



Resonant Power Converters for Renewable Energy Applications: A Comprehensive Review

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Studies on resonant power converters (RPCs) have received much attention due to the rapid growth of their potential in modern power and renewable energy applications such as photovoltaic, electric vehicles, wind, and fuel cells. Consequently, a significant number of studies focusing on RPC topologies for renewable energy applications is available. Generally, these studies have addressed several aspects, such as the development of their soft switching feature, smooth waveforms, high power density, and high efficiency. With this in mind, the present paper aims to review the development of the RPCs, challenges in their development, and comparison between common topologies as highlighted in literature. In addition, the use of RPCs in various applications of renewable energy is highlighted, focusing on some of the recently utilized topologies based on their constructions and achievements. There are still several issues and challenges in research that need to be considered for future improvement of the RPC performance in renewable energy applications. The improvement may require modifications on the circuit design or control strategies.

Keywords: resonant, DC–DC converters, renewable energy application, soft-switching, clean energy

1 INTRODUCTION

Electric vehicles (EVs), renewable energy systems (RES), smart grids, and solid-state transformers are some of the instances of modern industrial applications of clean energy in power electronics that have advanced rapidly over time. With this, much attention has been given to resonant DC–DC converters due to their characteristics and proven efficiency compared to normal converters. These resonant DC–DC converters, in particular, offer a better conversion rate, and can work at high switching frequencies and achieve soft switching (SS); they also result in a considerable size reduction in terms of the magnetic components of the system, such as the passive filters and transformers (Outeiro et al., 2016a). All these are necessary to meet the demands of industrial applications of power electronics applications. RPCs (resonant power converters) are also used. Furthermore, rather than incorporating extra equipment for each switch, RPCs use another way to accomplish the SS

Abbreviations: Ac, a capacitance ratio; AL, an inductance ratio; rs, frp, series/parallel resonant frequency; fs, switching frequency; fr, resonant frequency; Mv, voltage gain; Q, quality factor; Re, effective load resistance seen by RTN; Zi, RTN input impedance; is, RTN input current; ir, rectifier input current; EMI, electromagnetic interferences; RI, resonant inverter; Vs, RTN input voltage; Vr, rectifier input voltage; PF, power factor; SS, soft switching; Ws, angular frequency; ZVS, zero-voltage switching; ZCS, zero-current switching.

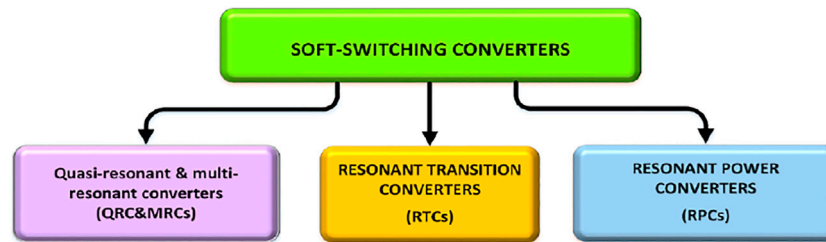


FIGURE 1 | Soft-switching converter family (Salem et al., 2018).

requirements. RPCs specifically structure them as a Resonant Tank Network (RTN) that consists of two, three, or more reactive elements that are connected with a converter in a cascade manner.

RTN might be classified according to their connection mechanisms and the number of employed tank elements (Outeiro et al., 2016a); however, the most prevalent 2-element type of RTN is the series resonant converter (SRC) and parallel resonant converter (PRC). An example of 3-element RTNs is the series-parallel RCs like LCC and LLC, whereas LCLC is an example of a multi-element RTN.

Furthermore, RPCs utilize other techniques to achieve the SS requirements rather than to embrace the additional equipment for each switch. Specifically, RPCs structure them as RTN using two, three, or multi-reactive components that are interconnected with the converter in cascade (Outeiro and Buja, 2015). Even though single-stage RCs are well-known and advanced in numerous applications, they still seem inappropriate for high input voltage applications. The current load on switching devices, in particular, has the potential to compromise and degrade both reliability and efficiency (Lee and Moon, 2011); hence, multilayer converters were developed, allowing the use of low-voltage switching devices in high-voltage applications (Liu et al., 2017; Salem et al., 2019).

Given the high interest on RPCs nowadays, the present paper aims to review the construction, classification, and development of RPCs and their applications. The paper also wishes to introduce the latest RPC technologies as reported in existing literature. The paper is organized in the following structure: **Section 2** highlights the structure and classification of RPCs. **Section 3** reviews the use of RPC in renewable energy applications while **Section 4** provides some recommendation for future work on RPCs in renewable energy application. Finally, **Section 5** concludes the paper.

2 RESONANT POWER CONVERTERS

There are many soft-switching converters (SSCs) that have been developed successfully in the last few decades. These converters have enabled power semiconductor devices in switch-mode power supplies (SMPS) to operate at preferred conditions, consequently resulting in better performance, high power density, and efficiency (Moradisizkoochi and Mohammed, 2017;

Geetha et al., 2018). In general, the SSCs can be grouped into three different families according to their operating principles (Outeiro and Buja, 2015): (1) quasi RCs (QRCs) and multi RCs (MRCs) (Liu et al., 1987; Moradisizkoochi and Mohammed, 2017; Geetha et al., 2018), (2) resonant-transition converters (RTCs) (Tuomainen and Kyyra, 2005; Martins et al., 2006), and (3) RPCs.

Figure 1 shows the SSC family.

Of the three types, RPCs have received greater attention due to the developments in their usage and the industrial application. Efforts have been placed to further enhance the soft-switching, smooth waveforms, and high efficiency of RPCs. RPCs are found to be ideal for use in high-voltage applications. This is due to their capacity to minimize switching losses and have low switching stresses, low EMI, and high power density (Outeiro et al., 2014). As a result, RPCs are the most preferred converters in industrial high-power systems compared to the traditional converters due to their features of working at high frequencies and achieving SS. Meanwhile, studies have suggested that certain aspects of RPCs need improvement, such as the wide load fluctuations, dependability, high power density, fewer number of components, high efficiency, tiny size, low cost, and light weight (Batarseh, 1994; Chien et al., 2013). This particular section focuses on RPCs in terms of their structure and number of reactive components.

2.1 Structure of Resonant Power Converters

The structure of RPC is produced by cascading different stages as depicted in **Figure 2** (Outeiro and Buja, 2015).

2.1.1 Control Switching Network

The CSN is the layer for the conversion of the supplied DC power into AC power. The CSN switches are programmed to quickly switch ON/OFF based on the working frequency for the generation of the output voltage or current that feeds the next step (Salem et al., 2018). The CSN (**Figure 3**) is controlled to produce a square voltage $V_s(t)$ where its frequency (f_s) is equal/close to the resonant frequency (f_r). This can be expressed by the Fourier series in **Eq. 1**. CSN is commonly used with either a half- or full-bridge configuration, but the employed configuration is determined by the required power. High-power applications are mostly operated with the full-bridge inverter while half-bridge configuration (with low voltage switch rates) is more ideal for high input voltage systems (Outeiro et al., 2014).

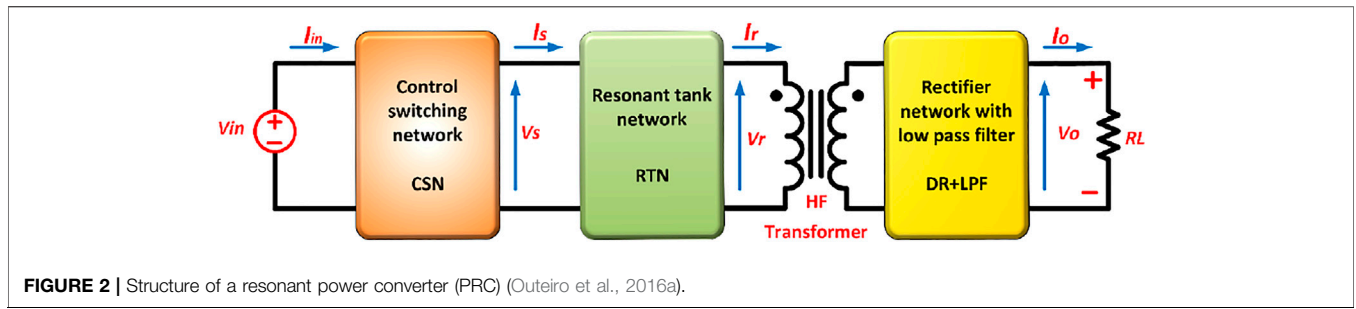


FIGURE 2 | Structure of a resonant power converter (PRC) (Outeiro et al., 2016a).

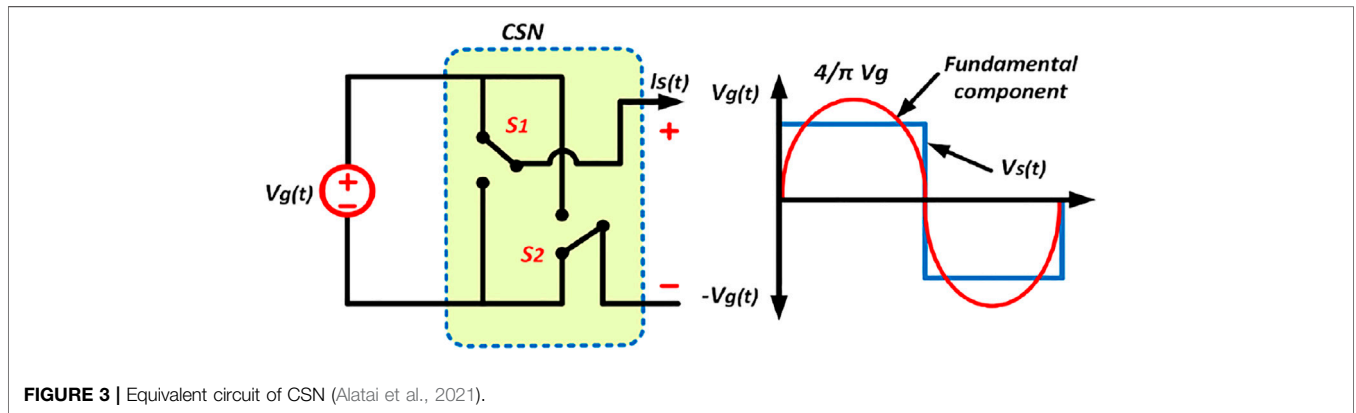


FIGURE 3 | Equivalent circuit of CSN (Alatai et al., 2021).

$$V_s(t) = \frac{4V_g}{\pi} \sum_{n=1,3,5,\dots} \frac{1}{n} \sin(n\omega_s t) \quad \text{with } n = 1, 3, 5, 7, \dots \quad (1)$$

Wide-band gap devices are used in resonant converters to improve power density and efficiency. These devices have a substantially higher figure of merit, allowing them to significantly boost power density and efficiency. Silicon carbide (SiC) devices can run at hundreds of frequencies to achieve higher power densities. The size of the passive components is reduced while operating at a higher switching frequency. The ON state resistance of the SiC-based MOSFETs is significantly lower than that of Si-based MOSFETs for the same conduction current rating. As a result, the conduction losses of the SiC-based MOSFETs are lower, making them more efficient. Hence, these devices are thought to be a good choice for on-board chargers (OBCs). Despite the benefits of SiC and GaN devices, there are a few drawbacks, such as their high cost, difficult gate driver design, and complex EMI protection design. Furthermore, increasing the working temperature from 50 to 150° reduces the efficiency of GaN and SiC by 4% (Deshmukh et al., 2022).

2.1.2 Resonant Tank Network

The RTN, also called a tuned circuit, resonant circuit, LC circuit, or tank circuit, is the next level. It is made up of reactive elements for the storage of vacillating energy at the circuit's resonant frequency. The RTN stage of RPCs is the most significant. In the high-frequency RTN, a stage is made up of 2, 3, or more elements. Capacitors (C) and inductors (L) are the devices for passive energy storage and can be coupled in a variety of ways. Electromagnetic interference (EMI) and harmonic distortion

(HD) are prevented by using these reactive components to generate current signals and sinusoidal voltage (Salem et al., 2018). This period can be selected by the frequency selective network because it serves as an energy buffer between the load and the CSN as seen in Figure 2. In resonance condition, the capacitance and inductance have equal impedances, paving the way for the generation of the resonant frequency (Salem and Yahya, 2019). RTNs can be classified based on either the number of utilized reactive elements in the RTN or the manner of connection of the elements. The group that is based on the connection mechanisms has three common representative resonant circuits, which are SRC, PRC, and SPRC (Salem et al., 2018). The second group that depends on the number of the reactive elements is classified into two-element resonant tank (second-order), three-element resonant tank (third-order), and multi-element resonant tank (fourth-, fifth-order . . .). These types have many topologies; as a result, the more members in an RTN, the more topologies are possible. However, not all element combinations can result in a resonant condition (Batarseh, 1994). The appropriate design and selection of RTN elements, as well as the appropriate selection of the control mechanism may conserve SS over a large load range; it also ensures constant converter output voltage, and improve power conversion capabilities and efficiency (Outeiro et al., 2016a).

2.1.3 Diode Rectifier Network With Low Pass Filter

This is the final stage in the structure of the resonance power converter. The input is a sinusoidal voltage and current waveforms, produced at the resonant frequency in the previous stage; this input works as a pass filter that eliminates

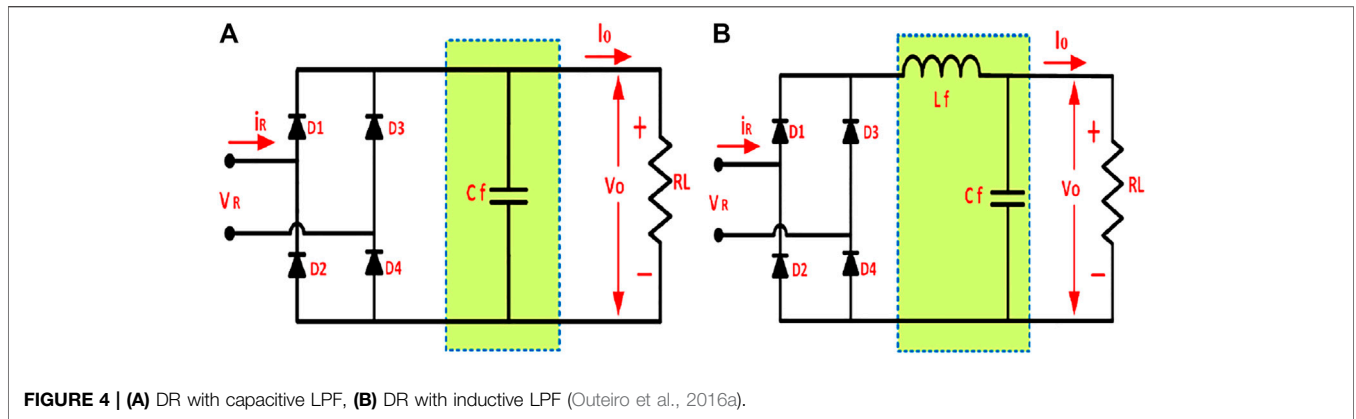


FIGURE 4 | (A) DR with capacitive LPF, (B) DR with inductive LPF (Outeiro et al., 2016a).

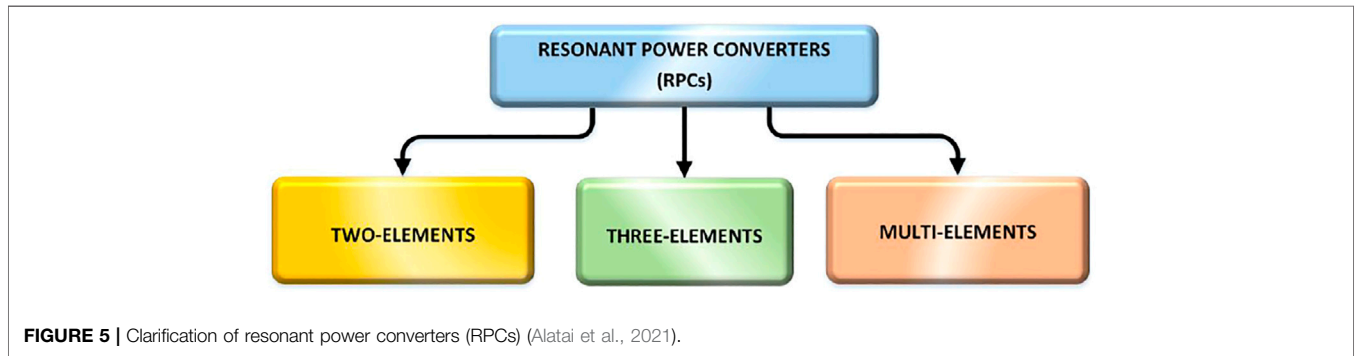


FIGURE 5 | Clarification of resonant power converters (RPCs) (Alatai et al., 2021).

the voltage harmonics of the core component generated by the CSN at its output. Then, it feeds the conditioning circuitry (CC) stage at its input as a pulse waveform. The CC stage consists of a diode rectifier DR and a low-pass filter (capacitive and inductive) LPF (Figure 4). The main function of the DR-LPF stage is to filter and rectify the AC signal that comes from the resonance tank in order to get the DC output signal that is required to supply the load. A filter (capacitive and inductive) determines the sink nature of the current/voltage of the load. The DR with both types of filter (capacitive and inductive) has been highlighted in several works (Outeiro et al., 2014; Salem et al., 2018).

2.2 Classification of Resonant Power Converters

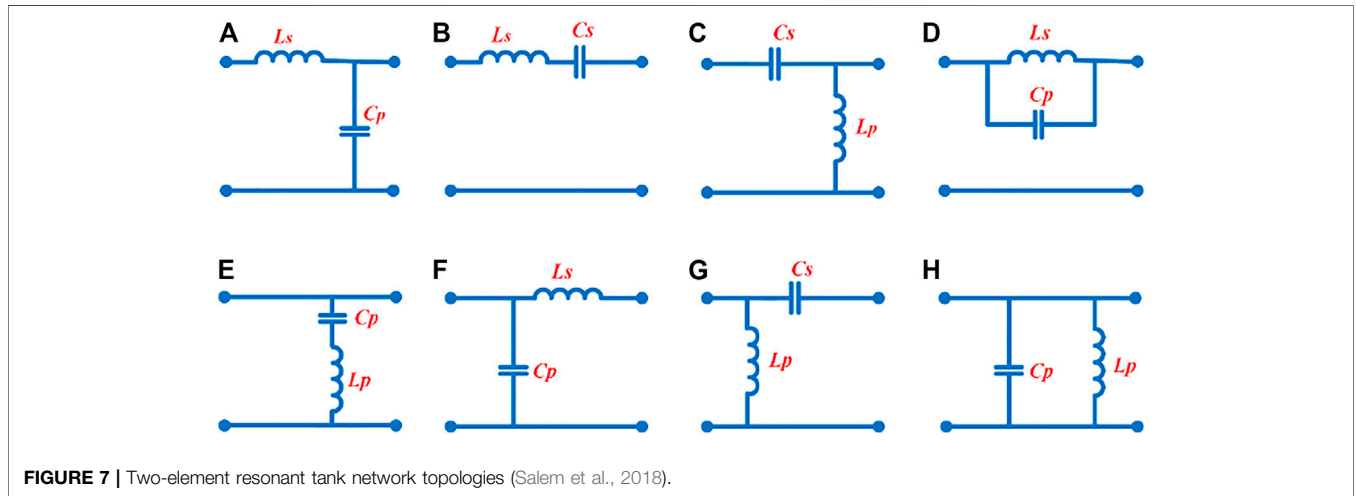
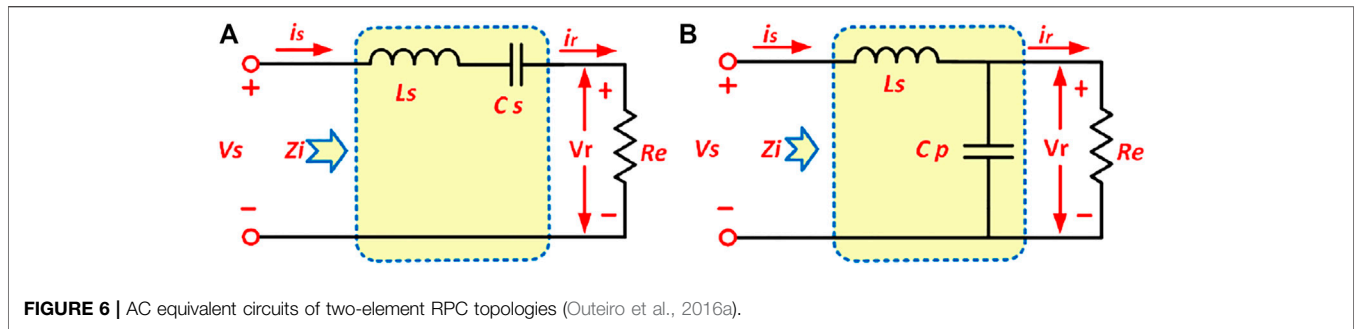
RPCs can be categorized based on the number of employed reactive components in the RTN; the classes include 2 elements, 3 elements, and multi-elements (Figure 5).

2.2.1 Two-Element Resonant Power Converters Topologies

The two-element RTN or the second-order RC is further categorized into SRC (Figure 6A) (Ibanez et al., 2015; Witulski et al., 1986; Salem et al., 2014) and PRC (Figure 6B), (Lin et al., 2013; Saha et al., 2018). As seen in Figure 7, 2-element RPCs are available in eight topologies that have simple circuit structure and minimal components; their storage tank is made up

of just two elements for energy storage. As in Figure 7, the topologies at the top (a–d) are ideal for voltage source inputs, while the ones in the bottom (e–h) are ideal for current source converters (Outeiro et al., 2016a). In SRC, the LC elements are connected in series with the effective load resistance R_e (Figure 6) (the topology b). Consequently, increases in R_e decreases the current through the CSN and RTN switches, and *vice versa*. SRCs exhibit lower EMI than the hard switched converters, which significantly reduces the size and switching-related losses. Hence, they offer high power supplies and achieved better conversion efficiency (Abdul-Hakeem et al., 2018; Bhuvaneshwari et al., 2018).

As indicated in Figures 7A,D,H, PRCs have one or both LC elements parallelly connected with the effective load resistance, R_e . These converters are capable of generating a constant regulated current that protects against short circuits. For a PRC, the output voltage can be increased and decreased. The output voltage of a PRC can be controlled from full load to no load by operating at a frequency above resonance. Furthermore, it is excellent for use in short circuits to the point that even when the load falls, the conduction losses remain constant in the semiconductor devices; the efficiency is also high for light loads (Bhuvaneshwari and Babu, 2016). Because of the low switching losses of this converter, it is ideal for use in high-frequency, high-power systems. PRC functions as a constant source of current when the resonant and switching frequencies are equal. However, at lower switching frequencies compared to the PRC, it is more of a constant voltage source for the output



voltage and has wide load fluctuation. It is the best choice for voltage regulators (Azura et al., 2014). At high input voltage, PRCs exhibit a high switch off current and high circulating energy, and those are the two major problems of PRCs (Huang, 2014). The disadvantage of SRC is the sharing of the input voltage between the load and the resonant impedance, which results in a DC gain of less than one. SRC is known to exhibit substantially higher nonlinear dynamics, which makes the control more difficult. On the other hand, the SRC output voltage cannot be adjusted when there is no load (Salem et al., 2017a). For the PRC, the voltage gain might be greater than one when compared to SRC. As a result, PRC has the ability to increase voltage. The operating area of PRCs, on the other hand, is substantially smaller. When the load is light, there is no need for much frequency fluctuation to control the output voltage (Huang, 2014). Also, based on Martinez et al. (2018), it was confirmed that parasitic resistances presented in the windings of the coupled inductors have a great impact on the voltage gain and the efficiency. In particular, it was observed that a converter with a large number of components increases the probability of parasitic resistance’s negative effect on voltage gain and efficiency. Also, by considering the analysis of power core loss of the resonant inductor L_r function, it was noticed that the volume, core cross-section area, number of turns, and the type of copper used in high-frequency inductors and transformers are the main impacts of copper losses. Thus, by using the proper

copper material with low inductance value, and reducing the size of volume and cross-section area, the effect on efficiency and voltage gain will be significantly decreased (Salem et al., 2022).

2.2.2 Three-Element Resonant Power Converters Topologies

There are 36 topologies in the third-order resonant tanks (three-element RTN) or higher-order resonant tanks. The three-component RPC has one additional element than the two-element RPCs. **Figure 8** illustrates some three-element RTN topologies (Severns, 1992), where resonant tanks A-1 to A-9 are composed of two inductors and one capacitor and RTNs B-1 to B-9 are composed of two capacitors and one inductor. These topologies with third-order resonant tanks (Huang et al., 2011; Tan and Ruan, 2016; Fei, 2018) have been suggested to eliminate the disadvantage of two-element topology as they are seen as a hybridization of the benefits of most 2-element RPCs (SRC and PRC) (Salem et al., 2020). These 3-element RPCs have features that make them suitable for both light and heavy load applications (Beiranvand et al., 2011). Furthermore, they are capable of efficiently transferring power from the source to the end-users.

Another benefit of 3-element RPCs is that the propagated waveform is frequently sinusoidal, which means that the THD of the output waveform is virtually zero. The EMI of a well-known procedure for mono-frequency waveform transfer is generally

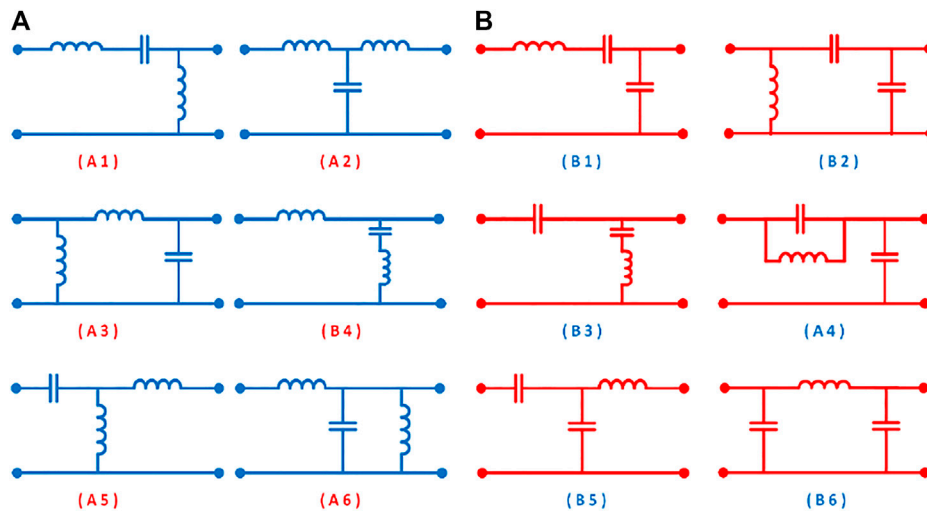


FIGURE 8 | (A) Topologies with 2L and 1C. **(B)** Topologies with 2C and 1L (Salem et al., 2018).

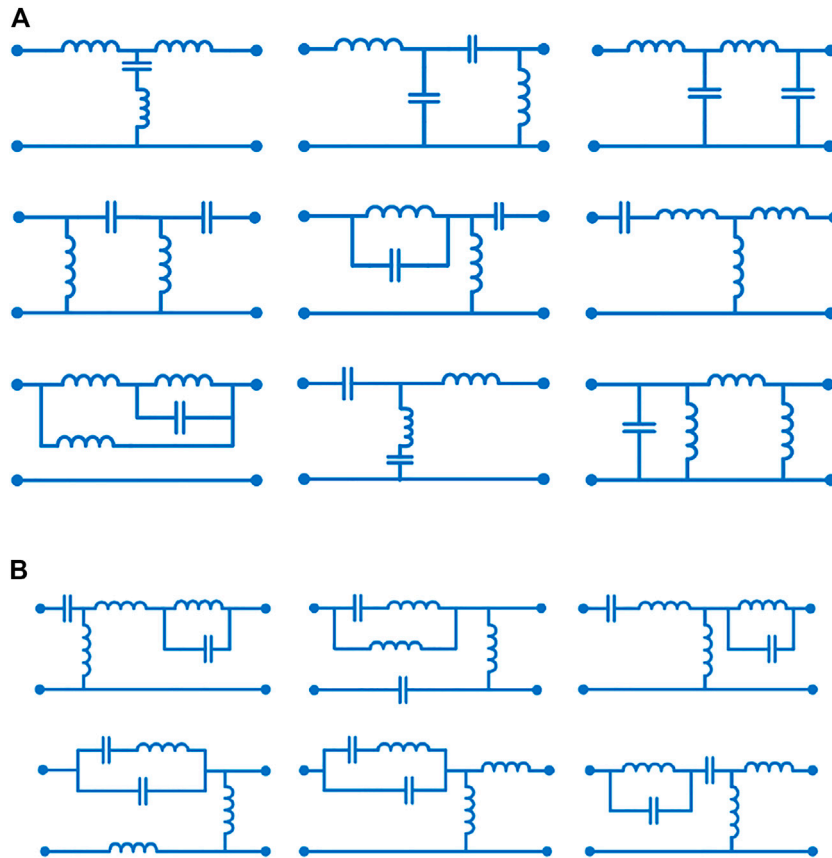


FIGURE 9 | (A) Topologies of 4-element resonant tanks (Salem et al., 2018). **(B)** Topologies of 5-element resonant tanks (Outeiro et al., 2016a).

low (Luo and Ye, 2016). These topologies work with half-bridge or full-bridge inverters. Compared to the conventional second-order RPCs, the higher-order RPCs have more desirable properties. Furthermore, the variety of resonant topologies allows the designer to select the most suitable topology for their application. The stable analysis of these converters, however, becomes more complex because they are high-order nonlinear systems (Batarseh, 1994). Three-element RCs have been explored and tested in a variety of systems. Among them are the LLC RC and LCC RPC, which are the most common 3-element RTNs. Many other topologies have also been studied, such as the CLL-RPC and LCL-RPC. Some of these topologies will be thoroughly reviewed later.

2.2.3 Multi-Element Resonant Power Converters Topologies

These are RTNs with four or more LC components; they exist in about 98 different topologies, some of which are shown in **Figure 9A**. (Batarseh, 1994). Five-element topologies exist in hundreds of topologies as seen in **Figure 9B**. Compared to three-element RPCs, multi-element RPCs have more benefits as most of the benefits of the lower-order RPCs are also found in the multi-element RPCs (Outeiro et al., 2016a). The RPC performance of multi-element RPCs is relatively high; they also offer reduced circulating energy and intrinsic current protection. Furthermore, these converters can work with a short output circuit. Multi-element RPCs can achieve zero current switching (ZCS) on the primary side of the device and zero voltage switching (ZVS) on the secondary side. These multi-element RPCs have a high power density and are DC–DC converters with a high efficiency (Fu et al., 2008). They achieve very low switching losses due to soft-switching action. Furthermore, the injection of the third-order harmonic improves the power process of these converters compared to standard RCs. Hence, the RMS and peak currents of the RTN are lowered, and the current and conduction losses are reduced in the devices as well. Third-order harmonics are also injected into the output voltage in this topology to boost the RMS value (Fu et al., 2008).

Multi-element topologies have been reviewed in a number of studies. The classification and a comparison of different topologies of multi-element RPCs are presented in Huang et al. (2011) and Outeiro and Buja (2015). The LCLC topology of fourth-order RTs is presented in Ang (2006) and Outeiro et al. (2016b). This topology combines the LLC and LCC properties. A common application area of the LCLC RCs is in PV systems where it is used in the maximum power point tracker (MPPT) (Conesa et al., 2009); it is also used in electric vehicle charging (Lu et al., 2015) and others. The LCLC RPC can also be used in high-voltage, high-efficiency applications (Zhao et al., 2017a). In Koscelnik et al. (2014), a review on multi-RPCs is presented and three topologies have been selected: LCTL, LCLCL, and LCL2C2. However, the topology of LCL2C2 is still not extensively investigated. The connection allows for multifunctional outputs such as DC, AC with HF, or LF. The LCL2C2 topology is also short-circuit proof; hence, LCL2C2 can be connected without a transformer and still achieve a 97% conversion efficiency. The system can also achieve THD approximately 4.5% and up to

93 W/in³ power density (Dobrucky and Koscelnik, 2005). LCTL topology can achieve up to 94% power density and THD of less than 5%; all these are in line with equipment requirements. At the point of equal switching frequency values, the voltage transfer function demonstrates that the resonant frequency gains equal one; however, the converter is unaffected by the load size in this situation. The same three topologies of multi-RPCs (LCTL, LCLCL, and LCL2C2) are described and analyzed in Dobrucky and Koscelnik (2005). The multi-RPC is a viable alternative to the existing DC–DC converters.

2.3 LLC Resonant Converter

This is one of the most common 3-element RPCs; they contain three reactive elements, which are a series inductor, a parallel inductor, and a series capacitor. The two inductors (L_s and L_p) together with the capacitor (C_s) form a RTN. **Figure 10A** depicts a circuit of the LLC RPC; it is seen as a normal SRC with an additional inductor parallel L_p to the load (Yang et al., 2002; Salem et al., 2018).

It is also worth highlighting that there is a topology similar to LLC in the number and type of reactive element, that is, CLL topology. Both topologies are found to have two inductors, and one capacitor ($2L + C_s$), with a different arrangement in the resonant tank. The series inductor in the CLL is connected to the RTN's output, whereas the series inductor in the LLC is connected to the RTN's input and is in series with the capacitor. The CLL equivalent circuit, as seen in **Figure 10B**, is made up of a capacitor C_s serially connected to the input (which serves as both a resonance aid and a direct current blocker), an inductor L_s serially connected to the load, and a second inductor L_p parallelly connected between the inductor L_s and the capacitor C_s . The CLL topology presents the same behavior and shortcomings as in LLC but is able to integrate the leakage inductance of the HF transformer in the RTN (Colak et al., 2015; Outeiro et al., 2016a).

The LLC topology generates two resonant frequencies across the whole operating scope, one of which depends on the series inductor L_s and capacitor C_s and is called series resonant frequency (f_{rs}), while the other is dependent on the three elements L_s , C_s , and L_p together, and it is called fundamental resonant frequency (f_{rp}) (Liu, 2017). f_{rs} and f_{rp} are shown in **Eqs. 2, 3** (Salem et al., 2018).

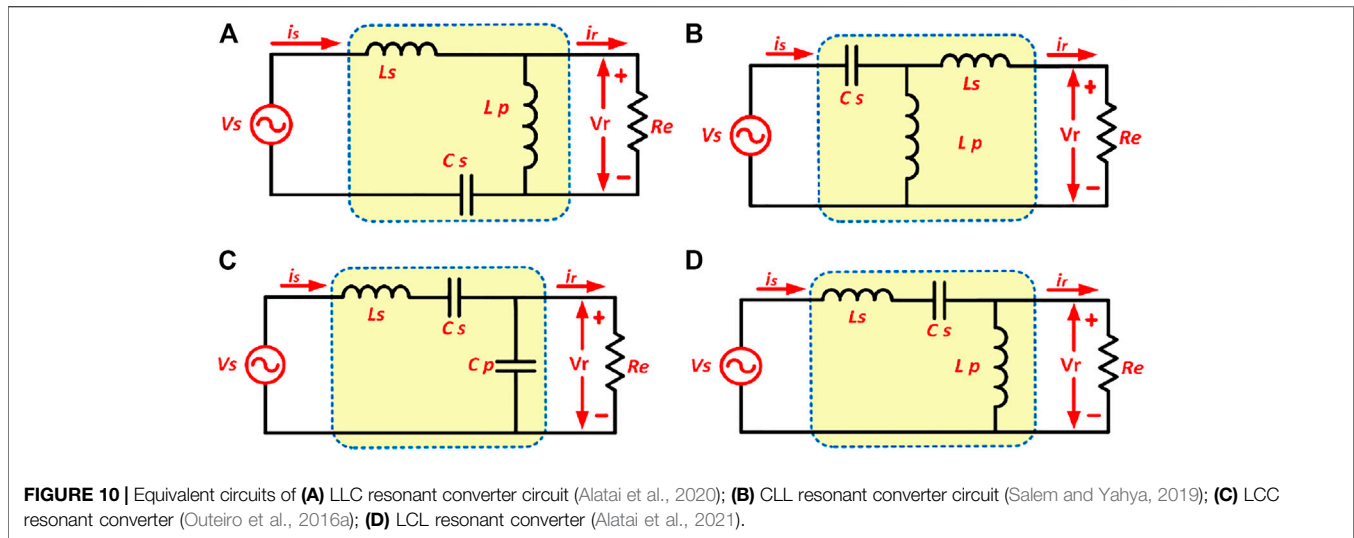
$$f_{rs} = \frac{1}{2\pi\sqrt{L_s C_r}} \quad (2)$$

$$f_{rp} = \frac{1}{2\pi\sqrt{(L_s + L_p) \cdot C_r}} \quad (3)$$

$$AL = \frac{L_s}{L_p} \quad (4)$$

$$M_V = \frac{1}{\sqrt{(1+A)^2 \left[1 - \left(\frac{f_r}{f_s} \right)^2 \right]^2 + \left[\frac{1}{Q} \left(\frac{f_s}{f_r} \right) \frac{A}{A+1} - \frac{f_r}{f_s} \right]^2}} \quad (5)$$

The two resonant inductances AL are related as established in **Eq. 4**; this is the most important concept when constructing the



LLC converter. The relationship between the input voltage and the output voltage is called the voltage-gain function, which provides the basis of the LLC RPC design; it is derived using Eq. 5. When it is operating at series resonant frequency, the LLC and SRC exhibit similar characteristics. Under light load situations, LLC functions more like PRC; however, it operates similarly to SRC under heavy loads. At the system resonant frequency, the peak gain occurs between the fundamental (frp) and series (frs) resonant frequencies (Liu, 2017; Salem et al., 2018).

The LLC RC has drawn much more attention because it gives many advantages over conventional RPCs with two elements (SRC and PRC). At the same time, it reduces their limitations. LLC topology by using an inductor parallel to the resonant capacitor can achieve no-load control, which is impossible to achieve in the SRC (Outeiro et al., 2016a). In this converter, however, excellent efficiency can be achieved when operating over a wide load range (no load to maximum load), a wide input voltage range, and a limited range of switching frequency, which makes wide output regulation range. The primary and secondary side rectifiers of an LLC can achieve ZVS and ZCS, respectively; they can also achieve minimal voltage stress on the secondary rectifier because this converter does not need to use secondary filter inductor voltage stress. Hence, there is a possibility of reducing the voltage stress on the diodes of the rectifier by twofold compared to the output voltage. This converter can also achieve ZVS + ZCS features with high efficiency in both forward and backward modes (Bhuvaneshwari and Babu, 2016; Cao et al., 2019). ZVS and ZCS can also be realized over the full operational range. Low switching losses are also recorded because they use ZVS and ZCS. ZVS can also be performed with no load, resulting in lower EMI losses. SS mechanisms are disabled, resulting in a MOSFET switching transistor with a minimal turn-off and low switch-off current losses. Both step-up and step-down functions can be implemented with LLC RPC with an additional wide range of input voltage *via* frequency control (Tian et al., 2016; Cao et al., 2018).

An additional benefit of the LLC converter is that it is easy to combine the magnetic components of this converter in one magnetic core; only one capacitor filter is needed on the secondary side, thereby reducing the complexity of the circuit (Cao et al., 2018). LLC topologies have been used in both half-bridge and full-bridge primary inverters; it has also been used with the secondary side of either center-tapped or full-bridge rectifiers (Huang, 2010). This converter provides high performance and becomes a good option for high-voltage applications. The topology is highlighted in many studies, for example, the design of LLC topology, analysis, simulation, and optimization of its parameters (Huang et al., 2016; Xu et al., 2017; Rusu et al., 2019; Tian et al., 2020). These converters are mostly preferred due to their higher energy conversion efficiency, high power density, and LLC RPCs. Among the applications that utilized LLC RPCs are electric vehicle battery chargers (Cetin and Yenil, 2018; Wei et al., 2018), photovoltaic applications (Rubino et al., 2013; Tayebi et al., 2018), induction heating applications (Phadungthin and Haema, 2017), x-ray imaging (Ou et al., 2019), and a novel hybrid full-bridge three-level LLC converter that can be implemented for fuel cell power systems (FCPSs) (Jin and Ruan, 2006). LLC RPCs can also be used in computer systems as front-end power supplies; it can also be used in other consumer devices like LCD, LED, and plasma displays in TV and flat panels, as well as for high-power LED lighting applications (Acar Vural et al., 2017; Ma et al., 2017). The SS performance, increased efficiency, decreased electromagnetic interference, and step-up voltage flexibility of LLC RPCs make them ideal for use in high-voltage systems (Samsudin et al., 2017).

2.4 LCC Resonant Converter

The LCC RPC is also one of the most common three-element RPCs. LCC topology contains three reactive elements, which are a series inductor (L_s), a series capacitor (C_s), and a parallel (C_p) capacitor. The two capacitors (C_s and C_p) and one series inductor L_s together form a resonant tank RTN. Figure 10C depicts the circuit diagram of the LCC RPC. These converters are regarded as

conventional SRC with an extra capacitor that is parallelly connected to the load; hence, it is commonly called a series-parallel RC (SPRC) (Salem et al., 2018; Nielsen, 2013). The LCC converter also has two resonant frequencies, which is due to the arrangement of the three reactive elements in the RTN. The first frequency based on the series elements (L_s , C_s) is called the series resonant frequency (f_{rs}) and the second one is based on all three tank elements (L_s , $C_s + C_p$), which is called the parallel resonant frequency (f_{rp}), (Eqs. 6, 7); note that $f_{rs} < f_{rp}$. The LCC topology is a combination of SRC and PRC characteristics. The series resonant frequency f_{rs} assists in operation, but the parallel resonant frequency f_{rp} dominates LCC. Subsequently, LCC has the same limitations as the PRC (Bhuvaneshwari and Babu, 2016). It is important to carefully select the ratio between the two resonant capacitors (AC) in LCC converters to ensure that it suits the required peak gain. **Equation 8** is used to determine the characteristics of the voltage gain of LCC converters with a capacitance ratio of 1 ($AC = 1$), with the voltage gain to light loads leaning toward the f_{rp} parallel resonant frequency, while the converter behaves more like a PRC parallel resonant. The peak voltage for high load conditions leans towards the f_{rs} and the LCC converter characteristics tend to be similar to the SRC characteristics, with a voltage gain closer to unity. Accordingly, the LCC converter has similar characteristics to the PRC converter, besides having the advantages of SRC attributes. However, the resonant components must be selected correctly (Outeiro and Buja, 2015).

$$f_{rs} = \frac{1}{2\pi\sqrt{L_s C_s}} \quad (6)$$

$$f_{rp} = \frac{1}{2\pi\sqrt{L_s \left(\frac{C_s C_p}{C_s + C_p}\right)}} \quad (7)$$

$$M_V = \frac{1}{\sqrt{(1 + A_C)^2 \left[1 - \left(\frac{f_s}{f_{rp}}\right)^2\right]^2 + \left[\frac{1}{Q} \left(\frac{f_s}{f_{rs}}\right) - \frac{A_C}{A_C + 1} \frac{f_{rs}}{f_s}\right]^2}} \quad (8)$$

The LCC converter is an effective topology for highly efficient power converters, allowing wide operation with high performance. Because of the low switching losses, the LCC RPC can operate at higher switching frequencies while retaining high and almost constant efficiency over the whole load and input voltage range (Pawellek et al., 2011; Deepika and Elakkiya, 2014). The LCC is also the better option for high output voltages because of the presence of capacitor at the output winding. At high voltage, the parasitic capacitances in windings and diodes usually cause ringing problems and additional power loss but not in the LCC topology. The parasitic capacitances are eliminated by the output capacitor (Nielsen, 2013). In the LCC converter, a large input voltage range is possible, but it will then suffer from high RMS currents over the whole input voltage range. Therefore, the resonance capacitors must be carefully chosen and must be special types to withstand high AC currents. In addition, high frequency of switching at low load may cause EMI problems (Nielsen, 2013). The high-magnitude current and the high frequency of resonant capacitors (C_r) entail that they must exhibit a low dissipation factor (DF). Electrolytic

and multilayer X7R ceramic capacitors, for example, have a high DF; hence, they are not recommended. The low DF of the NPO ceramic capacitors makes them employable despite their limited capacitance range. Capacitors consisting of metallized polypropylene film are commonly utilized in RPCs. These capacitors have a very low dielectric constant (DF) and can handle high-frequency current. It is advised that before selecting voltage rating, it should be derated based on the selected switching frequency (Huang, 2010). The topology of the LCC varies from that of the LLC by the order of both resonant frequencies. As such, LCC cannot work with an open circuit or short circuit in a safe manner (Outeiro et al., 2016a). Similar to the LLC converter, LCC converters have been studied extensively. Among the highlighted aspects are the design optimization, analysis of operation modes, and performance behavior (Liu et al., 2018; Chen et al., 2020). LCC RPC has been used and experimented in several industrial systems, among them, in battery chargers for PV systems (Rakhi et al., 2014), furnace power supply during electron beam melting (Haifeng and Peng, 2017), x-ray applications (Pernía et al., 2017), and xenon flash lamp simmer circuit (Song et al., 2019).

2.5 LCL Resonant Converter

The LCL RPC is considered a conventional SRC with an extra inductor in parallel (L_p) with the primary side of the high-frequency (HF) transformer or secondary side. However, the placement of the parallel inductor (L_p) on the secondary side will allow maximum usage of the magnetizing and leakage inductances of the HF transformer. This parallel inductor and the inductor (L_p) can also be integrated into the transformer. Moreover, the value of inductor required on the secondary side is smaller than required on the primary side. The rectifier bridge also has a small equivalent inductance at the input. Hence, this topology is also called “modified SRC” or “LCL-type SRC”. The LCL RTN circuit is depicted in **Figure 10D** (Bhat, 1994; Bhat, 1997). The RTN of an LCL converter comprises two resonant frequencies: f_{rs} , which is produced by the resonant elements L_s and C_s , and f_{rp} , which is determined by all tank components. If the switching frequency is greater than the resonance frequency and the gain is less than 1, the LCL converter will operate like a traditional SRC (Salem et al., 2017b). The operation of this converter for the entire load and specified supply voltage changes is within the lagging PF mode (Bhat, 1995). This converter mainly suffers from the magnetizing and leakage inductances of high-frequency transformers that serve as components of the resonant circuit. Hence, the parallel inductor is mostly small-sized, making the magnetizing inductance only profitable when L_p is placed on the secondary side. This circumstance can considerably lower the converter weight, size, and cost. Obviously, the magnetizing inductance is enough to be considered the parallel inductance (Almardy and Bhat, 2011; Almardy and Bhat, 2015), and the voltage of the output rectifier is attached to the output voltage. Additionally, the converter relies on SS when used for inverter switches based on switching frequency range. In comparison to the usual SRC- and LCC-type converters (Almardy and Bhat, 2011), the needed switching frequency variation for the wide changes in load and supply voltage is small. A slight increase in the switching

TABLE 1 | A comparison between the most common three-element topology (LLC, LCC, and LCL).

Comparative points	LLC	LCC	LCL
Advantages	<ul style="list-style-type: none"> ■ It can achieve ZVS across the whole operating range. It achieves low MOSFET turn-off current, meaning that the switching loss is low ■ Provides very high efficiency over a wide input voltage range and load variation range (Cao et al., 2019) ■ The voltage stress on the rectifier diodes can be minimized, and ZCS is achieved for the rectifier diodes, no reverse recovery loss of the rectifier (Cao et al., 2019) ■ The ripple of the input current and output filter is low (Jin and Ruan, 2006) ■ Can work in both step-down and step-up modes (Azura et al., 2014) ■ Its bidirectional design allows operation in both forward and backward modes and still achieve a good output power (Bhuvaneshwari and Babu, 2016) ■ The integration of the magnetic components into one magnetic core can be done with ease. The transformer's leakage inductance can also be utilized 	<ul style="list-style-type: none"> ■ The LCC is a better option for high output voltages, due to the parallel capacitor. Also, the parasitic capacitances are eliminated by the output capacitor (Nielsen, 2013) ■ Ability to operate above and lower resonant frequency ■ At low di/dt, the antiparallel diodes turn off and fails to generate reverse-recovery current spikes. Hence, it is safe to be operated above resonant frequency (Outeiro et al., 2016a) 	<ul style="list-style-type: none"> ■ This converter can be operated above resonance for the entire load and at specified supply voltage variations (Bhat, 1995) ■ The HF transformer has a magnetizing inductance that can be exploited as part of the resonant circuit (Almardy and Bhat, 2011; Almardy and Bhat, 2015) ■ The use of the magnetizing inductance of the transformer to enhance the conductivity of the RTN enables the LCL RPC to produce high gain output voltage with a wide ZVS range (Salem et al., 2017c)
Disadvantages	Difficult to achieve startup and short-circuit protection because of the flat gain above the frs. Hence, it is impossible to operate the LLC topology safely with an open circuit when the frequencies are close to frs; it can also not be safely operated with a short circuit when frequencies are close to frp (Fu et al., 2008; Outeiro et al., 2016a) (Pridala et al., 2018)	LCC operation with a short or open circuit is not safe (Outeiro et al., 2016a). Two large and expensive independent physical capacitors are required due to the high AC currents (Outeiro et al., 2016a). The efficiency level is just marginally higher at low input compared to high input voltage (Pawellek et al., 2011) <ul style="list-style-type: none"> ● Resonance capacitors must with stand high AC currents and must be specific types (Nielsen, 2013) 	One major drawback of LCL type SRC with inductive filter is that high voltage stresses on the output rectifier is observed (Bhatt, 2017)
Load variations	It has a wide load variation range. Up to 20% of the full load to full load (Salem et al., 2020)	It is not suitable for wide load variation, but it has a wider gain range	It has a wide load variation range by 50% (Salem et al., 2017c) and from 100% to 20% of the full load (Bhatt, 2017)
Voltage gain	It has a high voltage gain, with a recorded voltage gain equal to 5 in Salem et al. (2020) and 6.25 in Bhuvaneshwari and Babu (2016). An LLC converter can have a very high voltage gain of more than 10 (Kumar et al., 2018a)	LCC has the ability to provide a wider voltage gain compared to LLC and LCL (Outeiro et al., 2016a)	It has the ability to achieve high gain, as it was recorded equal to 3 in Salem et al. (2017c) and Bhatt (2017)
Efficiency	The efficiency of the proposed LLC converter in Salem et al. (2020) is 96.2% within the operating frequency range. A theoretical peak efficiency of 97.7% was obtained at full load (Cetin and Yenil, 2018). The prototype study showed a conversion efficiency of 96% (Cao et al., 2019)	<p>The peak efficiency in different loading conditions reached 94.8% (Ramezani et al., 2019)</p> <p>The maximum efficiency of the bidirectional three-phase LCC RC was about 92.2% during step-down mode and 91.7% during step-up mode (Ahn et al., 2019)</p>	<p>An LCL converter efficiency of 94.2% was achieved at full load (Du and Bhat, 2016) while the dual-tank LCL-type DC-DC converter achieved 94.3% efficiency using Si MOSFETs for the full load (Bhatt, 2017)</p> <p>The measured efficiency for the dual-tank LCL-type DC-DC converter using SiC MOSFETs is 97.1%, for the full load (Bhatt, 2017)</p>
Applications	LLC is applied in electric vehicle battery charger applications (Cetin and Yenil, 2018; Wei et al., 2018), in photovoltaic applications (Rubino et al., 2013; Tayebi et al., 2018), in induction heating applications (Phadunghin and Haema, 2017), and in x-ray imaging (Ou et al., 2019). It is suitable for fuel-cell power systems (Jin and Ruan, 2006). Besides, it is also widely adopted	LCC RPC is suited for high-voltage applications (Abdul-Hakeem et al., 2018) and has been used in battery chargers for PV systems (Rakhi et al., 2014), in furnace power supply during electron beam melting (Haifeng and Peng, 2017), in x-ray applications (Pernía et al., 2017), and for xenon flash lamp simmer circuit (Song et al., 2019)	This type of converter is good for use in low-voltage, high-output current systems, and it can be used in power systems and telecommunication (Bhat, 1994). It is good for applications such as space and radar high-voltage power supplies and it can also be used with a stand-alone wind generator (Bhat, 1997). Besides, it was applied and succeeded to achieve improvement in some (Continued on following page)

TABLE 1 | (Continued) A comparison between the most common three-element topology (LLC, LCC, and LCL).

Comparative points	LLC	LCC	LCL
	in other applications, such as for front-end power supplies in computer systems and consumer electronic devices such as LCD, LED, and plasma displays in TV and flat panels, as well as for high-power LED lighting applications. (Acar Vural et al., 2017; Ma et al., 2017). It is also suitable for high-voltage applications (Samsudin et al., 2017).		applications such as high-voltage application and electric vehicle battery charger application (Salem et al., 2017c).

frequency above the required level for full load operation will main the converter efficiency and confer other desirable features on the converter (Bhat, 1994); there will also be a decrease in the peak current passing through the switches as the load current reduces (Bhat, 1995; Almarady and Bhat, 2011). The LCL converter rely on a wide range of ZVS to achieve high gain output voltage by enhancing the RTN conductivity using the magnetizing inductance. This converter combines variable frequency and fixed frequency (duty-cycle) management to enable it to handle a wide range of load variations (Salem et al., 2017c). The LCL-type SRC has enhanced power densities and numerous desirable properties; hence, it is ideal for use as stand-alone generators and in space and radar high-voltage power supplies (Almarady and Bhat, 2015). It is also usable in electronic systems and power supplies (Bhat, 1994). Besides, it has been applied in high voltage systems and electric vehicle battery chargers (Gautam and Bhat, 2012; Salem et al., 2017c). The LCL RPC has been analyzed, designed, and published in several research works (Harischandrapa and Bhat, 2014; Du and Bhat, 2016; Almarady and Bhat, 2019).

2.6 Comparison Between Three-Element Resonant Power Converters Topologies

Resonant converters with three-element RTN have been widely studied and experimented in many industrial applications, among them are LLC, LCC, and LCL, which are the three configurations compared in Table 1.

3 RESONANT POWER CONVERTERS FOR RENEWABLE ENERGY SOURCES

Some of the applications of RPCs include grid-connected renewable energy converters such as solar, fuel cells, wind, and electric vehicle charging systems *via* wired or wireless power transfer. The integration of RES to grid requires high-efficiency converters with little current ripple. The fundamental requirement for power processing from RES is DC–DC converters. Among the various options for the DC–DC converter, RPCs can be a major contender due to their high efficiency and power density that can be achieved *via* SS at the high operating frequencies, low MI, and robustness (Outeiro et al., 2016b; Salem et al., 2018). As a result, RPCs are mostly used in PV systems (PVS), wind energy conversion systems (WECS), fuel cell systems (FCS), and grid connection interfaces.

3.1 Wind Energy Conversion Systems

The study by Fan et al. (2013) compared the performance of LCC RPC with that of the hard-switched full-bridge converter (HSFB) as a linkage to a wind energy electrical source (WECS). The study found the LCC RPC to be more efficient at above half load condition than the HSFB converter. The possibility of using an LCC RPC for WECS is demonstrated by the achieved experimental data. Another study by Moury and Lam (2015) proposed two modular MV step-up DC–DC converters for MVDC grid in wind energy systems; the system incorporates numerous modules of step-up resonant circuits and high-gain, high-frequency rectifiers. The suggested converters demonstrate the ability to obtain substantial voltage gain with a high-frequency transformer with a unity turn ratio while minimizing the power switch-related voltage stress. A highly efficient solution was proposed by Dincan et al. (2019) for wind turbines linked to MVDC networks; the primary side of the proposed system has SRC with LC tank. The architecture was proposed as a unique solution for DC–DC topologies with medium frequency, high voltage gain, and high power. The study by Shu et al. (2017) presented a system for offshore wind farm distribution that consisted of two transformers (one main and one auxiliary), two full-bridge inverters that share a bridge leg, and a voltage-doubler rectifier. A prototype was developed and used to demonstrate the design and working principle of the proposed converter. The SRC proposed by Dincan et al. (2018) has a resonant tank on the high-voltage side; the system was proposed as a solution for high-voltage DC wind turbines; the low transformer size and its high efficiency allow the control of the output power and improve efficiency.

3.2 Fuel Cells

This technology is chosen because of the benefits associated with resonant conversion, notably the minimization of switching losses. The inverter's turn-on losses are low because the switches are ZVS switched on. As a result, the switch off and conduction losses are considered for each IGBT; these were 23 W at full load and 17 W at 25% of the condition for the employed topology (Salem et al., 2022). The study by Outeiro and Carvalho (2013) presents a concept for the design of a DC–DC RPC for use in PEM fuel cell systems. Another work by Jin and Ruan (2006) describes a unique H-FB TL LLC converter for use in FC power systems. The suggested converter exhibited a high efficiency over a broad range of input voltage, as well as a

low input current ripple and an output filter. The use of an LLC RPC in a FC-based power system was presented by Boscaino et al. (2014); the system can be used in FC automobiles. The entire system exhibited excellent conversion efficiency due to the SS features of LLC RPC. In the work by Buccella et al. (2015), a nonlinear LLC RPC model was proposed in combination with an observer-based controller. The output stabilizing capability of the proposed system was demonstrated over a range of load variations; the system was found better than the conventional PID controller.

3.3 Electric Vehicles

RPCs are widely used in electric and hybrid electric vehicle (HEV) charging systems that require wired or wireless charging of the batteries. Wired EVs charging (Fang et al., 2015) and plugged-in EVs (Deng et al., 2014) require the introduction of RPCs to reduce size and achieve high efficiency. The study by Musavi et al. (2013) proposed a high-performance (H-P) LLC converter for use in a 2-stage battery charging system. The converter eliminates the low- and high-frequency ripple on the battery, thereby improving the battery life without expanding the charger's size. Different studies (Hua et al., 2016; Dalala et al., 2018; Kim et al., 2019; Subramaniam et al., 2019) have suggested other topologies that utilize RPCs for wired charging systems. In order to minimize costs while increasing vehicle performance, high-efficiency and high-power density battery charger designs are becoming increasingly critical in EVs (Emadi et al., 2008) for the improvement of vehicle performance and reduction of cost (Yilmaz and Krein, 2013). The on-board battery charger's design allows the possibility of charging the battery of vehicles from any power outlet. This end-user flexibility has encouraged interest in EVs (Whitaker et al., 2014). The optimization of the operation region of an LLC RPC for on-board battery charging system has been assessed in Cetin and Yenil (2018). The design optimization considers a wide range of load conditions and output voltage regulation, both of which are necessary for lithium-ion battery charging applications. At full load, the theoretical peak efficiency of the system was approximately 97.7%. There are numerous DC-DC RPCs for on-board battery charging systems in EVs (Lee, 2015; Çetin, 2017; Shen et al., 2018). Another charging system for electric and HEVs is the wireless power transfer (WPT) method, which has become an alternative to wired charging systems (Kan et al., 2017). The currently existing WPT systems are those for electric, electromagnetic, and magnetic power transfer. For the magnetic coupling system, RPCs are used to achieve high power transmission and maximum efficiency at close distance. Studies have documented the use of RPCs in WPT for EVs and HEVs (Li et al., 2015; Samanta and Rathore, 2015; Na et al., 2019).

3.4 Induction Heating

The popularity of RPCs for IH has increased tremendously due to its efficiency, quick heating, precise power control, and safety compared to the conventional heating systems. RPCs are the main component for achieving the expected performance in such systems (Salem et al., 2018). For this purpose, half-bridge, full-bridge, and multi-inverter have been utilized as resonant inverters. The study by Haema and Phadunghin (2018)

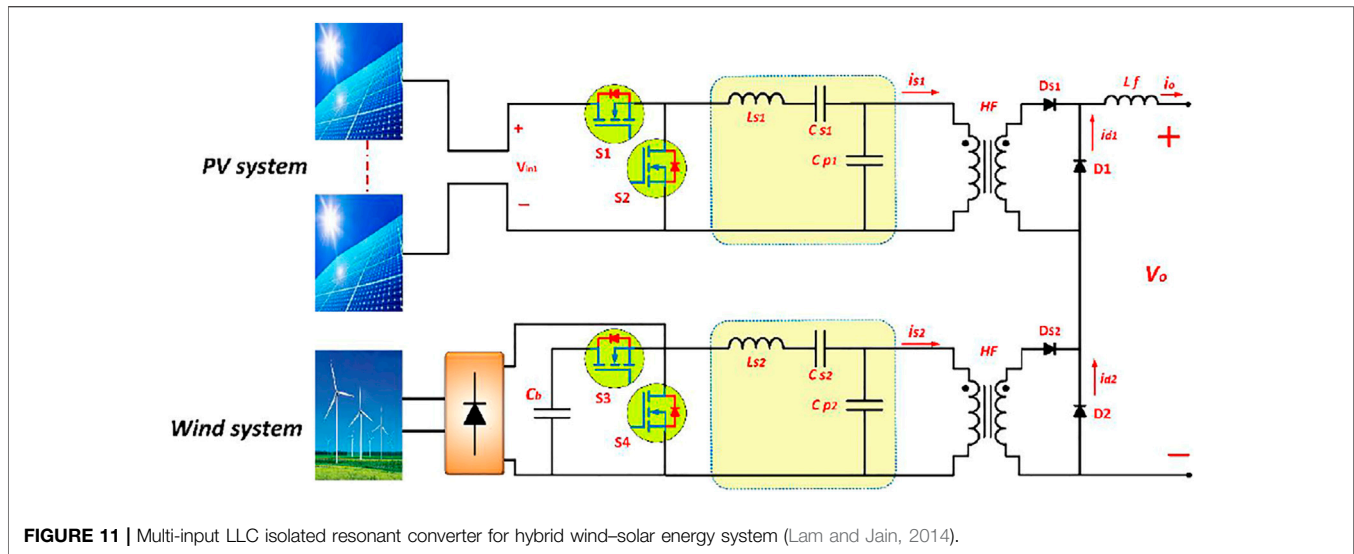
suggests the creation of an LLC resonant inverter (RI) for use in saw blade induction heating. The use of half bridge RI in the saw blade IH application is aimed at the provision of good power supply for IH, with suitable output power and great efficiency. The development of a high-frequency full-bridge series RI for use in induction-heating cooking equipment has been described by Bhaskar and Vishwanathan (2012). The system is simple in design and operation, and it is also quite inexpensive. The work of researchers in Kumar et al. (2018b) proposed a full-bridge parallel RI (FBPRI) for industrial IH applications that improves the performance and efficiency of the traditional IH systems using a pulse density modulation (PDM) technology. The suggested technique ensures the achievement of ZVS/ZCS condition and lower switching losses under various loads. In the IH system described in Neogi et al. (2019), a high-frequency series RI (HFSRI) was used. The reliability of the proposed system was validated through a stability study of the high-frequency inverter circuit that forms the core of the IH system. It was proven that systems with higher stability are more reliable. A multiphase RI with vertical coupled coils was presented by Gomes et al. (2020) for use in IH systems; the phase-shift control strategy of the proposed system improves the power capability of the system.

3.5 Photovoltaic Systems

The RPCs are widely used in PVs due to their high power density and efficiency. The SS techniques in such systems reduce the switching losses significantly (Outeiro et al., 2016b). In Ragab et al. (2017), a full-bridge LLC RPC has been proposed for a grid-connected double-stage photovoltaic (PV) system to step up the output voltage of the PV array. The proposed converter has the advantages of wide input regulation capability and SS, which allows for high-frequency and high-efficiency operation compared to traditional isolated converters. A half-bridge series-parallel RPC (HBSPRPC) was proposed by Rakhi et al. (2014) for a PV system and secondary battery interface. The design of the converter was aimed at keeping the battery free of high- and low-frequency current ripples. A study by Vakacharla and Rathore (2019) presented a stand-alone SS current-fed LCC-T RPC for the PV/FC system. The suggested converter can achieve SS over a great range of input and load variations, higher gain, continuous input current with minimum ripples, lower harmonic content, higher efficiency, and higher power density. In LaBella and Lai (2014), a novel isolated hybrid RPC was presented for PV applications with numerous operating modes (Buck, pure series resonant RC, and boost mode); these modes were implemented using a simple topology with few components. The power conversion efficiency of the proposed converter is high over a wide range of input-voltage and output-power. Several RPC topologies for grid-linked PV systems have been proposed in Zhao et al. (2017b), Altin et al. (2019), Jean-Pierre et al. (2019), and Tayebi et al. (2019).

3.6 Some Recently Proposed Resonant Topologies for RESs

Independent converters have the primary function of maximizing power extraction from renewable energy sources (such as wind or solar) under varying environmental conditions.



Multi-input converters have been proposed to reduce the required number of components *via* sharing the output stage of many converters. However, under specific load levels, most of the works provided mostly lose soft-switching functions in the power switches. Hence, an asymmetrical PWM (APWM) multi-input isolated RC is presented for a 1-kW PV-wind integrated system by Jean-Pierre et al. (2019) (see **Figure 11**); the aim of this proposal is to realize soft-switching for varying load circumstances, as well as to offer isolation in the power electronics interface.

Each module has an APWM LCC resonant isolated converter with a series resonant capacitor (C_s) and a series resonant inductor as its input stage (L_s). High-frequency rectification is provided by two diodes (D_{s1} and D_{s2}) at the output of the high-frequency transformer. In each module, the parallel diode and the output inductor (L_f) are shared between all the input modules, with L_o operating in continuous conduction mode (CCM) to supply steady current to the output. This converter ensures individual and simultaneous activity of the input sources, but this is dependent on the source availability. To achieve ZVS turn-on in all switches, the LCC resonant circuit must be driven above resonance in each module. The turn-off switching losses can be reduced by adding a tiny snubber capacitor across each switch. The connection of an AC input (single-phase or three-phase) to an AC voltage normally requires the inclusion of a power factor correction (PFC) front-end stage to reduce the input-sourced current harmonics. On the other hand, the two-stage method tends to increase the number of controllers, the overall number of circuit components, and the circuit cost. The connection of the input module to an AC voltage demands the integration of the APWM RC in each module with the front-end PFC converter using switch M_4 , which is shared by the APWM RC and PFC stage. The testing and verification of the system was verified and tested with a switching frequency of 70 kHz and a voltage output of 100 V. To simulate five series-connected solar panels, the converter's first module was connected to a 175-V DC source (each 35 V). A 1-kW permanent magnet generator with a 300-V

rated voltage was connected to the second module. At full load, the converter achieved 92.2% conversion, and at 20%, it achieved 89.6%.

For multi-energy integration systems, bidirectional RCs are considered a better option. Examples of this configuration include battery storage, UPS, motor drives, and vehicle to grid (V2G) applications. Their performance in high-frequency solid-state transformers is also satisfactory. To expand the number of connected devices using a single converter, several upgrades and modifications have been made. Multiport converter topologies have been developed as a result of this demand. Several RC configurations have been integrated with PV systems and battery storage as multiport structures. The study by Lam and Jain (2014) described a half-bridge LLC RC in which two inputs are coupled to one PV and one battery storage system. A non-isolated resonant multiport switching capacitor was presented by Nasiri and Jean-Pierre (2020) for renewable energy and battery storage.

Figure 12 shows a multiport RC design with a PV system, battery energy storage, and utility grid as the three primary components. A common DC bus V_{dc} is shared between the PV and battery energy storage systems; it serves as the input or output of the RC depending on the operation mode. The configuration of the battery energy storage was done using a bidirectional buck-boost converter that is connected in parallel to the PV; this configuration forms the two bidirectional converter ports at node A. Through the voltage source inverter, the utility grid serves as the other port of the converter. The high-frequency transformer transports power from node A to node B. The renewable energy source is designated by the letter V_{pv} , which stands for the PV system's voltage. The input capacitor is C_{pv} , the battery storage voltage is V_{bat} , and the bidirectional buck-boost converter's inductance is L_{bat} . V_{dc} and V_o can be used as either the input or output DC voltage of the LLC RC based on the operating mode. C_{dc} and C_o constitute the DC bus capacitor. To obtain the MPPT, the current in the energy storage system of the battery is regulated. The grid-connected 3-phase voltage source inverter may transmit power either from the PV and battery

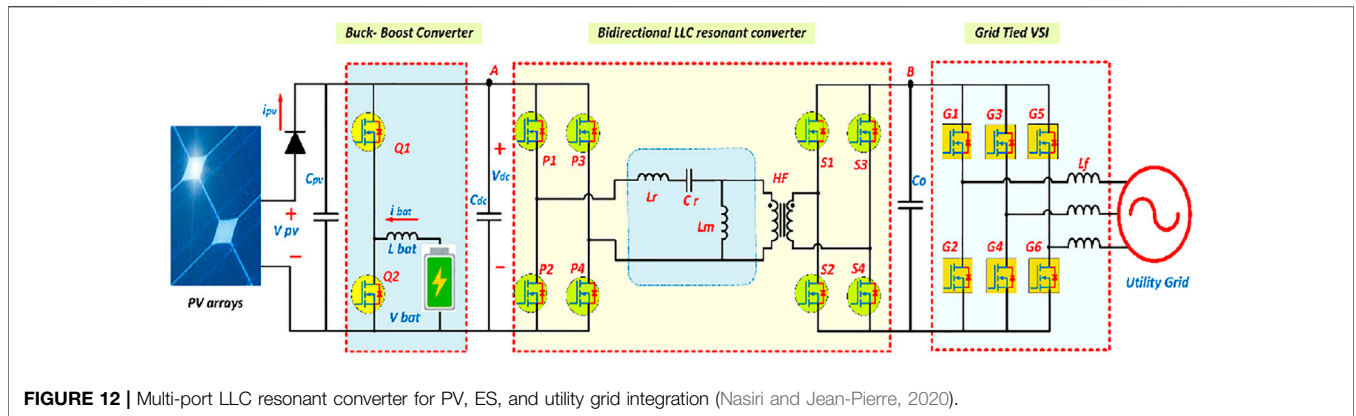


FIGURE 12 | Multi-port LLC resonant converter for PV, ES, and utility grid integration (Nasiri and Jean-Pierre, 2020).

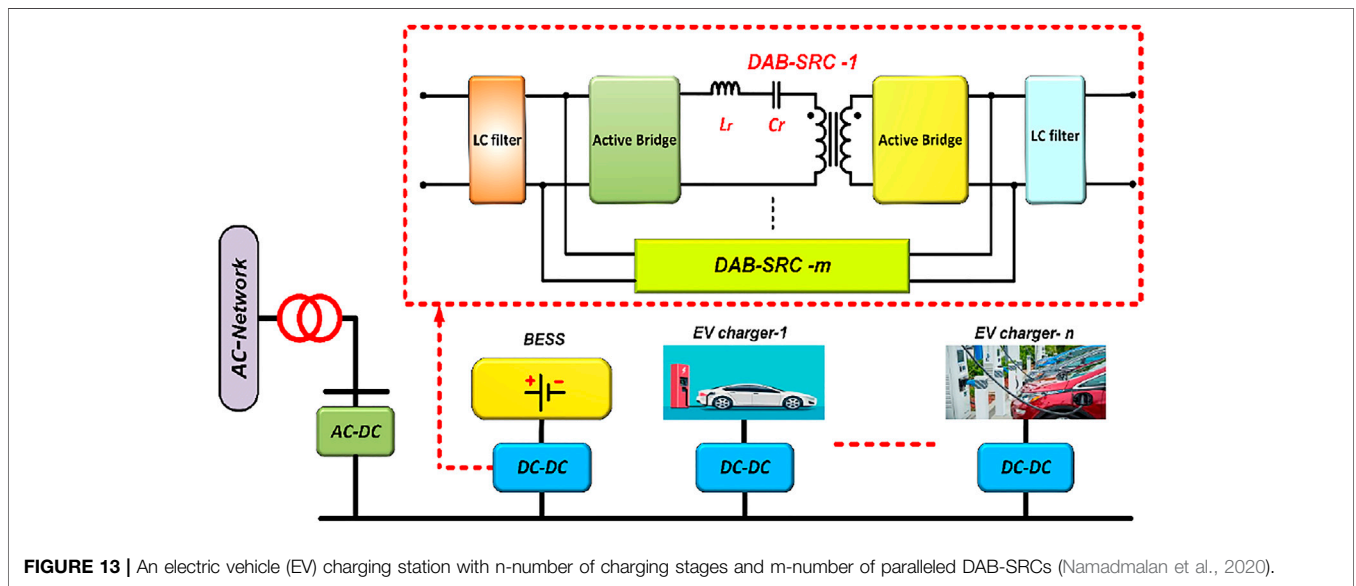


FIGURE 13 | An electric vehicle (EV) charging station with n-number of charging stages and m-number of paralleled DAB-SRCs (Namadmalan et al., 2020).

storage to the grid or from the grid to the battery storage. The power can come from a combination of solar panels, battery storage, and/or the grid. As a result, this converter arrangement can operate in two different modes: forward and backward. The validation of the system was done using LLC RC, Buck-Boost converter, and voltage source inverter (VSI) with switching frequencies of 20–60, 30, and 10 kHz, respectively; the grid voltage and frequency of V_g, f_g 230 V/50 Hz were also utilized. A stable power flow was maintained between the ports; the main voltage values at each port was kept constant regardless of the operation mode. This system can use only one transformer to combine two sources and offer galvanic isolation to the grid (Namadmalan et al., 2020).

A dual-active bridge SRC (DAB-SRC) is a common structure for the regulation of bidirectional power flow in high-power devices such as fast charging of EVs (Kala et al., 2017). Figure 13 depicts an EV charging stage using DAB-SRCs to enable V2G bidirectional power flow capability (Jebaselvi et al., 2013). DAB-SRC also has the advantage of being able to be deployed in a

modular framework without the requirement for additional input or output filters.

This approach has the major problem of tuning the power and frequency of the power converters using minimum phase displacement or circulating current (Lin and Chu, 2016). This problem was addressed by proposing a self-tuning approach with fast dynamics and no tolerance sensitivity. This approach was used recently to tune the power and frequency of wireless charging of EVs using the IPT technology [137]. The study by Jin et al. (2014) relied on the self-tuning loop’s parameters to obtain the design parameters for the DAB-SRC, such as DC-link voltages, minimum and maximum transferred power, switching frequency bandwidth, and temporal displacement between the two active bridges. This basic design increased the performance of bidirectional DAB-SRCs utilizing the self-tuning approach; this is due to the establishment of an intrinsically constant time delay between the two active bridges from light load to full load; hence, ZVS was obtained for all the switches.

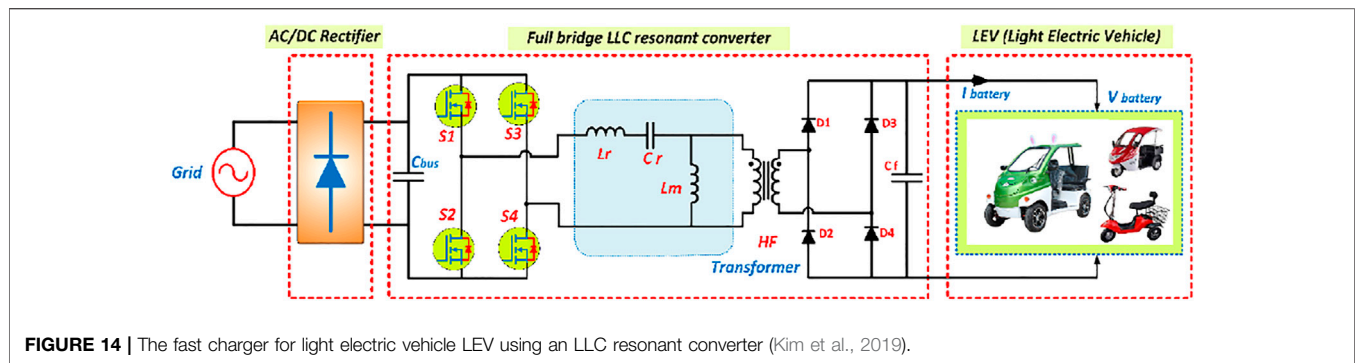


FIGURE 14 | The fast charger for light electric vehicle LEV using an LLC resonant converter (Kim et al., 2019).

The depiction of the fast charger system is shown in **Figure 14**. AC/DC rectifier, full-bridge LLC RC, and a light electric vehicle (LEV) battery. The DSP (TMS320F28335) was utilized to control and sense the system voltage and current in the fast charger. The MOSFET gate (Dalala et al., 2018) is the switching component of the LLC converter. The switching stress can be reduced by adopting a soft start to lower the inrush current at the initial start. System control was achieved using pulse frequency modulation (PFM) and PI control. A different control mechanism for lowering charging time is required in the case of an LEV battery with LIB and SC. This system's input and output voltages are roughly 250–300 VAC (voltage alternating current) and 25.6–33.6 VDC (voltage direct current), respectively. The SC output voltage is approximately 048 V while the control current for the system is 30 A.

In the ZVS region, this fast-charging device uses an LLC RC with SS features. Air and environmental pollutants have reduced the use of lead-acid batteries. Hence, this LEV system with a Li-ion battery (LIB) of 800 Wh and SC of 50 Wh is considered a fast-charging scheme as the charging time is about 1 h. Furthermore, in the CC mode, the highest output current (30 A) conversion efficiency was 96.4%.

4 CHALLENGES AND FUTURE WORK RECOMMENDATIONS

The rapid growth of power electronics devices and technology has increased the application of RES in power grid. This has led to concerns about the power quality, intermittent nature, reliability, and protection of energy transmitted to the grid. As a result, many grid regulations and standards exist for grid-connected RES to preserve grid power quality (Jebaselvi et al., 2013; Kala et al., 2017). From the present literature review, some research areas, and future challenges in the PRCs and their renewable energy systems (RESS) applications are highlighted:

- The intermittent nature of the power provided by grid-connected RES is one of the major challenges. The worldwide energy share of renewables is expected to rise even further in the future. As a result, researchers should

pay more attention to the issue of injected power fluctuations in the grid.

- RPCs have found wide application in various power conversion systems recently. This is mostly owing to its attractive features, such as higher power density and efficiency in comparison to traditional PWM converters. However, there are still a number of issues and research challenges in the field of RPCs that must be addressed to improve their performance. It may require making modifications either on the circuit design or control strategy to eliminate them, and thus improve the performance of these converters.
- The LLC RPC is a promising converter and has several advantages that enable it to perform better than other RPC topologies. As a result, it has become a popular power source for a variety of applications. The LLC RPC, however, has a number of challenges, including start-up, SR driving mechanism, short-circuit protection, magnetic design, and EMI noise reduction (Huang, 2014; Outeiro et al., 2016a; Outeiro et al., 2016b; Cao et al., 2018; Rusu et al., 2019). This necessitates further investigation.
- High-voltage systems are better operated using multi-phase and multi-level RPCs. However, when compared to SLCs, there are notable restrictions, such as output current imbalances between phases, difficulty in the analysis of the control systems and operating modes, as well as the need for numerous electromagnetic components and switching devices. As a result, they have become unworkable in terms of size and cost (Jin et al., 2014; Lin and Chu, 2016; Salem et al., 2018).

5 CONCLUSION

RPCs have been investigated in many aspects in this paper; this review covered the significant development of RPCs as a solution to the problems of EMI and switching losses. Resonant converters were also classified from numerous perspectives in this review. In addition, the highlighted topologies were compared in various aspects such as merits, drawbacks, and efficiency. In terms of applications, this article focused on renewable energy systems that utilized RPC. This

review also covered most of the notable studies on RPCs, which have been utilized in renewable energy sources, with the hope of providing insight into the current challenges of RPCs in renewable energy applications.

AUTHOR CONTRIBUTIONS

AB and MS contributed to design and conceptualization and writing. MA contributed to editing and writing some parts of

the work. DI, MK, and SA contributed to writing, analysis, and editing.

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