High Frequency MOSFET Charging Circuit Using Series Parallel DC-DC Resonant Converter for Wireless Power Application

N A A Nuawi¹, M F M Zin¹*, E A Kadir¹ and M N Seroji²

¹Faculty of Electrical Engineering, University Teknologi MARA, Terengganu (Dungun Campus, 23000 Dungun, Terengganu, Malaysia)
²Faculty of Electrical Engineering, University Teknologi MARA, Shah Alam (40450 Shah Alam, Selangor, Malaysia)

*Corresponding author: mazratul204@uitm.edu.my

Abstract. This paper proposes a new circuit topology of high frequency switching DC-DC Series Parallel Loaded Resonant Converter (SPLRC). The circuit is proposed to be used for a wireless power transmission application that required fast-charging operation. Most of the components used here are low-cost and commercially available in the market. Then, the purpose circuit is transformed into a different equivalent circuit that can efficiently analyze AC and DC modes. For each model, the operation for the converter is first described and explained. A full detailed circuit simulation is then carried out to find out the workability of the purpose converter. From the simulation, optimization is carried out. Here the components value is obtained. MATLAB R2018A is used for simulation purposes rather than being tested again using PSIM software to further prove the validity of the model. All the finding is explained and discussed, here, from the simulation result, it is confirmed that a high-frequency switching circuit is operated as expected.

1. Introduction

Nowadays, high frequencies driver in wireless power transfer is widely used, especially since the advent of amplitude-modulated radio in the early 20th century. Small and medium-sized autonomous electronic devices that involve periodic battery recharging have broad applications in portable communication devices, office equipment, pharmacy, automobile, and so on. Nevertheless, due to the presence of friction contacts, the use of conventional conductive power interfaces affects the efficiency of devices that restrict their use or renders them totally unacceptable, as in implants [1]. Wireless power always about freedom and convenience from power cords; it also influences the way suppliers can manufacture devices. An efficient wireless power transfer method would enable advances in such diverse areas as embedded computing, mobile computing, sensor networks, and micro robotics [2]. To operate wireless power transmission, the signal's frequency to be transmitted and received needs to be high compared to the standard frequency of 50Hz. Most hard switching converters have low-efficiency difficulties, with bulky magnetics resulting in a low frequency of switching [3]. It seems high power losses is depending on the high switching technique [4]. Hard-switching in DC-DC converters is prone to high switching losses as it requires switching on and off with the full load current. Nevertheless, switches only turn on and off in soft-switching resonant DC-DC converters when the voltage across or the current through them is zero, thus reducing or eliminating switching losses [5].
Wireless power transfer has been acknowledged as one of the marginal methods to transfer power quickly and conveniently. Another work has proposed a low-cost project. Previous researchers have presented a variation of technique and approach as a solution to the problem. Mainly in this project, an advanced power converter will be developed in wireless power transfer. The driver consists of a High-frequency DC-AC converter with a design example of a 240 V supply than using an adapter to produce 24 V DC input. Generally, the energy dissipation in the power inverter increases with the operating frequency [6]. After that, a switching frequency of 120k Hz and 600 W power output converter will be used as the second stage of an AC to DC converter. Hence, an advanced topology of the DC to AC converter for the transmitter side and an AC to DC converter topology for the receiver side will be designed.

The research study focused on a high-speed switching circuit using high capacity gate and low voltage value Mosfet, which commercially available in the market. The aim is to develop and design a high-frequency Mosfet driver that can drive Mosfet, mainly within class E configurations. Compared to other switching power amplifiers, Class-E has fewer components, yielding high reliability [7]. Furthermore, to develop the proposed high-speed switching circuit and test for wireless power transfer application.

2. Basic Principal of Resonant Converter

2.1 Series Loaded Resonant Converter (SLRC)

For SLRC, the resonant current rather than the voltage is rectified and smoothed to form DC output in figure 1. It is again assumed that the Mosfet body diodes include the half-bridge antiparallel diodes. Since the rectifier is current-fed, the output filter only consists of a shunt-connected capacitor. The current-fed happens because the filter must have the capacity to absorb abrupt changes in the rectifier output current. It is assumed that there is negligible ripple voltage across the output smoothing capacitor. The sinusoidal rectifier input current defines that the operation of the circuit. The converter also a strong candidate with the capability for current source output behavior with a high impedance output. Nonetheless, SLRCs behave differently with constant current input compared to traditional constant voltage input [5]. Meanwhile, the converter's power throughput is controlled by operating the converter closer to, or further from, the natural resonant frequency, thereby effectively varying the impedance of the resonant tank.

2.2 Parallel Loaded Resonant Converter (PLRC)

Based on figure 2, the PLRC showed that the MOSFET body diodes form the half-bridge antiparallel diodes. Previous studies showed huge potential developments to capable of operating under zero-voltage switching (ZVS) turn-on of switches and zero-current switching (ZCS) turn-off of diodes and works in a narrow switching frequency [8]. The sinusoidal capacitor voltage is rectified by the diode bridge and smoothed by the L-C filter to form the DC output. The rectifier and smoothing circuit operation is identical to a mains-fed equivalent, although the input frequencies are very different. DC load voltage, \( V_o \) has a value of \( \frac{2}{\pi} V_c \), where \( V_c \) is the sinusoidal \( V_m \)'s peak.

\[
V_o = \left(\frac{2}{\pi}\right)V_c
\]  

(1)

Rectifier current, \( I_{rect} \) is a square wave of \( \pm I_o \), which is in phase with \( V_c \), while output current is the DC load current. Therefore, current in the resonant tank is a sum of sinusoidal current \( I_{xy} \) and the rectifier's square wave current.
2.3 Series Parallel Loaded Resonant Converter (SPLRC)

To overcome the limitations of the basic SLRC and PLRC, the combined series-parallel-loaded converter, as shown in figure 3, is frequently used. The converter is produced by splitting the resonant capacitor into two components \( C_r \) and \( C_p \). The load is connected in parallel with \( C_f \). The principal features of the SPLRC are a voltage-fed rectifier circuit with an L-C filter. The filter capacitor ripple current may be controlled by the filter inductor's appropriate choice, and therefore the circuit is suitable for high output applications. Next, at heavy load, the parallel capacitor \( C_p \) is effectively shorted by the rectifier circuit's relatively low input resistance. L-Cr dominates the resonant tank's operation, and the converter takes on the characteristics of a series-loaded converter. In particular, the resonant current \( I_{xy} \) falls as the load is reduced, resulting in good part-load efficiency.

Figure 3 shows that the basic series-parallel loaded resonant converter used for the proposed project. Only a fundamental component is considered for the analysis as in figure 5, so equivalent ac resistance, \( R_{eff} \) is:

\[
R_{eff} = \frac{\pi^2}{8} R
\]

Where \( R \) is load resistance.

Furthermore, \( I_{xy} \) is insensitive to input voltage for a fixed output voltage and current. At light load, \( C_p \) is no longer effectively shorted since the rectifier input resistance is increased. The converter, therefore, takes on the characteristics of a parallel-load converter - most importantly, that the output voltage may be regulated at the light and zero loads.
3. Design of Converter

AC analysis or fundamental frequency analysis (FFA) is the most popular, simple, and effective method of analyzing DC-DC resonant converters [4]. In this method, the energy transfer from source to the load is assumed to be contributed only by the fundamental component while harmonics are neglected. Though this method is only approximate and not accurate, it is preferred owing to its simplicity, the lesser computation time for solving, and practical ease of implementation. Hence, researchers continue to use this method for analyzing resonant converters [4], [5]. The assumption made in the converter:

1. All the diodes and switches are ideal, and switches communicate linearly.
2. The passive components behave linearly.
3. All resonant components and filter capacitors assumed lossless.

The converter used by following the specifications bellow:

- \( V_{in} = 240 \text{ V} \)
- \( V_{dc} = 24 \text{ V} \)
- \( f_s = 120k \text{ Hz} \)
- \( P_o = 600 \text{ W} \)
- \( C_{DC} = 500\mu \text{ F} \)
- \( C_o = 500\mu \text{ F} \)
- \( L_o = 1\mu \text{ H} \)
- Power Switches = MOSFETs

Figure 4 shows the proposed converter of DC-DC SPLRC for wireless power transmission. The design of a resonant converter often starts by designing the resonant network.

\[
\omega_o = \frac{1}{\sqrt{L_s C_s}} = \frac{\omega_s}{\omega_n}
\]  

(3)

- \( L_s = \) Inductor series of a resonant tank
- \( C_s = \) Capacitor series of a resonant tank
- \( \omega_s = \) Switching frequency

Where normalized frequency, \( \omega_n \):

\[
\omega_n = \frac{\omega_s}{\omega_o}
\]  

(4)
Quality factor, \( Q \), of the SPLRC:

\[
Q = \frac{\omega_0 L_s}{R_l}
\]  
(5)

As component stresses are directly a function of \( Q \), so value of \( Q \) should be chosen as low as possible.

\[
\left| \frac{V_o}{V_{in}} \right| = \left| \frac{0.5}{\pi^2} \frac{C_p}{C_s} \left[ 1 + \frac{C_p}{C_s} \left[ 1 - \omega_n^2 + jQ \left[ \frac{1}{\omega_n} - \frac{1}{\omega_n^2} \right] \right] \right| \right|
\]  
(6)

**Figure 6.** Gain curve for SPLRC for \( C_p/C_s = 0.5 \).

**Figure 7.** Gain curve for SPLRC for \( C_p/C_s = 1 \).

**Figure 8.** Gain curve for SPLRC for \( C_p/C_s = 2 \).

**Figure 9.** Gain curve for the proposed converter by using \( C_p/C_s = 0.5 \).

The quality factor to design the proposed converter can be analyzed from figure 6 to figure 9, gain versus normalized frequency, for SPLRC when the value of \( C_p/C_s = 0.2 \), 1, 2. Thus, the value of normalized frequency, \( \omega_n \) for the proposed design, can be obtained from the converter’s gain value. Since the value of gain for the converter is 0.7, the value for \( \omega_n \) is 1.6037 for \( Q = 0.5 \), as shown in figure 9. The lower value of \( Q \) corresponds to light load condition and higher value for full load condition.

**4. Result and Discussion**

This section represents the simulation of the proposed SPLRC. DC power supply of 240 V was step down by using adapter to 24 V at 50 Hz is used as shown in figure 10 by using PSim. The simulation work on suggested SPLRC is performed using 120k Hz of switching frequency, \( f_s \). The value of \( Q \) is 0.5 with \( \omega_n \) of 1.6037 as stated from previous section. The components value for the design was calculated by using MATLAB R2018A as well as experimental components value are shown in table 1.
A straightforward technique to understand resonant topologies’ characteristics is by looking at their gain curve plot, as discussed in section B part III. The curves show that if the resonant converter operates above the resonant frequency (the right side of the gain curve), the controller won’t regulate the output voltage. Once the opposite condition happens, the same is true. The curves also imply that Q decreases as the load increases. The gain curve becomes flat, and, hence, major frequency modifications are expected to ensure the desired output voltage. Therefore, open circuit control is unlikely even if there is no resonant peak or selectivity. The high Q value is desirable to achieve better control in the series resonant converter. The trade-off, however, is that if Q is too high, then the output control mechanism becomes very nonlinear. The minor shift in the switching frequency will produce a significant change in the output voltage, and the operating frequency also could be shifted quite near to the resonant peak by the circuit. The condition destabilize the power supply in turn.
The converter will work with a very low Q to avoid the non-linear gain curve characteristics, so the curve should be flat at virtually any frequency, as shown in figure 12. Even more observation of figure 12 poses the issue of regulating the output voltage; how can you control the output when the voltage stays the same at either frequency? The proposed design solves this problem. A parallel capacitor is placed after series of inductors and capacitors at a resonant tank. To control the output voltage, the filter capacitor ripples current is governed by the appropriate choice of the filter inductor. Therefore the circuit is suitable for high output applications, as shown in figure 13. It takes on a parallel-load converter's characteristics, most notably that the output voltage may be regulated at the light and no load. In the case of the two switches or Mosfets operate above the resonant frequency, Fo the resonant tank now acts as inductive impedance resulting in the resonant current, I_{xy} lags the resonant voltage, V_{xy} as illustrated in figure 14.

Due to the resonant current I_{xy}, the antiparallel diode D1 conducts negatively prior to transistor Q1 conduction during turn-on. Since D1 is already on-state, the system Q1 voltage is zero, so the transistor can operate with zero-voltage across it. The mechanism's voltage increases to the off-state level so that the incoming diode is forward-biased until the current can fall. The transistor's turn-off condition is similar to the conventional square wave converter as the loss exists at turn-off in switching devices. The results of simulation of SPLRC using calculation and experimental shown as table 2 for voltage output, V_o and current output, I_o.
Table 2. Results of the simulation using PSim

| Simulation of SPLRC from calculation | Experimental simulation of SPLRC |
|--------------------------------------|----------------------------------|
| $V_o$                                | 0.005                            |
| $I_o$                                | 0.008                            |
|                                      | 0.58568                          |
|                                      | 1.17136                          |

5. Conclusion
A new circuit topology of high frequency switching DC-DC Series Parallel Loaded Resonant Converter (SPLRC), including wireless power transmission application, was proposed in this paper. The converter switches operated in constant voltage with constant high frequency. Wireless power transmission is one of the famous areas of research nowadays. The implementation of an advanced converter for wireless power transfer is significant to society and the economy. Hence it is a concern that the proposed advance high-frequency DC-DC converter or inverter topology for the transmitter side could successfully develop to transfer the power with high efficiency to the load. Nevertheless, another concern is to ensure the synthesized advanced AC-DC converter or rectifier for the receiver part can execute as a complete wireless power transmission interface that can feed the DC load with improved power conversion efficiency by DC source.

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References
[1] Pavlov G, Vinnichenko I, Pokrovskiy M, and Tarabanov N 2019 Electromagnetic Processes in Serial-To-Parallel Resonant Converter for Contactless Charging of Electric Vehicle Battery 2019 IEEE 39th Int. Conf. Electron. Nanotechnology, ELNANO 2019 - Proc 668–673.
[2] Stancil D D and Goldstein S C 2009 Magnetic Resonant Coupling As a Potential Means for Wireless Power Transfer to Multiple Small Receivers IEEE Trans. Power Electron. 24(7) 1819–1825.
[3] Patii D, Rathore A K, Srinivasan D, and Panda S K 2014 High-frequency soft-switching LCC resonant current-fed DC/DC converter with high voltage gain for DC microgrid application IECON Proc. (Industrial Electron. Conf. 4293–4299.
[4] Ghalib M A and Abdalla Y S 2013 Design and Implementation of a Pure Sine Wave Single Phase Inverter for Photovoltaic Applications Int. Conf. Informatics, Electron. Vis.1–8.
[5] Khalil-Abaker M, Shi J and Kalam A 2016 Design of a 100W bi-directional LCC series-parallel resonant DC-DC converter 2016 Australas. Univ. Power Eng. Conf. 1–5.
[6] Jiang C, Chau K T, Liu C and Lee C H T 2017 An overview of resonant circuits for wireless power transfer Energies 10(7) 1–20.
[7] Chen W, Chinga R A, Yoshida S, Lin J, Chen C and Lo W 2012 A 25.6 W 13.56 MHz wireless power transfer system with a 94% efficiency GaN Class-E power amplifier IEEE MTT-S Int. Microw. Symp. Dig. 25–27.
[8] Kim M, Noh S and Choi S 2015 New parallel loaded resonant converter with wide input and output voltage range 9th Int. Conf. Power Electron. - ECCE Asia "Green World with Power Electron. ICPE 2015-ECCE Asia 515–520.