Single-Stage High-Efficiency LLC Resonant Converter

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ABSTRACT

The fundamental requirement of battery charger consists of light weight, simple in structure and maximum efficiency. In order to achieve maximum efficiency, the losses are reduced with the soft-switching techniques. In this paper, single stage structure using half bridge (HB) resonant converter is implemented with addition of one resonant capacitor and two relays. The resonant converter has the reliability to make use of transformer leakage and magnetising inductor as a part of resonant elements and provides ZVS and ZCS operation thereby reducing switching losses. The relay alters the turns-ratio of the coupled transformer with reference to the input voltage level. Thus, the conduction losses in the primary side of the transformer is decreased because of the smaller wire resistance at lower input voltage levels. Moreover, the additional elements can be easily placed in the conventional system. The prototype was designed to operate at universal AC input with low line and high line and 17V/65W output focusing adapters for variable input voltage levels.

Keywords – Battery charger, soft-switching, resonant converter, variable voltage level.

1. INTRODUCTION

Nowadays, consumers prefer to use the portable equipment for data processing because of light weight and smaller in size. Recently, the usage of mobile appliances like mobile phone, tablet PC, and laptop computer are enormously growing because of their compactness and performance resemblance to desktop computer.

Due to this, the demand for adapters are exponentially increasing because of the requirement of the mobile devices. Hence, adapters with small size which can manage to operate at high power for speed charging is mandatory to improve the performance of mobile devices. This leads to the requirement of adapters which can operate at high switching frequency with high efficiency.

The two-stage structure includes the power factor correction (PFC) stage is generally developed for the adapters having output greater than 70W. The input voltage of DC/DC stage is not widely changed due to the employment of PFC stage [1-2].

In order to reduce the cost and to make the adapters compact, manufacturers tried to eliminate the use of PFC stage thereby providing single stage structure.

Meanwhile, low line (90 Vac-132 Vac) and high line (180 Vac-250 Vac) are referred to as worldwide AC input voltage. The voltage level is varied with respect to the one country to another or one region to another region, low line or high line is used correspondingly. The manufacturers designed the adapters to operate in worldwide AC input voltage. The diode bridge rectifies the AC input voltage (90 Vac-250 Vac) to DC voltage (127 Vdc-380Vdc). Thus, in single stage structure the front-end voltage of DC/DC stage is not constant.

For wide input voltage applications, to reduce the component count and cost, isolated DC/DC converter is used for the adapters below 70W output [3-9]. However, in transformer magnetizing inductor L_1, the DC-bias current is very large which makes the transformer bulky in size. In telecom industry, LLC resonant converter is widely used because of its compatibility to regulate the output voltage and provides high efficiency at resonant frequency [4-5]. Recently, manufacturers used GaN /SiC FET's to develop the high frequency switched flyback converter but due to the large turn off loss on primary switch its efficiency is considerably decreased.

The half bridge (HB) LLC converter has desirable features such as zero voltage switching (ZVS), switching losses is very small, soft commutation of secondary rectifier, small-sized transformer and low voltage stress on primary switch which can considerably produce high efficiency and is used in high frequency operation [10]. For wide input voltage applications, the HB LLC resonant converter has critical limitation since it is modelled with low K- factor (i.e) $K=\frac{L_1}{L_l}$ [7-9]. Thus, the conduction losses and switching loss are still large due to the large RMS value and turn off switching currents.

In LLC series resonant converter greater performance is attained by means of increasing voltage gain with large L_1 [7-9]. This method of gaining high voltage gain uses diverse control schemes and auxiliary circuits. It also reduces the bulky size of the transformer and makes the adapters preferred to use at high switching frequency thereby minimising the size and can be used at low electromagnetic interference (EMI) to reduce the ripples of the supply.

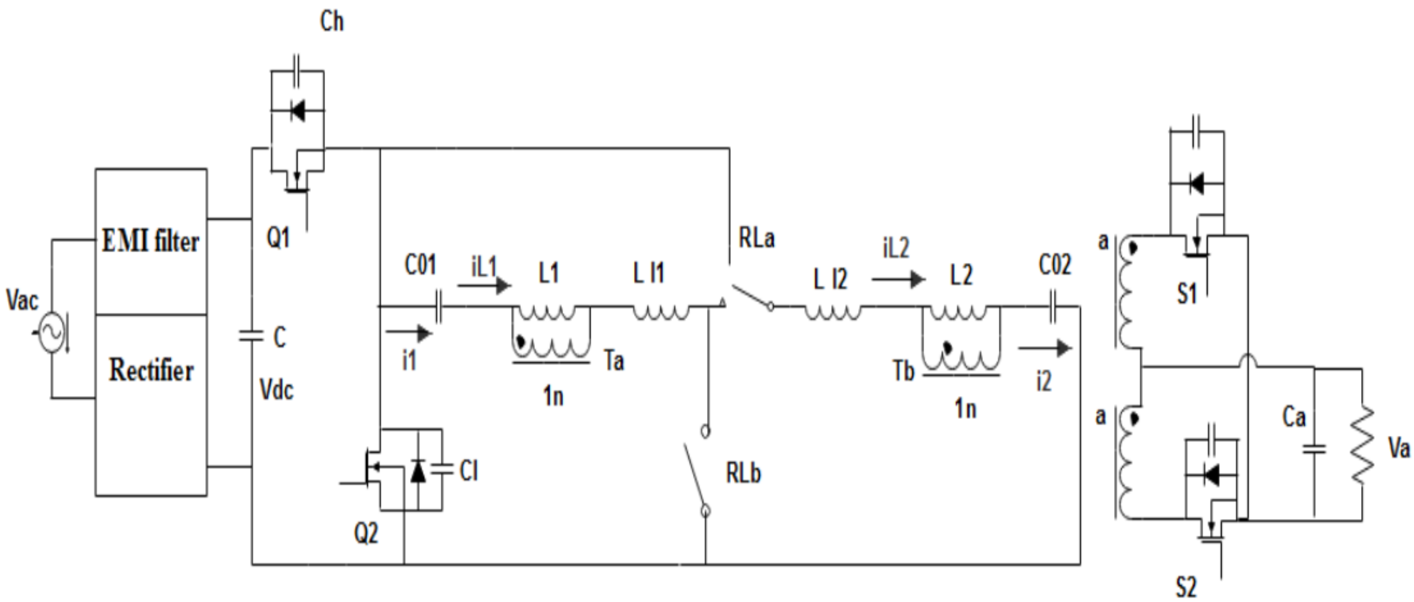

Fig.1. Representation of proposed LLC converter

By increasing the secondary turns of the transformer, high voltage gain is obtained in the converter [7]. The transformer secondary winding makes the circuit complex and uses additional semiconductor devices. The control method commonly known as pulse width modulation (PWM) is selected in HB LLC converter [18] and asymmetric control method in PWM is proposed with HB LLC converter [19]. Due to their PWM techniques, these strategy can approach high voltage gain. However, PWM control techniques expands the volume of the transformer.

An Adaptive link voltage variation (ALVV) is suitable to satisfy the problems faced during varying input voltage conditions and this scheme is designed to provide constant resonant frequency irrespective of output voltage variations with the help of LLC resonant converter.

2. DESIGNING PRINCIPLE

In medium to high power applications, LLC resonant converter is the key factor to produce high efficiency and high-power density. High efficiency is produced due to the achievement of ZVS of the switches thereby reducing the current/ voltage of the switch. Though it provides many advantages, structural arrangement and control algorithm are difficult.

For wide input voltage application, a new single stage high efficiency HB LLC converter is proposed. It contains relay and one resonant capacitor. The coupled transformer similar to centre-tapped transformer is employed in the preferred converter.

With respect to voltage conditions, the relay changes the turns ratio of the coupled transformer, thereby decreasing the necessary voltage gain range. By means of this, the converter has reduced primary conduction and turn-off losses when compared to conventional system. In addition, the proposed converter has large value of $L_1$and L_2. The parallel connection of the coupled transformer at low value of input voltage produces low range of total wire resistance of the transformer in primary side. The smaller size of additional components makes the converter to maintain the power density at desired value.

3.FUNDAMENTAL APPROACH

The proposed converter model is detailed in Fig.1. In addition, the converter utilizes one small size package containing two relays and resonant capacitor C_0 and the coupled transformer is used in alternate to the centre-tapped transformer in HB single-stage LLC converter. The suggested converter makes use of relay for altering the turns ratio of the transformer either in series or parallel with respect to the fluctuation of applied voltage.

Several speculations are done for the ease of the mode evaluation.

i. Transformer T_1 and T_2 are quite alike. The leakage inductance ($L_{l1} and\ L_{l2}$) and magnetizing inductance ($L_1\ and\ L_2$) and turns ratio are similar to each other.
ii. The final output voltage is persistent.

For low input voltage (90 Vac-132 Vac), the parallel connection of the coupled transformer is described in Fig.2 and the preferred converter is accomplished by three different stages at switching frequency.

The stages of the converter at low input voltage is explained below:

Stage 1 (t_1- t_2): In stage1, the switch Q_1 is in ON condition. The magnetizing current of the inductor (i_{L1} and i_{L2}) is gradually increased, when $nV_a/2$ is applied to magnetizing inductor L_1 and L_2. The sinusoidal shape of the primary current i_1 and i_2 is due to the resonance between C_0 and L_l. The parallel resonant path of this stage and its corresponding circuit diagram is shown in Fig.4.

Stage 2 (t_2 - t_3): At time t_2, the switch Q_1 is in OFF condition when the primary current i_1 and i_2 become equal to i_{L1} and i_{L2}. The capacitor C_{02} discharges and the capacitor C_{01} charges because of the energy stored in L_1 and L_2.The zero voltage across the switch Q_2 is achieved by the gradual decrease in the drain source voltage of the switch Q_2. Eventually, the anti-parallel diode connected across the switch Q_2 begins to conduct. Thus, the switch Q_2 is operated at ZVS condition.

Since, stage 3 operating procedure is similar to stage 1 and hence its description is neglected.

When applying high input voltage (180 Vac-264 Vac), the series connection of the coupled transformer is described in Fig.3 and the preferred converter is characterized by three stages of operation.

Stage 1 (t_1 - t_2): In stage 1, Q_1 is in ON condition. When ${}^{nV_a}/_2$ is applied to L_1 and L_2, the magnetizing current of the inductor (i_{L1} and i_{L2}) are gradually increased. The sinusoidal shape of the primary current i_1 and i_2 is due to the resonance between C_0 and L_l. At this stage, the frequency at resonant is similar to the low input voltage level. The series resonant path of this stage and its corresponding circuit diagram is shown in Fig.5.

Stage 2 (t_2 - t_3): At time t_2, i_1 gradually increases and becomes equal to i_{L1}. (i.e) $i_1 = i_2$; $i_{L1} = i_{L2}$ and hence Q_1 is in OFF condition. Charging of capacitor C_{01} and discharging of capacitor C_{02} occurs because of the energy is stored in L_1 and L_2. The zero voltage across the switch Q_2 is achieved by the gradual decrease in the drain source voltage of the switch Q_2. Eventually, the anti-parallel diode connected across the switch Q_2 begins to conduct. Thus, the switch Q_2 is operated at ZVS condition. Since, stage 3 operating procedure is similar to stage 1 and hence its description is neglected.

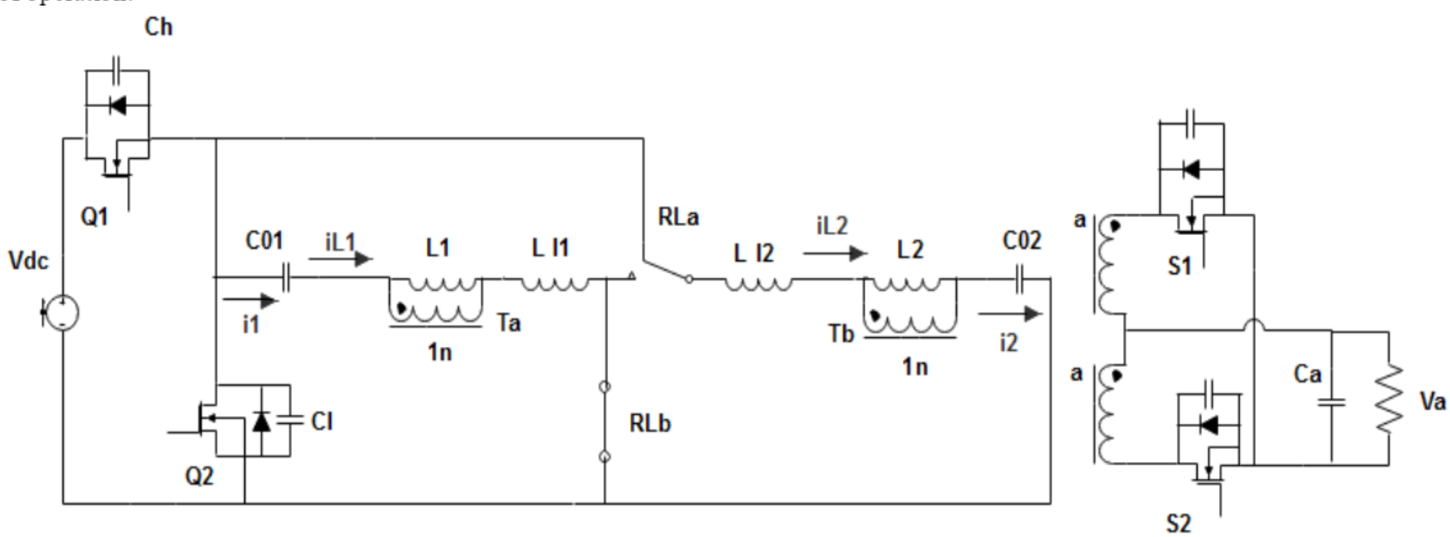

Fig.2 Circuit diagram at low voltage level (90 Vac-132 Vac)

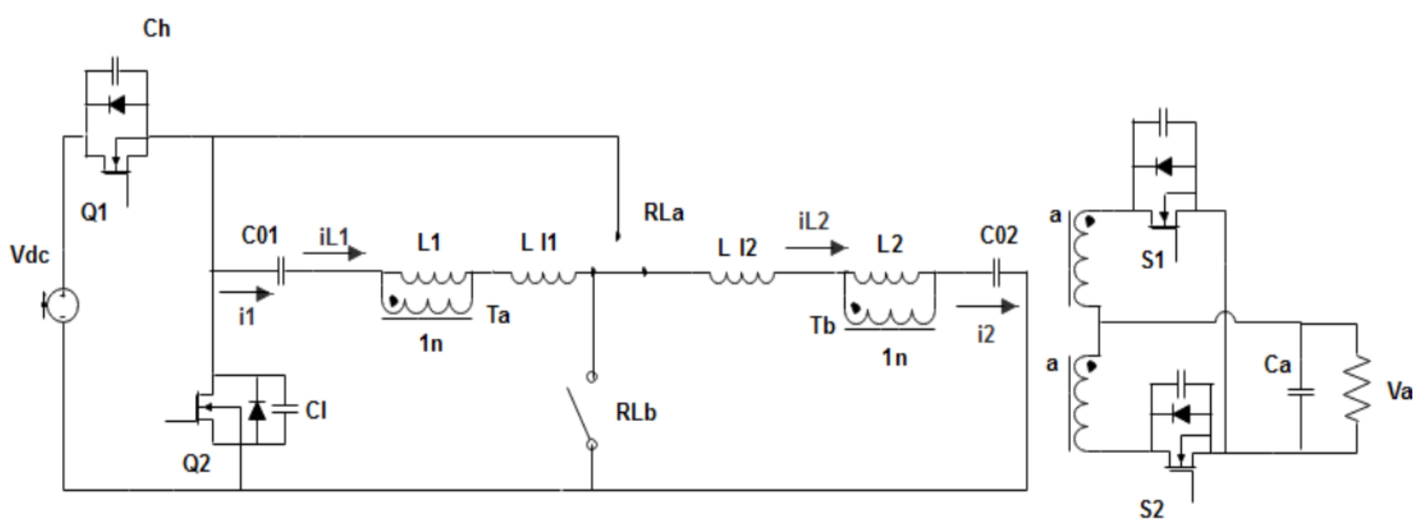

Fig.3 Circuit diagram at high voltage level (180 Vac-264 Vac)

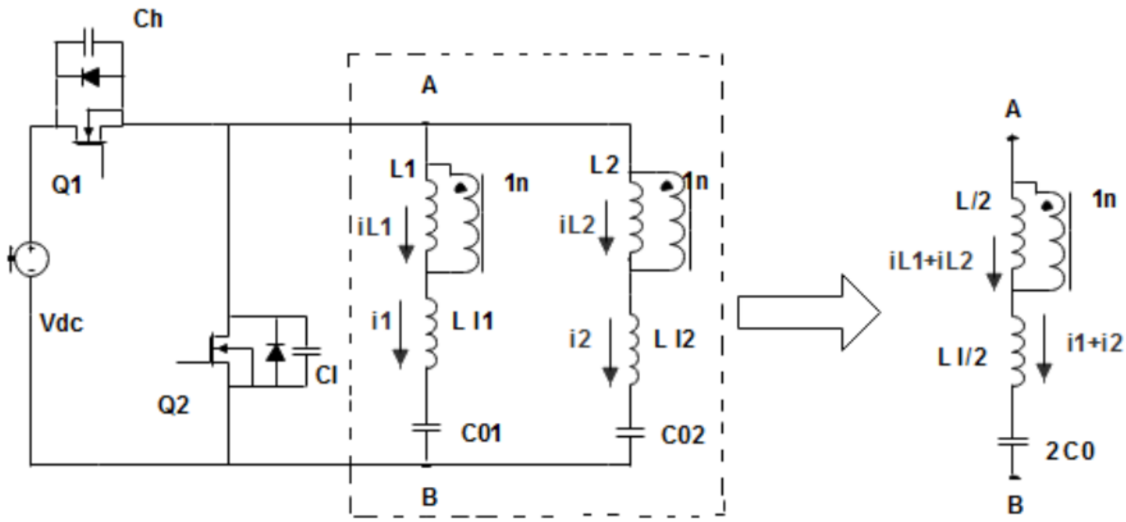

Fig.4 Equivalent circuit diagram for low level range

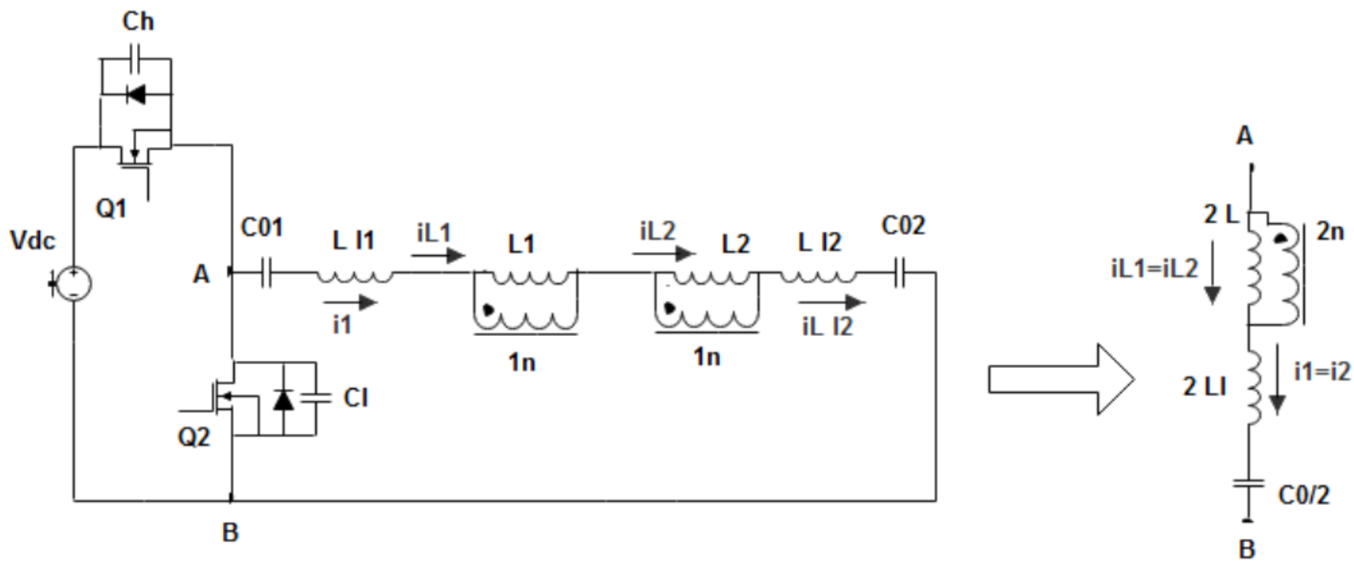

Fig.5 Equivalent circuit diagram for high level range

4. MODELLING ANALYSIS

To make the evaluation ease, several speculations are made as follows, $L_1 = L_2 = L$; $L_{l1} = L_{l2} = L_l$; $C_{01} = C_{02} = C_0$.

The proposed converter at low input voltage has two parallel resonant paths as shown in Fig.4, the resonant frequencies are modelled as F_{f1} and F_{f2}.

$$F_{f1} = \frac{1}{2\pi\sqrt{L_{l1}\ C_{01}}} = \frac{1}{2\pi\sqrt{L_l\ C_0}} \quad \text{- - - (A)}$$

The resonant frequency F_{f2} is given below,

$$F_{f2} = \frac{1}{2\pi\sqrt{L_{l2}\ C_{02}}} = \frac{1}{2\pi\sqrt{L_l\ C_0}} \quad \text{- - - (B)}$$

In parallel connection of coupled transformer, the corresponding magnetic inductance is described as *L/2* and leakage inductance ($L_{l,E}$), capacitance ($C_{0,E}$) are described as $L_l/_2$ and $2C_0$ accordingly.

$$F_{f3} = \frac{1}{2\pi\sqrt{(L_{l1}+L_{l2})(C_{01}||C_{02})}} = \frac{1}{2\pi\sqrt{L_l\ C_0}} \quad \text{- - -(C)}$$

From the above A, B, C equation it is clear that the frequency at resonance condition is similar to $\frac{1}{2\pi\sqrt{L_l\ C_0}}$.

In series connection of coupled transformer, the corresponding magnetic inductance is described as $2L$. The values of $L_{l,E}$ and $C_{0,E}$ can be described as $2L_l$ and $C_0/2$ accordingly.

The operation of preferred converter is similar to HB LLC converter and so the voltage gain is analysed as,

$$M=\frac{V_a}{V_{ac}}=\frac{1}{2n\sqrt{\left\{1+\frac{1}{K}\left[1-\left(\frac{F_f}{F_W}\right)^2\right]\right\}^2+\left\{\frac{\pi^2 Q}{8n^2}\left[\left(\frac{F_W}{F_f}-\frac{F_f}{F_W}\right)\right]\right\}^2}},\text{(D)}$$

Where k= $L_{,E}/L_{l,E}$; Q = $(L_{l,E}/C_{0,E})^{0.5}/R_0$ and F_w is the frequency at switching.

At high input voltage, the conventional converter operates at resonant region and at other voltage level it operates at below the resonant region. The converter has voltage gain with narrow switching frequency (Δf_S) = 90 KHz with K=4.8.

The turns ratio of the preferred converter at low and high input voltage level is given by $n/2$ and n respectively. The preferred converter has its voltage gain with narrow switching frequency (Δf_S) = 90 KHz and K= 13.2. The relation between the switching frequency and voltage gain is described in Fig.6.

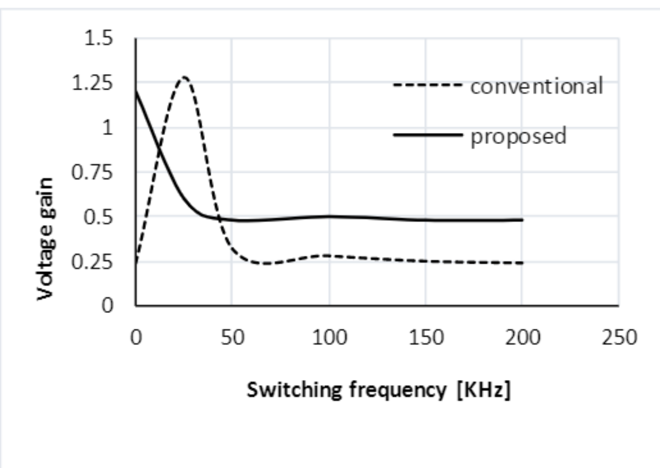

Fig 6. Relationship between gain and switching frequency

5. SIMULATED RESULTS

The preferred resonant converter performance is analysed using the MATLAB software and the output are analysed. The primary side current is similar to the sinusoidal shape because of the resonance between the capacitor and inductor and its waveform is shown in the Fig.7. The output of secondary side of the coupled transformer is an ac output and is rectified by using the synchronous rectifier and its waveform is shown in Fig.8.

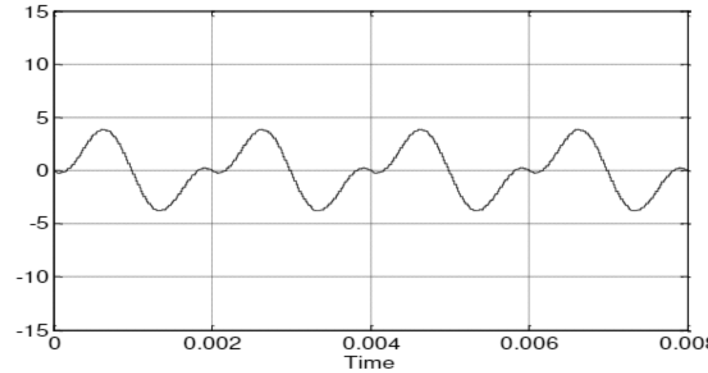

Fig 7. Output wave of primary current

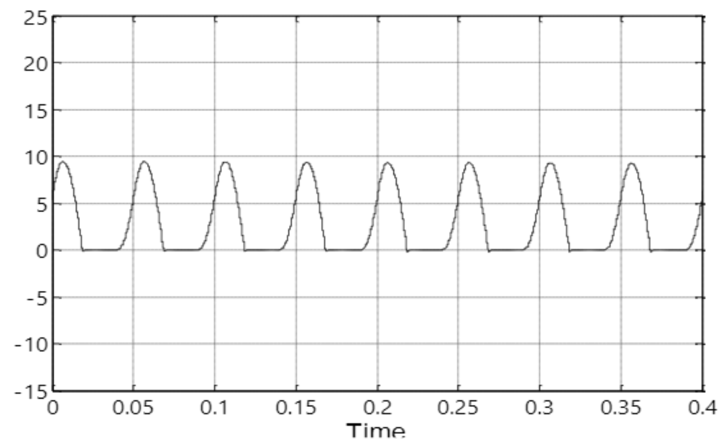

Fig 8. Output wave of synchronous rectifier

6. CONCLUSION

This paper reduces the use of auxiliary components in HB LLC converter for the application of wide input voltage level produces increased efficiency of the adapters targeting the tablets. The needed voltage gain of the preferred converter is decreased, since the use of relay makes the coupled transformer to be connected in series or parallel according to the applied voltage. The large magnetizing inductance minimises the primary side conduction losses, turn-on and turn-off losses of the converter. When input voltage is low, the parallel connection of the coupled transformer makes the converter has reduced wire resistance on primary side of transformer. Furthermore, the conduction losses of the converter are diminished. Though the overall size of the preferred converter is slightly increased due to supplementary components like relay and capacitor, this package can be easily inserted to the existing system.

For entire load conditions, the performance and ability of the preferred converter is greatly improved. Thus, because of the small size and compatibility of the preferred converter makes it efficient to use in wide voltage range.

Table 1. Component list of proposed converter

AC Input voltage	90 V ~ 250 V
DC Output voltage	16.5 V ~ 17.5 V
Transformer	$N_p : N_s = 24:\ 4$
	$L_1 = L_2$ = 250 µH
Resonant capacitor	$C_{01} = C_{02}$ = 40 nF
Resonant frequency	160 Hz
Relay	TX2-12V-TH (single pack of two relays)

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