Overview on second & third order resonant switch mode power converter for variable input voltage applications

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Abstract— DC-DC converters have wide applications in the field of battery charger, distributed generation, power supplies and so on. There are various isolated and non-isolated topologies available which has to be chosen based on the size, cost, weight, application, power range and duty of the converter. Due to increasing applicability of DC-DC converters, it is essential to enhance the efficiency, controllability and output regulation to a step ahead. Resonant converters at high frequency has gained attention in the market to a large scale due to its low size and weight. With the developing enthusiasm for this subject, it is essential to have a detailed review to sum up and update a unique reference about the soft switching configurations for better performance of the converter. The paper provides a brief overview in two and three element soft switching configurations. Moreover, The current technologies evolved in the field of resonant converters are also briefed for wide input voltage applications.

Keywords— DC-DC Converter, Soft switching, ZVS, ZCS, isolated/non isolated converters.

1. Introduction

DC-DC converters are widely employed in the fields related to automation, battery chargers, distributed generation, power supplies, LED Drivers, laptop adaptors, Electric vehicles and so on. The DC-DC converter behaves as an interface between the input supply and the output-load while changing the levels of voltages between them. It can be done by controlling the switching elements with the most suitable modulation schemes and designing the reactive components so as to obtain the desired output. For variable inputs like renewable energy sources, more specifically photovoltaic systems, the output greatly depends on the climatic/operating conditions which are often unpredictable and highly variable. Output of such systems needs to be regulated for a broad input range of voltage. In order to deal with such conditions, the converters ought to be equipped with appropriate control strategies so as to obtain regulated output while keeping up high efficiencies. As a result, DC-DC converters and related switching elements needs to be chosen appropriately as its choice is very crucial in the gross quality determination of the system as a whole [1]. There are numerous DC-DC converters available currently. The isolated converter topologies includes flyback, Dual active full/half bridge, forward, push pull converters and so on whereas buck, boost, buck-boost, cuk and sepic-zeta converters [2]-[3] are the non-isolated topologies [4]-[6]. An efficient DC-DC converter requires high power density, limited losses, less cost and reduced size.

In earlier days, the converter output often being controlled using discrete components like resistive load and diodes. Unlike linear regulators which generates high heat dissipation, the switched mode regulators utilize semiconductor switching devices like transistors, MOSFETS etc to convert input DC supply to pulsating output. Moreover, switched mode regulators consists of inductive and capacitive elements handling rectifiers and regulators for regulating the output to a predefined value. However, the switching losses during the switch-on and switch-off tend to interrupt the performance of the converter. As the operating frequency increases, the number of switch turn on and off transitions per unit time is more [7]-[8]. Consequently, it increases the switching losses at the transition period due to the non-zero values of voltage and current. This happens as the switching device will not turn on immediately when a voltage is applied to the gate. It takes a small delay to reach the steady state. Other limitations of hard switching includes limited frequency, high EMI, bulky structure and weight.
Despite these disadvantages, hard switched converters are widely used, studied and implemented in a wide range of applications [9]. In soft switching, the limitations can be reduced to some extend by forcing the switch to turn on at zero voltage condition, ZVS and zero current condition (ZCS) during the switch turn off. Moreover, Soft switching can help reduce the size of the circuit by allowing lossless switching transitions at high frequencies [10]. Figure 1 shows the DC-DC converter classification based on the switching operation.

**Figure 1:** DC-DC Converter topologies

In this paper, different soft switching DC-DC converter configurations are mentioned and examined based on the recent development in respect of efficiency, steady state oscillation, number of components and voltage gain. The merits and demerits of the recent improvement within this scope are also pointed. This paper is arranged as the following. Section II showcases the classification of soft switching topologies. In Section III and IV, the second order and third order resonant topologies are analysed and the advantages and commonly used topologies are presented. Eventually, section V draws the conclusion.

2. **Soft Switching Converter Topologies**

Figure 2 shows the switching transition for the conventional hard switching and soft switching during turn on and turn off periods. During turn on, hard switching makes high switching losses as the switch allows the current to flow through it before completely opening the switching element. Soft switched DC-DC Converters have wide applications as they can improve the performance of converter circuits by reducing the switching losses and electro-magnetic interference. The switching losses can be minimized by achieving the Zero Current/Zero voltage switching (ZVS/ZCS). At Resonance, the resonant components inductor and capacitor elements charges and discharges simultaneously. The converters using this as the principle are called as resonant converters [11]. A series-parallel
combined resonant converter uses the reactive elements providing the hybridized features of series and parallel resonance [12]. Series Parallel Hybrid Resonant Converters are possible by arranging the Resonant Capacitor and Inductor in different orientation. Some of the commonly used topologies includes LLC, LCC, LCLC, LCCL Converters and so on. The switching frequency and the quality factor determines whether buck/boost operation need to be performed. Soft switching converters are classified depending on the operating principles as (a) Resonant power converters(RPC) (b) Multi and Quasi resonant converters(QRC) (c)Resonant transition converters(RTC).

2.1 Resonant Power Converters(RPC)

An efficiently designed resonant converter can attain resonance over the entire load and line range. A classical DC-DC resonant converter be made up of three portions- a control switching circuit, a resonant tank and a rectification network [13]. Figure 3 shows the basic structure of DC-DC resonant power converter. The initial controlled pulsating network switches the input dc to high frequency square waves for generating the current and voltage at the input side of the resonant tank. Commonly used switching topologies includes half bridge and full bridge inverter which is chosen according to the power requirements. The resonant tank network(RTN) consists of inductor and capacitive elements which charges and discharges allowing back and forth energy transfer in the network. The resonant tank is responsible to reduce the stresses and switching losses in the network. The quality of the resonant converter is assessed considering the losses and resonant bandwidth. This can be analysed using Q factor for which larger the value of Q factor can reduce the oscillations and minimise the degree of damping. To achieve the desired degree of damping the soft switched converters can be grouped as series resonant converters(SRC), parallel resonant converter( PRC) and hybrid/ series parallel resonant converters. The simplest resonating network includes SRC or PRC comprises of a resonant inductor or a resonant capacitor connected in series or parallel respectively with the load and the power supply. Proper isolation guarantees the converter usage at high power applications. The resonant tank output is fed to the rectifier network which aims at rectifying the sinusoidal output to pulsating DC and then filter it to required DC output waveform.

![Figure 3. Structure of DC-DC resonant converter](image)

Series parallel resonant converters includes combination of SRC and PRC which includes many popular topologies. It includes LLC, LCL, CLC, CLL where LLC and LCC are most popular.

2.2 Quasi Resonant(QRC) Converter

Noise and heat developed can be suppressed using QRC which combines a resonant switch along with the resonant element. While operated at higher frequencies QRC improves the output power quality. For high voltage applications, to reduce the size of the circuit, switching frequency is increased. However, high switching frequency leads to increased switching stresses which requires a large heat sink. One of the demerits of Quasi resonant converter is that it can operate either at ZVS or at ZCS but not both concurrently by resonating only at a particular region in the cycle. It involves both resonant and non resonating intervals in its operation. By arranging an inductor in series with the switch allows ZCS during turn off and arranging a capacitor in parallel with the resonant switch allows ZVS during turn on thereby reducing switching losses.

For ZVS, the resonant capacitor, \( C_r \) is connected side by side with the switching element, \( S \) keeping resonant inductor, \( L_r \) in cascade with \( C_r \) and \( S \). However, for ZCS, \( C_r \) is kept in parallel with the series combination of \( L_r \) and \( S \). Figure 4 shows examples of Quasi resonant converters which satisfies
ZCS and ZVS condition respectively. A multistage dual direction converter using two half-bridge gallium nitride modules is discussed in [14]. A reduced voltage stresses as a result of ZVS is achieved during turn on. Moreover, GaN switches reduces on-resistance and faster switching speed compared with Si based switches. It minimizes switching losses during turn off as well. In [15], A dual quasi flyback resonant converter is designed and implemented with auto regulated structure for parallel/series input. In order to improve the performance of the converter, the input transformer structure can be varied to either cascade/parallel based on the input voltage.

![ZVS-Quasi Resonant Converter- Buck Converter](image1.png)

![ZCS-Quasi Resonant Converter- Buck Converter](image2.png)

**Figure. 4:** DC-DC Buck converter satisfying a) ZVS-QRC and b) ZCS-QRC

### 2.3 Resonant Transition Converter (RTC)

Resonant transition converter (RTC) is a modified quasi resonant converter with the combination of four elements. Unlike, quasi resonant converter ZCS and ZVS can be obtained from RTC concurrently as shown in figure 5 (b) and 5 (c). In addition to the resonant elements $L_r$ and $C_r$, RTC includes the auxiliary components switch, $S_2$ and diode, $D_2$. However, it increases the current stresses in the main switch. A high performing LCL-T resonant converter is discussed in [17] achieving load independent output current for automotive LED drives. It helps control the brightness of LED by achieving regulated output current using phase shift control modulation strategy at fixed frequency. Moreover, a detailed analysis is done for LCL-T resonant converter and compared with LC, LCLC multi resonant converters which then proved to have better efficiency than the said topologies. In [18], a variable structure multi resonant converter which can operate in FB-CLTCL, FB-LCLCL and HB-LCLCL modes (FB-Full bridge and HB- Half bridge) based on different switching configurations is analyzed and implemented. The resonant converter operates at high conversion efficiency and has wide voltage gain with narrow bandwidth.

### 2.4 Multi resonant converter (MRC) Converters

MRC’s are selected to get rid of the demerits of current and voltage oscillations and thereby to achieve ZVS as shown in figure 5(a). To reduce the effect of leakage inductance of transformer and parasitic components of switching elements, soft switching is implemented using a forth order LLCC-Load resonant converter (LRC) in [16]. It consists of a half bridge inverter isolated with a full bridge rectifier with elevated potentiality in line as well as load regulation with wide variation in the input.

![Multi resonant LCC resonant switching](image3.png)

**Figure. 5:** a) Multi resonant LCC resonant switching b) ZVT- switching c) ZCT switching

### 3. Second Order/ Two Element Resonant Tanks

Number of resonant elements decide the transfer function order. The smallest resonant network is possible making use of a resonant inductor and capacitor in series or parallel combinations with load
and the supply. There are eight possible resonant tank combinations in the two element resonant topologies. However, not all of them can work as a resonant converter with pulsating voltage source inputs due to the lack of voltage regulation capability and requirement of current sources.

3.1 Parallel Resonant Converter (PRC)

Figure 6(b) and 6(c) shows parallel resonating tank circuit consisting of reactive elements. PRC consist of two resonating elements, a resonant inductor, $L_r$, and a resonant capacitor, $C_r$ in parallel to the load and the supply. In PRC, the energy stored in inductor and the capacitor is continuously oscillating which makes the resultant current between them to zero. The instantaneous values of inductor and capacitor currents are always equal which is the basic principle behind the resonant oscillation. Parallel resonant converter allows amplification of the input signal and provide high gain nearby the resonant frequency. A combined topology based on a three phase inverter with two-LLC resonant tank interleaved converter topology is explained in [19] with less number of switching elements and other components. Comparing to conventional isolated three phase interleaved topology, cost and size of the equipment is considered lower. The topology achieves ZVS above resonant frequency for all the switches used [20].

3.2 Series Resonant Converter (SRC)

Figure 6 (a) shows a series resonating circuit which helps to regulate the output. Series resonance doesn’t help to amplify the input signal. Instead, it can only provide a buck function for which the gain can only be unity or lower. SRC is a promising solution for regulating the input voltage over a wide range of input voltage. A bridgeless isolated serial resonating circuit is proposed on the transformer secondary to improve the power factor with less switching elements over wide input voltage ranges [21]. In [22], an efficient isolated converter for electric vehicle -V2G application is discussed with full bridge inverter primary and voltage doubler secondary. The proposed bidirectional topology allows step up/step down capability in forward and reverse direction respectively providing high conversion ratio and high efficiency over wide battery voltage range. A dual mode rectifier type series resonant DC-DC converter [23] is configured with advantages including efficiency and input voltage range improvement. The proposed dual mode rectifier is configured on the secondary side of the isolation transformer with voltage gain range doubled for PV applications.
4. Three Element Resonant Tank

Three element resonant topology consist of 3 resonating elements which combines the advantages of both SRC and PRC. It includes two inductors and one capacitor or vice versa. For three element resonant topologies, thirty six possible configurations are possible by arranging the inductor and capacitors in different orientations. In these, twenty three can be utilized in combination with a voltage source. In these 23, 15 can be used in voltage and current regulation. Eight of the configurations have notch resonance making it difficult to control. The commonly used third order resonant networks includes LLC, LCL, CLC, CLL were LLC and LCC being the most popular. Voltage gain of LCC is better than LLC which makes LCC being more used in applications were high output voltage is required. Such an LCC and LLC resonating circuit is shown in figure 7(a) and 7(b). The main benefit of resonant converters is that the converter can achieve soft switching over wide load ranges. As a result, it is important to analyse the necessary conditions of resonance. The switch achieves zero voltage by allowing the parasitic capacitor energy of the switch to discharge completely. Enough dead time has to be provided to the switches to discharge the output capacitor of MOSFET to zero. These topologies can be categorized as the combination of a half and full-bridge inverter and a full-bridge or centre-tapped rectifier on the primary and the secondary side respectively, were the centre-tapped rectifier are not in priority as a result of the elevated voltage stress on the diodes. The output voltage or current can be controlled in a broad area by changing the switching frequency for LLC. In [24], a dual output topology with LLC resonant tank is discussed capable of achieving high power density and satisfying the ZVS and ZCS condition. Instead of using two separate DC-DC converters, the proposed topology discussed the converter allowing multiple outputs of 200–400 V for the traction and 48 V for auxiliary supplies using switched frequency and phase angle control respectively.

![Fig 7 (a): LCC resonant tank (b) LLC resonant tank circuit](image)

5. Conclusion

In the paper, different soft switching DC-DC converter topologies are mentioned and examined based on the recent development in terms of efficiency, steady state oscillation, number of components and voltage gain. Resonant converters have a vast class of topologies on the basis of number of passive storage elements and auxiliary elements. Different second and third order resonant tank configurations are investigated pointing out the merits and demerits of each configuration. Moreover, the most commonly evolved resonant configurations are identified and integrated.

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