International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 3 Issue 7, July - 2014

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 auxillary 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 nad 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 results 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 need 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 auxillary switch in the traditional circuit.The resonance condition of the new converter is powered by the the auxillary switch which makes the resoance condition and temporarly 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_r,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 swithc to turn off.The inductor L_r 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 auxillary energy transfer element.Dm is the freewheeling diode.Inductor L_f and capacitor C_f are used as a low pass filter circuit which filter high frequency ripple signal and provides a stable source for charging.Diode D_f prevents the flow of energy from battery to the circuit.The elements L_r and C_r represents a series resoanant 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.

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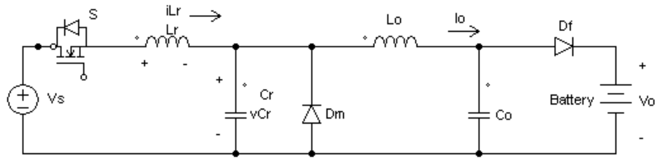

Fig.1 Battery charger circuit using ZCS converter

In the ZCS resoannt 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 there by 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 asjusted 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 aforesaid porblems a new ZCS converter is being proposed.Here an auxillary switch is inserted in series with the resonant capacitor.The main and the auxillary switch can be operated in synchrony with out any isolation devices as shown in Fig.2

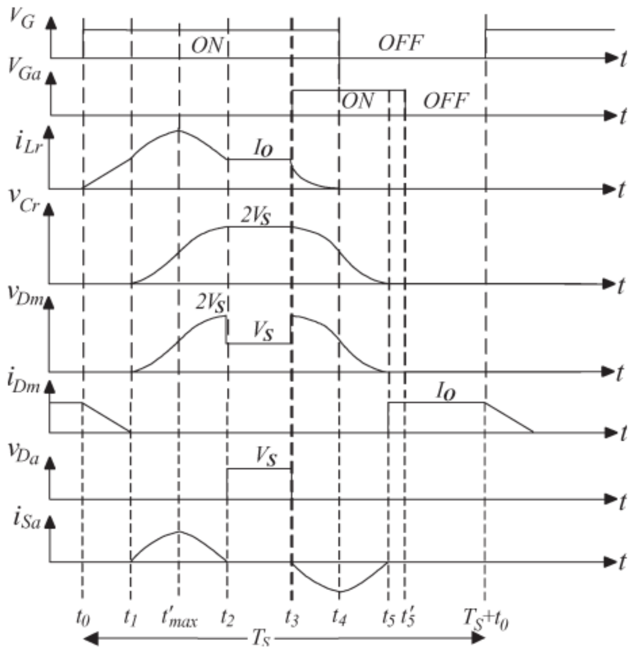

Fig.3 Waveform of the proposed charger

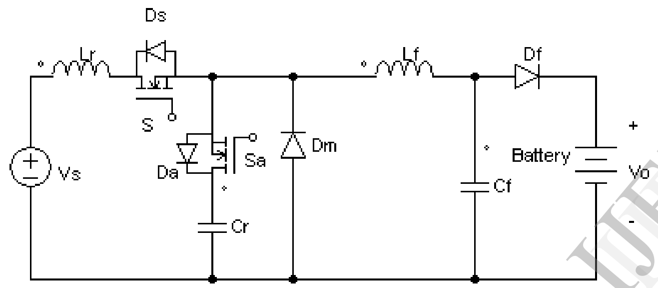

Fig.2 Battery charger circuit using proposed ZCS converter

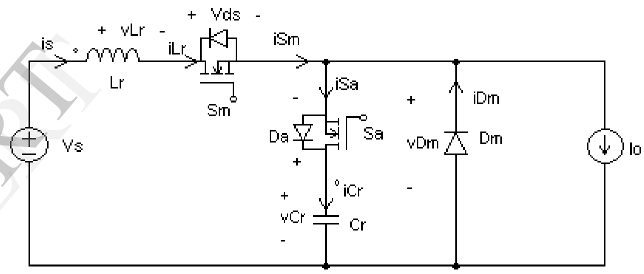

Fig.4 shows the equivalent circuit of the proposed converter

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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 $Z_o= (L_r/C_r)^{1/2}$

4) resonant angular frequency $wo=1/(L_rC_r)^{1/2}$

5)switching period T_s

6)resonant frequency $f_r=w_o/2\pi$

7)switching frequency f_s

Some of the assumptions made for the analysis are,

1)semiconductor used are ideal

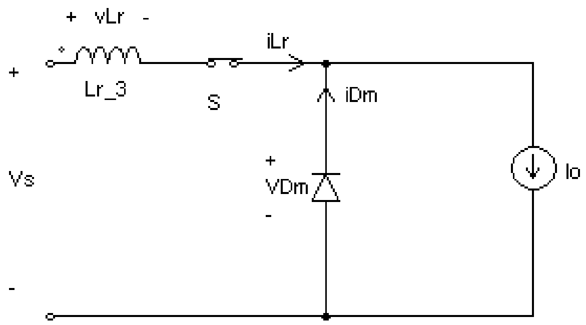
2)no forward voltage drop during turn on

3)no leakage current during turn off

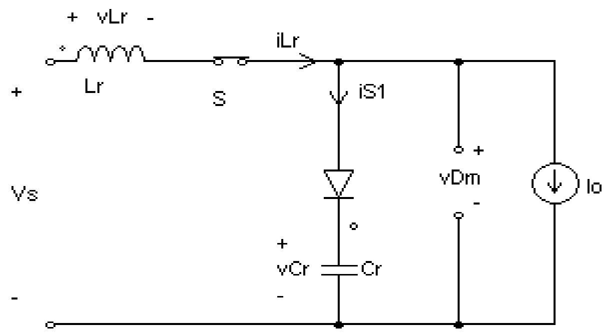
4)no resistance for the resonant inductor and capacitor

5) filter inductance L_o and filter capacitance C_o are larger than the resonant inductor L_r and resonant capacitor C_r

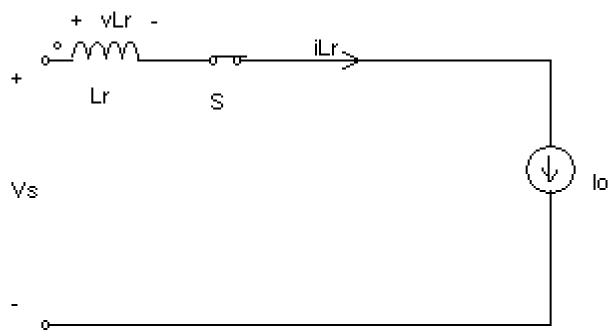
The total operating modes of the converter are divided into six modes in one switching cycle.The operating principle are discussed below



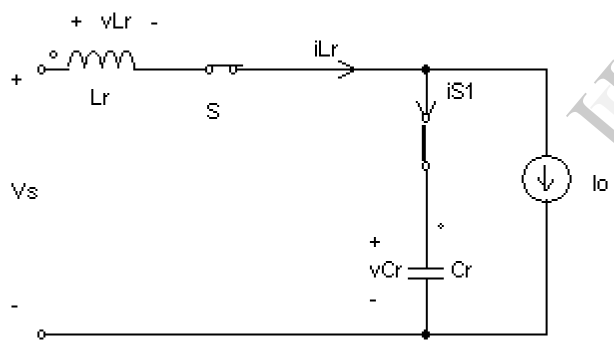
Mode I



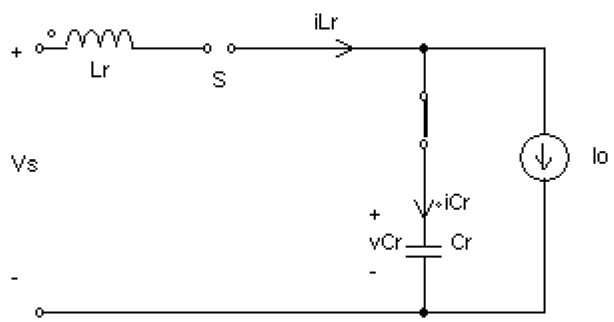
Mode II



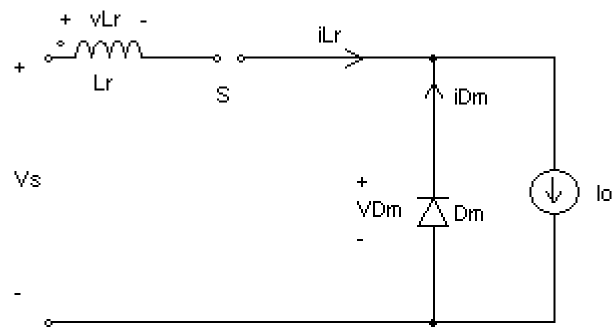
Mode III



Mode IV



Mode V



Mode VI

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 ($t_o \le t < t_1$): The main switch S_m and auxillary 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_o.Gate signal is applied to the main switch during the starting of this mode.The inductor current i_{Lr} rises linarly during this mode.Current through Dm is the difference between i_{lr} and I_o.This mode ends when D_m turns off.The governing equations are

$$v_{DS}(t)=0 \quad (1)$$

$$V_s=v_{Lr}=L_r\frac{di_{Lr}}{dt} \quad (2)$$

$$iL_r(t)=\frac{V_s}{L_r}(t-to) \quad (3)$$

$$v_{Cr}(t)=0 \quad (4)$$

$$v_{Dm}(t)=0 \quad (5)$$

$$i_{Dm}(t)=I_0-\frac{V_s}{L_r}(t-t_o) \quad (6)$$

$$v_{Dm}(t)=0 \quad (7)$$

$$i_{Sa}(t)=0 \quad (8)$$

Δt_1 is the time interval between t_1 and t_2

$$\Delta t_1=t_1-t_0=\frac{L_r I_0}{V_s} \quad (9)$$

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

$$v_{DS}(t)=0 \quad (10)$$

$$i_{Sa}(t)=\frac{V_s}{Z_0}\sin w_0(t-t_1) \quad (11)$$

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$$i_{Lr}(t)=I_0+\frac{V_s}{Z_0}\sin w_0(t-t_1) \quad (12)$$

$$V_{cr}(t)=\frac{1}{C_r}\int_{t_1}^{t}\frac{V_s}{Z_0}\sin w_0(\tau-t_1)d\tau$$
$$=Vs[1-\cos w_0\,(t-t_1)] \quad (13)$$

$$V_{dm}(t)=Vs[1-\cos w_0\,(t-t_1)] \quad (14)$$

Maximum resonant inductor current $i_{Lr}(t)$ occurs at t'_{max}
Peak capacitor voltage occurs at $t=t_2$

$$W_0(t_2-t_1)=\pi$$

When $i_{Lr}(t)=I_0$ peak capacitor voltage is 2Vs
The operating time in this mode is given by

$$\Delta t_2=t_2-t_1=\frac{\pi}{w_0} \quad (15)$$

The interval ends when current through diode Da is reduced to zero.

Mode III ($t_2 \le t<t_3$): Main switch is in on condition and load current Io flows through S_m and the voltage across C_r is clamped at $2V_s$.

$$I_{Lr}(t)=I_0 \quad (16)$$

$$V_{Cr}(t)=2V_s \quad (17)$$

$$V_{dm}(t)=V_s \quad (18)$$

$$V_{da}(t)=V_s \quad (19)$$

Time interval for this mode and mode I are assumed to be same

$$\Delta t_3=t_3-t_2=\frac{L_r I_0}{V_s} \quad (20)$$

mode IV ($t_3 \le t<t_4$): At the time $t=t_3$ the auxillary 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 charactersitics governing equations are as follows

$$v_{DS}(t)=0 \quad (21)$$

$$i_{Sa}(t)=-\frac{V_s}{Z_0}\sin w_0(t-t_3) \quad (22)$$

$$i_{Lr}(t)=I_0-\frac{V_s}{Z_0}\sin w_0(t-t_3) \quad (22)$$

$$V_{cr}(t)=\frac{1}{C_r}\int_{t_3}^{t}-\frac{V_s}{Z_0}\sin w_0(\tau-t_3)d\tau+2V_s$$
$$=Vs[1+\cos w_0\,(t-t_3)] \quad (23)$$

$$V_{dm}(t)=V_s[1+\cos w_0\,(t-t_3)] \quad (24)$$

Time interval of this mode is

$$\Delta\, t4=t_4-t_3=\frac{1}{w_0}\left[\sin\frac{I_0 Z_0}{V_s}\right] \quad (25)$$

Mode V ($t_3 \le t<t_4$): 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 $t=t_5$.

$$v_{Cr}(t)=-\frac{I_0}{C_r}(t-t_4)+v_{Cr}(t) \quad (25)$$

$$v_{Cr}(t)=-\frac{I_0}{C_r}(t-t_4)+Vs[1+\cos w_0\,(t_4-t_3)] \quad (26)$$

$$v_{Cr}(t)=v_{Dm}(t) \quad (26)$$

$$i_{Sa}(t)=-\frac{V_s}{Z_0}\sin w_0(t-t_4) \quad (27)$$

$$\Delta t_5=t_5-t_4=\frac{C_r V_s}{I_0}[1+\cos w_0\,(t_4-t_3)] \quad (28)$$

Mode VI ($t_5 \le t<t_0+T_s$): At the time $t=t_5$,the charging current is commutated from the resonant capacitor to the diode D_m with soft switching.The auxillary 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.

$$V_{ds}(t)=V_s \quad (29)$$

$$I_{Dm}(t)=I_0 \quad (30)$$

The time interval is given by

$$\Delta t_6=T_s-[\Delta t_5+\Delta t_4+\Delta t_3+\Delta t_2+\Delta t_1] \quad (31)$$

IV) NORMALIZED VOLTAGE GAIN

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The normalized voltage gain is found out by equalizing the energy supplied E_a and the energy absorbed by the battery E_0.The equation is given by

$$E_s=\int_{t_0}^{T_s+t_0} V_s i_s(t)dt \quad (32)$$

The normalized voltage is obtained by equating the time interval equations (9),(15),(20),(25),(28),(31) discussed above.

$$E_s=V_s I_0\left\{\frac{t_1-t_0}{2}+(t_2-t_1)+(t_3-t_2)+(t_4-t_3)+(t_5-t_4)\right\} \quad (33)$$

Energy absorbed by the battery over one switching cycle is,

$$E_0=\int_{t_0}^{T_s+t_0} I_0 V_0\,dt=I_0 V_0 T_s \quad (34)$$

Equating the input and output expressions,

$$\frac{V_0}{V_s}=\frac{1}{T_s}\left\{\frac{t_1-t_0}{2}+(t_2-t_1)+(t_3-t_2)+(t_4-t_3)+(t_5-t_4)\right\} \quad (35)$$

Normalized voltage gain,

$$M=f_s\left\{\frac{3L_r M}{2R_0}+\frac{\pi}{2\pi f_0}+\frac{1}{2\pi f_0}\left[\sin^{-1}\left(\frac{M}{Q}\right)\right]+\frac{C_r R_0}{M}\left\{1+\cos\left[\sin^{-1}\left(\frac{M}{Q}\right)\right]\right\}\right\} \quad (36)$$

$$\text{Let } \sin^{-1}\left(\frac{M}{Q}\right)=\alpha$$

The equation is simplified to

$$M=f_s\left\{\frac{3M}{2Q}+\pi+\alpha+\frac{Q}{M}[1+\cos\alpha]\right\} \quad (37)$$

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	$F_{ns}=\frac{f_s}{f_0}$

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 voltgae V_0=5V
3)Switching frequency f_s=18kHz
4)Time period T_s=50μsec
5)Output current I_0=1A
6)Normalised switching frequency f_{ns}=0.3
7)Equvalent 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 $L_r=\frac{Z_0}{W_0}$=13.269μH
12)Resonant capacitor $C_r=\frac{1}{W_0 Z_0}$=0.53μF
13)Filter inductor $L_0=100L_r$=1.326mH
14)Filter capacitor $C_0=100C_r$=53.1μF

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

1)$\Delta t_1= \frac{L_r I_0}{V_s}$=1.10575μsec
2) $\Delta t_2= \frac{\pi}{w_0}$=8.33μsec
3) $\Delta t_3= \frac{L_r I_0}{V_s}$=1.10575μsec
4) $\Delta t_4=\frac{1}{w_0}\left[\sin\frac{I_0 Z_0}{V_s}\right]$=1.1396μsec
5) $\Delta t_5=\frac{C_r V_s}{I_0}[1+\cos w_0 (t_4-t_3)]$=12.719μsec
6) $\Delta t_6=T_s-[\Delta t_5+\Delta t_4+\Delta t_3+\Delta t_2+\Delta t_1]$=25.6μsec

Duty cycle of the switches
1)For main switch
$D=\frac{T_{ON}}{Ts}$=0.233
2)For auxillary switch
$D_a=\frac{\Delta T_4+\Delta T_5}{T_s}$=0.277

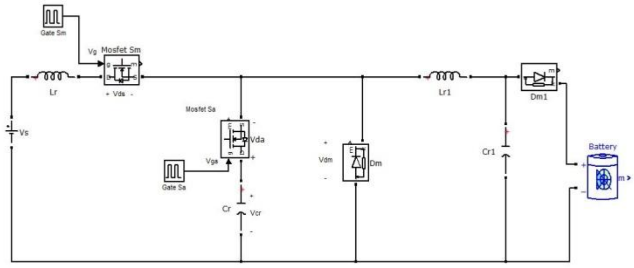

Fig 6. Simulink Model

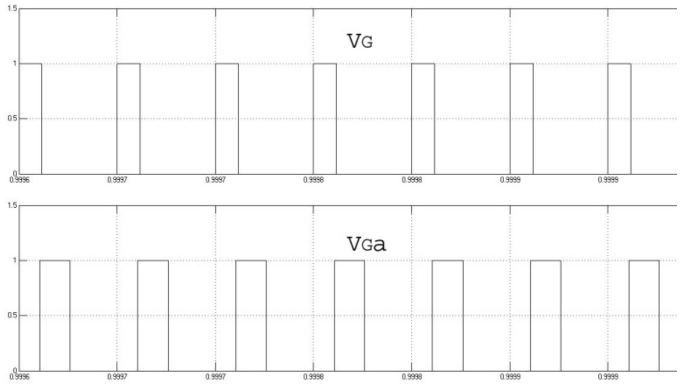

Fig.8 Trigger signal V_G and control signal V_{Ga}

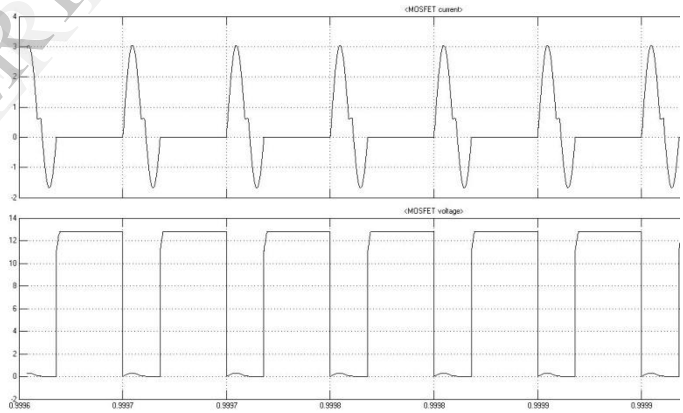

Fig.9 Main switch current and voltage

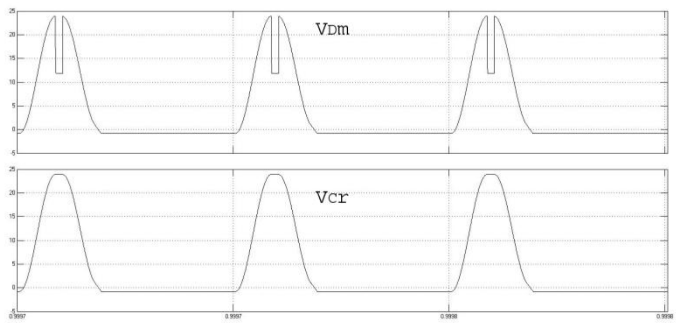

Fig.10 Freewheeling diode voltage V_{Dm} and auxillary switch voltage V_{Da}

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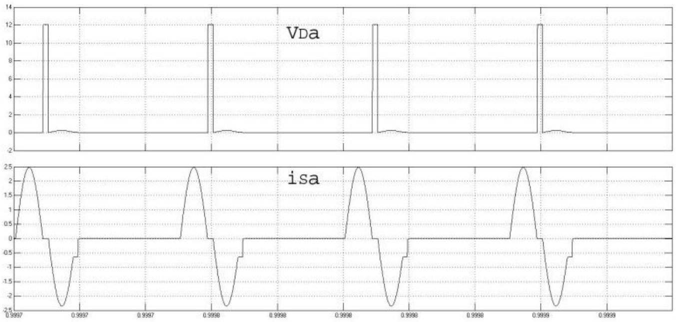

Fig.11 Voltage and current waveform of ausillary switch

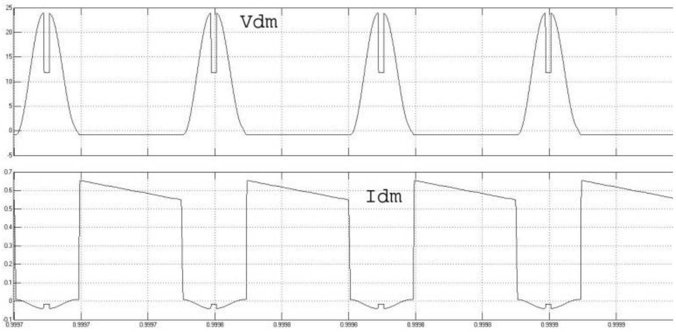

Fig.12 Freewheeling diode D_m current and voltage waveform

VI CONCLUSION

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

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