# Battery Chargers with Parallel – Loaded Resonant Converters

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***Abstract*—This paper presents the study conducted on parallel – loaded resonant (PLR) converter for battery charging application to improve the performance of traditional switching – mode charger circuits. The charging voltage can be regulated by varying the switching frequency that was set at continuous conduction mode (CCM). The simulation is done to simplify the charger circuit analyses and present an efficient, small – sized and cost – effective switched mode converter for battery charger, 12V – 48Ah battery. The simulation is done by using PSIM software to obtain the satisfaction performance of battery charger using PLR converter.**

***Keywords-battery charger, parallel – loaded resonant converter (PLR), soft – switching converter.***

## I. INTRODUCTION

In renewable generation systems, communications systems, electrical vehicles and computer systems are electrical energy storage elements. Although there are many kinds of batteries that can be used, the lead – acid battery can afford to store a reasonable amount of electrical energy and is adopted widely in the industrial field [1]. As the chemical reaction of the charging and discharging processes of the lead – acid battery will agitate the electrolyte and the stored – energy capability. To store the electrical energy of the battery, a delicate designed battery charging system must be used. Therefore, the usable life of the battery can also be reduced significantly. How to maintain the maximum capacity of lead – acid battery and extend its usable life is an important design problem for a charge, so many charging schemes have been proposed to improve this problem. Hence, we need to develop a high performance charger circuit in a battery energy storage system (BESS) [2].

There are two categories of battery charger which are linear – mode converters and switch – mode converters. The idea of implementing resonant switch in common switch – mode power supplies, is an attempt to reduce the losses in switches in switching during zero voltage/zero current states. This ideas lead to better overall efficiency from power supply, beside improves the power density of the same topology [3]. There are three types of resonant converter topologies which are Series Resonant Converter (SRC), Parallel Resonant Converter (PRC), and Series – Parallel Resonant Converter (SPRC). To solve this problem, soft switching resonant converter is implemented in the battery charger, using parallel – loaded resonant (PLR) converter. By altering the switching frequency, the regulation of the converter is done and thus changing the quality of the resonant components, to give the desired output voltage levels, as shown in Fig. 1. Besides soft switching of power switches, resonant converter also lead to low switching losses, which in turn result in greater charger efficiency, higher switching at operating frequency. Three advantages of linear – mode converters are: simplicity of design, no electrical noise in input, and low cost. Furthermore, switch – mode converter may be a simple way of converting a direct current (DC) source to a lower dc voltage and charging a battery, at high efficiency battery charger applications. In additions, the size and weight of the charger is reduced.

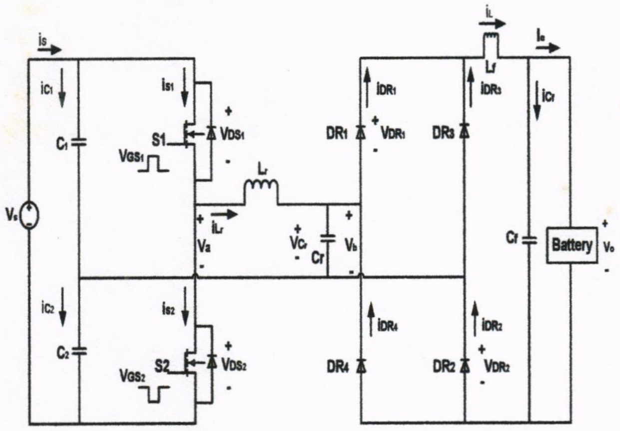

Fig. 1: Parallel - loaded resonant converter
for battery charger

Several factors concerning battery life span and capacity are depending on charge mode, maintenance, temperature, and age. But, the charge mode has a huge impact on battery life and capacity. Therefore, the batteries should be charged with current and voltage levels with low ripple. Thus, a high performance battery charger is necessary in the BESS in order to minimize the power losses and also to guarantee that the charging system is efficient [2]. PLR with high frequencies and soft switching technique is used to reduce the charging current ripple and extend battery life.

The PLR converter is able to control the output voltage at no load by running the frequency above resonance which consists of a parallel combination of a capacitor and inductor as the resonant tank. Through the capacitor, the output current is low, therefore reducing the conduction of the losses and the ripple voltage of converter. In addition, the PLR is inherently short circuit protected. Beside, the output voltage at resonance is a function of load and can rise to very high values at no load if the operating frequency is not raised by regulator. Hence, the PLR converter is very suitable for battery charger application. PLR is generally recommended at energy conversion stage due to its simple circuitry and typical input characteristic. The PLR converter can be operated either below or above resonance. The operating above resonance can overcome the disadvantages of PLR converters operating below resonance [4]. Consequently, the work carried out here is operation above resonance.

## II. METHODOLOGY

Fig. 2 presents the rectifier stage of half – bridge PLR converter for the battery charger. An output inductor filter, $L_f$ produces essentially a constant current from the bridge output to the load. By given a larger inductor filter to the output terminal, the charging current may be assumed to be constant. The switching frequency of the active power switches is assumed to exceed the resonant frequency such that the resonant current is continuous.

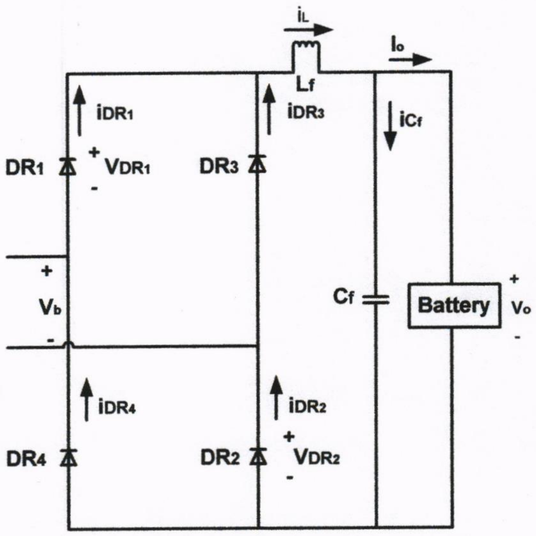

Fig. 2: Simplified equivalent output stage of the half – bridge parallel - loaded resonant (PLR) converter for battery charger.

In this project, the process involved are collecting, analysing data, and thus comparing data between theoretical calculation values with simulation result values. Flow chart in Fig. 3 summarizes the process of the project:

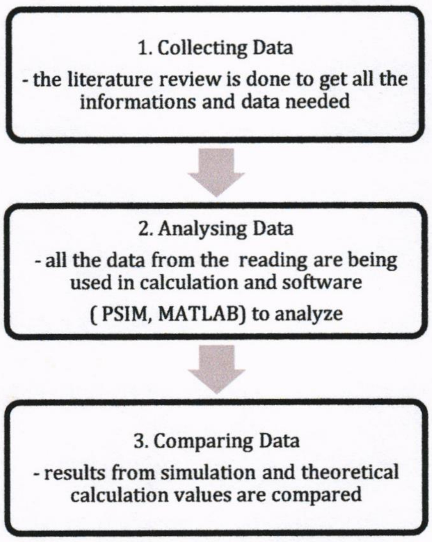

Fig. 3: The work flow chart

Justification of the circuit in Fig. 1 is that the power transferred from the half – bridge into the resonant tank is solely due to the fundamental component of the half – bridge output voltage, since the current drawn from the half – bridge is a fundamental frequency sine wave. The rectifier and load network is replaced by a resistor which draws equal current to the fundamental component of current drawn by rectifier. It is because the rectifier input voltage is a sine wave, and also the power transferred through the rectifier is due to the fundamental component of current. Fig. 4 below shows the circuit design work flow.

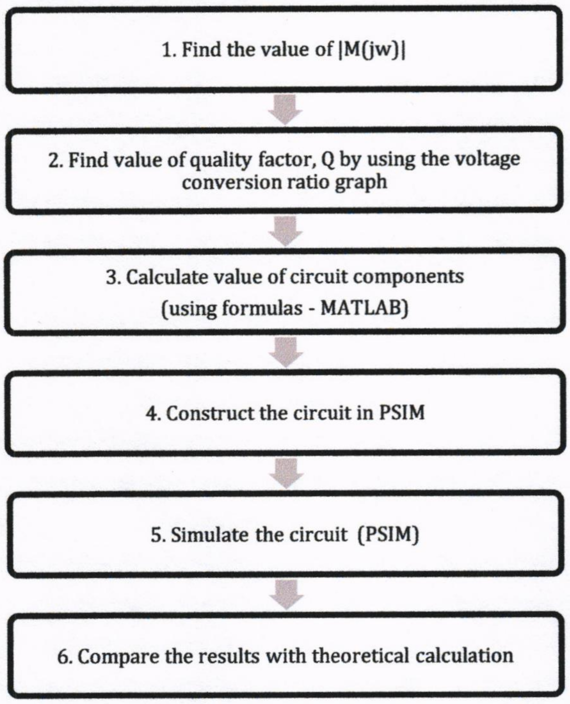

Fig. 4: Circuit design flow chart

## III. CIRCUIT DESCRIPTION AND OPERATING PRINCIPLES

### A. *Circuit Description*

By using the soft – switching method, it gives advantage of reducing the losses and extending the use life of the battery. In this paper, the proposed battery charger with PLR converter is shown in Fig. 1. The central part of a resonant converter is an $L_r - C_r$ circuit, known as tank circuit, which is maintained in continuous oscillation close to its natural frequency by switching action on semiconductor devices which the most common configuration are half and full – bridge. A DC output maybe obtains by rectifying and smoothing either the resonant voltage or current. In the half – bridge and $R_L - L_f - C_f$ circuit, the resistor represents the energy loss or load in circuit and in this case as the battery charger, the load waveforms being alternating current (AC). In order to supply power to DC load, the AC resistor is replaced by a rectifier, filter and DC load resistor as the battery charger. The effect of the rectifier and DC load network on the resonant tank is very similar that AC load energy is extracted from resonant network producing a damping effect, but however the resonant network remains same. The converter is shown in Fig. 1. The MOSFET body diodes are from the half – bridge and anti – parallel diodes. The sinusoidal capacitor voltage is rectified by the diode bridge and smoothed by the L – C filter to form DC output. The operation of the rectifier and smoothing is identical to mains – fed equivalent, although the input frequencies are very different.

The two capacitors, $C_1$ and $C_2$, on input are large and split the voltage of the input source. For the half – bridge topology, each bidirectional power switches has an active power switch and anti – parallel diode. The transistors are operated in anti – phase with duty – ratios of 0.5 over a switching period, T and at an angular frequency, $\omega_n$, close to the natural frequency of the $L_r - C_r$ network. The active power switches are driven by non – overlapping rectangular – wave trigger signal $\upsilon_{GS1}$ and $\upsilon_{GS2}$ with dead time. Thus, we may represent the effect of the power switches using an equivalent square – wave switching between $\pm V_s / 2$. The resonant capacitor voltage is rectified to obtain DC bus. The DC bus can be varied and closely regulated by controlling the switching frequency. Because the DC – to – DC power conversion, in this case, is achieved by rectifying the voltage across capacitor, $C_r$, a large filtering inductance $L_f$ is needed to minimize the loading effect of the output circuit and to ensure it the current through it is mostly DC.

The rectifier operation is assumed smoothing inductor current, continuous with negligible ripple. The DC load voltage $V_o$ has a value $\frac{V_b}{\pi}$, $V_b$ being amplitude of the sinusoidal input voltage. The rectifier input current, $I_{rect}$ or $i_b$, is a square – wave of $\pm I_o$ which is in phase with $V_b$, is positive or negative respectively. $I_o$ is the DC load current. The current in the resonant tank capacitor is, therefore the sum of the sinusoidal current $I_{Lr}$ and the square – wave current drawn by the rectifier. Under heavy load conditions, this may result in a slight distortion of the sinusoidal capacitor voltage. With these observations, the PLR can be modelled as a series *LC* circuit and the square – wave current source $\pm I_o$ in parallel with resonant converter. The simplified equivalent circuit for the battery charger with PLR converter is given in Fig. 5.

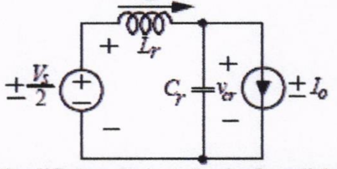

Fig. 5: Simplified equivalent circuit of parallel - loaded resonant (PLR) converter for battery charger

### B. *Circuit Operating Principles*

In resonant – switch topologies, resonant elements are used to shape the voltage across switch and/or the current through it. Some kind of snubber circuits are used to achieve the intended voltage and current waveforms for the switches [5]. The Fig. 6 shows the idealized voltage and current waveform of the half – bridge PLR converter for a switching frequency, $f_s$ above the resonant frequency, $f_o$. By operating above resonant frequency, the current flowing into resonant – circuit will be approximately sinusoidal, as the higher – order components are generally well attenuated. The sinusoidal current waveform lags the voltage waveform. When the voltage waveform reaches its zero crossing point, the current is still negative, allowing zero voltage switching (ZVS).

When the power switches is turn on at zero current and zero voltage, the freewheeling diodes do not need the fast reverse – recovery characteristics. During the positive half – cycle of the voltage across the resonant capacitor, through diode $D_{r1}$ and $D_{r2}$, the power is supplied to the battery charger. During the negative cycle, the power is fed to the battery through $D_{r3}$ and $D_{r4.}$ The parallel DC – DC converter can be analyzed on the assumptions that the voltage across the capacitor, $C_r$ is sinusoidal, taking only the fundamental frequencies of the square – wave voltage input and square – wave current into the bridge [6]. In addition, the filter inductor $L_f$ at the output terminal of the full – bridge is usually large, and therefore the output current through the inductor $L_f$ can be treated as a dc current in each switching cycle. Furthermore, $S_1$ and $S_2$ are on and off alternatively, applying a square – wave voltage across the PLR resonant circuit.

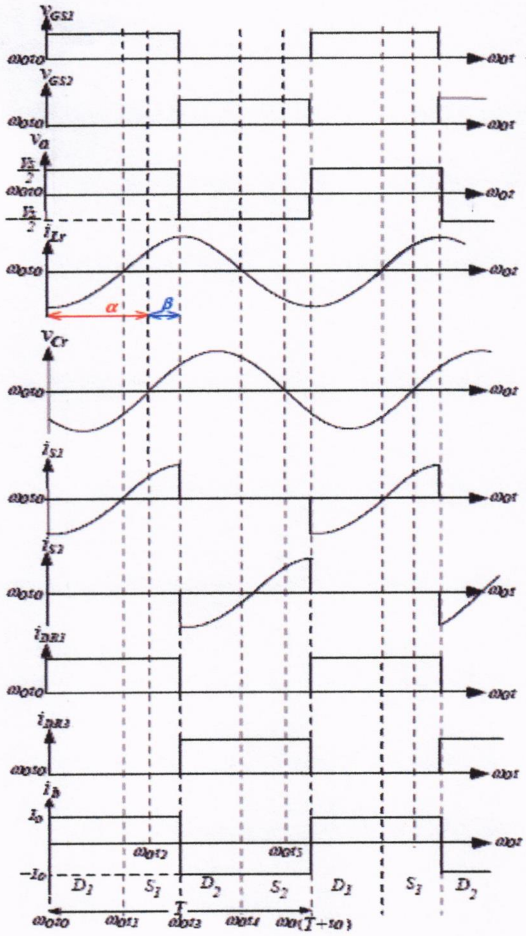

Fig. 6: Idealized voltage and current waveforms

Since the load current, $I_o$ is assumed constant, the input current to the output rectifier full – bridge, $v_b$ is $I_o/2$ when $v_{cr}$ is positive and is – $I_o/2$ when $v_{cr}$ is negative [4]. The equivalent circuit is shown in Fig. 7.

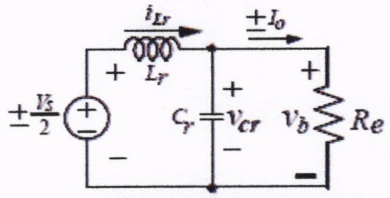

Fig. 7: Equivalent ac circuit of half - bridge parallel - loaded resonant converter for battery

Analysis can be carried out for the PLR converter. Using the equivalent resistance, $R_e$ from Fig. 3, PLR converter for battery charger is analyzed based on the fundamental frequency of the Fourier series of the voltages and currents.

$$V_o = \frac{1}{\pi}\int_0^{\pi} V_{b_1} \sin \omega t . d(\omega t) = \frac{2V_{b_1}}{\pi} \qquad (1)$$

Filter inductor current or load resistor current:

$$I_o = \frac{V_o}{R} \qquad (2)$$

$V_o$ is an amplitude of the fundamental frequency of $v_b$:

$$V_{b_1} = \frac{\pi V_o}{2} \qquad (3)$$

$I_{b_1}$ is the amplitude of the fundamental component of square – wave current, $i_b$ drawn by the rectifier:

$$I_{b_1} = \frac{4I_o}{\pi} = \frac{4V_0}{\pi R} \qquad (4)$$

Therefore, by definition the output resistance in the equivalent circuit of PLR converter is determined from the voltage to the current at the input terminal of the full – bridge rectifier. Equation thus defines resistance:

$$R_e = \frac{V_{b_1}}{I_{b_1}} = \frac{\frac{\pi V_o}{2}}{\frac{4I_o}{\pi}} = \frac{\pi^2 R}{8} \qquad (5)$$

$V_{a_1}$ is the amplitude of the fundamental frequency of the input square wave:

$$V_{a_1} = \frac{4\left(\frac{V_s}{2}\right)}{\pi} \qquad (6)$$

Solving for output voltage in phasor circuit of Fig. 7:

$$\frac{V_{b_1}}{V_{a_1}} = \left| \frac{1}{1 - \frac{X_L}{X_C} + j\frac{X_L}{R_e}} \right| \qquad (7)$$

Since a resonant circuit forces a sinusoidal current only the power of the fundamental component is transferred from the input source to the resonant circuit. Therefore, only the fundamental component of this converter needs to consider. Equation below defines the voltage transfer function of the PLR converter. Combining (3) and (6) with (7), the relationship between output and input of converter is:

$$\frac{V_o}{V_s} = \frac{4}{\pi^2 \sqrt{\left(1 - \frac{X_L}{X_C}\right)^2 + \left(\frac{X_L}{R_e}\right)^2}} \qquad (8)$$

Where:

$$\omega_o = \frac{1}{\sqrt{LC}} \qquad (9)$$

$$Q = \frac{R}{\omega_o L} \qquad (10)$$

Other than that, the actual converter output voltage may then be calculated. The magnitude and phase of the resonant current may be calculated and used to infer the device current waveforms in the half – bridge. The DC gain of the PLR converter is finally given by:

$$\left|\frac{V_o}{V_s}\right| = \frac{\frac{4}{\pi^2}}{\left|1-\left[\frac{\omega}{\omega_o}\right]^2 + j\frac{8}{\pi^2}\left[\frac{\omega}{\omega_o}\right]\frac{1}{Q}\right|} \qquad (11)$$

Rearranging,

$$\left|\frac{V_o}{V_s}\right| = \frac{1/2}{\left|\frac{\pi^2}{8}\left[1-\left[\frac{\omega}{\omega_o}\right]^2\right] + j\left[\frac{\omega}{\omega_o}\right]\frac{1}{Q}\right|} \qquad (12)$$

Q is defined as quality factor or loading (damping). A low Q corresponds to heavy damping of resonant tank. The tank is heavily damped for low values of load resistance. The reactance $X_L$ and $X_c$ depend on the switching frequency. By changing the switching frequency of the converter, the output voltage can be regulated. The normalized output voltage $V_o/V_s$ ratio or |M(jw)| is plotted as a function of $f_s/f_o$ at various loaded quality factors, $Q$. These curves are accurate above resonance where the resonant circuit filters harmonics of the input square waves [7].

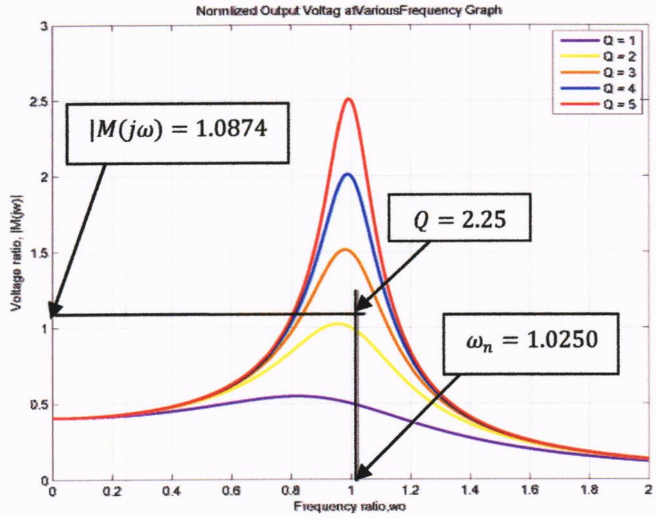

Fig. 8: Normalized output voltage at various switching frequencies

Fig. 8 shows that the half – bridge PLR converter output voltage can be larger than the input voltage [8]. The converter is appropriate for use in situations that required low input voltage and high output current. Small variation of $\omega_n$ results in large variations of |M(jω)|. Resonant peak is very close to $\omega_n = 1$ for large of Q and output voltage can be bigger than input voltage.

## IV. RESULTS AND DISCUSSION

The PLR converter has been simulated using PSIM software while theoretical calculation is done by using MATLAB programming. The analysis has been carried out as well for the PLR converter to investigate the output of PLR converter under load variation and switching frequency variation. The charger battery is replaced by $R_L$. The conditions of the simulation parameters for circuit design are shown below in Table I, while the full circuit of PLR converter is referred in Fig. 1. Calculations via MATLAB are done using MATLAB programming. The results are tabulated in Table I.

TABLE I
CALCULATION OF DESIGN CIRCUIT PARAMETER
FOR PLR CONVERTER

| **Parameter** | **Calculation Value** |
|---|---|
| **Inductor, $L_r$** | 4.0809 uH |
| **Capacitor, $C_r$** | 0.9699 nF |
| **Inductor, $L_f$** | 1 mH |
| **Capacitor, $C_f$** | 50 uF |
| **Resistor, $R_L$** | 4.6154 Ω |
| **Switching frequency, $\omega_s$** | 512.55 krad/s |
| **Resonant frequency, $\omega_o$** | 502.65 krad/s |
| **Normalizes frequency, $\omega_n$** | 1.0250 |
| **Quality factor, Q** | 2.2500 |
| **Voltage ratio, \|M(jω)\|** | 1.0874 |
| **Output voltage, $V_o$** | 29.9032 V |
| **Input Voltage, $V_s$** | 27.5V |
| **Output Current, $I_o$** | 6.4790 A |

The waveforms of the simulations are taken within three last cycles for duration of 0.1sec. Fig. 9 shows the waveform of the trigger signals $V_{GS1}$ and $V_{GS1}$, while Fig. 10 display the voltage and current waveform of the active power switch, $S_1$. The voltage and the current waveform for the input terminal of resonant tank is depict in Fig. 11. Fig. 12 showed the voltage waveform of resonant capacitor $v_{Cr}$ and the current waveform of resonant inductor, $i_{Lr}$. The input voltage and the output voltage waveform of the resonant tank terminal are illustrated in Fig. 13. The output voltage waveform of the full – bridge rectifier is illustrated in Fig. 14 while voltage and current waveforms of the rectifier diode $D_{R1}$ and $D_{R2}$ are displays in Fig. 15. Fig. 16 shows the output voltage and output current of the PLR converter. From the waveform in Fig. 16 the output is a smooth DC voltage and current, which the ideal circuit due to the LC filter.

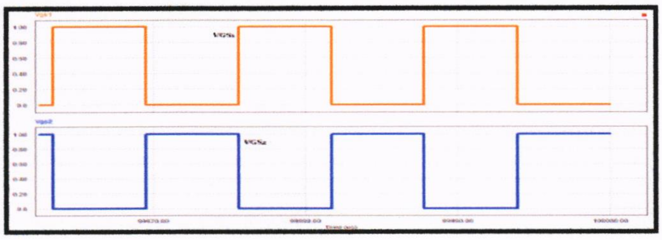

Fig. 9: Trigger signals of power switches

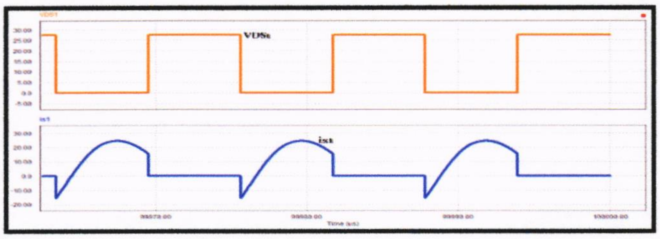

Fig. 10: Voltage and current waveforms of active power switch, $S_1$.

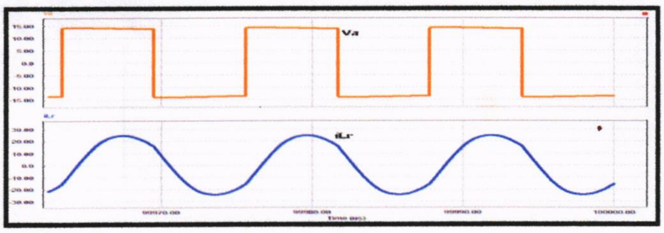

Fig. 11: Voltage and current waveforms of the input terminal of resonant tank

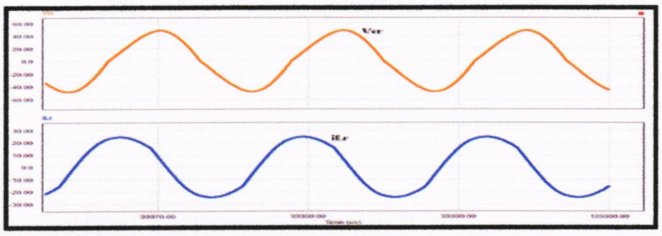

Fig. 12: Voltage waveform of resonant capacitor and current waveform of resonant inductor

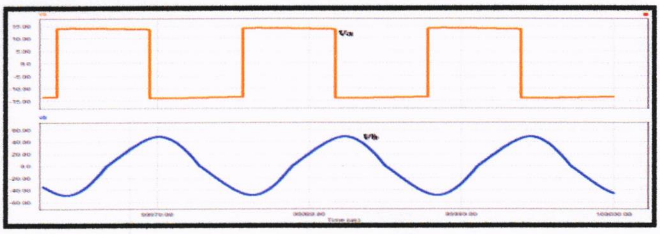

Fig. 13: Input and output voltage waveforms of resonant tank

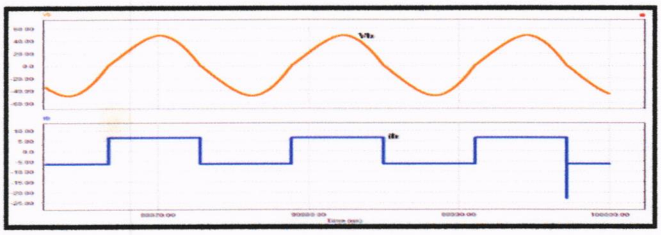

Fig. 14: The output voltage waveform of the resonant tank terminals and the input current waveform of the full-bridge rectifier

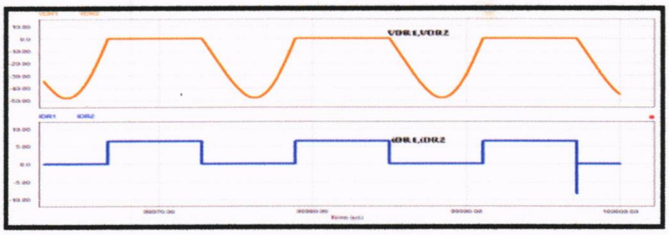

Figure 15: Voltage and current waveforms of rectifier diodes $D_{R1}$ and $D_{R2}$

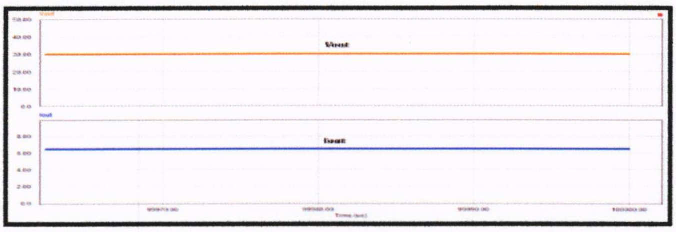

Figure 16: Charging voltage and current waveform of battery terminal

The simulation is done at the operating point above resonant frequency. Fig. 9 and Fig. 10 shows that both the resonant inductor current and resonant capacitor voltage increase after $Q_1$ is switched on and remains conducting until it is switched off naturally when the resonant inductor current reaches zero. Thereafter, the anti – parallel diode, $D_1$, starts to conduct and feed the stored energy in the resonant tank circuit to the input source. The system is operated in anti – phase with duty ratios of 0.5 and at angular frequency, $\omega_n$, close to the natural frequency to the LC – network. For the next half – cycle repeats the same way as the first half – cycle except that the direction of the resonant inductor current and the polarity of the of the resonant capacitor voltage are reversed.

Zero – voltage switching (ZVS) is achieved by forcing the current flowing through the switch to reverse. When the switch current reverses, the body diode clamps the voltage to a low value. As a consequence there is no transistor turn on loss and there are no rapid voltages or currents change. Also there is gentle diode turn off transient since the anti – parallel transistor conducts immediately after the diode. This principle is known as ZVS [9].

Fig. 11 illustrated that the current flowing into the resonant circuit is approximately sinusoidal. The sinusoidal current waveform lags the voltage waveform. When the voltage waveform reaches its zero crossing point, the current is still negative, allowing ZVS.

TABLE III
OBSERVATION FOR VARYING SWITCHING FREQUENCY, $f_s$ AT INPUT VOLTAGE, Vs 27.5 V.

| **$f_s$ (kHz)** | **Predicted Values** | | **PSIM Results** | |
|---|---|---|---|---|
| | **$V_o$(V)** | **$I_o$(A)** | **$V_o$(V)** | **$I_o$(A)** |
| **60** | 21.6748 | 4.6962 | 22.2742 | 4.8260 |
| **70** | 28.3737 | 6.1476 | 29.6743 | 6.4294 |
| **80** | 30.9375 | 6.7031 | 31.1456 | 6.7482 |
| **82** | 29.9032 | 6.4790 | 29.7645 | 6.4489 |
| **90** | 23.0002 | 4.9834 | 22.4026 | 4.8539 |
| **100** | 15.4678 | 3.3514 | 15.1513 | 3.2828 |
| **110** | 10.9362 | 2.3695 | 10.8108 | 2.3423 |

The output current of PLR converter is regulated by changing its switching frequency. As in the Table III, the average output voltage increases with increasing switching frequency below the resonant frequency of about 80kHz. However, the average output voltage decreases with increasing the switching frequency above the resonant frequency.

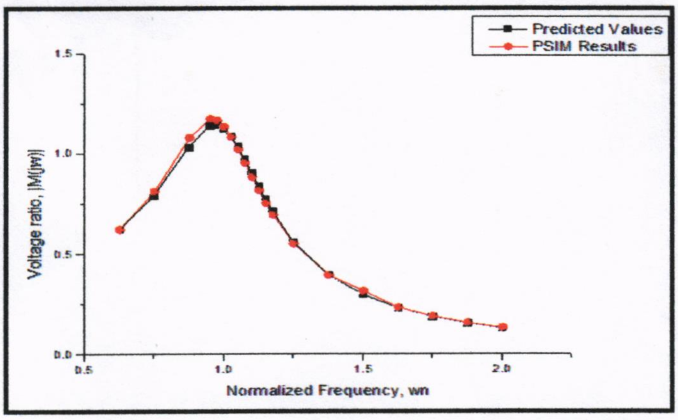

Fig. 17: PSIM Results and Predicted Values
for voltage ratio, |M(jw)|

Comparison the values of the voltage ratio, $|M(j\omega)|$ between simulation and prediction values is done. The simulations results of normalized frequency, $\omega_n$ at 0.750, 0.875, 0.950, 0.975 and 1.500 are slightly higher than prediction values. The results of the simulations are almost agreed with the prediction values that are done by MATLAB programming.

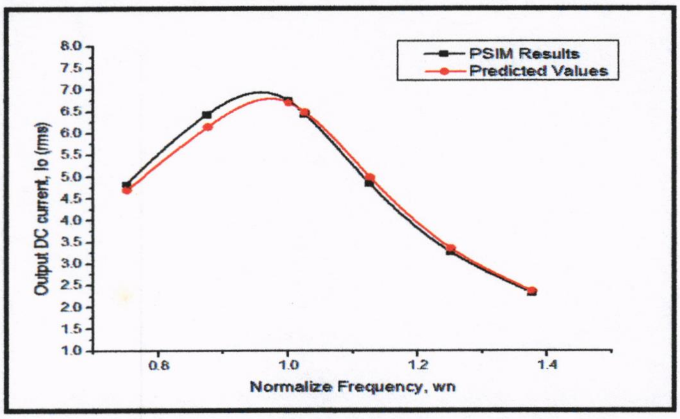

Fig. 18: PSIM Results and Predicted Values
for output DC current, $I_o$ (rms).

From the graph, there are a few points that are slightly different between the simulation values and predicted values. Comparison the values of the output DC current, $I_o$ (rms), between simulation and prediction values are done. From the graph, the results of the simulations are almost agreed with the prediction values.

TABLE IV
OBSERVATION ON LOAD VARIATION

| **Load, $R_L(\Omega)$** | **Quality Factor, Q** | **Predicted Values** | | **PSIM Values** | |
|---|---|---|---|---|---|
| | | **Output Voltage, $V_o$(V)** | **Output Current, $I_o$(A)** | **Output Voltage, $V_o$(V)** | **Output Current, $I_o$(A)** |
| 4.0000 | 1.9500 | 25.8393 | 6.4598 | 25.9758 | 6.4939 |
| 4.5000 | 2.1937 | 29.0300 | 6.4511 | 29.1689 | 6.4820 |
| 4.6154 | 2.2500 | 29.7644 | 6.4489 | 32.3433 | 6.4687 |
| 5.0000 | 2.4375 | 32.2074 | 6.4425 | 32.3433 | 6.4687 |
| 5.5000 | 2.6812 | 35.3690 | 6.3431 | 35.4973 | 6.4561 |

Table IV shows the response of the PLR converter to a load resistance variation from 4.0Ω to 5.5Ω with a constant input supply voltage, $V_s$ at 27.5 V and approximately constant load current of 6.5A. With a load resistance of 4.0 Ω, the output voltage is 25.9758 V with switching frequency 82kHz to yield a load current approximately of 6.5A. As can be seen, the output voltage increase to 35.4973 V as the load resistance increases to 5.5 Ω in order to maintain a constant load current. As the load resistance increases, the ripple current flows through the resonant inductor increases. However, its average value remains practically similar to that for a 6.5A. The quality factor, Q increases when the load resistance increases. This satisfied the equation (10) while both the resonant frequency, $\omega_o$ and resonant inductor, $L_r$ are constant.

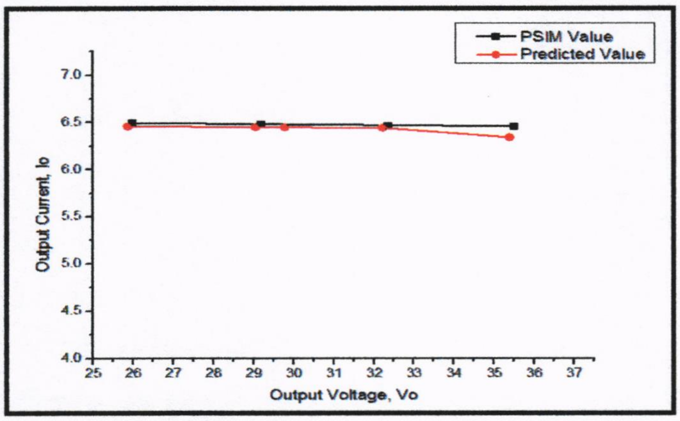

Fig. 18: Output Dc current vs output DC voltage

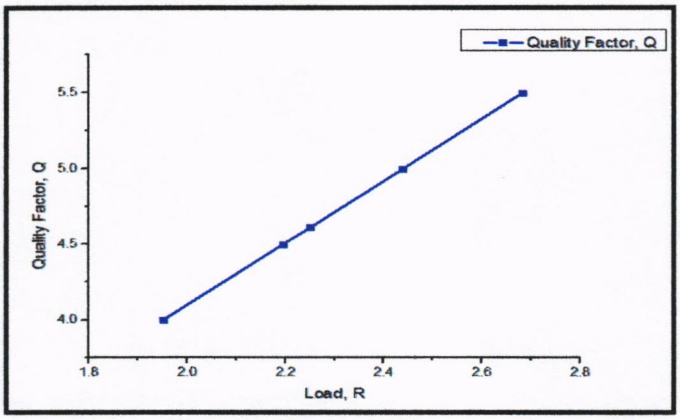

Fig. 20: Load variation

Fig. 20 shows that load, $R_L$ is varying linearly with quality factor, $Q$ in order to maintain constant load current, $I_o$ approximately to 6.5 A. The quality factor, Q increases when the load resistance increases. This satisfied the equation (10) while both the resonant frequency, $\omega_o$ and resonant inductor, Lr is constant.

At no load condition ($R_L = \infty$, $Q = \infty$) would present zero damping to the resonant tank. Result is very large voltage across resonant components (and rectifier diodes) due to the large circulating (reactive) energy [10].

## V. CONCLUSION

This work is conducted with a PLR converter with full – bridge rectifier for battery charger application. DC – DC converter system is simulated by using PSIM software with LC filter at the output and compared with the predicted values. The electrical performances of the PLR converter have been analyzed by simulation runs and indicate that the output of the inverter is nearly sinusoidal. The output of the rectifier is pure DC due to the presence of LC filter at the output. From the characteristic impedance of the resonant tank, the charging current can be determined by varying the switching frequency of the converter. It was found out that when the quality factor, Q increase, the output voltage will increase as well. When the load is increase, the output voltage will increase as well. Resonant converter is used to reduce switching losses in various converter topologies by taking advantages of voltage or current oscillations. Switches are opened and closed when the voltage or current is at or near zero. Others advantages of the PLR converter are:

- Low switching losses due to lossless snubber operation.
- Output regulated down to zero load with only a small variation in switching frequency.
- Resonant current insensitive to load current implying poor part – load efficiency.
- Resonant current increase with input voltage for a fixes output voltage and current.
- Suitable for high output currents since filter capacitor ripple current may be limited by appropriate choice of filter inductor.

The PLR converter is suitable for low – output voltage and high – current applications. This is due to the inductor limits the ripple current carried by the output capacitor. PLR converter structure is much simpler and cheaper than the other control mechanisms which required many components.

As a conclusion, this converter is less than ideal for application which may have large input voltage range and which requires it to operate considerably below its maximum design power while maintaining very high frequency. Conversely, the converter is better suited to applications which run from a relatively narrow input voltage range and which present a more or less constant load to the converter near the maximum design power. The simulation results closely agree with the prediction values.

In the course of the continuation of the research, a details analysis and investigation of the PLR converter topology will be performed and verified on an experimental for parallel loaded transformer less DC power supply application.

## ACKNOWLEDGMENT

I would like to wish thank you to Dr. Mohammad Nawawi Seroji and other contributors for guiding, invaluable advice and support in the preparation of this study. I would also like to acknowledge my deepest warmest gratitude to my parents, family members and friends for being so understanding and supporting me.

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