedance Z_0, equivalent load resistance R_{ac} and switching frequency f_s.

$$Q = \frac{Z_0}{R_{ac}} \qquad (2)$$

$$L_n = \frac{L_m}{L_r} \qquad (3)$$

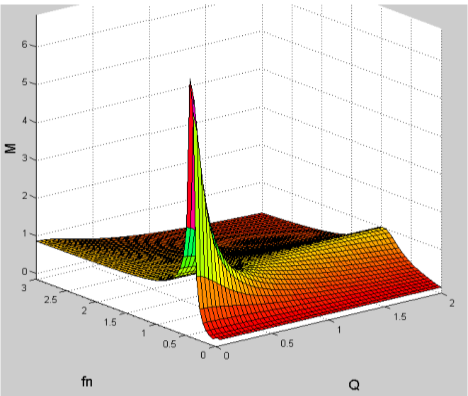
$$f_n = \frac{f_s}{f_r} \qquad (4)$$

For LLC converters, there are two resonant frequencies. One is defined by the resonant components L_r and C_r, and the other is define by L_m, C_r, and load condition. The two resonant frequencies are:

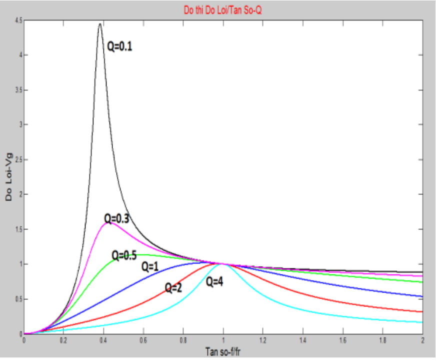
$$f_{r1} = \frac{1}{2\pi\sqrt{(L_r + L_m)C_r}} \qquad (5)$$

$$f_{r2} = \frac{1}{2\pi\sqrt{L_r C_r}} \qquad (6)$$

In order to choose operating region, or to determine which frequency range can be used, the variation of voltage gain M with respect to different quality factors Q and normalized frequencies f_n will be investigated. Figure 4a shows the relation in the form of a 3-D surface, in Figure 4b the voltage gain is plotted with values of $L_n = 5$ and Q varies from 0.1 to 4. For convenience in designing, L_n is recommended to be from 3 to 10 [22-24]. Lower values of L_n can offer higher boost gains, in addition to a wider range of operating frequency, meaning more flexible control and regulation [22], which is valuable in applications with wide input voltage range.



(a)



(b)

Figure 4: DC characteristics of LLC resonant converter

As indicated by Figure 4, when the load is heavier, the quality factor Q will also decrease, such that the switching frequency has to be further increased in order to achieve the same DC gain. For 28-V Vout 12-V Vin operation, the switching frequency coud be set to the resonant frequency of f_{r1} at light loads and increase to f_{r2} at heavy loads. Fortunately, this operating point is in the inductive region of the voltage gain characteristic, where resonant tank current lags squarewave input voltage, which is a necessary for ZVS operation. From the required characteristic of the battery application, maximum gain M_{max} and minimum gain M_{min} can now be determined. Then minimum operating frequency f_{nmin}, the maximum operating frequency f_{nmax} and the maximum quality factor Q_{max} can then be calculated, according to (7) - (9) [23-25].

$$f_{n\min} = \sqrt{\frac{1}{1 + L_n\left(1 - \frac{1}{M_{\max}^2}\right)}} \qquad (7)$$

$$f_{n\max} = \sqrt{\frac{1}{1 + L_n\left(1 - \frac{1}{M_{\min}}\right)}} \qquad (8)$$

$$Q_{\max} = \frac{1}{L_n}\sqrt{\frac{1 + L_n\left(1 - \frac{1}{M_{\max}^2}\right)}{M_{\max}^2 - 1}} \qquad (9)$$

From equations (2), (3), (4), (7), (8), (9) resonant tank parameters can be calculated as:

$$L_r = \frac{Q_{\max}.R_{ac}}{2\pi f_r} \qquad (10)$$

$$C_r = \frac{1}{(2\pi f_r)^2.L_r} \qquad (11)$$

$$L_m = L_n.L_r \qquad (12)$$

As an example, Table 1 shows design parameters for the battery charger under consideration.

Table 1. Design parameters

Parameters	**Value**
Input voltage V_{in}	18-36 VDC
Output voltage V_{out}	11-13.8V DC
Maximum output power P_{out}	120 W
Switching frequency f_s	80-120 kHz
Resonant frequence f_r	150 kHz
Series resonant inductor L_r	1 μH
Series resonant capcitor C_r	1.15 μF
Magnetizing inductance L_m	5.8 μH
Transformer turn's ratio n	2:1:1

Proposed Control Schemes:

Control system of DC/DC converter must ensure the desired operation condition and increase its stability [8]. In battery charging applications, control circuit can provide over-current protection, under-voltage lockout and maintain output voltage during input voltage drop out. Control algorithms may be done in analog or digital fashions. Analog control circuits are well known and easy to use, while digital controllers offers more sophisticated solutions [26]. Digital control systems are widely used in switching power converters [27].

In this paper, a digital control system with pulse frequency modulation (PFM) is used to drive the switches (MOSFETs) in the LLC converter in order to control battery voltage and current and to maintain ZVS for primary switches and secondary switches in the sychronous rectifier. Current generated by PV panels must be stabilized through a control loop to extract maximum power from the PV whilst solar insolation and battery state of charge are continuously varying.

In this application, the traditional four-stage charging algorithm will not be used, and battery voltage and current are used to determine the battery state-of-charge and to set charging current according to maximum available power from PV panels.

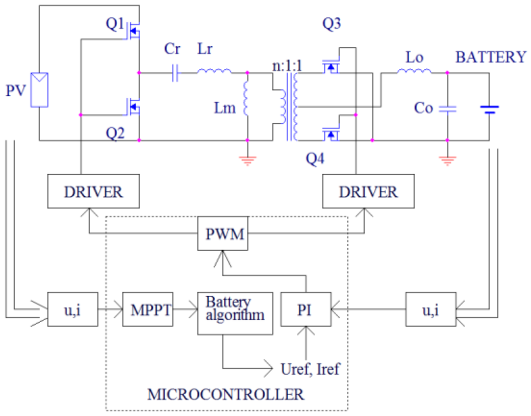


Figure 5: Block diagram of the control system

Figure 5 shows the block diagram of the digital control system for the proposed charger. Digital controller will set charging current command according to the measured data. It collects battery voltage and current and determine battery state of charge, then calculate charging current from the maximum PV power. Gating signals for the converter are then generated according to current charging command, current feedback and desired switching frequency. Ratings of the PV panel is selected so that maximum charging current can be tolerated by the battery, and power transfer is stopped if the battery is full, disregarding to the available power from the PV panel.

Simulation of the Proposed Control Scheme:

For design verification and digital control system proposal, simulation in LTSpice has been made. Figure 6 shows the simulation model of the LLC battery charger according to the design values provided in Table 1. Figures 7 and 8 show simulation waveforms of the M2, M4 driver voltage (V_{gs2}, V_{gs4}), voltage across M2, M4 (V_{ds2}, V_{ds4}), and resonant tank current ILr at Vin = 33 V.

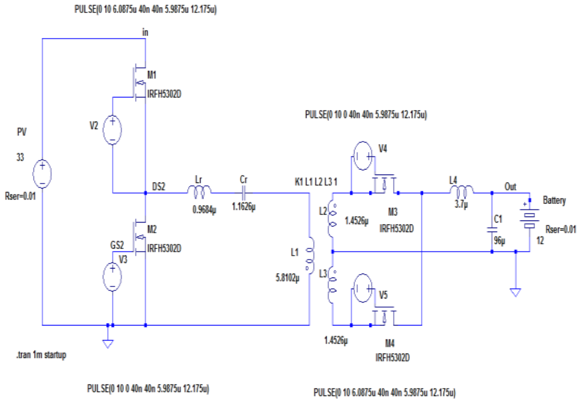


Figure 6: Model of LLC battery charger in LTSpice

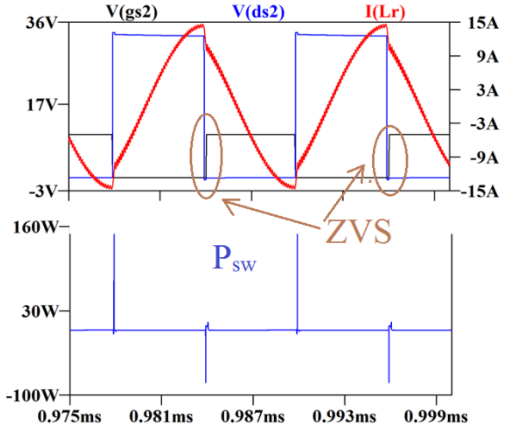


Figure 7: Simulation waveforms of primary side

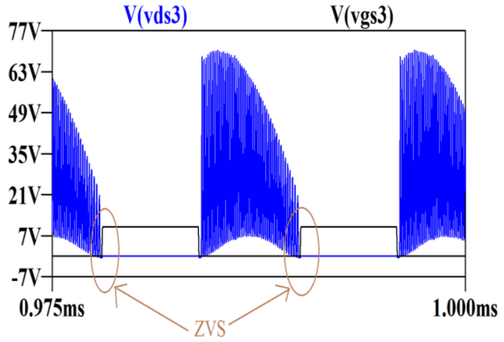


Figure 8: Simulation waveforms of secondary side

As shown in Figures 7 and 8, the switching frequency is f_s = 83.33 kHz at battery voltage of 12 V and charging current of 4.9 A and all switches achieve ZVS turn on, thus the power switching losses is small (about 0.18 W). Simulated efficiency versus output current of the converter is provided in Figure

9 for output voltage of 12 V, achieving a peak efficiency of 98%.

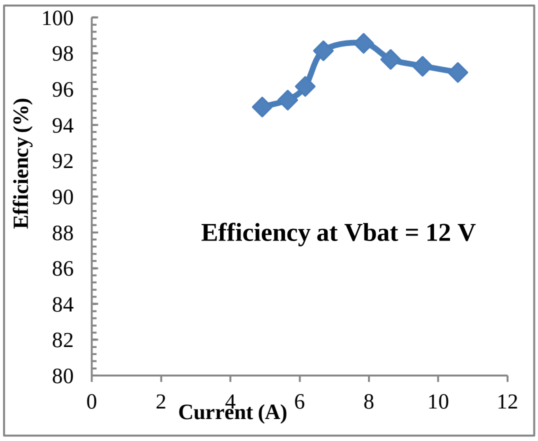


Figure 9: Efficiency at different outputs

Results and Discussion:

To verify the feasibility of the proposed control technique on DC/DC converters, a laboratory prototype has been built, as shown in Figure 10.

Figure 10: Laboratory prototype of soft switching battery charger

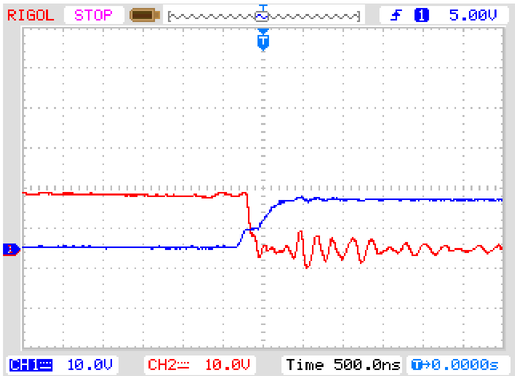


Figure 11: Miller effect on hard switching converters (Vgs: blue – CH1, Vds: red – CH2)

For comparison purposes, a typical hard switching waveform, depicting gate-source voltage and drain-source voltage of a MOSFET, is shown in Figure 11. It can be seen that a plateau region is visible on the gate-source voltage waveform under hard switching conditions. However, that plateau region is eliminated in soft switching conditions, as illustrated in Figure 12, which was measured on the prototype shown in Figure 10.

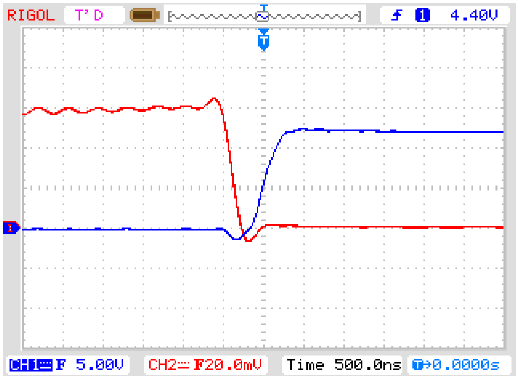
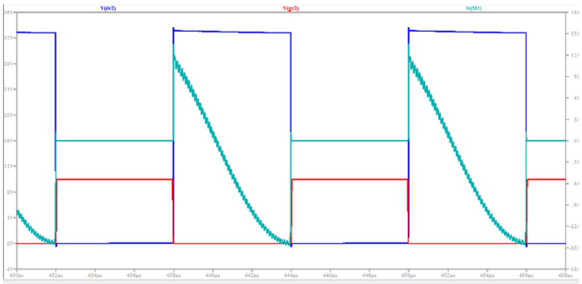
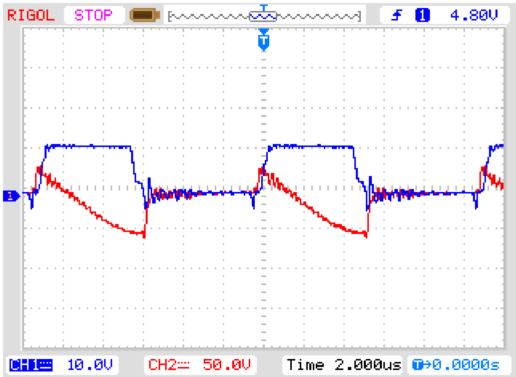


Figure 12: Soft switching waveforms of the proposed converter (Vgs: blue – CH1, Vds: red – CH2)

Another way to verify that soft switching has been achieved is to compare the simulated and experimental waveforms on active switches, i.e. MOSFETs, as shown in Figure 13. A resemblance between simulated and experimental voltages and currents can be seen, confirming the achievement of soft switching conditions.



(a) Simulation waveforms (Vds: blue, Vgs: red, Ids: green)



(b) Experimental waveforms (Vds: blue, Ids: red)

Figure 13:) Waveforms on primary side (Vds- Yellow and Vgs-blue top, Ids blue bottom).

Similar resemblance can also be observed when simulated secondary side waveforms in Figure 8 are compared to experimental ones in Figure 14.

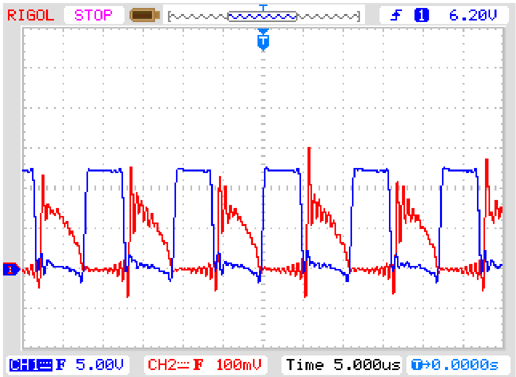


Figure 14: Experimental waveform on secondary side (Vgs: blue, Vds: red)

Obviously, soft switching has been achieved on the proposed converter.

Conclusion:

This paper has presented an LLC converter for lead-acid battery chargers, supplied by PV systems. Description of operating principles, design procedures, and power control algorithm for the proposed LLC converter have been provided. Simulation of the proposed soft switching converter at different output voltages (11 – 13.8 V) under different load currents (4 - 12 A) and input voltages (18 – 36 V) has been done and described, with maximum efficiency of 98%, due to reduced switching losses and rectifying losses. The soft switching condition has been verified by experiments on a laboratory prototype, confirming the feasibility of the proposed solution. Therefore, the LLC converter is recommended for high efficiency battery charging applications.

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