Design And Implementation of a Battery Charger With Soft Switching Technique

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Abstract—A new soft switching technique with zero current switching is developed for a battery charger circuit with buck converter. The proposed new circuit is obtained by placing an auxiliary circuit in series with the resonant capacitor which significantly decrease the switching losses in the power switches. The new battery charger with a buck converter has many advantages like simple structure, simple control, low cost, light weight, high efficiency etc. The operating principle and the design aspects of the charger circuit are analysed. The required values of the resonant inductance and resonant capacitance are calculated from the characteristic curve and functions derived from the required circuit. A charger circuit is designed for a 3.7-V 1020mAh lithium ion battery and the simulation is done in matlab.

Index Terms—Buck converter, Zero current Switching, soft switching, battery charger.

I. INTRODUCTION

Rechargeable batteries are widely used in our day to day life which include mobile phones, laptops, cameras, digital clock, UPS etc. The batteries used in these devices require a charging circuit. The life and the charging process of the battery depends on the type of the charging circuit. Linear power regulators which are used in the conventional charging schemes can handle only low power levels and moreover they have a low efficiency and low power density. The recent trend is the development of pulse width modulation (PWM) in the dc-dc converter for the charging process where semiconductor power switches are used. The switches in this mode operates in a switch mode where a whole of the load current is turned on and off during each switching session. The switch mode operation results in high switching losses and stress. The efficiency of the switch mode system lies in the incrementation of the frequency but this adversely affects the switching loss and the magnetic interference. To remove the above mentioned shortcomings soft switching technique is used. Zero voltage switching (ZVS) and zero current switching (ZCS) are the commonly used methods. The above mentioned techniques result in either zero voltage or zero current across the switch. ZCS eliminates the turn on losses and decrease turn off losses by slowing down the increase in voltage resulting in lowering of the overlap between the voltage and current. But it is required to have a large resonant capacitor for efficient lowering of the switching loss. In ZCS the switch current is forced to zero before the switch voltage rise. For high efficiency applications the ZCS are generally used.

The converters are required to have a high operating frequency so as to reduce the size of the passive components and also to achieve high power density. The traditional ZCS converter operates with constant on time control and it needs to operate in a large switching range, making filter design perfect. The primary feature of the proposed ZCS PWM converter is the addition of an auxiliary switch in the traditional circuit. The resonance condition of the new converter is powered by the auxiliary switch which makes the resonate condition and temporarily stops for time that can be controlled there by removing the weakness of fixed conduction or cut off time in a normal quasi-resonant converter.

A new high efficiency battery charger with ZCS buck converter is analysed and designed which has a simple structure, low switching losses and high efficiency. Following the introduction the circuit configuration is discussed in section II, section III describes the operating principle, normalized voltage gain is discussed in IV, design and simulation is discussed in section V and conclusion in VI.

II. CIRCUIT CONFIGURATION

Resonant converters are used for the soft switching implementation in the charger circuit due to their simple operation and low switching losses. Fig.1 shows the circuit of a ZCS converter which has an extra resonant tank circuit consist of resonant inductor $L_m$, resonant capacitor $C_r$ and diode $D_{m}$. This additional LC tank circuit is placed in the converter to make a zero current situation for the switch to turn off. The inductor $L_p$ is used to limit the di/dt of the switch and is connected in series to the power switch $S$. The capacitor $C_r$ is placed as an auxiliary energy transfer element. $D_m$ is the freewheeling diode. Inductor $L_i$ and capacitor $C_i$ are used as a low pass filter circuit which filter high frequency ripple signal and provides a stable source for charging. Diode $D_i$ prevents the flow of energy from battery to the circuit. The elements $L_p$ and $C_r$ represents a series resonant circuit where the oscillations are started by the turning off of the diode $D_m$. Here the soft switching technique is implemented in both the switch and the diode.
In the ZCS resonant converter, when the switch S is turned on the inductor starts to oscillate with the capacitor in resonance condition. The resonance inductor makes the current to zero thereby making the main switch turned off with ZCS condition. The turn on time of the main switch is decided by the resonant time of the resonant inductor and resonant capacitor. It operates in fixed on time control and the output is adjusted by changing the off time of the switch. The control produces harmonics at unpredictable frequencies and this makes the design of filter difficult.

To mitigate the aforementioned problems, a new ZCS converter is being proposed. Here an auxiliary switch is inserted in series with the resonant capacitor. The main and the auxiliary switch can be operated in synchrony without any isolation devices as shown in Fig. 2.

**III OPERATING PRINCIPLE**

For analysis purpose the output inductor is assumed to be a large to be considered as a current source $I_o$. The circuit parameters are defined below:

1) Resonant inductor $L_r$
2) Resonant capacitor $C_r$
3) Characteristic impedance $Z_0 = (L_r/C_r)^{1/2}$
4) Resonant angular frequency $\omega_0 = 1/(L_rC_r)^{1/2}$
5) Switching period $T_s$
6) Resonant frequency $f_r = \omega_0/2\pi$
7) Switching frequency $f_s$

Some of the assumptions made for the analysis are:

1) Semiconductor used are ideal
2) No forward voltage drop during turn on
3) No leakage current during turn off
4) No resistance for the resonant inductor and capacitor
5) Filter inductance $L_o$ and filter capacitance $C_o$ are larger than the resonant inductor $L_r$ and resonant capacitor $C_r$.
Fig. 5 Circuit representation of the converter for various operating modes. (a) Mode I. (b) Mode II. (c) Mode III. (d) Mode IV. (e) Mode V. (f) Mode VI

Mode I \((t_0 \leq t < t_1):\) The main switch \(S_m\) and auxiliary switch \(S_a\) are in off condition and the diode \(D_m\) is in on condition. Current through \(D_m\) is equal to the charging current \(I_0.\) Gate signal is applied to the main switch during the starting of this mode. The inductor current \(i_{L_r}\) rises linearly during this mode. Current through \(D_m\) is the difference between \(i_{L_r}\) and \(I_0.\) This mode ends when \(D_m\) turns off. The governing equations are

\[
\begin{align*}
    v_{DS}(t) &= 0 \quad (1) \\
    \frac{V_t}{I_0} &= L \frac{di_{L_r}}{dt} \quad (2) \\
    v_{D_m}(t) &= 0 \quad (3) \\
    i_{D_m}(t) &= I_0 - \frac{V_t}{I_0} (t-t_0) \quad (4) \\
    v_{D_m}(t) &= 0 \quad (5) \\
    i_{D_m}(t) &= I_0 - \frac{V_t}{I_0} (t-t_0) \quad (6) \\
    v_{D_m}(t) &= 0 \quad (7) \\
    i_{S_a}(t) &= 0 \quad (8) \\
\end{align*}
\]

\(\Delta t_1\) is the time interval between \(t_1\) and \(t_2\)

\[\Delta t_1 = t_1 - t_0 = \frac{L_i I_0}{V_t} \quad (9)\]

Mode II \((t_1 \leq t < t_2):\) In this mode the diode \(D_m\) becomes reverse biased and turned off. The main switch remains on and \(i_{L_r} = I_0\) at \(t = t_1.\) \(i_{L_r} = I_0\) current passes from \(D_m\) to \(D_a,\) the body diode of the auxiliary switch \(S_a.\) The current pass through resonant capacitor \(C_r\) which makes a resonant condition with the resonant inductor \(L_r.\) The circuit parameters are given below.

\[
\begin{align*}
    v_{DS}(t) &= 0 \quad (10) \\
    i_{D_a}(t) &= \frac{V_t}{Z_o} \sin \omega_0 (t-t_1) \quad (11) \\
\end{align*}
\]
\[i_{Ls}(t) = I_0 + \frac{V_s}{Z_0} \sin \omega_0 (t-t_1)\]  
\[V_{cr}(t) = \frac{1}{C_r} \int_{t_1}^{t} \frac{V_s}{Z_0} \sin \omega_0 (t'-t_1) dt\]  
\[V_{ad}(t) = V_S [1 - \cos \omega_0 (t - t_1)]\]  
Maximum resonant inductor current \( i_{Ls}(t) \) occurs at \( t_{max} \)  
Peak capacitor voltage occurs at \( t = t_2 \)  
When \( i_{Ls}(t) = I_0 \) peak capacitor voltage is \( 2V_s \)  
The operating time in this mode is given by \( \Delta t_5 = t_5 - t_4 = \frac{I_0}{V_s} \)  
(20)  

**Mode III** \( (t_2 \leq t < t_3) \): Main switch is in on condition and load current \( I_0 \) flows through \( S_m \) and the voltage across \( C_r \) is clamped at \( 2V_s \)  
\[i_{Ls}(t) = I_0 \]  
\[V_{cr}(t) = 2V_s \]  
\[V_{ad}(t) = V_s \]  
\[V_{ad}(t) = V_s \]  
Time interval for this mode and mode I are assumed to be same \( \Delta t_5 = t_5 - t_4 = \frac{I_0}{V_S} \)  
(20)  

**Mode IV** \( (t_3 \leq t < t_4) \): At the time \( t = t_3 \) the auxiliary switch \( S_a \) is turned on with ZCS. A reverse resonance condition is generated. At the end of this mode the main switch \( S_m \) is turned off with ZCS. The characteristics governing equations are as follows  
\[V_{cr}(t) = 0\]  
\[i_{ad}(t) = \frac{V_s}{Z_0} \sin \omega_0 (t-t_3)\]  
\[i_{Ls}(t) = I_0 - \frac{V_s}{Z_0} \sin \omega_0 (t-t_3)\]  
\[V_{cr}(t) = \frac{1}{C_r} \int_{t_3}^{t} \frac{V_s}{Z_0} \sin \omega_0 (t'-t_3) dt + 2V_s\]  
\[= V_S [1 + \cos \omega_0 (t - t_3)]\]  
(23)  

Time interval of this mode is \( \Delta t_4 = t_4 - t_3 = \frac{1}{Z_0} \sin \frac{i_{Ls}(t_4)}{V_s}\)  
(25)  

**Mode V** \( (t_4 \leq t < t_5) \): In this mode the main switch is in off condition and the charging current flows through the switch. The resonant capacitor is in discharging mode and this mode comes to an end when voltage \( V_{cr} \) falls to zero at \( t = t_5 \).  
\[V_{Cf}(t) = -\frac{V_s}{Z_0} (t - t_4) + V_{Cf}(t)\]  
(25)  

**Mode VI** \( (t_5 \leq t < t_6) \): At the time \( t = t_5 \) the charging current is commutated from the resonant capacitor to the diode \( D_m \) with soft switching. The auxiliary switch is turned off with soft switching technique. This mode is the off state of the converter and the duration can be controlled by the gate signal of the main switch.  
\[V_{ad}(t) = V_s\]  
(29)  
\[I_{ad}(t) = I_0\]  
(30)  

The time interval is given by \( \Delta t_6 = T_s [\Delta t_5 + \Delta t_4 + \Delta t_3 + \Delta t_2 + \Delta t_1]\)  
(31)  

**IV. NORMALIZED VOLTAGE GAIN**

The normalized voltage gain is found out by equalizing the energy supplied \( E_s \) and the energy absorbed by the battery \( E_0 \). The equation is given by  
\[E_s = \int_{t_0}^{T_s} V_c i_c(t) dt\]  
(32)  

The normalized voltage is obtained by equating the time interval equations \( (9),(15),(20),(25),(28),(31) \) discussed above.  
\[E_s = V_s I_0 \left( \frac{t_1-t_0}{2} + (t_2 - t_1) + (t_3 - t_2) + (t_4 - t_3) + (t_5 - t_4) \right)\]  
(33)  

Energy absorbed by the battery over one switching cycle is,  
\[E_0 = I_0 V_0 \left( t_3 - t_2 + (t_2 - t_1) + (t_3 - t_2) + (t_4 - t_3) + (t_5 - t_4) \right)\]  
(34)  

Equating the input and output expressions,  
\[\frac{V_0}{V_s} = \left( \frac{t_1-t_0}{2} + \left( t_2 - t_1 \right) + \left( t_3 - t_2 \right) + \left( t_4 - t_3 \right) + \left( t_5 - t_4 \right) \right)\]  
(35)  

Normalized voltage gain,  
\[M = f \left( \frac{3Lm}{2R_0} + \pi + \frac{\pi}{2} \left[ \sin^{-1} \left( \frac{M}{Q} \right) \right] + \frac{C_r R_0}{M} \left[ 1 + \cos \left( \sin^{-1} \left( \frac{M}{Q} \right) \right) \right] \right)\]  
(36)  

Let \( \sin^{-1} \left( \frac{M}{Q} \right) = \alpha \)  
\[M = f \left( \frac{3M}{2Q} + \alpha + \frac{Q}{M} [1 + \cos \alpha] \right)\]  
(37)
Normalized voltage gain \( M = \frac{V_0}{V_s} \)

Normalized load \( Q = \frac{R_0}{Z_0} \)

Charging current \( I_0 = \frac{V_0}{R_0} \)

Normalized switching frequency \( F_{ns} = \frac{f_s}{f_0} \)

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<thead>
<tr>
<th>Performance Parameters</th>
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<tr>
<td>Normalized voltage gain</td>
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<tr>
<td>Normalized load</td>
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<td>Charging current</td>
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<td>Normalized switching frequency</td>
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Table.1 Performance Parameters

V) DESIGN AND SIMULATION

For the experiment purpose a 3.7V-1020mAh lithium ion battery is used. The circuit parameters of the charger circuit were fixed.

1) Input voltage \( V_s = 12V \)
2) Output voltage \( V_0 = 5V \)
3) Switching frequency \( f_s = 18kHz \)
4) Time period \( T_s = 50\mu sec \)
5) Output current \( I_0 = 1A \)
6) Normalised switching frequency \( f_{ns} = 0.3 \)
7) Equivalent output impedance \( R_0 = \frac{V_0}{I_0} = 5\Omega \)
8) Characteristics impedance \( Z_0 = \frac{R_0}{Q} = 5\Omega \)
9) Normalized voltage gain \( M = \frac{V_0}{V_s} = 0.42 \)
10) Resonant frequency \( f_0 = \frac{f_s}{f_{ns}} = 60kHz \)
11) Resonant inductor \( L_r = \frac{f_s}{f_0} = 13.269\mu H \)
12) Resonant capacitor \( C_r = \frac{1}{\omega_0 f_0} = 0.53\mu F \)
13) Filter inductor \( L_0 = 100L_r = 1.326mH \)
14) Filter capacitor \( C_0 = 100C_r = 53.1\mu F \)

The time intervals for various modes were calculated based on the circuit parameters

1) \( \Delta t_1 = \frac{L_r I_0}{V_s} = 1.10575\mu sec \)
2) \( \Delta t_2 = \frac{V_0}{w_0} = 8.33\mu sec \)
3) \( \Delta t_3 = \frac{V_0}{I_0} = 1.10575\mu sec \)
4) \( \Delta t_4 = \frac{1}{w_0} \left[ \sin \frac{I_0 V_0}{V_s} \right] = 1.1396\mu sec \)
5) \( \Delta t_5 = \frac{I_0}{w_0} \left[ 1 + \cos \omega_0 (t_4 - t_3) \right] = 12.719\mu sec \)
6) \( \Delta t_6 = T_s \left[ \Delta t_1 + \Delta t_2 + \Delta t_3 + \Delta t_4 + \Delta t_5 + \Delta t_6 \right] = 25.6\mu sec \)

Duty cycle of the switches

1) For main switch \( D = \frac{T_{on}}{T_s} = 0.233 \)
2) For auxiliary switch \( D_a = \frac{T_{on}}{T_s} = 0.277 \)

Fig 6. Simulink Model

Fig.8 Trigger signal \( V_G \) and control signal \( V_{Ga} \)

Fig.9 Main switch current and voltage

Fig.10 Freewheeling diode voltage \( V_{Dm} \) and auxiliary switch voltage \( V_{Da} \)
VI CONCLUSION

This paper deals with a new zero current buck dc-dc converter having an auxiliary resonating circuit for the battery charger. This is much simpler and cheaper than other circuits having a large number of components. The operating principle and analysis for a mobile phone battery is been analysed.

VII REFERENCE


