Design and Analysis of Series Loaded Resonant Converter fed by Standalone/PV Source

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Abstract. The deficiency of power is an enormous issue due to higher growth demands among the utility customers which led the focus on renewable energy sources for electricity generation. Solar energy has gained high popularity due to highly abundant, clean, economical and sustainable when compared to other alternative energy sources. The DC-DC converter topologies are used in solar photovoltaic (PV) applications for power conversion due to less cost, highly reliable, highly efficient, and robust operation. These converters incorporate a wide variety of voltage variations and protection against overvoltage. In the recent times, solar power converters using various soft switching techniques due to high switching frequencies which reduce the size, cost, weight and loss of the converter. The series resonant power converters are one such soft switching converter which is widely employed due to their high-efficiency with the benefit of low switching losses. The paper confers on the analysis of Series Loaded Resonant Converter with low loss switching by applying solar PV as an input source. The converter behaviour is observed in various operating modes concerning the resonant frequency. The design parameters of the proposed converter are validated in MATLAB/SIMULINK environment.

1. Introduction

The demand for energy is increasing at a considerable rate in every country. Higher demand for electrical energy and depletion fossil fuels necessitates the use of renewable energy [10],[11]. This environmental aspects put restrictions on the use of conventional energy sources. Various types of power converters are used in such applications. For applications involving PV and battery, DC-DC converters are commonly used. In certain instants, there may be need to step-up and step-down the dc input supply. In some applications, there is need for bidirectional power transfer. They are used to match the loads of the power supply. Because of this ease, today the DC-DC converters are increasingly found in applications such as regulated power supply, domestic, automobile, battery charging, etc. These converters are also useful as power sources with multiple outputs for control circuits. [1].

In the last few decades, the attempts were redirected towards the use of resonant converters. The idea was to include a resonant tank in the converter to create sinusoidal waveforms of current and/or voltage using lossless/soft switching [4]. These low loss switching such as zero-voltage switching (ZVS) or zero-current switching (ZCS) can be shaped for power switches for achieving transient free waveform and also allows the switches to work at higher frequencies and in turn reduces electromagnetic interference (EMI). The performance of SLRC will undergo low loss switching, when the switching frequency is higher or
lower than the resonant frequency, [7]-[9]. The majority of works have covered the operation of half bridge resonant converter. Few converters with half and full-bridge configurations have been discussed for medium and high voltage levels and evolved in many industry applications [7]. This study presents the design and analysis of series loaded resonant converter, working at various operating modes to achieve soft switching across all power switches. The paper is organised as follows: Brief discussion of series loaded resonant converter with low loss switching in section 2, circuit description and analysis of series resonant converter in section 3, modes of operation of SRC in section 4, discussion of simulation and validation of series resonant DC-DC converter using MATLAB/SIMULINK software in section 5.

2. Series Loaded Resonant Converter with Low Loss Switching

Resonant Power Converters are named after the concept resonance. This happens when the reactance of inductor and capacitor cancel each other in LC resonant circuit. Resonant power converter operates in such a manner that switching losses are minimized [12]. The devices are switched on and off when the voltage across the device is zero or current through switch is zero. This results in zero voltage or zero current switching respectively. The switching losses are proportional to the product of voltage across and current through the switch. The low loss switching maintains one of the parameters that is either voltage across or current through the switch close to zero during switching. This makes their product close to zero and switching losses becomes almost zero. In turn, this enhances the efficiency of power conversion and also higher switching frequencies can be used for power conversion. Other benefit of this is reduction in size of inductor, capacitor and transformer. This reduces overall weight and volume of the converter making it compact. In these converters, the shapes of voltages and currents being close to sinusoidal, dv/dt and di/dt are reduced. This reduces EMI effects [13]. Depending on low loss switching, the behaviour of ZVS and ZCS are carried out in four possible ways:

1. A capacitor when connected in parallel with the main switch the circuit acts for ZVS OFF condition. During turn-on, the voltage across the capacitor is zero, and it cannot change the state of the switch to OFF condition at the same time. So, in switch OFF period, the voltage rests close to zero, which is true in the case of modern power switches as they operate rapidly during switching instants and therefore quasi resonant condition that is ZVS OFF is reached. Nevertheless, during turn-on, special consideration is to be ensured for the voltage to be zero across the switch, otherwise short circuit occurs which may lead to the damage of main switch. A capacitor when connected in parallel, the current flowing through the switch is determined and hence, ZCS ON and OFF conditions may not be attained.

2. An inductor when connected in series with the main switch, ZCS ON condition is achieved. This takes place as the current through the inductor will be zero when the switch is OFF, and when it is turned ON, the change cannot take place instantaneously. So during switching-off period the current remains close to

![Figure 1. Possible switching configurations of active/main switch.](image-url)
zero, and at this instant quasi ZCS ON state is reached. Hence, care must be taken to make sure that zero current flows in the inductor during the switch turn-on state.

3. The diode when connected in parallel with the main switch approaches to attain ZVS ON/OFF during the conduction period of the diode. This happens when the diode is in forward bias, it’s voltage is clipped, so quasi ZVS ON and OFF of the main switch can be reached. Some switches, such as BJT’s, cannot conduct for negative current through it as the current flowing through the switch is zero but in switches like MOSFETs a value sharing with the diode takes place if the switch has bidirectional conductivity.

4. In this configuration, the diode when connected in series with the main switch, it operates in discontinuous mode. In this condition, the flow of current in the diode is blocked. Therefore, no current flows through the diode and ZCS ON and OFF can be achieved. Hence it is be noted that the above analysis is based on ideal operation of active/main switch. These switching configurations are depicted in the Figure 1.

3. Circuit Description and Analysis of SLRC

The operational circuit of the SLRC is illustrated in Figure 2. Each part of the converter carries out a specific operation. The input DC source fed to the switching network of SLRC is supplied by the PV array at standard irradiance and temperature. The switches of full bridge inverter undergo commutation according to the switching frequency, to generate square wave output voltage. To reduce EMI and harmonic distortion, a resonant tank containing inductor (L) and Capacitor (C) components are connected in series to generate sinusoidal voltage and/or current signals [2],[4]. It acts as an energy buffer between output and input. The output of resonant tank is fed as input to rectifier network and filtered using capacitor component to produce the desired DC output voltage.

In SLRC circuit, the tank circuit is connected in series with the load which acts as a voltage divider. So, the input voltage is shared between the impedance of the tank circuit and the effective resistance. The impedance of resonant tank varies with the frequency of driving voltage, as represented in Figure 3.

In this paper, we have considered the resonant tank impedance to be 53.4 ohms and at resonant frequency of 85.1 KHz. At this point, the current from the tank circuit flows to the output. The parameters of resonant are estimated and determined for the resonant frequency and the tank impedance using the below equations:

![Figure 2. Schematic diagram of SLRC](image)
Determination of Design Parameters:

\[ R_o = \frac{\sqrt{L}}{\sqrt{C}} \]

Multiply & divide by \( \sqrt{L} \)

\[ R_o = \frac{L}{\sqrt{LC}} = \frac{L}{1/\omega_o} \]

\[ \Rightarrow L_r = \frac{R_o}{\omega_o} \quad (1) \]

On substituting values of \( R_o, \omega_o \) in eqns.(1), we get

\[ L_r = \frac{R_o}{\omega_o} = \frac{53.45}{2\pi \times 85.1\text{kHz}} = 100\mu\text{H.} \quad (2) \]

\[ \omega_o = \frac{1}{\sqrt{LC}} \]

Squaring on both sides

\[ \omega_o^2 = \frac{1}{LC} \]

\[ C_r = \left[ \frac{1}{\omega_o \sqrt{L}} \right]^2 \quad (3) \]

On substituting values of \( \omega_0, L_r \) in eqn. (3) we get

\[ C_r = \frac{1}{L_r \omega_o^2} = \frac{1}{(2\pi \times 85.1\text{kHz})^2 \times 100\mu\text{H}} = 35\text{nF} \quad (4) \]

Quality factor \( Q = \frac{R_o}{R_L} \quad (5) \)

\[ R_e = \frac{V_{R1}(t)}{I_R(t)} = \frac{9}{V} \frac{V}{I} \quad (6) \]

\[ R_L = \frac{\pi^2}{8} R_e = 1.23 R_e \quad (7) \]

The relation between switching frequency and resonant frequency is given by

\[ F = \frac{f_s}{f_r} \quad (8) \]
4. Modes of operation of SLRC

The operation of SLRC is mainly categorised into three parts based on mode of conduction, switching frequency, and soft switching technique. According to the load parameters and control for the limits of $F>0$, $Q>0$ the main switches are to be operated in various modes [7, 9]. Based on the ranges of the switching frequency, the modes of operation are classified as illustrated in Table 1.

| Conduction Modes        | Frequency Period | Switching Condition | ZVS |
|-------------------------|------------------|---------------------|-----|
| Discontinuous Conducton Mode | $0.5 \leq F \geq 1$ | Turn-On Turn-Off | No Yes |
| Continuous Conducton Mode | $0.5 \leq F \geq 1$ | Turn-On Turn-Off | No Yes |
| Continuous Conducton Mode1 | $F \geq 1$ | Turn-On Turn-Off | Yes No |

In steady state, the SLRC above the resonant frequency is operated in four modes. The end point of the previous mode defines the initial values of current and voltage in the present mode. The operational waveforms for different modes are depicted in Figure 5.
Figure 5. Operational waveforms of SLRC

**MODE 1**: In this mode, the current flows through the diodes of the switches S1 and S4, forming the tank. In this mode, the load is supplied energy and the remaining reverts to the source. Thus the current $I_{LR}$ (current in the resonant inductor) falls to zero at $\omega_0 t_0$. This deviate the current from its original diode path and shifts to the power switch path. Thus, the switches S1 and S4 are turned on using ZVS. The expressions for the resonant voltage and current are given by

$$I_{LR}(t) = \frac{1}{Z_o} [V_{in} - V_o - V_{cr}(0)] \sin \omega_o t$$

$$V_{cr}(t) = V_{in} - U_o - [V_{in} - V_o - V_{cr}(0)] \sin \omega_o t$$

**MODE 2**: In this mode, switches S1 and S4 are forcibly turned off at $\omega_0 t_1$. This happens due to zero crossing of the voltage across the resonant capacitor $V_{cr}$. This result in hard switching, however, can be eliminated with small parallel capacitors connected to the switches. Further, this current starts flowing through the diodes of switches S2 and S3 resulting in the power stage. Thus, the source supplies energy to the resonant tank, thereby resulting in zero current by the end of this mode, due to the tank’s negative voltage. The expressions for voltage and current are given by:

$$I_{LR}(t) = \frac{1}{Z_o} [V_{in} - V_o - V_{cr}(1)] \sin \omega_o (t - t_0) + I_{Lr}(1) \cos \omega_o (t - t_0)$$

$$V_{cr}(t) = V_{cr}(1) + \frac{I_{Lr}(1)}{\omega_o} \sin \omega_o (t-t_o) + [V_{in} - V_o - V_{cr}(1)] [1 - \cos \omega_o (t - t_o)]$$

**MODE 3**: This mode starts at $\omega_0 t_2$, with diodes of switches S2 and S3 in on state, resulting in resonance between the tank elements. The current flow through the diodes of switches S2 and S3 turns on the switches at ZVS. In this mode, the load is supplied with the energy available in the tank; hence with the resonant current the polarity of the tank reverses. Also, the voltage of the resonant capacitor is shifted and reaches the maximum value when the current reaches zero. The resonant current and the voltage are expressed as

$$I_{LR}(t) = \frac{1}{Z_o} [-V_{in} + V_o - V_{cr}(2)] \sin \omega_o (t - t_2)$$
\[ V_{cr}(t) = V_{in} + V_o - [V_{in} + V_o - V_{cr}(2)] \cos \omega_o (t - t_2) \]  

**MODE 4:** In this mode at \( \omega_o t_3 \), due to hard switching off of the switches S2 and S3 the current flow deviates from the diodes of switches S1 and S4, and slowly the resonant current reaches the value zero at \( \omega_o t_4 \). The expressions for the resonant current and voltage are given by

\[
I_{lr}(t) = \frac{1}{Z_o} [V_{in} - V_o - V_{cr}(3)] \sin \omega_o (t - t_3) + I_{lr}(3) \cos \omega_o (t - t_3)
\]

\[
V_{cr}(t) = V_{in} + V_o + I_{lr}(3)Z_o \sin \omega_o (t - t_3) - [V_{in} + V_o - V_{cr}(3)] \cos \omega_o (t - t_3)
\]

5. Simulation Results and Discussion:

In this paper, the design parameters of series loaded resonant converter are analyzed and simulated using MATLAB/SIMULINK software. In this section, the converter waveforms and the conduction modes are discussed based on switching frequency period. The design parameters used for the simulation are tabulated.

| TABLE 2. Design Parameters of SLRC |
|-----------------------------------|
| **PARAMETERS** | **VALUES** |
| DC input value | 40V |
| Switching frequency | 20 KHz \( \leq f_s \leq 100 \) KHz |
| Resonant frequency | 85.1 KHz |
| Resonant inductor | 100 µH |
| Resonant capacitor | 35 nF |
| R Load | 23 Ω |
| Impedance | 53.4 Ω |

In this section, the converter waveforms and the conduction modes are discussed based on switching frequencies between 20KHz to 100kHz. The design parameters of SLRC are tabulated and simulated using MATLAB/SIMULINK software. The input to the full bridge switching network consists of four switches is fed from a PV source and the switches are triggered alternately. From the instant, \( t = t_s / 2 \) the switches S1 and S3 are triggered for 0.5 duty ratio for the first half cycle. On the other hand from \( t = t_s / 2 \) to \( t = t_s \) switching instant, the switches S2 and S4 are triggered for the second half cycle to produce a square wave voltage and is fed to the resonant tank. The figure 6 represents the driving voltage across the switches and the total inverter output voltage. This paper, the design parameters of series loaded resonant converter are analyzed.
In order to investigate the SLRC behaviour based on the three conduction modes, we have considered the frequency periods at various switching frequencies between 20 KHz and 100 KHz.

**Figure 6:** The voltage across the switches S1, S3 & S2, S4 and inverter output voltage

![Voltage Waveforms](image)

(a). Continuous Conduction Mode-1  (b). Continuous Conduction Mode  (c). Discontinuous Conduction

(F ≥ 1)  \hspace{2cm} (0.5 ≤ F ≥ 1)  \hspace{2cm} (0.5 ≤ F ≥ 1)

**Figure 7.** The figures(a), (b) and (c) represents the tank current in various modes.

**Figure 8.** Zero Voltage Switching (ZVS) Output

To achieve ZVS operation, the converter is switched above resonant frequency of the tank circuit. This results in cancellation of capacitive reactance by a part of inductive reactance. And still some value of inductive reactance is left over in the resonant circuit. Hence, resonant tank is mainly inductive. this makes the tank current to lag the inverter output voltage. It can be observed that the tank current lags the square wave voltage. This feature helps in achieving ZVS operation.
Figure 9. The filtered DC output voltage of the rectifier. The tank current which is close to the sine wave is rectified by the rectifier and filtered by output filter capacitance to produce DC output voltage. It is shown in figure 9.

6. Conclusion

The above discussed resonant converter finds are wide applications in renewable systems, LED drivers, battery chargers, regulated power supplies and bidirectional power conversion systems. They offer advantages such as high efficiency, compactness, low EMI, etc. The low loss switching is achieved by ZVS or ZCS operation of the switching devices.

Based on the soft switching techniques described, the devices behaviour, the devices in the inverter are turned on and off by ZVS. The diodes in the rectifier are operated with ZCS. Thus, the switching losses on the switching devices are reduced. In this paper, the operation states analysis of a SLRC above resonant frequency is described. The condition for operating the proposed converter in above resonance mode is achieved by selecting the characteristic impedance of the resonant tank has been discussed. This converter can be used for high frequency DC-DC power conversion with Photovoltaic (PV) or any other DC source. The validity of the work under any condition of frequency ranges has been presented using MATLAB/SIMULINK software.

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