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# Closed loop control analysis of half-bridge 1] resonant converter based battery charger

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*Series Resonant Converters (SRC) popularly known as Line Level Controlled (LLC) converters are the most suitable topology of DC-DC power supply. The closed loop voltage regulation of a Half-Bridge (HB) Line-Level-Controlled (LLC) converter using PI controller is presented in this paper. Major objective of PI controller is to modulate frequency and duty ratio of gate signals. A voltage controlled oscillator (VCO) is generating the gating signals which will drive the MOSFETs for getting a regulated output voltage. The optimum LLC switching frequency ranges are derived so that converter can operate at higher efficiency. In this converter the primary switches (MOSFET) are operated with Zero Voltage Switching (ZVS) and secondary switches (Diodes) with Zero Current Switching (ZCS) to have lower losses and hence to obtain higher efficiency. Finally the theoretical results are verified by simulating the converter in MATLAB[1]/Simulink™ circuit Simulator. The results obtained from simulation clearly signify the controller performance for adjustment of output voltage in case of variation in input line voltage and output current through the load. If the above observations are looked closely then it clearly indicates that the controller is executing the functions of regulating the output voltage. Whenever there is any variations in input line and output load then the output voltage across the load is able to follow the reference signal.*

***Keywords:*** *SRC, FB and HB topology, ZVS, ZCS, PI controller*

## 1.0 INTRODUCTION

Small size, high reliability and high efficiency are the major advantages of a battery charger. Resonant converters are gaining popularity as reported in recent papers due to their structure simplicity, high efficiency and less Electro Magnetic Interference (EMI). Among all battery charging topologies, the most common and efficient topology used are series resonant converters. The circuit essentially consists of a single phase DC-AC inverter, a resonant tank circuit [Resonant Inductor ($L_r$) and Resonant Capacitor ($C_r$)], a high-frequency transformer followed by a single phase AC-DC center-tapped rectifier[1], [2]. The Proportional-Integral (PI) controller is regulating the output load current and voltage output,which will control the performance of the converter [3], [4]. In reference to the survey done, the HBS-LLC-RC is found to be best suitable topology than compared to other resonant converters applied for charging battery. [1]

## 2.0 HBLLC RESONANT CONVERTER

Figure 1 shows the circuit diagram of an HB-LLC converter essentially consists of a HB resonant inverter, a current-driven High Frequency Transformer (HFT) with a center-tapped rectifier.

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With respect to circuit schematic, an *LLC* converter resembles an SRC. In HB topology the magnetizing inductance $L_m$ of HFT is higher than the resonant inductance $L_r$ in resonant tank circuit for which $L_m$ participates in resonance with $L_r$ and $C_r$ under some conditions of load which results in change of performance characteristics of resonant tank.

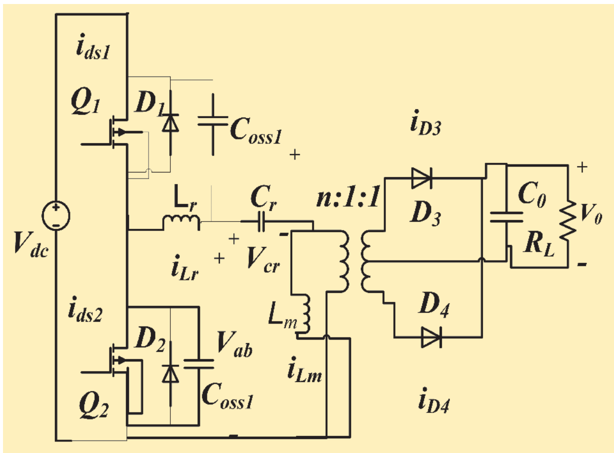


FIG. 1 LLCRESONANT DC/DC CONVERTER CIRCUIT SCHEMATIC

The circuit equivalent of the *LLC* resonant converter is shown in Figure 2 where $(R_i)$ is load equivalent of secondary resistance seen in primary side. It can be expressed as $[R_i = \frac{8n^2 R_L}{\pi^2}]$ .The output of inverter is a symmetrical square waveform ($v_{ab}$) with the magnitudes of $(+V_{in/2})$ and $(-V_{in/2})$ which can be obtained by complementary conduction of power switches ($Q_1$) and ($Q_2$).

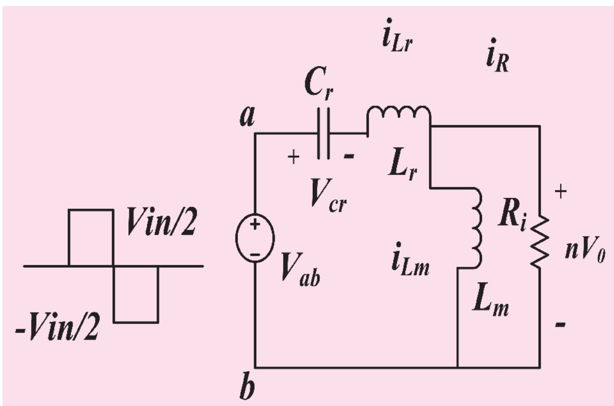


FIG. 2 SIMPLIFIED EQUIVALENT SCHEMATIC OF LLC RESONANT CONVERTER CIRCUIT

The voltage gain of converter can be formulated as in equation 1 [5]:

$$G(Q,k,f_n) = \frac{1}{\sqrt{\left(1+k-\frac{k}{f_n{}^2}\right)^2 + Q^2\left(f_n{}^2-\frac{1}{f_n{}^2}\right)^2}} \qquad ...(1)$$

with the parameters:

Quality factor: $Q = \frac{Z_0}{R_{ac}} = \frac{\sqrt{\frac{L_r}{C_r}}}{R_{ac}}$

where $R_{ac} = n^2 \frac{8}{\pi^2}\frac{V_0^2}{P_0}$ with $P_o$ as output power, Normalized Frequency: $f_n = \frac{f_{sw}}{f_{r1}}$

The second relationship between gain and normalized frequency can be expressed as in equation 2 [6].

$$G = \frac{2n(V_0+V_f)}{V_{in}} = [1+\frac{\pi^2}{4k}(1-f_n^{-1})]^{-1} \qquad ....(2)$$

## 3.0 OPERATION OF LLC-SRC

The first operation cycle of an LLC converter in Figure 1 can be divided into two modes as shown in Figure 3 and 4 [21]. The first two modes in half switching cycle are explained clearly which is continuing in similar fashion in the next half cycle.

**Mode 1:** This mode starts when the voltage across $Q_1$ reduces to zero before it turns on. As $Q_1$ gets turn on, the resonant current $i_{Lr}$ through the resonant tank circuit increases in a sinusoidal fashion due to resonance between $L_r$ and $C_r$. The magnetizing inductance $L_m$ is fixed to the output voltage*n* $V_0$ which gets linearly charged. Thus the magnitude of magnetizing current $i_{Lm}$ linearly increase. The diode $D_3$ of rectifier gets turn on under the condition of ZCS and hence the HFT secondary terminals starts supplying power to the load. The mode ends with magnitude of $i_{Lr}$ becoming same as $i_{Lm}$, which results in reduction of energy transfer to the load, thus reducing the current through diode $i_{D3}$ to zero causing it to turn off.

**Mode 2:** The mode gets started with $i_{Lr} = i_{Lm}$ and continues to remain until both currents have same magnitude. Eventually, the rectifier circuit at the secondary side of transformer gets isolated from the input side which results in power transfer to the load to be zero. The $L_m$ becomes in series with $L_r$ and $C_r$ which causes resonance thus resulting in flow of current only in primary side of the transformer. The mode ends with $Q_1$ gets turn off and voltage across the switch increases. The operation continues to remain the same for the next half switching cycle.

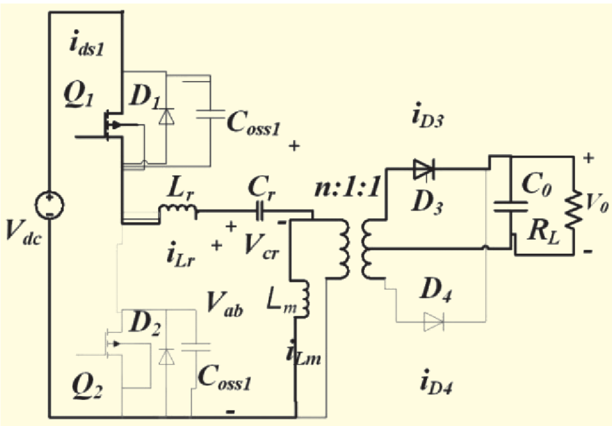


FIG. 3 EQUIVALENT CIRCUIT FOR CONVERTER IST MODE OF OPERATION

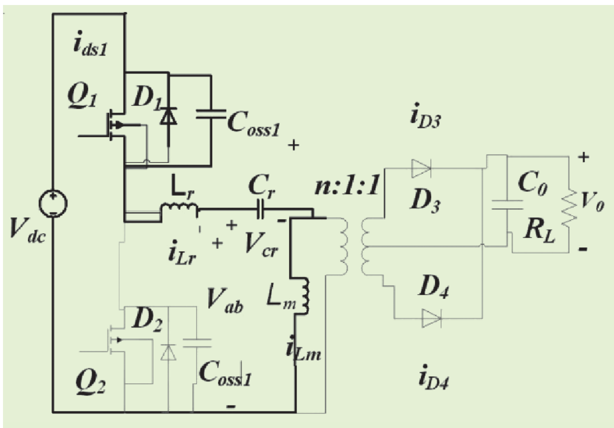


FIG. 4 EQUIVALENT CIRCUIT FOR CONVERTER 2ND MODE OF OPERATION

### 3.1 Design Specifications

The specifications of LLC converter is shown in Table 1.

| TABLE 1 | |
|---|---|
| HALF-BRIDGE LLC CONVERTER | |
| **Electrical Specifications** | |
| Input Voltage, ($V_{in}$) | (380 - 420) V |
| Output Voltage, ($V_o$) | (28 - 72) V |
| Output Current, ($I_o$) | (16 - 25) A |
| Maximum Power, ($P_o$) | 1.8 kW |
| Primary Resonant Frequency, ($f_H$) | 200 kHz |
| Secondary Resonant Frequency, ($f_L$) | 85.287 kHz |
| Switching Frequency | (94.6 - 226.6) kHz |
| **Component Parameters** | |
| Resonant Inductor ($L_r$) | 1.855 μF |
| Magnetizing Inductor ($L_m$) | 8.356 μH |
| Resonant Capacitor ($C_r$) | 34.2 μF |
| Transformer Turn Ratio (n:1:1) | 9:1:1 |

### 3.2 Simulation Results

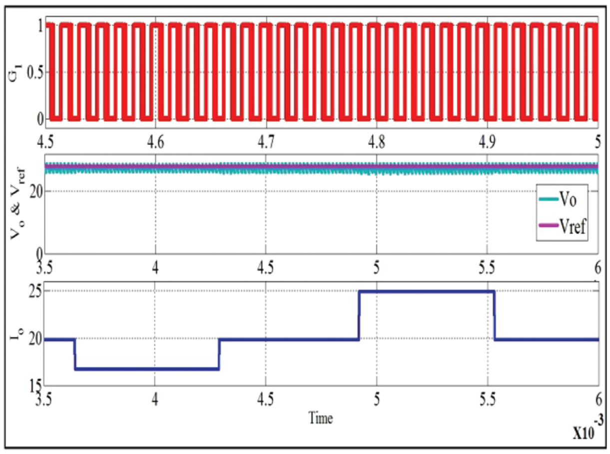


FIG. 5 (A) GATE PULSE TO THE SWITCH (Q1), (B) OUTPUT VOLTAGE ACROSS THE LOAD (V0) AND REFERENCE VOLTAGE [28 VOLTS], (C) STEP VARIATION OF OUTPUT LOAD CURRENT WITH LOAD VARIATION.

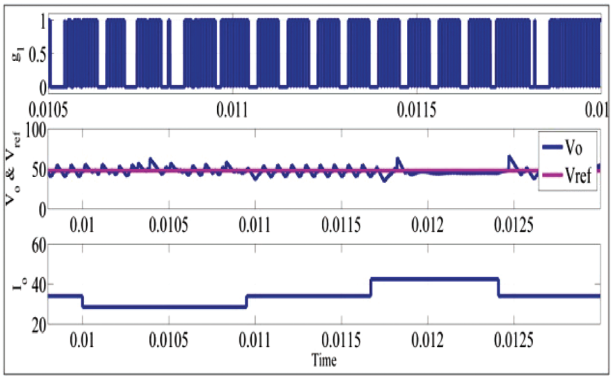


FIG. 6 (A) GATE PULSE TO THE SWITCH (Q1), (B) OUTPUT VOLTAGE ACROSS THE LOAD (V0) AND REFERENCE VOLTAGE [48 VOLTS], (C) STEP VARIATION OF OUTPUT LOAD CURRENT WITH LOAD VARIATION.

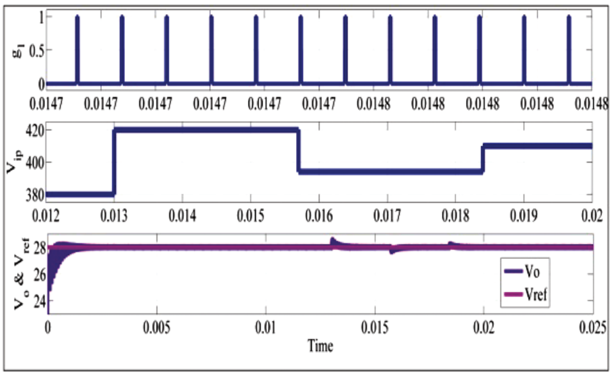


FIG. 8 (A) GATE PULSE TO THE SWITCH (Q1), (B) CONVERTER INPUT SOURCE VOLTAGE VARIATION, (C) OUTPUT VOLTAGE ACROSS THE LOAD (V0) AND REFERENCE VOLTAGE [28 VOLTS].

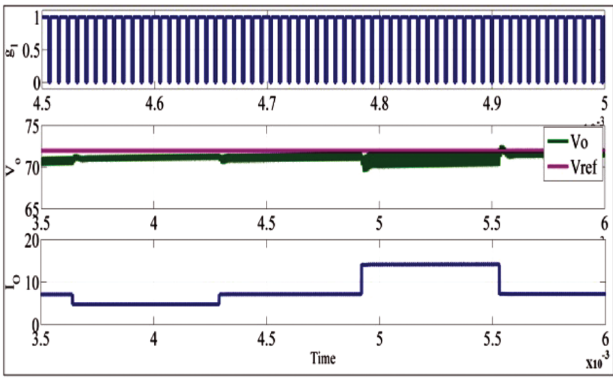


FIG. 7 (A) GATE PULSE TO THE SWITCH (Q1), (B) OUTPUT VOLTAGE ACROSS THE LOAD (V0) AND REFERENCE VOLTAGE [72 VOLTS], (C) STEP VARIATION OF OUTPUT LOAD CURRENT WITH LOAD VARIATION.

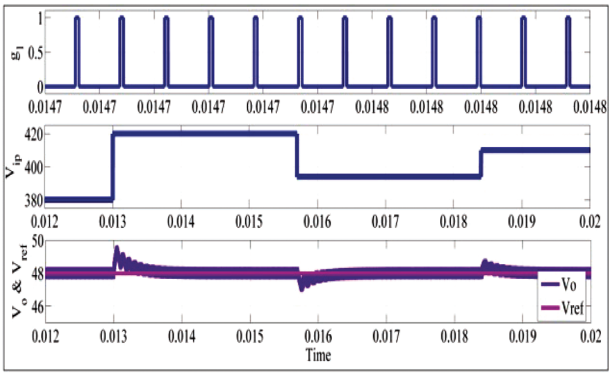


FIG. 9 (A) GATE PULSE TO THE SWITCH (Q1), (B) CONVERTER INPUT SOURCE VOLTAGE VARIATION, (C) OUTPUT VOLTAGE ACROSS THE LOAD (V0) AND REFERENCE VOLTAGE [48 VOLTS].

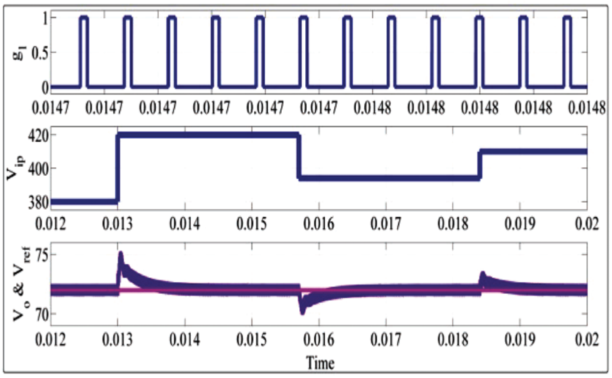


FIG. 10 (A) GATE PULSE TO THE SWITCH (Q1), (B) CONVERTER INPUT SOURCE VOLTAGE VARIATION, (C) OUTPUT VOLTAGE ACROSS THE LOAD (V0) AND REFERENCE VOLTAGE [72 VOLTS].

Figure (5 to 7) clearly depicts the controller operation for variation in current through load by 20% ,at reference output voltage levels of 28 V, 48 V and 72 V respectively. From the waveform it is observed that the controller is adjusting the variation in load current with the increase or decrease of load. The important observation is that the increase of load current variation is more with the increase in output voltage magnitudes.

Figure (8 - 10) represents the consequence of variation in input voltage in stepped form and the response of controller on its regulation. Voltage input to the converter varies in stepped form from (420 to 380) volts which gets regulated to the nominal value of 400 V.

From the above waveforms it can be observed that the controller is adjusting the variation in input voltage in less time for higher reference load voltage than that of its lower voltage counterpart.

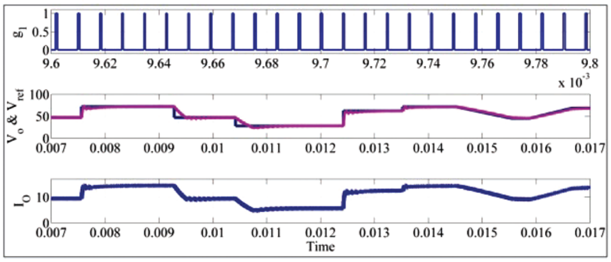


FIG. 11 (A) GATE PULSE TO THE SWITCH (Q1), (B) STEP AND LINEAR VARIATION OF REFERENCE VOLTAGE AND TRACKING OF OUTPUT VOLTAGE (V0) ACROSS THE LOAD, (C) OUTPUT LOAD CURRENT WITH REFERENCE VOLTAGE VARIATION.

Figure 11 presents the regulation of output voltage with variation in reference output voltage in stepped and linear form at different levels of output voltage. The output voltage is being regulated by the controller which is synchronous to reference signal magnitude changes. The adjustment is fast at lower voltage levels than that of the higher voltage.

## 4.0 CONCLUSIONS

In the paper, design and simulation analysis of half-bridge LLC converter for resistive load is presented together. Simulation analysis has been done in MATLAB/Simulink™ circuit simulator and its results has been compared with theoretical analysis. Results and observations shows the operation of controller for load voltage regulation in case of simultaneous variations in input line voltage and output current through load. It indicates the continuous tracking of controller with variations in line and load current in stepped form and also following the reference signal variations in stepped and linear form. So from the above observations it can be concluded that the LLC converter operated with closed loop control satisfies the necessities of DC-DC stage power conversion, which is equally applicable for charging of battery.

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