

## A Study on the Effect of Load Variation on Quality Factor for Single-Phase Half-Bridge Resonant Converter

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**Abstract** — This paper studies on the effect of load variation on quality factor for the three types of half-bridge loaded resonant converter topologies; series resonant, parallel-resonant and series-parallel (hybrid) resonant for use in low output voltage power supply applications. The relationship between input voltage and output voltage (voltage gain/ratio) is used along with resonant frequency for determining parameters value to investigate the effect of quality factor (Q) on load variations. The results show that the hybrid resonant converter, which combines the best characteristics of the series-loaded resonant converters and parallel-loaded resonant converters, have the same characteristics with the series-loaded resonant converter in terms of quality factor on load variations. Computer simulation model was developed using MATLAB/Simulink and selected results are presented to verify the studies.

**Keywords** - series-loaded resonant converter, parallel-loaded resonant converter, hybrid resonant converter, quality factor

### I. INTRODUCTION

Nowadays, compact design of electrical appliances with higher efficiency, higher power density and higher component density receiving renewed interest and have become common in power supply designs to meet the energy saving requirements and high power quality. Thus, to fulfil the requirements of higher power and component density in order to develop compact design of any electrical circuit, need to use the high switching frequency operation. However, when a switch turns *ON* or *OFF* it takes a small amount of time (delay time) for its voltage or current to fully drop to zero hence experiences switching losses where the losses are increase by increasing the switching frequency.

In order to reduce the higher switching losses in the semiconductors resulting from higher frequency operation, it is desirable to use resonant power conversion due to the potential of these types of converters to achieve both higher switching frequencies operation with lower switching losses. The main idea of resonant converters is to provide soft switching transitions in order to be able to increase the switching frequency operation in order to decrease the passive filter requirements and/or the output current ripple thus reducing the disturbing noise of the converter.

There are several types of resonant converter topologies; series, parallel and hybrid topology where all of these types of converter operate in essentially the same way: A square pulse of voltage or current generated by the power switches is applied to a resonant circuit. Energy circulates in the resonant circuit, and some or all of it is then tapped off to supply the output.

While there have been many published performance studies of half-bridge resonant converters as in [1-7], none has specifically investigated the effect of the impact of quality factor and load variations on the converter's performance. The focus of this paper is therefore to studies on the behaviour of the series resonant topology, parallel resonant topology and a combination series-parallel (hybrid) resonant topology on the effect on load variation on the value of quality factor. The initial studies uses a fix parameters of the input voltage, output voltage, switching frequency, quality factor (Q) and output power. The behaviour of the resonant voltage and current are investigated. Then, the study are carried by varying the load (reduce the load and increase the load) to investigate the behaviour of the quality factor, Q. In addition, the performance of these three types of resonant converter is analysed based on load variations. Finally, computer simulation model based on MATLAB/Simulink were modelled to verify the performance of these resonant converter.

This paper is organized as follows; Section II discuss a review on loaded resonant converter which is consist of the circuit description and operation principles of the series, parallel and hybrid resonant converter. In Section III, the computer circuits simulation modelled are introduced. Section IV shows the selected results from MATLAB/Simulink and discussion to verify the studies. Finally, conclusions of this study are given in Section V.

II. A REVIEW OF RESONANT CONVERTER

There are many resonant-converter topologies uses for high switching frequencies and soft switching technique. These types of converters are; the series resonant converter, parallel resonant converter, and hybrid resonant converter, depending on the manner by which energy is extracted from the resonant tank that explicitly discuss in the next subsequent section.

Loaded resonant converters that was defined as converters that utilize the soft-switching techniques and by considering the load is part of the resonant circuit, operates by inverting a DC input into an AC waveform and then rectifying the AC waveform back into a DC waveform [9]. Basically, its circuit configuration consists of an inverter circuit, a resonant tank, a rectifier circuit and an output LC filter. While, for the resonant tank, mainly consists of an inductor and capacitor, can be configured in series, parallel or hybrid configurations, where the current naturally commutates to zero limiting switching losses, hence could improving the converter’s efficiency by properly set the timing of the switching signal.

A. Series-Loaded Resonant Converter

Generally, the series loaded resonant converter is configures by employing an inverter, an inductor, a capacitor, and a bridge rectifier. The direct current (DC) from the source is inverted to a form of alternating current (AC) that flow through the resonant tank, then rectified at the output terminals by a bridge rectifier to form back the output direct current (DC). This type of resonant converter shows a low voltage gain variation with the switching frequency operation. In addition, the current carried by the power switches and resonant tank for the series loaded resonant converter is relatively loaded independently due to the lower input impedance at the resonant frequency. This phenomenon then causes large conduction losses in the equivalent series resistance and ripple voltage, due to a very high current flow through the resonant tank and the switches.

Usually, the series resonant converter is form from one or two half-bridges forming a half or full-bridge converter. For this circuit configuration, a series resonant tank that consists of an inductor, a capacitor is connected between the output terminals of inverter and input terminals of bridge rectifier. The rectifier is connected in series with the resonant tank which acts as a current source for the rectifier resulted output voltage source. The behaviour of the circuit is varying depending on whether the converter output frequency is below, at or above the resonance frequency of the LC circuit to determine zero-voltage switching (ZVS) and zero-current switching (ZCS). The basic series resonant DC to DC half-bridge converter is shown in Figure 1, whilst the equivalent circuit as in Figure 2. The voltage gains of the output voltage with the input voltage equation for the  $C_p = C_s$  can be expressed as Equation [1-3].

$$\left| \frac{V_o}{V_s} \right| = \frac{1/2}{\left| 1 + \frac{\omega_s^2 L_s C_s}{8} \left[ \frac{2Z_{eq}}{Z_{eq}} - \frac{1}{Z_{eq}} \right] \right|} \tag{1}$$

where,

$$Z_{eq} = \frac{1}{\sqrt{\frac{1}{Z_{eq}^2} + \frac{1}{Z_{eq}^2}}} \tag{2}$$

and

$$Z_{eq} = \frac{Z_{eq} Z_{eq}}{Z_{eq}} \tag{3}$$

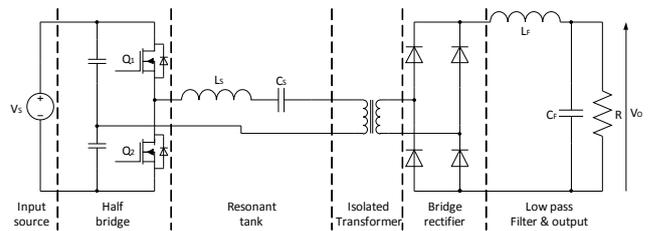


Figure 1. Basic series resonant DC-DC half-bridge converter.

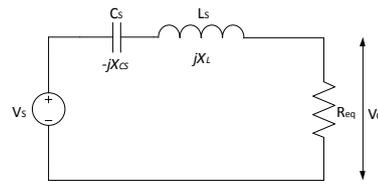


Figure 2. Equivalent circuit for the series resonant converter.

Basically, there are three modes of operation for the series loaded resonant (SLR) converter that are determined by the switching frequencies ( $\omega_s$ ) relationship with the resonant frequency ( $\omega_o$ ) of the resonant tank; Discontinuous Conduction Mode (DCM) and Continuous Conduction Mode (CCM). The DCM occurs when the switching frequency is less than half of the resonant frequency whilst the CCM occurs when the switching frequency ranges from 50% to 100% of the resonant frequency or above the resonance frequency [9].

B. Parallel-Loaded Resonant Converter

The parallel-loaded resonant converter that is similar to the previously discussed series-loaded resonant converter is capable to vary the output voltage at no-load condition by setting the switching frequency operation above the resonance frequency. For a parallel resonant converter, the output inverter is connected in parallel with the resonant capacitor as shown in Figure 3. Usually, a transformer is used to interface between the resonant circuit and the rectifier circuit in order to adapt the load voltage to the DC link voltage used, hence provides a galvanically isolated output voltage. This type of converter represents a voltage source to the rectifier circuit, hence, the output filter of the rectifier must be a current source due to the use of an

inductor filter. Due to the lower output current that flow through the capacitor, resulted to the lower conduction losses and converter's output voltage ripple besides inherently short circuit protected.

One of the advantages of the parallel-loaded resonant converter is its capability to both step up and step down the DC output voltage. However, near resonance frequency, they exhibit a current-source characteristic, although the output characteristics are again elliptical affected to the DCM under heavy loading. Besides, this type of converter do not suitable to some conventional power supply applications due to the features of current stresses and conduction loss in the power switches depend on the output voltage, and are nearly independent of load current [10]. Figure 4 shows an equivalent circuit for the parallel loaded resonant converter, whilst the equation of the voltage gains of the output voltage with the input voltage for the  $C_p = C_s$  can be expressed as Equation [4-6].

$$\left| \frac{V_o}{V_s} \right| = \frac{1/2}{\left| \frac{Z_p}{8} (1 - \left( \frac{\omega}{\omega_0} \right)^2) + j \frac{Z_p}{8} \left[ \frac{\omega}{\omega_0} \right] \right|} \quad (4)$$

where,

$$Z_p = \frac{1}{\sqrt{\frac{1}{L_p} + \frac{1}{C_p}}} \quad (5)$$

and

$$\left( \frac{\omega}{\omega_0} \right)^2 = \frac{Z_p}{Z_s} \quad (6)$$

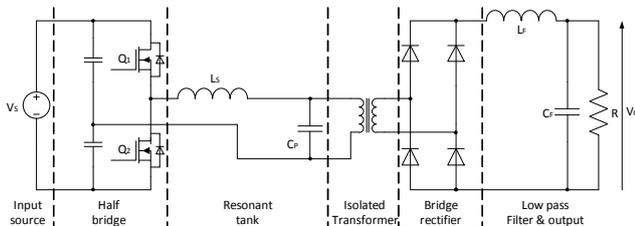


Figure 3. Basic parallel resonant DC-DC half-bridge converter.

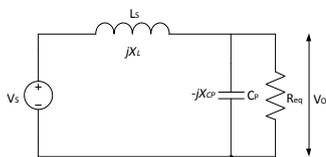


Figure 4. Equivalent circuit for the parallel resonant converter.

### C. Hybrid Resonant Converter

The hybrid resonant converter configures the best characteristics of the series-loaded resonant converters and parallel-loaded resonant converters. The combination of these two circuit configuration creates a resonant tank that is

the same as that of the parallel-loaded resonant converter, except for an additional capacitor in series with the resonant inductor. The advantage of hybrid resonant converter is the output voltage could be control to operate over a wider input voltage ranges and load ranges from no-load condition to the full-load condition [5].

The hybrid resonant converter can be operated both in either below resonance or above resonance. However, the operation below the resonance frequency has many disadvantages such as use of RC snubbers and  $di/dt$  limiting inductances, whilst needed for fast recovery diodes across the switches, etc. hence, need to operate the hybrid loaded resonant converter above resonance frequency in order to overcome the stated problems.

The disadvantage of the hybrid resonant converter is the analysis of circuit operation and the design of circuit parameters are complex due to the capacitive output stage is decoupled from the resonant stage for a significant period during the switching cycle. Besides, at switching frequency near to the resonant frequency, the hybrid converter cannot operate safely with a short-circuit condition.

The function of the resonant tank is to filter out the higher harmonic voltages, resulted a pure sinusoidal waveform of current at the input of resonant circuit that allows classical AC analysis techniques to be used. By using classical AC analysis, resulted sinusoidal waveform of current and voltage in the resonant tank generated by the square wave input voltage can be computed. The equivalent circuit of hybrid resonant converter is as shown in Figure 5, whilst the voltage gains of the output voltage with the input voltage for the  $C_p = C_s$  based on the equivalent circuit as in Figure 6 below can be expressed as Equation [7-9].

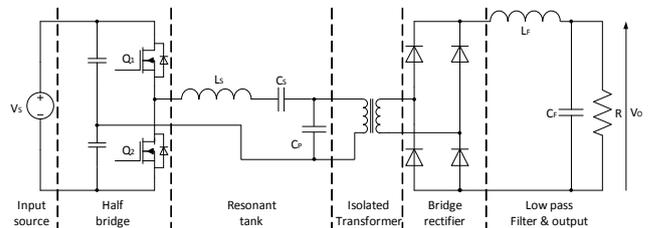


Figure 5. Basic Hybrid resonant DC-DC half-bridge converter.

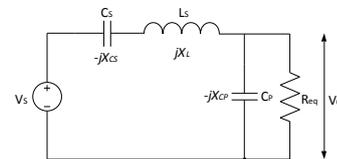


Figure 6. Equivalent circuit for Hybrid resonant converter.

$$\left| \frac{V_o}{V_s} \right| = \frac{1/2}{\left| \frac{Z_p}{8} \left[ 1 + \frac{Z_p}{Z_s} \left[ 1 - \left( \frac{\omega}{\omega_0} \right)^2 \right] + j \frac{Z_p}{8} \left[ \frac{\omega}{\omega_0} \right] - \frac{1}{Z_s} \right] \right|} \quad (7)$$

where,

$$Q_{sp} = \frac{1}{\sqrt{\frac{R}{L_s C_s}}} \tag{8}$$

and

$$Q = \frac{Q_{sp}}{Q_{sn}} \tag{9}$$

### III. COMPUTER SIMULATION MODEL

The computer simulation models are carried out using MATLAB/Simulink to investigate the behaviour and characteristics of the resonant converters. The subsystem is used for circuit model design to improve clarity of modelling by breaking up complex models into a hierarchical set of smaller models for systematic structured implementation. For the initial studies, the simulation parameters used are listed as in Table I below.

TABLE I. SPECIFICATION AND COMPONENT PARAMETERS

Output voltage	47 V
Switching frequency	50 kHz
Quality factor, Q	5
Output power	1000 W

#### A. Series-Loaded Resonant Converter

The top level main model of single-phase half-bridge series loaded resonant converter is shown in Figure 7. This circuit configuration model consists of inverter circuit, series resonant tank and bridge rectifier circuit. The controller unit used to generate pulse width modulation (PWM) to control an inverter circuit is shown in Figure 8. A constant representing reference signal used to vary the modulation index is compared with the triangular waveform to represent carrier signal in order to generate the required PWM signal. A NOT gate is then used to invert the generated signal which is used for negative cycle operation. A transformer is used to provide galvanically isolated output voltage that is necessary for some applications. The design is oriented to applications with low output voltage that require to consider an energy conservation. The electrical specifications of the designed converter are calculated based on equation (1) to (3), and the results are as tabulated in Table II:

TABLE II. SPECIFICATION AND COMPONENTS PARAMETER FOR THE SERIES-LOADED RESONANT CONVERTER

Input voltage:	113 V
Output voltage:	47 V
Rated output power:	1000 W
Rated output current:	21 A
Switching frequency:	50 kHz
Quality factor, Q:	5
Load resistor, $R_L$ :	2.209 $\Omega$
Series inductor, $L_s$ :	37.12 $\mu\text{H}$
Series capacitor, $C_s$ :	0.3 $\mu\text{F}$

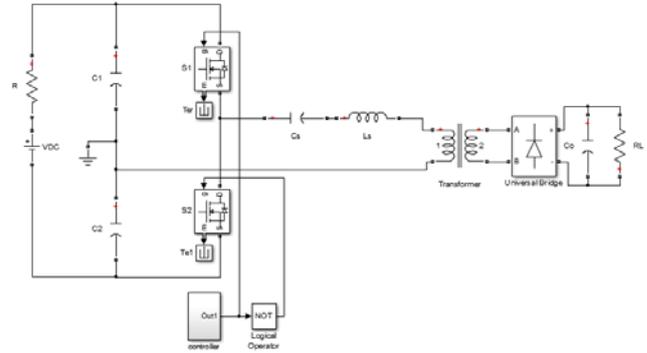


Figure 7. Computer simulation model of series-loaded resonant converter.

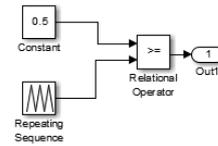


Figure 8. Computer simulation model of controller circuit.

#### B. Parallel-Loaded Resonant Converter

The computer simulation model of the half bridge parallel-loaded resonant converter is as shown in Figure 9. The active power switches are controlled to generate a square wave voltage by a controller. The design objective for the parallel-loaded resonant converter is similar with the series-loaded resonant converter as discussed in the previous subsection where the parameters used are calculated based on equation (4) to (6), and the results are as tabulated in Table III.

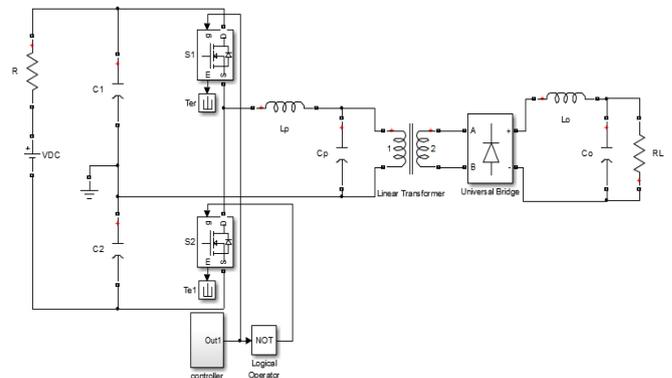


Figure 9. Computer simulation model of parallel loaded resonant converter.

TABLE III. SPECIFICATION AND COMPONENTS PARAMETER FOR THE PARALLEL-LOADED RESONANT CONVERTER

Input voltage:	113 V
Output voltage:	47 V
Rated output power:	1000 W
Rated output current:	21 A
Switching frequency:	50 kHz
Quality factor, Q:	5
Load resistor, $R_L$ :	2.209 $\Omega$
Series inductor, $L_S$ :	1.96 $\mu\text{H}$
Parallel capacitor, $C_P$ :	10 $\mu\text{F}$

C. Hybrid Resonant Converter

Figure 10 shows the computer simulation model circuit for single-phase half-bridge hybrid loaded resonant converter topology. Similar with the previous both the series and parallel loaded resonant converters, the hybrid resonant converter also applies a square wave of output voltage from the inverter to the resonant tank. The hybrid resonant converter is modelled by splitting the resonant tanks into a series inductor ( $L_s$ ), series capacitor ( $C_s$ ) and parallel capacitor ( $C_p$ ), with the load being connected in parallel configuration with the  $C_p$ . Specifications of parameters for the hybrid resonant converter are calculated based on equation (7) to (9), and the results are as tabulated in Table IV:

TABLE IV. SPECIFICATION AND COMPONENTS PARAMETER FOR THE HYBRID RESONANT CONVERTER

Input voltage:	113 V
Output voltage:	47 V
Rated output power:	1000 W
Rated output current:	21 A
Switching frequency:	50 kHz
Quality factor, Q:	5
Load resistor, $R_L$ :	2.209 $\Omega$
Series inductor, $L_S$ :	37 $\mu\text{H}$
Series capacitor, $C_S$ :	0.3 $\mu\text{F}$
Parallel capacitor, $C_P$ :	0.3 $\mu\text{F}$

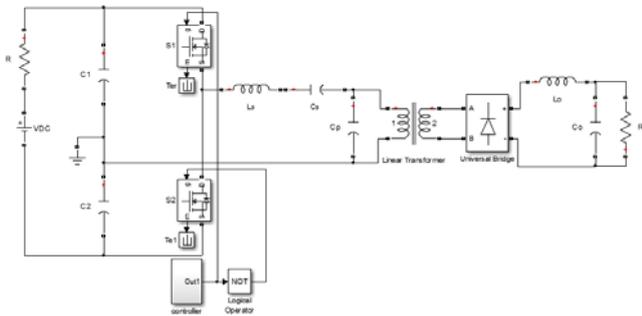


Figure 10. Computer simulation model of hybrid resonant converter.

IV. RESULTS AND DISCUSSIONS

The normalized voltage gain ( $V_o/V_{in}$ ) is plotted as a function of normalized frequency,  $\square_n = (\square_s/\square_o) = (f_s/f_o)$  at

various loaded quality factor, Q for the series loaded resonant converter is shown in Figure 11. In the series-loaded resonant converter, the resonant tank behaves like a capacitive load if the switching frequency lower than the resonance frequency resulted to the resonant current  $i_L$  waveform leads the fundamental of the inverter output voltage waveform. Consequently, the resonant circuit appears as an inductive load when the switching frequency higher than the resonant frequency, creates resonant current waveform  $i_L$  lags the fundamental of the inverter output voltage waveform as shown in Figure 12 whilst Figure 13 shows the output voltage and current waveforms. The quality factors, Q depends on the value of load resistance. A low Q, corresponds to a high value of load resistance, lower output power, hence, heavy damping of the resonant tank. Figure 14 shows the graph of Q plotted against output power. It is observed that, the value of Q is proportionally increased by the increased of the output power.

Unlike the series resonant converter, the rectifier output current for the parallel resonant converter is not determined by the resonant inductor current. However, the rectifier output voltage for the parallel resonant converter is dependent on the resonant capacitor ( $C_p$ ) voltage. Figure 15 shows the normalized voltage gain ( $V_o/V_{in}$ ) is plotted as a function of normalized frequency,  $\square_n$  at various loaded quality factor, Q for the parallel loaded resonant converter whilst the resonant current with the output voltage waveforms is as shown in Figure 16. The plot shows that the output voltage for Q=5 can be controlled with small change in switching frequency whilst by reducing the value of up to Q=1, the voltage conversion ratio becomes relatively insensitive to frequency changes. Figure 17 shows the output voltage and current waveforms for the parallel loaded resonant converter whilst Figure 18 shows the graph of Q plotted against output power. It is seen that, the value of Q is proportionally decreased by the increased of the output power.

The voltage gain equation for the hybrid resonant converter is plotted as shown in Figure 19. It shows that the voltage conversion ratio for the hybrid resonant converter is depend on the ratio of parallel capacitor ( $C_p$ ) and the series capacitor ( $C_s$ ),  $C_p/C_s$  that also determines the parallel loaded resonant converter or the series loaded resonant converter characteristics. Therefore, by increasing the value of parallel resonant capacitor ( $C_p$ ), the voltage gain becomes insensitive to frequency changes affected to the less sensitive of voltage conversion in the resonant curve. Figure 20 shows that the resonant current waveform leads the output voltage waveform of an inverter circuit. The output voltage and current waveform is as shown in Figure 21. Figure 22 shows the parameters of Q are plotted as a function of output power for the hybrid resonant converter. It is shown that the characteristics of the hybrid resonant converter is similar with the series loaded resonant converter, where the value of Q is increased by the increased of the output power.

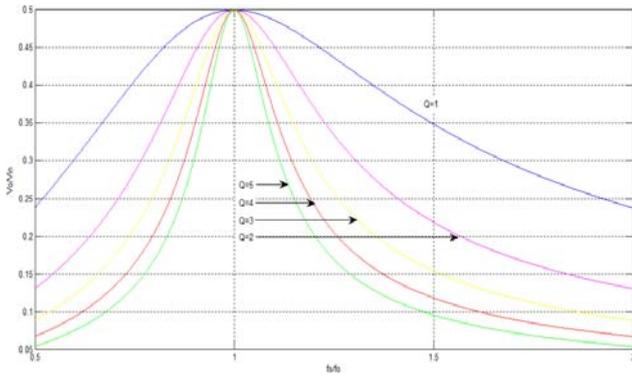


Figure 11. Normalized output voltage at various switching frequency for the series resonant converter.

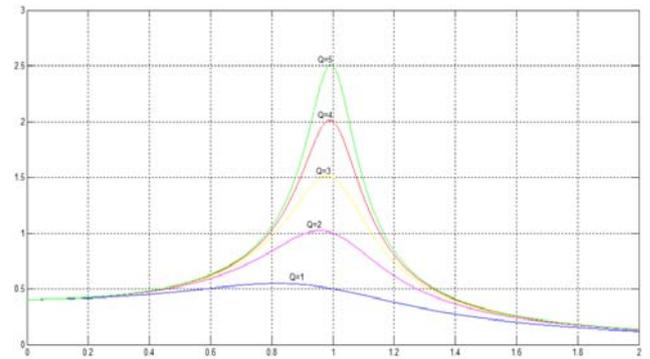


Figure 15. Normalized output voltage at various switching frequency for the parallel resonant converter.

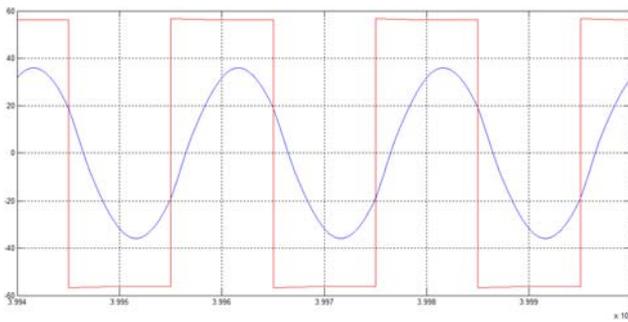


Figure 12. Resonant current waveform  $i_L$  lags the fundamental of the inverter output voltage waveform.

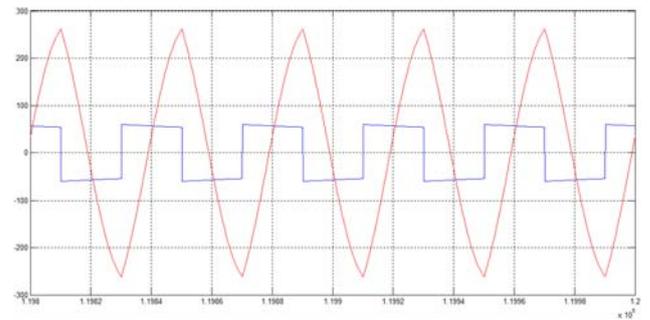


Figure 16. Resonant current waveform with the inverter output voltage waveform.

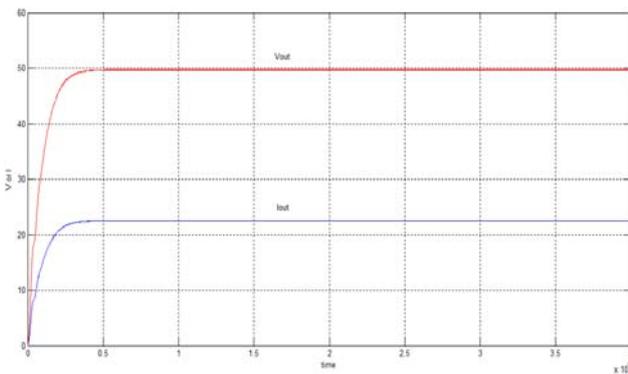


Figure 13. Output voltage and current waveform.

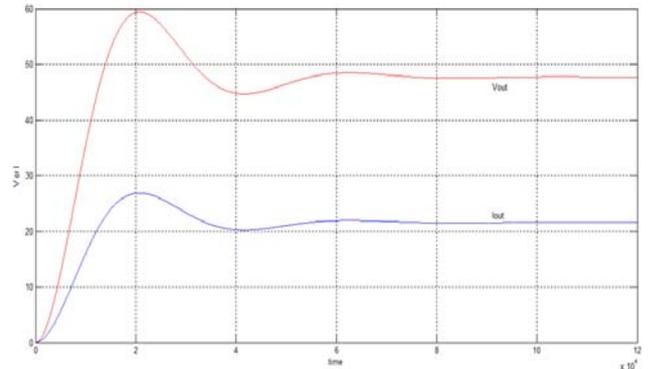


Figure 17. Output voltage and current waveforms.

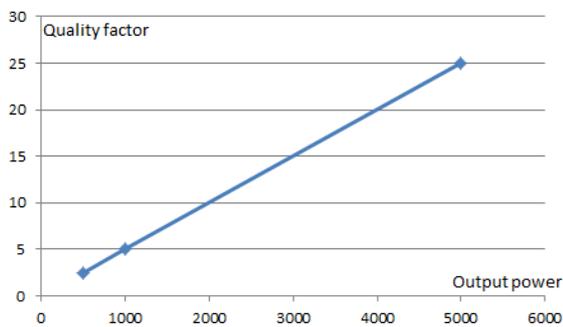


Figure 14. Q plotted against output power for series resonant converter.

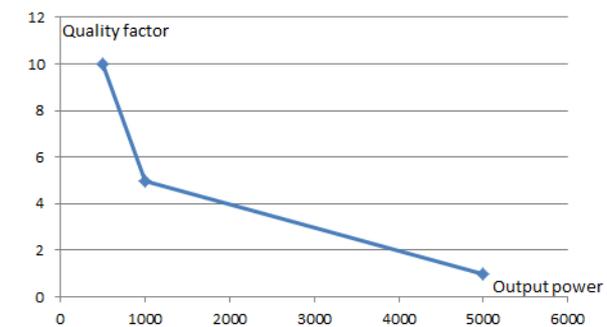


Figure 18. Q plotted against output power for parallel resonant converter.

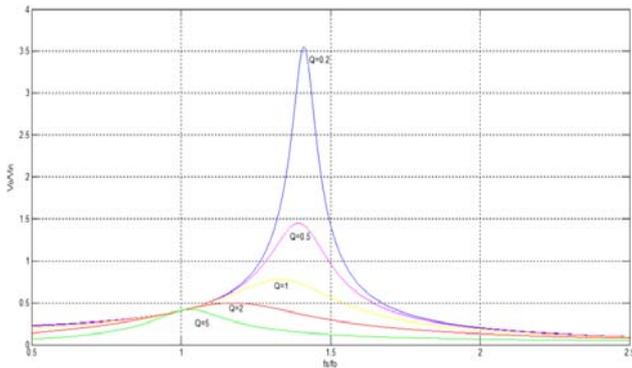


Figure 19. Normalized output voltage at various switching frequency for the hybrid resonant converter.

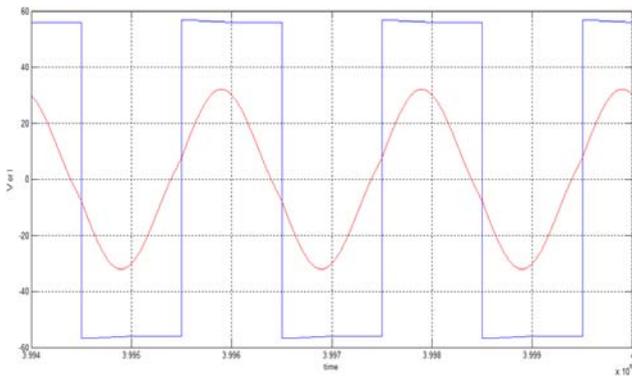


Figure 20. Resonant current waveform with the inverter output voltage waveform.

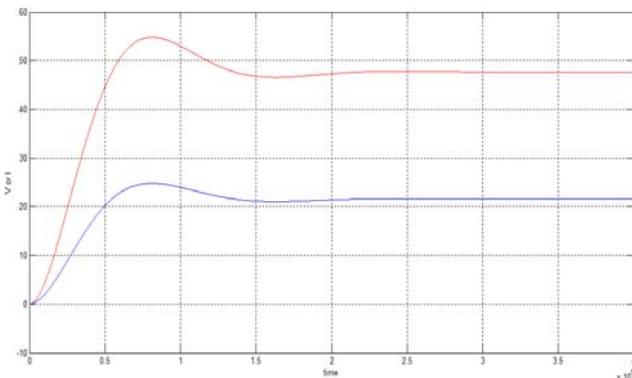


Figure 21. Output voltage and current waveforms. Current is the smaller magnitude waveform.

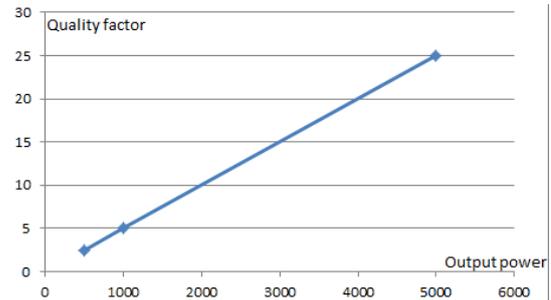


Figure 22. Q plotted against output power for hybrid resonant converter.

### V. CONCLUSION

In this paper, a comprehensive study is conducted to evaluate the behaviour of three types of resonant topologies; the series loaded resonant converter, parallel loaded resonant converter and hybrid resonant converter in terms of quality factor, Q on load variations. The results showed that for the series loaded resonant converter, the value of Q proportionally increase by increasing the output power whilst the value of Q proportionally decrease by increasing the output power for the parallel loaded resonant converter. It is also showed that for the hybrid resonant converter, the value of Q increase by increasing the output power which is similar with the series loaded resonant converter characteristics. In fact, for the hybrid resonant converter, the quality factor, Q should be as small as possible in order to increase the sensitivity of the converter. With only a small variation in normalized frequency,  $\omega_n$  resulted to a large range of the regulate output voltage whilst the use of high value of Q could cause over sensitivity problem in the power flow. This phenomenon is contrary for the series and parallel resonant converter, the used of small value of Q could cause the voltage conversion ratio becomes relatively insensitive to normalized frequency changes.

Further work is required to examine alternative circuit configurations such as the use of full-bridge switching configuration instead of the half bridge and closed loop control.

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