Transactions on Energy Systems and
Engineering Applications

Article

An evaluation on industrial applications using leakage inductance and series capacitance converter

Gundala Srinivasa Rao[1], Tellapati Anuradha Devi[2], Kambhampati Venkata Govardhan Rao[3,*], Thalanki Venkata Sai Kalyani[3] Malligunta Kiran Kumar[4], B. Srikanth Goud[5], CH Naga Sai Kalyan[6], K. S. Bhargavi[7], Srungaram Ravi Teja[4] and M. Sai Prasad Reddy [8]

[1] Electrical and Electronics Engineering, CMR College of Engineering & Technolocy, Hyderabad, Telangana, India.
[2] Electrical and Electronics Engineering, Vardhaman College of Engineering, Shamshabad, Telangana, India.
[3] Electrical and Electronics Engineering, St. Martin's Engineering College, Secunderabad, Telangana, India.
[4] Electrical and Electronics Engineering, Koneru Lakshmaiah Education Foundation, Guntur, India.
[5] Electrical and Electronics Engineering, Anurag University, Hyderabad, Telangana, India.
[6] Electrical and Electronics Engineering, Vasireddy Venkatadri Institute of Technology, Nambur Guntur India.
[7] Electrical and Electronics Engineering, Vignan Institute of Technology and Science, Pochampally, Yadadri Bhuvanagiri, Telangana, India.
[8] Electrical and Electronics Engineering, Vignana Bharathi Institute of Technology , Hyderabad, Telangana, India.
* Correspondence: kv.govardhanrao@gmail.com

Received: 25 October 2023; Accepted: 25 September 2024; Published: 10 February 2025

Abstract: The Leakage Inductance and Series Capacitance (LLSC) resonant converters are exhaustively employed in a wide assortment of industries involving consumer electronics due to their benefits of good efficiency, higher power density, immunity to electromagnetic interference, low EMI and harmonic distortion, wide production extends, voltage stress is lowered and frequency at high operating characteristic. Three of the most prominent converters with LLSC topologies are explored along with thorough analyses of their merits and disadvantages. The background of LLSC resonant converters are also discussed. A significant amount of research is also being done regarding large - scale production of LLSC resonant converters, namely in order to charge electric automobiles (EVs), solar systems, LED lighting drivers, and power supply for LCD TVs. Eventually, the growth of LLSC resonant converter is explained.

Nomenclature

LLSC	Leakage Inductance and Series Capacitance
EMI	Electromagnetic Interference
EVs	Electrical Vehicles

How to cite this article: Gundala Srinivasa Rao; Tellapati Anuradha Devi; Kambhampati Venkata Govardhan Rao; Thalanki Venkata Sai Kalyani; Malligunta Kiran Kumar; B. Srikanth Goud; CH Naga Sai Kalyan; K. S. Bhargavi; Srungaram Ravi Teja; M. Sai Prasad Reddy . An evaluation on industrial applications using leakage inductance and series capacitance converter. *Transactions on Energy Systems and Engineering Applications*, 6(1): 574, 2025. DOI:10.32397/tesea.vol6.n1.574

LED	Light Emitting Diodes
$LLSCRC$	LLSC Resonant Converter
$SMPS$	Switch Mode Power Supplies
ICS	Integrated Circuits
ZVS	Zero Voltage Switching
ZCS	Zero Current Switching
LCD	Liquid Crystal Display
PFM	Pulse Frequency Modulation
EMC	Electromagnetic Compatibility
$TL - LLSCRC$	Three Level LLSC RC
PFC	Power Factor Correction
OBC	On-Board Controller
$BI - OBC$	Bidirectional OBC
$BI - LLSCRC$	Bidirectional LLSC RC
$PVCell$	Photo Voltaic Cell
PQ	Power Quality
$MPPT$	Maximum Power Point Tracking
TV	Television
DC	Direct Current
AC	Alternating Current
$SiCdevices$	Silicon Carbide devices
$GaNdevices$	Galliun Nitrade Devices

1. Introduction

The first time the LLSC resonant converter (LLSC RC) construction was made was in 1988 [1], but for a very long time it has not been in the spotlight and has not been employed substantially in real world applications owing to its challenging simulation analysis and sophisticated operation. The basic LLSC RC configuration showing all parts is depicted in Figure 1.

Switch mode power supplies (SMPS) were created to function at specific frequencies in relation to the current need for high power density, which is expected at the devices used in Power Electronic circuit development [2,3]. High-frequency, though, explains severe electromagnetic interference (EMI) pollution

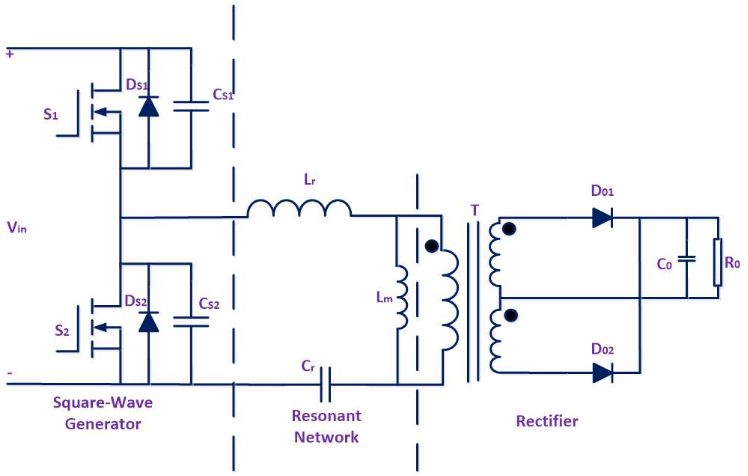

Figure 1. LLSC RC configuration showing all parts.

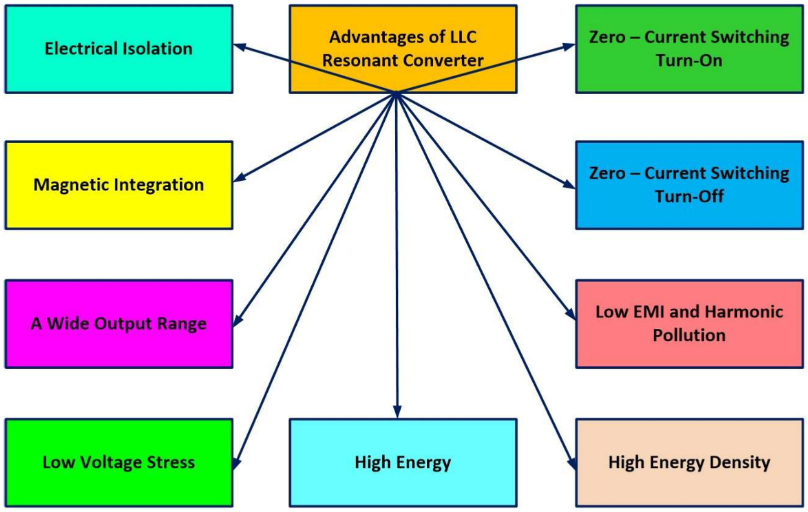

Figure 2. The LLSC resonant converter's benefits.

and switching energy usage [4,5]. As a result, during the past ten years, scholars from all over the world are being curious on converter topologies with a easy on-off switching functionality and at large working frequency characteristic [6]. The benefits of old resonant converters and forms LLSC resonant converter, and positives are such as DC isolation, steady no-load performance, reduced capacitor filter current ripple needs modification of resonant current as load, and improvements in the voltage modulation and easy on – off switching cycle range. As a result, academics have started undertaking in-depth study on it. LLSC resonant converters have developed and are currently used in a variety of industrial applications as a result of extensive resonant converter research and the development of many controls integrated circuits (ICs).

Two switches with opposite duty ratios of 0.5, along with the body diodes and parasitic capacitors, make up the square-wave generator. A high-frequency transformer, a resonant inductor Lr, a magnetising inductor Lm, and a resonant capacitor Cr make up the resonant network. A capacitor filter, two to four diodes, and a transistor are the standard components of a rectifier network [7]. The LLSC resonant converter, as depicted in Figure 2, parasite parameters could indeed attain ZVS turn-on, secondary winding diodes uses ZCS for turn-off, electrical disconnection from the electric grid, without the use of any additional components. As a result, it may be used for various loading scenarios and lower the size and complexity of the utility grid. It can also increase the converter's overall efficiency and stop the load from negatively impacting the power grid.

Since more than ten years ago, applications based on LLSC resonant converters have developed swiftly due to the advantages indicated above. Examples include a laptop adapter [8,9], a power supply for LCD TVs [10,11], a driver for LED lights [12], a battery charger [13], and an EV charging station [14–16]. LLSC RC primary features are Electrical isolation, high energy density, and easy and comfortable switching operations [17,18], all of which increase product efficiency and safety which reduces harmonic pollution and EMI and increasing final weight of system.

The benefits of the LLSC resonant converter [19,20] will be discussed in this paper, along with an examination of its core ideas. Additionally, this article analyses the various topologies of typical LLSC RC, offers a brief description on actual uses of LLSC RC across a range of industries, and predicts the future course of LLSC resonant converter development [21,22].

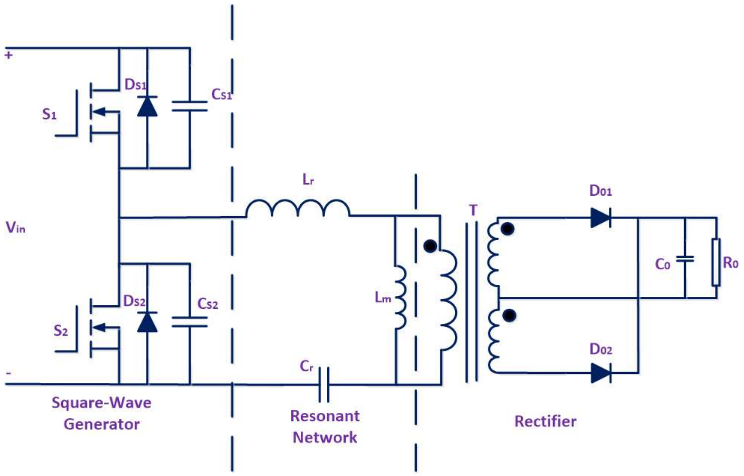

Figure 3. ZVS condition of S1 operation modes.

2. Benefits of the LLSC RC

Without the use of auxiliary circuits or unique control techniques, the LLSC resonant converters can perform a number of favourable functions, which are listed in more detail below.

2.1. Switching on ZVS

If the LLSC RC runs in the inductive zone, the resonant current lags the voltage at the input port. As a result, if changes are made in switching state, the current at LLSC RC never abruptly changes and instead keeps moving in the original direction. Therefore, as shown in Figure 3 [22], the parasitic capacitors at the ends of the switches will allow the resonant current to discharge one of them (CS1) and charge the other one. (CS2). The body diode (such as DS1) is switched on when the symbiotic capacitor is fully depleted. When switch S1 is turned on with the resonant current lowered to zero, the voltages and switching current do not match; hence no active power is produced. Soft switching is done with the least amount of switching losses possible [23, 24].

2.2. Switching on ZVS

The ZCS is made possible by the magnetising inductor of the transformer regularly taking part in the resonance. The output voltage across the diode, as illustrated in Figure 4, restricts the magnetising inductor while it is not a part of the resonance; but, when it is, the current at the LLSC RC passes into both the magnetising inductor and transformer primary end. As a result, the diode turns on and sends energy starts at the grid source to the load. When the current at LLSC RC equals power flow through the magnetising inductor, the reverse voltage shuts off the diode rectifier on the secondary winding. As a result, the transformer's main side is no longer sending any current, which means the main side is also no longer transmitting any current. ZCS increases the stability and effectiveness of the LLSC [25, 26] resonant converter while protecting the switching parts.

2.3. High competence

ZVS and ZCS can be achieved using the LLSC resonant converter with a minimum of switching losses and no diode reverse recovery. As a result, all switching component losses are decreased, increasing the converter's overall efficiency.

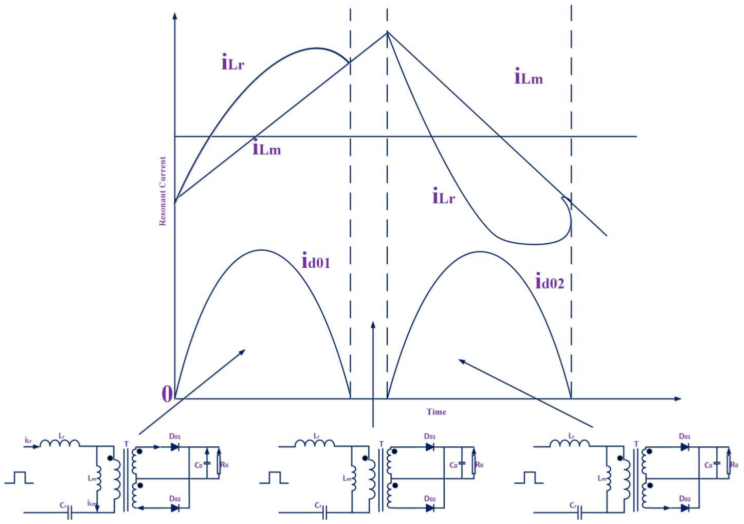

Figure 4. Modes of operation for the ZCS condition.

2.4. Resonant Inductor and its Magnetic Combination Concept

The leaky inductor is completely utilised in the LLSC resonant converter since the magnetising and resonant inductors are merged frequency at transformer, depicted in Figure 5 [23]. This produces a reduced overall converter size, a higher energy density, as well as immunity to electromagnetic interference and voltage conversion [27–29].

2.5. High Energy Density

The transformer volume can be decreased by using a high on and off cycles of switches. The magnetising and resonant inductors are also part of the transformer, which helps the LLSC resonant converter attain a high-power density.

2.6. Electrical remoteness

The LLSC RC detaches the load from the excitation by using the high-frequency transformer. The load cannot harm the electrical grid; hence the grid is not harmed.

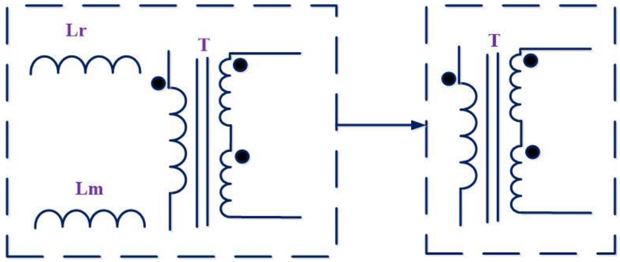

Figure 5. Resonant inductor, magnetising inductor, and transformer magnetic integration.

2.7. Output at a wider extent

The LLSC resonant converter can modify the impedance of the resonant parts and change the gain in order to manage the output in accordance with its gain expression by manipulating the pulse frequency modulation (PFM) of the switching frequency [20,30,31] as

$$G(s)_{LLC} = \frac{\frac{8n^2}{\pi^2}R_0//sL_m}{\frac{1}{sC_r} + sL_r + \frac{8n^2}{\pi^2}R_0//sL_m} \tag{1}$$

where n is the transformer's turns ratio; R_0 is the load, C_r is the value of the resonant capacitor, L_r is the value of the resonant inductor, and L_m is the value of the magnetising inductor.

This allows the LLSC resonant converter to operate under a variety of loading conditions. The LLSC resonant converter [32,33] may still react by changing the output potential or current at output via PFM management to provide operational stability and if load varies fast or the voltage supply encounters a specific malfunction.

2.8. Minimal EMI and harmonic pollution

Due to its nearly sinusoidal resonant current waveform and the elimination of potential and surges at current on the diode rectifier, the LLSC RC has low harmonic pollution and strong electromagnetic compatibility (EMC) [34,35].

2.9. Low voltage restraint

On the secondary side of the transformer, the magnetising inductor serves as a filter, obviating the requirement for an inductor filter and lowering the voltage restraint on the diode rectifier.

3. Three well-liked LLSC resonant topologies utilised in commercial applications.

The three-level (TL) LLSC RC, the full-bridge LLSC RC, and the half-bridge LLSC RC are the three basic LLSC resonant converter designs employed in industrial applications [35,36].

3.1. LLSC RC half bridge configuration

The LLSC RC half bridge configuration is made up of two switches, resonant elements, two diodes, and an outlet capacitor, as shown in Figure 6. Only under situations of high input voltage, low input current, low output voltage, and high output current is the half-bridge LLSC resonant converter ever used. Applications include Remote heat exchangers, communication and computer supplies, battery chargers, and LCD TV power supplies are a few products that use this architecture [37–39].

The half-bridge LLSC RC has the following benefits and drawbacks in comparison to other LLSC resonant converter configurations.

Benefits

1. The primary side of the transformer's current flows in continuously, ensuring that the magnetic core is fully utilised, and that magnetic bias is prevented.
2. The transformer's primary side experiences less voltage stress.
3. The components are inexpensive and the structure is straightforward [40–42].

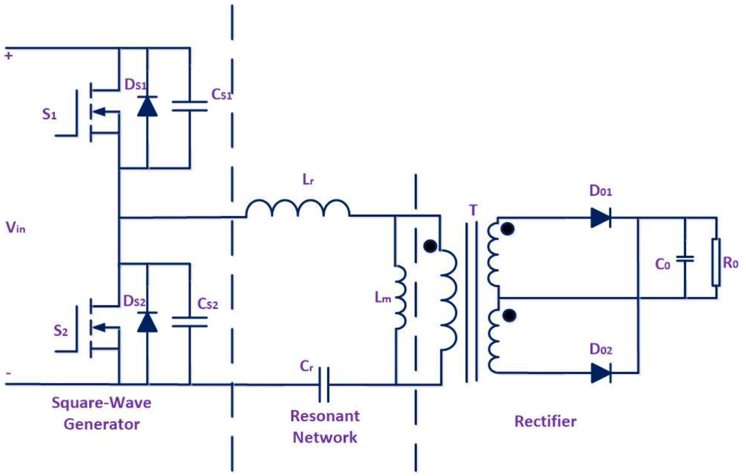

Figure 6. The half-bridge LLSC resonant converter topology.

Drawbacks

1. Due to the doubled current stress via the full-bridge LLSC resonant converter compared to the switches and transformer's primary side, the bridge capacitors will suffer large losses.
2. The transformer's secondary side has large current ripples that could lead to potential oscillations and spikes.
3. A wider switching frequency range is required by a large input voltage range. The converter system may be impacted by the anticipated high input since it will result in an severe on - off frequency and increase the negative impacts of the symbiotic parameters [43,44]

3.2. LLSC RC in full bridge topology

The full-bridge LLSC RC is composed of resonant components, four switches, an output voltage at capacitor, two diodes, and is seen in Figure 7. It is best suited for high and medium power transfers. This architecture is frequently used in induction heating systems, solar power equipment, battery packs, welding operations, and power supplies for X-ray equipment[45].

The full-bridge LLSC resonant converter has the following benefits and drawbacks in comparison to other LLSC resonant converters.

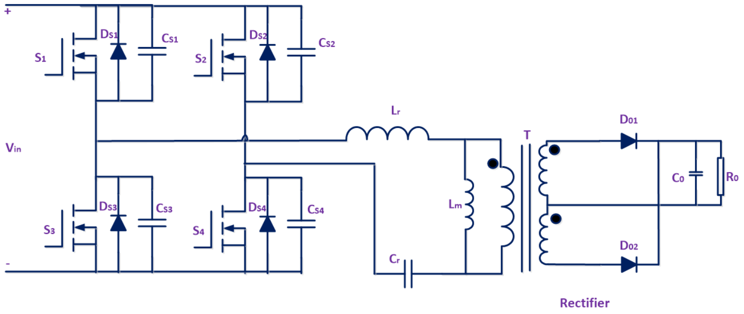

Figure 7. The topology of the full-bridge LLSC resonant converter.

Benefits

1. The converter's consistent current at input and low ripple at current can reduce pollution due to EMI and improve dependability.
2. This sort of converter is best suited for medium to high settings since the switches are less responsive to voltage and current shocks [46, 47].

Drawbacks

1. Complex design is required because of the sophisticated topological structure and auxiliary circuits.
2. The cost of the switch components is rather expensive because four switching drivers are required.
3. The substantial current ripple on the voltage peaks and oscillations could be caused by the transformer's secondary side [48–50].

3.2.1. Differences between Half Bridge and Full Bridge Resonant Converters

Table 1. Differences between FB-LLSC and HB-LLSC

S.No.	Full Bridge Resonant Converter	Half Bridge Resonant Converter
1	These produce a square wave along with no DC offset	These give back a square wave.
2	The output amplitude is equal to the input voltage (Vin)	The output is half of the input voltage (Vin/2)
3	It reduces the current stress	It creates more stress on the Capacitor
4	Heat Dissipation will be less.	It prevents body diode reverse recovery

3.3. TL-LLSC RC

The TL-LLSC RC is made up of four switches, resonant elements, four switches, and three capacitors, depicted in Figure 8. Use the TL-LLSC RC only for creating high power, wide output range systems. The architectural approach is usually used for EV inputs [51, 52].

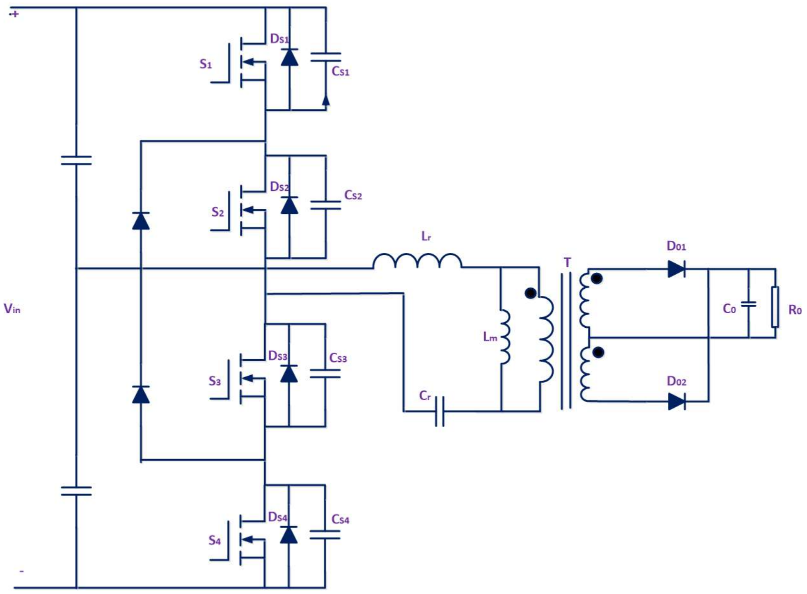

Figure 8. The design of TL-LLSC RC.

These are the benefits and drawbacks of the TL-LLSC in compared to other LLSC resonant converters:

Benefits

1. It is best for usage in improved power situations and employed in lowering the on off switching cycles range because the voltage stress on the switches is decreased to half of the input voltage [53–55].
2. There are low harmonics in the output voltage.

Drawbacks

1. Complex initial effort is required when creating designs for the 4 idle times.
2. The TL-LLSC RC structure requires for four switches and four diodes, which increases the complexity of the converter [56,57].
3. A significant voltage gain is needed to provide a stable voltage at the output end from a low potential input. However, it can only effectively address the trouble of input instability in a limited range due to the lesser efficiency at low input potential and high resonant element stress [58–60].

4. Industries that use LLSC RC

LLSC RC are often employed PV, power supplies for LCD TV, and other key goods because of their beneficial design and features including electrical isolation, gentle switching, greater energy density, and the potential for larger frequency operation.

4.1. LED light driver LLSC RC

Excellent LED lighting has been lauded as the most trusted lighting choice due to its adaptability and range of uses because of its reduced size, high illuminating life, reduced power losses, and environmental friendliness [61–63]. Uncontrollable rectifier bridge-based LED drivers do, however, suffer from a number of shortcomings that result in energy waste, EMI, and harmonic pollution [64–67]. Designing an LED driver with broad adjustability, high durability, and reduced power losses is therefore essential. The LED driver, a crucial component of LED lighting equipment, must also be portable, have a high power density, be economical to manufacture, and have outstanding electromagnetic compatibility. As a result, LLSC resonant converters are frequently used in LED driving devices [68–71]. A two-stage system that lowers EMI and harmonic pollution while simultaneously raising power factor is commonly provided by coupling the LLSC resonant converter to a Boost power factor correction (PFC) converter above it [58, 72, 73]. Figures 9 and 10 show two commonly used Boost topologies, the interleaved parallel Boost PFC converter and the classic Boost PFC converter. The second LLSC RC generates steady current generation and electrical isolation [74–76].

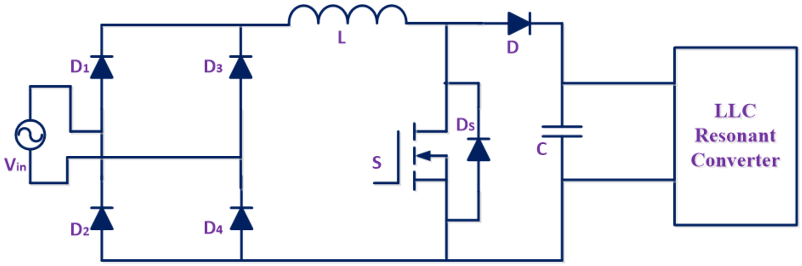

Figure 9. Boost PFC + LLSC resonant conversion LED driver.

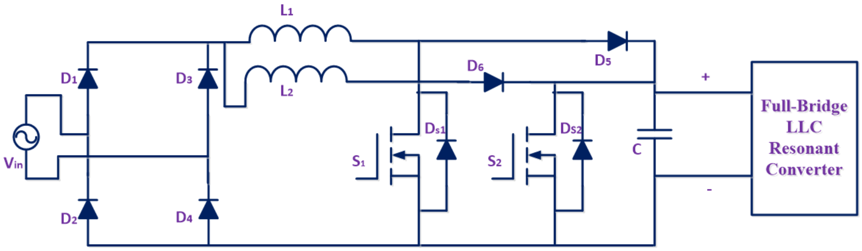

Figure 10. Figure showing LCD drivers with interleaved boost PFC and LLSC RC.

4.2. LCD TV with LLSC resonant converter

Due to their enhanced visual effects and environmental friendliness, LCD TVs have been developed [77–79]. Manufacturers have set high standards for their constructed power supply, including compact size, minimum interference, and light weight, in response to market demands for thin and light LCD TVs [80–82]. This is particularly true for big LCD TVs (those that are larger than 101.6 cm). It is challenging to achieve these criteria with conventional converter options, like flyback or forward converters, due to the high power. The LLSC resonant converter's high switching frequency, which lowers harmonic and EMI pollution, allows for the transformer to be tiny, light, and electrically isolated. As a result, LCD TV power supplies frequently adopt LLSC RC-based utility power systems [83–85]. The most common setup is depicted in Figure 11 and consists of a second-stage half-bridge LLSC RC and a PFC.

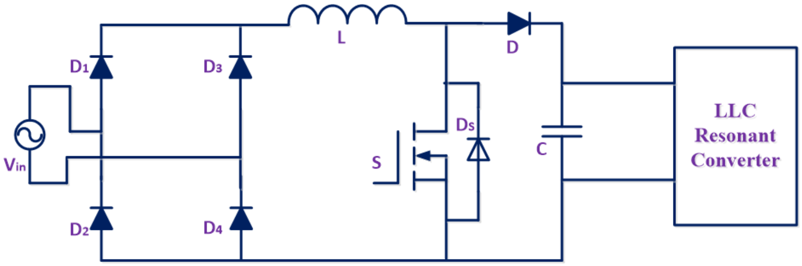

Figure 11. 11 Boost PFC and half-bridge LLSC resonant converter LCD TV power supply.

4.3. An EV charging station's LLSC resonant converter

Due to their low impact on the environment and effective use of energy, electric vehicles are quickly displacing internal combustion engines as the preferred means of transportation [86, 87]. The availability of acceptable driving range, high-power and speedy charging, and practical charging equipment, however, limits the growth of EV charging infrastructure [88–90]. Relatively high power delivery and rapid switching frequency, EV chargers must account for energy losses when they are being designed. The cost of converter devices ought to be exorbitant, and there should be as few EV charging stations as is practical while taking into account the cost of building integrated power plants [91–93]. As a consequence, the charging converter needs to be extremely effective, shockproof, and energy dense. Thus, LLSC RC play a vital mark in the EV chargers thanks to their soft-switching ability, great magnetic integration, widely applied in various range, and high efficiency [94–96].

The on-board controller (OBC) frequently employs Boost PFC + LLSC two-stage architecture to adjust to the operating circumstances of a broad input and output [97–99]. While the boost stage raises the wide-range input potential of 200-400V to the bus potential of 410 V, enhancing the power factor and reducing EMI pollution, the LLSC resonant stage is in charge of the wide-output range, high efficiency, and electrical isolation. Attention has also been drawn to the Bidirectional (Bi) OBC's capacity to start charging in forward mode and output AC current to the electric grid in reverse mode.

1. Full-bridge LLSC resonant converter with OBC of Boost PFC The single-phase Boost converter is good for high voltage and has a straightforward structure with low hardware costs, as demonstrated in Figure 12, but it also has a large filter volume, significant current stress, and ripple.

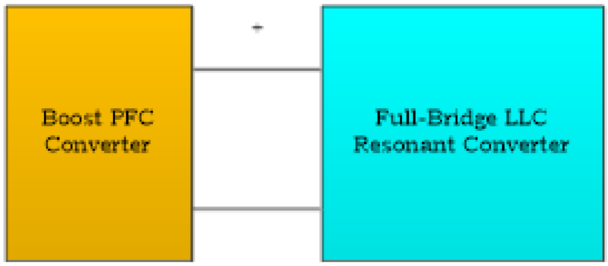

Figure 12. Complete bridge RC with OBC of PFC with boost converter.

2. OBC of complete bridge LLSC and bridgeless Boost PFC resonant converter. Because it lacks a rectifier bridge, as illustrated in Figure 13, the bridgeless converter offers a significant efficiency advantage, but the power factor is difficult to enhance, and the current ripple is substantial. Wide input ranges are suitable for this topology. But for accurate control, costly Hall sensors are needed due to the bridgeless PFC converter's strong common mode EMI [100–102]. In order to lower the cost of manufacturing, several academics and engineers advise employing the differential sampling method.

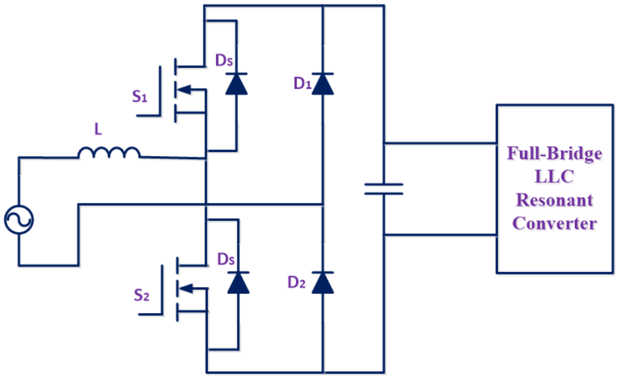

Figure 13. Full bridge with OBC of LLSC and bridgeless Boost PFC RC.

3. OBC of full-bridge LLSC RC and bridgeless Boost PFC with twin transformers. As shown in Figure 14, double transformers can reduce transformer high while increasing energy density. It is also straightforward to control in actual use. But OBC's size and weight are also increased by the two transformers [103, 104].

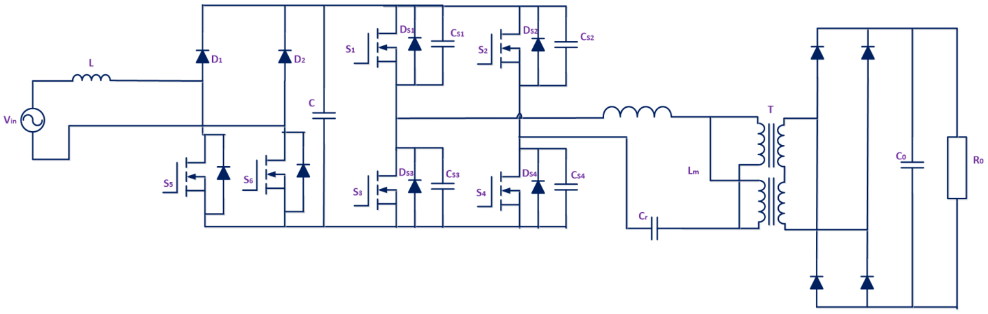

Figure 14. OBC of full-bridge LLSC RC and bridgeless Boost PFC with twin transformers.

4. Parallel interleaved PFC with OBC and a full-bridge LLSC resonant converter. The advantages of the first interleaved parallel Boost PFC converter are shown in Figure 15. It has a high energy density and low ripple current, to start. As a result, the output potential of the wide-range input is stabilised and the load on the current switches is reduced. Thirdly, it can exactly lower the converter's inductor and capacitor values. Fourth, it is simpler to construct a tiny radiator and converter dependability is increased since the current at input current is shared by two channels. Despite this, there is a significant energy loss due to the high equivalent series resistance [105–107].

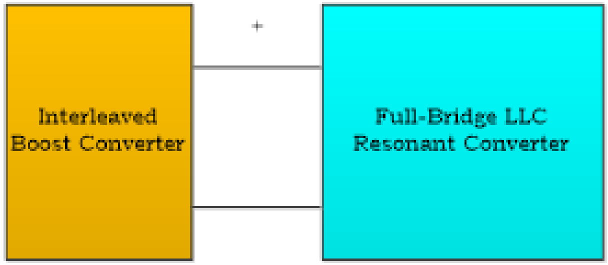

Figure 15. Parallel interleaved PFC with OBC and a full-bridge LLSC resonant converter.

5. Bi-LLSC RC with Bi - OBC. The Bi-LLSC resonant converter, which can be shown in Figure 16, replaces two converters, leading to a lower converter volume and a higher energy density [108, 109]. Additionally, good bidirectional efficiency and a broad selection of bidirectional output are attained. However, it can be challenging to properly create or tune the parameters. When the resonant network is working at maximum or low output, there is a lot of reactive power going through it, and both the switch-off and resonant currents are large.

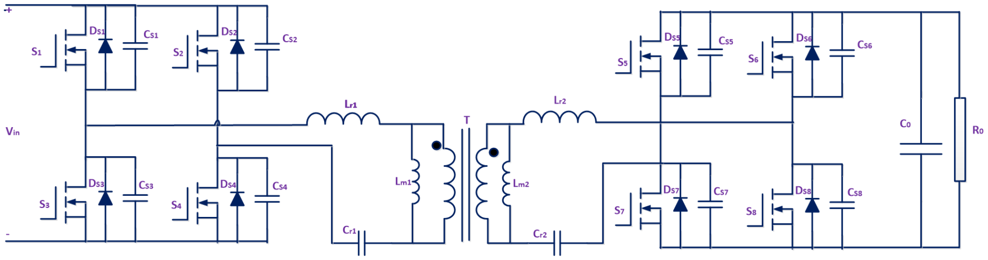

Figure 16. Bi-LLSC RC with OBC.

4.4. In PV, LLSC RC

Due to its environmental friendliness, solar power generation has been extensively exploited and industrialised in light of the energy crisis [110,111]. The solar grid-connected inverter, a crucial component of the photovoltaic system, holds the clue to enhancing the effectiveness and dependability of the entire solar PV power generating system, extending its lifespan, and lowering its financial costs [112,113]. However, current leakage will happen as a result of between the photovoltaic panel and the ground is a parasitic capacitor, which not only puts people at risk but also safety in danger but also harms the electronics parts. As a result, photovoltaic systems must be electrically isolated [113–115]. The LLSC resonant converter's ability to achieve It is possible to drastically lower switching losses of power devices through easy on off cycles of the products, electrical isolation, and magnetic integration, which boosts efficiency, extends the life of the devices, and improves PQ and safety [116–118].

The solar inverter is composed of the DC-DC Boost PFC stage, the DC-DC LLSC resonant stage, and the DC-AC inverter stage.

1. **Full-bridge LLSC resonant converter and a full-bridge inverter comprise the photovoltaic inverter system:** Figure 17 depicts the general layout of a grid connected LLSC photovoltaic inverter. The high output at PV cell package is amplified by the DC-DC Boost converter in order to achieve maximum power point tracking (MPPT) [119–121]. Electrical isolation and high frequency operation are handled by the LLSC resonant converter. The electricity for the load is supplied by the inverter, which is connected to the electrical grid.

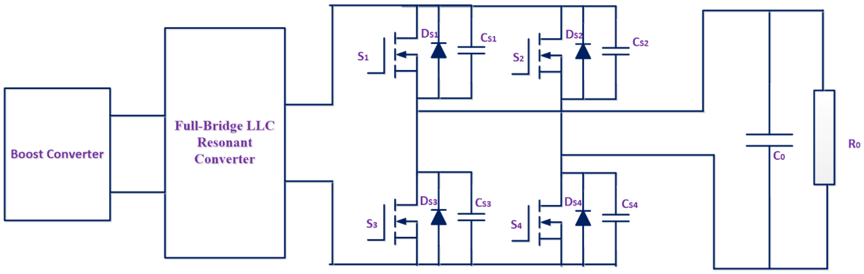

Figure 17. Full-bridge LLSC resonant converter and a full-bridge inverter comprise the PV I system.

2. **Full-bridge LLSC resonant converter and a full-bridge inverter comprise the photovoltaic inverter system:** In Figure 18, it can be shown that the interleaved Boost converter can follow the reduce the filter size, increase the power point, and increase the photovoltaic array's wide-range output voltage to the designated bus voltage.

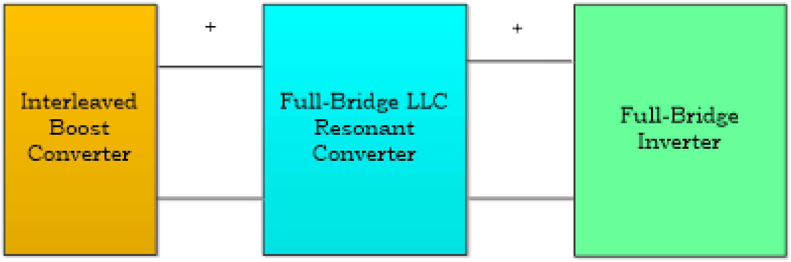

Figure 18. Photovoltaic system with full-bridge LLSC resonant interleaved parallel Boost PFC and converter.

3. **A PV with a full-bridge inverter, Boost converter, and Bi-LLSC RC:** The bidirectional LLSC resonant converter can regulate power in both directions, isolate the electrical system, recover energy, and maintain the stability of photovoltaic systems, as shown in Figure 19. The inverter also acts as a peak cut, giving the load or power system additional energy.

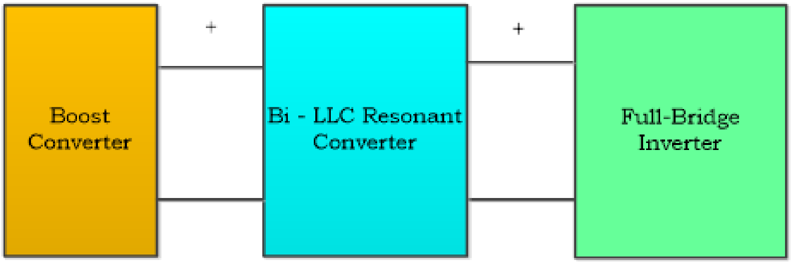

Figure 19. Photovoltaic system with a full-bridge inverter, Boost converter, and Bi-LLSC resonant converter.

5. The LLSC Resonant converter's future development

There are numerous issues that need to be resolved despite substantial research on the LLSC resonant converter. Numerous components must be associated in parallel or in series to assure the stability and dependability of converters in silicon-based devices, increasing the cost of the device and heightening on off cycle losses. SiC-based devices can perform maximum if they have superior thermal conductivity, a wider band gap, a faster drift threshold speed, and a stronger breakdown electric field [50, 51]. The reliability and efficiency of the converters can be increased while using fewer components by switching to SiC-based devices in place of silicon-based ones [122–125]. Power electronic converters are continuously improving toward low weight, compact size, and modularization thanks to SiC devices. They also created the groundwork for a breakthrough in technology for distributed power and micro grid applications using PV and storage in converters [126, 127]. GaN devices can switch huge value of voltage in just a few nanoseconds, and they can take the role of Si equipment for severe-frequency environments with frequencies of over one million Hz. Its low on-resistance, rapid switching, lack of reverse recovery loss, narrow on-voltage threshold range, and advantageous high-frequency properties make this achievable. The radiator and transformer's compatibility. Because of the LLSC RC's high switching frequency, smaller transformers with higher frequencies can be used. The larger radiator components and higher switching losses brought on by the more frequent switching cycles would result in a larger radiation system. Finding a reasonable compromise between the volume at transformer and the volume at radiator is necessary to increase the converter system's density. The application of magnetic integration.

Particularly in Bi-LLSC resonant converters, high magnetic component counts will lead to decreased energy density and increased losses. It magnetic integration is important to amalgamate numerous discrete magnetic components into a magnetic component of single integration and minimise the volume and weight of converter in order to decrease losses in energy and ripples at output and progress the converter's overall presentation. The trade-off between circulating conduction losses and switching losses. The converter's efficiency is at its peak and its circulating current is at its lowest when it is operating at the resonant point. The switching loss, however, reduces and the circulating current, which increases, leading to an increase in conduction loss when the on off cycles is adjusted and the effective point shifts to the sub-resonant zone. On - off losses rise when the set point approaches the super-resonant zone because the mingling current minimises, but the secondary does not reach ZCS. Therefore, it needs to be thoroughly assessed in a limited gain range and a constrained, high-efficiency operational region. In direction to optimise the system plan, loss supply at the resonant point is considered.

6. Conclusions

The work done here is regarding the background review of LLSC resonant converter. The benefits of LLSC resonant converters are then discussed in detail, along with the advantages and drawbacks of the three topologies of LLSC resonant converters that are most frequently used in industrial applications. The applications of LLSC resonant converters in many industries are also examined, with a focus on LCD TV power supplies, LED drivers, solar systems, and OBCs. Finally, it is expected and discussed how LLSC resonant converter technology will develop in the future.

Funding: The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Author contributions: KVGR: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. GSR: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. BSG: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. MKK: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. TVSK, SRT: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. TAD, KSB: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization.

Disclosure statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

[1] Do-Hyun Kim, Min-Soo Kim, Sarvar Hussain Nengroo, Chang-Hee Kim, and Hee-Je Kim. LLC resonant converter for LEV (light electric vehicle) fast chargers. *Electronics (Basel)*, 8(3):362, March 2019.

[2] Bo Yang, F C Lee, A J Zhang, and Guisong Huang. LLC resonant converter for front end DC/DC conversion. In *APEC. Seventeenth Annual IEEE Applied Power Electronics Conference and Exposition (Cat. No.02CH37335)*. IEEE, 2003.

[3] Daocheng Huang, Shu Ji, and Fred C Lee. LLC resonant converter with matrix transformer. In *2014 IEEE Applied Power Electronics Conference and Exposition - APEC 2014*. IEEE, March 2014.

[4] Junming Zeng, Guidong Zhang, Samson Shenglong Yu, Bo Zhang, and Yun Zhang. LLC resonant converter topologies and industrial applications — a review. *Chin. J. Electr. Eng.*, 6(3):73–84, September 2020.

[5] Yanjun Zhang, Dehong Xu, Min Chen, Yu Han, and Zhoong Du. LLC resonant converter for 48 V to 0.9 V VRM. In *2004 IEEE 35th Annual Power Electronics Specialists Conference (IEEE Cat. No.04CH37551)*. IEEE, 2004.

[6] Maikel Fernando Menke, Alysson Raniere Seidel, and Rodrigo Varella Tambara. LLC LED driver small-signal modeling and digital control design for active ripple compensation. *IEEE Trans. Ind. Electron.*, 66(1):387–396, January 2019.

[7] Mohammad Ali Saket, Navid Shafiei, and Martin Ordonez. LLC converters with planar transformers: Issues and mitigation. *IEEE Trans. Power Electron.*, 32(6):4524–4542, June 2017.

[8] Pedro S Almeida, Henrique A C Braga, Marco A Dalla Costa, and J Marcos Alonso. Offline soft-switched LED driver based on an integrated bridgeless boost–asymmetrical half-bridge converter. *IEEE Trans. Ind. Appl.*, 51(1):761–769, January 2015.

[9] Lokesha M H and S G Srivani. LLC resonant converter design and development. In *2014 Annual IEEE India Conference (INDICON)*. IEEE, December 2014.

[10] Rui Zhou, Qianqian Jiao, and Yincan Mao. Natural convection cooled SiC-based LLC resonant converters in wide voltage range battery charger application. In *2019 IEEE Energy Conversion Congress and Exposition (ECCE)*. IEEE, September 2019.

[11] Zhijian Fang, Tao Cai, Shanxu Duan, and Changsong Chen. Optimal design methodology for llc resonant converter in battery charging applications based on time-weighted average efficiency. *IEEE Trans. Power Electron.*, 30(10):5469–5483, October 2015.

[12] Xiang Fang, Haibing Hu, Z John Shen, and Issa Batarseh. Operation mode analysis and peak gain approximation of the LLC resonant converter. *IEEE Trans. Power Electron.*, 27(4):1985–1995, April 2012.

[13] Kondreddy Sreekanth Reddy and Sreenivasappa Bhupasandra Veeranna. Modified full bridge dual inductive coupling resonant converter for electric vehicle battery charging applications. *Int. J. Power Electron. Drive Syst. (IJPEDS)*, 13(2):773, June 2022.

[14] Adiraju Prasanth Rao, K. Sudheer Reddy, and Sathiyamoorthi V. *Automated soil residue Levels Detecting device with IoT interface*, page 123–135. November 2020.

[15] Jong-Bok Baek, Ji-Tae Kim, and Bo-Hyung Cho. Low-profile AC/DC converter for laptop adaptor. In *2011 Twenty-Sixth Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*. IEEE, March 2011.

[16] Ettore Scabeni Glitz and Martin Ordonez. MOSFET power loss estimation in llc resonant converters: Time interval analysis. *IEEE Trans. Power Electron.*, 34(12):11964–11980, December 2019.

[17] Dmitri Vinnikov, Andrii Chub, Elizaveta Liivik, and Indrek Roasto. High-performance quasi-z-source series resonant DC–DC converter for photovoltaic module-level power electronics applications. *IEEE Trans. Power Electron.*, 32(5):3634–3650, May 2017.

[18] Le Anh Dao Ta, Ngoc Dat Dao, and Dong-Choon Lee. High-efficiency hybrid LLC resonant converter for on-board chargers of plug-in electric vehicles. *IEEE Trans. Power Electron.*, 35(8):8324–8334, August 2020.

[19] Zhizhong Li, Tianwen Wu, Guidong Zhang, and Ru Yang. Hybrid modulation method combining variable frequency and double phase-shift for a 10 kw LLC resonant converter. *IET Power Electron.*, 11(13):2161–2169, November 2018.

[20] Ke Jin and Xinbo Ruan. Hybrid full-bridge three-level LLC resonant converter- a novel DC-DC converter suitable for fuel cell power system. In *IEEE 36th Conference on Power Electronics Specialists, 2005*. IEEE, 2006.

[21] Yanxia Shen, Wenhui Zhao, Zhe Chen, and Chengchao Cai. Full-bridge LLC resonant converter with series-parallel connected transformers for electric vehicle on-board charger. *IEEE Access*, 6:13490–13500, 2018.

[22] Mohamed Salem, Vigna K Ramachandaramurthy, P Sanjeevikumar, Zbigniew Leonowicz, and Venkata Yaramasu. Full bridge LLC resonant three-phase interleaved multi converter for HV applications. In *2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*. IEEE, June 2019.

[23] Wei Qian, Juncheng Lu, Hua Bai, and Scott Averitt. Hard-switching 650-V GaN HEMTs in an 800-V DC-grid system with no-diode-clamping active-balancing three-level topology. *IEEE J. Emerg. Sel. Top. Power Electron.*, 7(2):1060–1070, June 2019.

[24] Borislav Dimitrov, Suleiman Sharkh, Andrew Cruden, and Iosko Balabozov. Implementation of a DC current sensing transformer with h-bridge MOSFET rectifier in a resonant LLC converter. In *2018 20th International Symposium on Electrical Apparatus and Technologies (SIELA)*. IEEE, June 2018.

[25] Sajad A Ansari, Jonathan N Davidson, and Martin P Foster. Fully-integrated transformer with asymmetric primary and secondary leakage inductances for a bidirectional resonant converter. *IEEE Trans. Ind. Appl.*, 59(3):3674–3685, May 2023.

[26] Chainarin Ekkaravarodome, Kohji Higuchi, and Kamon Jirasereeamornkul. Implementation of ZVDS class-DE bridge rectifier with series-parallel matching network for high-step up ZVS push-pull resonant converter. In *2020 International Conference on Power, Energy and Innovations (ICPEI)*. IEEE, October 2020.

[27] Jianguang Ma, Xueye Wei, Liang Hu, and Junhong Zhang. LED driver based on boost circuit and LLC converter. *IEEE Access*, 6:49588–49600, 2018.

[28] Ch Naga Sai Kalyan, Anuradha Devi Tellapati, Thalanki Venkata Sai Kalyani, B Srikanth Goud, Kambhampati Venkata Govardhan Rao, and I Vijaya Kumar. Revealing the effect of excitation cross coupling on the lfc performance in two area hybrid source system. In *2024 International Conference on Integrated Circuits and Communication Systems (ICICACS)*, pages 1–6. IEEE, 2024.

[29] Bo Yang, Rengang Chen, and F C Lee. Integrated magnetic for LLC resonant converter. In *APEC. Seventeenth Annual IEEE Applied Power Electronics Conference and Exposition (Cat. No.02CH37335)*. IEEE, 2003.

[30] Guangdi Li, Jin Xia, Kun Wang, Yan Deng, Xiangning He, and Yousheng Wang. Hybrid modulation of parallel-series LLC resonant converter and phase shift full-bridge converter for a dual-output DC–DC converter. *IEEE J. Emerg. Sel. Top. Power Electron.*, 7(2):833–842, June 2019.

[31] Ke Jin and Xinbo Ruan. Hybrid full-bridge three-level llc resonant converter- a novel dc-dc converter suitable for fuel cell power system. In *2005 IEEE 36th Power Electronics Specialists Conference*, pages 361–367, 2005.

[32] Hamid Amini Moghadam, Sima Dimitrijev, Jisheng Han, Daniel Haasmann, and Amirhossein Aminbeidokhti. Transient-current method for measurement of active near-interface oxide traps in 4H-SiC MOS capacitors and MOSFETs. *IEEE Trans. Electron Devices*, 62(8):2670–2674, August 2015.

[33] Mohamed Salem, Vigna K Ramachandaramurthy, Awang Jusoh, Sanjeevikumar Padmanaban, Mohamad Kamarol, Jiashen Teh, and Dahaman Ishak. Three-phase series resonant DC-DC boost converter with double LLC resonant tanks and variable frequency control. *IEEE Access*, 8:22386–22399, 2020.

[34] Kambhampati Venkata Govardhan Rao, Malligunta Kiran Kumar, and B Srikanth Goud. An independently controlled two output half bridge resonant led driver. *Electric Power Components and Systems*, 52(7):1094–1114, 2024.

[35] Hamed Valipour, Mohammad Mahdavi, and Martin Ordonez. Resonant bridgeless AC/DC rectifier with high switching frequency and inherent PFC capability. *IEEE Trans. Power Electron.*, 35(1):232–246, January 2020.

[36] Ming Shang, Haoyu Wang, and Qi Cao. Reconfigurable LLC topology with squeezed frequency span for high-voltage bus-based photovoltaic systems. *IEEE Trans. Power Electron.*, 33(5):3688–3692, May 2018.

[37] A. Amudha, M. Siva Ramkumar, G. Emayavaramban, S. Divyapriya, P. Nagaveni, V.M. Mansoor, and M. SivaramKrishnan. Retracted: Resonant converter l3c for e-vehicle for charing a pv battery. *Materials Today: Proceedings*, 37:2599–2606, 2021. International Conference on Newer Trends and Innovation in Mechanical Engineering: Materials Science.

[38] K V Govardhan Rao and Malligunta Kiran Kumar. A literature review on reduction of harmonics using active power filter. In *AIP Conference Proceedings*, volume 2512, page 020083. AIP Publishing, 2024.

[39] You-Chun Huang, Yao-Ching Hsieh, Yi-Cheng Lin, Huang-Ren Chiu, and Jing-Yuan Lin. Study and implementation on start-up control of full-bridge llc resonant converter. In *2018 IEEE Transportation Electrification Conference and Expo, Asia-Pacific (ITEC Asia-Pacific)*, page 1–5. IEEE, June 2018.

[40] Ettore Scabeni Glitz, Jhih-Da Hsu, and Martin Ordonez. Power loss estimation in llc synchronous rectification using rectifier current equations. *IEEE Trans. Ind. Electron.*, 67(5):3696–3704, May 2020.

[41] Guidong Zhang, Zhong Li, Bo Zhang, and Wolfgang A Halang. Power electronics converters: Past, present and future. *Renew. Sustain. Energy Rev.*, 81:2028–2044, January 2018.

[42] Kambhampati Venkata Govardhan Rao, Malligunta Kiran Kumar, Srikanth B Goud, Tellapati Anuradha Devi, Gundala Srinivasa Rao, Ambati Giriprasad, Isnvr Prashanth, and Thalanki Venkata Sai Kalyani. A new brushless DC motor driving resonant pole inverter optimized for batteries. *Int. J. Power Electron. Drive Syst. (IJPEDS)*, 14(4):2021, December 2023.

[43] Georg Pledl, Matthias Tauer, and Dominik Buecherl. Theory of operation, design procedure and simulation of a bidirectional LLC resonant converter for vehicular applications. In *2010 IEEE Vehicle Power and Propulsion Conference*. IEEE, September 2010.

[44] Fengyi Zhang, Yubin Wang, Fan Wang, and Jia Ming. Synchronous rectification control strategy for bidirectional full-bridge LLC resonant converter. In *2019 22nd International Conference on Electrical Machines and Systems (ICEMS)*. IEEE, August 2019.

[45] Xiaoqiang Guo, Marcelo C Cavalcanti, Alexandre M Farias, and Josep M Guerrero. Single-carrier modulation for neutral-point-clamped inverters in three-phase transformerless photovoltaic systems. *IEEE Trans. Power Electron.*, 28(6):2635–2637, June 2013.

[46] Khairul Safuan Muhammad and Dylan Dah-Chuan Lu. Single-phase single-stage ZCS boost PFC rectifier with reduced switch count. In *2014 Australasian Universities Power Engineering Conference (AUPEC)*. IEEE, September 2014.

[47] Kambhampati Venkata Govardhan Rao, Malligunta Kiran Kumar, B Srikanth Goud, Mohit Bajaj, Mohamad Abou Houran, and Salah Kamel. Design of a bidirectional DC/DC converter for a hybrid electric drive system with dual-battery storing energy. *Front. Energy Res.*, 10, November 2022.

[48] Junwei Liu, Ka Wing Chan, Chi Yung Chung, Nelson Hon Lung Chan, Ming Liu, and Wenzheng Xu. Single-stage wireless-power-transfer resonant converter with boost bridgeless power-factor-correction rectifier. *IEEE Trans. Ind. Electron.*, 65(3):2145–2155, March 2018.

[49] Yijie Wang, Na Qi, Yueshi Guan, Carlo Cecati, and Dianguo Xu. A Single-Stage LED driver based on SEPIC and LLC circuits. *IEEE Trans. Ind. Electron.*, 64(7):5766–5776, July 2017.

[50] Kambhampati Venkata Govardhan Rao and Malligunta Kiran Kumar. The harmonic reduction techniques in shunt active power filter when integrated with non-conventional energy sources. *Indones. J. Electr. Eng. Comput. Sci.*, 25(3):1236, March 2022.

[51] Ibrahim Demirel and Burcu Erkmen. A very low-profile dual output LLC resonant converter for LCD/LED TV applications. *IEEE Trans. Power Electron.*, 29(7):3514–3524, July 2014.

[52] B Singh, B N Singh, A Chandra, K Al-Haddad, A Pandey, and D P Kothari. A review of single-phase improved power quality ac dc converters. *IEEE Trans. Ind. Electron.*, 50(5):962–981, October 2003.

[53] Weiming Lin, Hongxing Chen, and Yuncheng Fang. A single-stage pfc by integrating quasi-bridgeless boost and llc converter. In *2018 IEEE International Telecommunications Energy Conference (INTELEC)*. IEEE, October 2018.

[54] M.Z. Youssef and P.K. Jain. A review and performance evaluation of control techniques in resonant converters. In *30th Annual Conference of IEEE Industrial Electronics Society, 2004. IECON 2004*, volume 1, page 215–221. IEEE.

[55] Yijie Wang, Yueshi Guan, Kailin Ren, Wei Wang, and Dianguo Xu. A single-stage led driver based on bcm boost circuit and llc converter for street lighting system. *IEEE Transactions on Industrial Electronics*, 62(9):5446–5457, September 2015.

[56] Chuan Shi, Haoyu Wang, Serkan Dusmez, and Alireza Khaligh. A sic-based high-efficiency isolated onboard pev charger with ultrawide dc-link voltage range. *IEEE Transactions on Industry Applications*, 53(1):501–511, January 2017.

[57] Guangdi Li, Jin Xia, Kun Wang, Yan Deng, Xiangning He, and Yousheng Wang. A single-stage interleaved resonant bridgeless boost rectifier with high-frequency isolation. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 8(2):1767–1781, June 2020.

[58] Rahul Pandey and Bhim Singh. A power factor corrected resonant ev charger using reduced sensor based bridgeless boost pfc converter. *IEEE Transactions on Industry Applications*, 57(6):6465–6474, November 2021.

[59] Markus Andresen, Johannes Kuprat, Vivek Raveendran, Johannes Falck, and Marco Liserre. Active thermal control for delaying maintenance of power electronics converters. *Chinese Journal of Electrical Engineering*, 4(3):13–20, September 2018.

[60] Mehdi Abbasi and John Lam. A bridgeless ac/dc high voltage gain converter with three-phase modular series-output connected configuration for mvdc grid applications. *IEEE Transactions on Power Electronics*, 35(10):10323–10337, October 2020.

[61] Utsab Kundu, Kalyan Yenduri, and Parthasarathi Sensarma. Accurate zvs analysis for magnetic design and efficiency improvement of full-bridge llc resonant converter. *IEEE Transactions on Power Electronics*, 32(3):1703–1706, March 2017.

[62] SRIKANTH GOUD, B Sai Kumar, B Sai Sri Vindhya, D Bharath Kumar, E Laxman Kumar, O Chandra Shekar, A Ajitha, Kambhampati Venkata Govardhan Rao, Thalanki Venkata Sai Kalyani, et al. Switched quasi impedance-source dc-dc network for photovoltaic systems. *International Journal of Renewable Energy Research (IJRER)*, 13(2):681–698, 2023.

[63] Muntasir Alam, Wilson Eberle, Deepak S. Gautam, Chris Botting, Nicholas Dohmeier, and Fariborz Musavi. A hybrid resonant pulse-width modulation bridgeless ac–dc power factor correction converter. *IEEE Transactions on Industry Applications*, 53(2):1406–1415, March 2017.

[64] Danish Shahzad, Maida Farooq, Saad Pervaiz, and Khurram K. Afridi. A high-power-density high-efficiency soft-switched single-phase universal input to 28-v isolated ac–dc converter module designed for paralleled operation. *IEEE Transactions on Power Electronics*, 37(7):8262–8280, July 2022.

[65] Ziyu Zhao and Jian Zong. A llc resonant full - bridge converter with fractional order pid controller. In *2019 International Conference on Intelligent Informatics and Biomedical Sciences (ICIIBMS)*, volume 26, page 250–255. IEEE, November 2019.

[66] Venkata Ravi Kishore Kanamarlapudi, Benfei Wang, Nandha Kumar Kandasamy, and Ping Lam So. A new zvs full-bridge dc–dc converter for battery charging with reduced losses over full-load range. *IEEE Transactions on Industry Applications*, 54(1):571–579, January 2018.

[67] Jianqiang Liu, Jiepin Zhang, Trillion Q. Zheng, and Jingxi Yang. A modified gain model and the corresponding design method for an llc resonant converter. *IEEE Transactions on Power Electronics*, 32(9):6716–6727, September 2017.

[68] C.-H. Chang, C. Lin, and C.-W. Ku. A high efficiency solar array simulator implemented by an llc resonant dc/dc converter. In *The 2010 International Power Electronics Conference - ECCE ASIA -*, volume 2, page 2603–2609. IEEE, June 2010.

[69] Rahul Pandey and Bhim Singh. A high efficiency modular ev charger using bridgeless and resonant converters. In *2020 IEEE Industry Applications Society Annual Meeting*, volume 3, page 1–6. IEEE, October 2020.

[70] Avinash Kumar, Ranjeet Kumar Singh, and B Krishna Naick. A highly efficient pv and fuel cell powered full bridge bidirectional llc resonant converter. In *2018 International Electrical Engineering Congress (iEECON)*, volume 6, page 1–4. IEEE, March 2018.

[71] Pakpoom Chansri, Nongnuch Noicharoen, and Kritsada Phetphoi. A high power led driver with class d zvs series resonant converter. In *International Conference on Electrical, Control and Computer Engineering 2011 (InECCE)*, volume 34, page 457–460. IEEE, June 2011.

[72] Rahul Pandey and Bhim Singh. A power factor corrected llc resonant converter for electric vehicle charger using cuk converter. In *2018 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)*, volume 8, page 1–6. IEEE, December 2018.

[73] Rudiger Schwendemann, Fabian Sommer, and Marc Hiller. A resonant supplied cascaded h-bridge cell for a series hybrid cascaded h-bridge converter used as a power hardware in the loop emulator. In *2020 IEEE 21st Workshop on Control and Modeling for Power Electronics (COMPEL)*, page 1–8. IEEE, November 2020.

[74] Rahul Pandey and Bhim Singh. A power-factor-corrected llc resonant converter for electric vehicle charger using cuk converter. *IEEE Transactions on Industry Applications*, 55(6):6278–6286, November 2019.

[75] Xiaoqiang Guo. A novel ch5 inverter for single-phase transformerless photovoltaic system applications. *IEEE Transactions on Circuits and Systems II: Express Briefs*, 64(10):1197–1201, October 2017.

[76] M.J. Ryan, W.E. Brumsickle, D.M. Divan, and R.D. Lorenz. A new zvs lcl-resonant push-pull dc-dc converter topology. *IEEE Transactions on Industry Applications*, 34(5):1164–1174, 1998.

[77] Bhim Singh and Radha Kushwaha. A pfc based ev battery charger using a bridgeless isolated sepic converter. *IEEE Transactions on Industry Applications*, 56(1):477–487, January 2020.

[78] Kambhampati Venkata Govardhan Rao, Malligunta Kiran Kumar, B Srikanth Goud, D Krishna, Mohit Bajaj, Parvesh Saini, and Subhashree Choudhury. Iot-powered crop shield system for surveillance and auto transversum. In *2023 IEEE 3rd International Conference on Sustainable Energy and Future Electric Transportation (SEFET)*, pages 1–6. IEEE, 2023.

[79] Dianbo Fu, Ya Liu, Fred C. Lee, and Ming Xu. A novel driving scheme for synchronous rectifiers in llc resonant converters. *IEEE Transactions on Power Electronics*, 24(5):1321–1329, May 2009.

[80] Jee-Hoon Jung, Jong-Moon Choi, and Joong-Gi Kwon. Design methodology for transformers including integrated and center-tapped structures for llc resonant converters. *Journal of Power electronics*, 9(2):215–223, 2009.

[81] Wei-Hsin Liao, Yi-Hwa Liu, and Shun-Chung Wang. Design and implementation of a digitalized power supply for large scale lcd tv. In *2010 8th IEEE International Conference on Industrial Informatics*, volume 1, page 786–791. IEEE, July 2010.

[82] Huang-Jen Chiu, Yu-Kang Lo, Ting-Peng Lee, Shann-Chyi Mou, and Hsiu-Ming Huang. Design of an rgb led backlight circuit for liquid crystal display panels. *IEEE Transactions on Industrial Electronics*, 56(7):2793–2795, July 2009.

[83] Hang-Seok Choi. Design consideration of half-bridge llc resonant converter. *Journal of power electronics*, 7(1):13–20, 2007.

[84] Haoyu Wang, Serkan Dusmez, and Alireza Khaligh. Design and analysis of a full-bridge llc-based pev charger optimized for wide battery voltage range. *IEEE Transactions on Vehicular Technology*, 63(4):1603–1613, May 2014.

[85] L.A. Barragan, J.M. Burdio, J.I. Artigas, D. Navarro, J. Acero, and D. Puyal. Efficiency optimization in zvs series resonant inverters with asymmetrical voltage-cancellation control. *IEEE Transactions on Power Electronics*, 20(5):1036–1044, September 2005.

[86] Mostafa Noah, Tomohide Shirakawa, Kazuhiro Umetani, Jun Imaoka, Masayoshi Yamamoto, and Eiji Hiraki. Effects of secondary leakage inductance on the llc resonant converter. *IEEE Transactions on Power Electronics*, 35(1):835–852, January 2020.

[87] Mingkai Mu and Fred Lee. Design and optimization of a 380v-12v high-frequency, high-current llc converter with gan devices and planar matrix transformers. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, page 1–1, 2016.

[88] Sebastian Rivera, Bin Wu, Samir Kouro, Venkata Yaramasu, and Jiacheng Wang. Electric vehicle charging station using a neutral point clamped converter with bipolar dc bus. *IEEE Transactions on Industrial Electronics*, 62(4):1999–2009, April 2015.

[89] Alex Buus Nielsen, William Gerard Hurley, Pooya Davari, Maeve Catherine Duffy, Frede Blaabjerg, and Bo Vork Nielsen. Design and optimization methodology of transformer for 700/400 v series resonant dc/dc converters with enhanced power density. In *2020 IEEE Energy Conversion Congress and Exposition (ECCE)*, volume 4, page 3484–3491. IEEE, October 2020.

[90] Shuilin Tian, Fred C. Lee, and Qiang Li. Equivalent circuit modeling of llc resonant converter. In *2016 IEEE Applied Power Electronics Conference and Exposition (APEC)*, volume 2, page 1608–1615. IEEE, March 2016.

[91] J.A. Sabate, R.W. Farrington, M.M. Jovanovic, and E.C. Lee. Effect of fet output capacitance on zvs of resonant converters. *IEEE Transactions on Aerospace and Electronic Systems*, 32(1):255–266, January 1996.

[92] Seyed Milad Tayebi, Haibing Hu, Sam Abdel-Rahman, and Issa Batarseh. Dual-input single-resonant tank llc converter with phase shift control for pv applications. *IEEE Transactions on Industry Applications*, 55(2):1729–1739, March 2019.

[93] Hangseok Choi. Analysis and design of llc resonant converter with integrated transformer. In *APEC 07 - Twenty-Second Annual IEEE Applied Power Electronics Conference and Exposition*, volume 3, page 1630–1635. IEEE, February 2007.

[94] Chao Fei, Qiang Li, and Fred C. Lee. Digital implementation of adaptive synchronous rectifier (sr) driving scheme for high-frequency llc converters with microcontroller. *IEEE Transactions on Power Electronics*, 33(6):5351–5361, June 2018.

[95] Jong-Woo Kim, Jung-Pil Moon, and Gun-Woo Moon. Duty-ratio-control-aided llc converter for current balancing of two-channel led driver. *IEEE Transactions on Industrial Electronics*, 64(2):1178–1184, February 2017.

[96] Qingqing He, Quanming Luo, Kun Ma, Pengju Sun, and Luowei Zhou. Analysis and design of a single-stage bridgeless high-frequency resonant ac/ac converter. *IEEE Transactions on Power Electronics*, 34(1):700–711, January 2019.

[97] Hao Wen, Jinwu Gong, Xiaonan Zhao, Chih-Shen Yeh, and Jih-Sheng Lai. Analysis of diode reverse recovery effect on zvs condition for gan-based llc resonant converter. *IEEE Transactions on Power Electronics*, 34(12):11952–11963, December 2019.

[98] B.R. Lin and S.F. Wu. Analysis of a resonant converter with two transformers and voltage doubler rectifier. *IET Power Electronics*, 4(4):400, 2011.

[99] Liang Hong, Hao Ma, Jun Wang, Jianhua Du, and Binlei Wang. An efficient algorithm strategy for synchronous rectification used in llc resonant converters. In *IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society*, volume 28, page 2452–2456. IEEE, October 2016.

[100] Zhiyuan Hu, Laili Wang, Yajie Qiu, Yan-Fei Liu, and Paresh C. Sen. An accurate design algorithm for llc resonant converters—part ii. *IEEE Transactions on Power Electronics*, 31(8):5448–5460, August 2016.

[101] Venkata Ravi Kishore Kanamarlapudi, Benfei Wang, Ping Lam So, and Zhe Wang. Analysis, design, and implementation of an apwm zvzcs full-bridge dc–dc converter for battery charging in electric vehicles. *IEEE Transactions on Power Electronics*, 32(8):6145–6160, August 2017.

[102] Mehdi Abbasi and John Lam. An sic-based ac/dc ccm bridgeless onboard ev charger with coupled active voltage doubler rectifiers for 800-v battery systems. In *2020 IEEE Applied Power Electronics Conference and Exposition (APEC)*, pages 905–910, 2020.

[103] Jingyu Wang, Chunfang Wang, Shuo Zhang, Hao Yuan, Quanlei Zhang, and Dongxue Li. Constant-current and constant-voltage output using hybrid compensated single-stage resonant converter for wireless power transfer. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 10(5):6371–6382, October 2022.

[104] K. N. Mude and K. Aditya. Comprehensive review and analysis of two-element resonant compensation topologies for wireless inductive power transfer systems. *Chinese Journal of Electrical Engineering*, 5(2):14–31, June 2019.

[105] Guidong Zhang, Junming Zeng, Samson Shenglong Yu, Wenxun Xiao, Bo Zhang, Si-Zhe Chen, and Yun Zhang. Control design and performance analysis of a double-switched llc resonant rectifier for unity power factor and soft-switching. *IEEE Access*, 8:44511–44521, 2020.

[106] Fariborz Musavi, Marian Craciun, Deepak S. Gautam, and Wilson Eberle. Control strategies for wide output voltage range llc resonant dc–dc converters in battery chargers. *IEEE Transactions on Vehicular Technology*, 63(3):1117–1125, March 2014.

[107] Mrs. A. Santhi Mary Antony and Dr. D. Godwin Immanuel. Bridgeless pfc rectifier for single stage resonant converter with closed loop and improved dynamic response. In *2020 3rd International Conference on Intelligent Sustainable Systems (ICISS)*, volume 8, page 1523–1530. IEEE, December 2020.

[108] A. Kats, G. Ivensky, and S. Ben-Yaakov. Application of integrated magnetics in resonant converters. In *Proceedings of APEC 97 - Applied Power Electronics Conference*, volume 2 of *APEC-97*, page 925–930. IEEE.

[109] *Focus on Powder Coatings*, 2021(2):5–6, February 2021.

[110] Ingilala Jagadeesh and Vairavasundaram Indragandhi. Comparative study of dc-dc converters for solar pv with microgrid applications. *Energies*, 15(20):7569, October 2022.

[111] W.A. Tabisz and F.C.Y. Lee. Zero-voltage-switching multiresonant technique-a novel approach to improve performance of high-frequency quasi-resonant converters. *IEEE Transactions on Power Electronics*, 4(4):450–458, October 1989.

[112] Yuqi Wei, Quanming Luo, Si Chen, Pengju Sun, and Necmi Altin. Comparison among different analysis methodologies for llc resonant converter. *IET Power Electronics*, 12(9):2236–2244, July 2019.

[113] Khairul Safuan Bin Muhammad and Dylan Dah-Chuan Lu. Zcs bridgeless boost pfc rectifier using only two active switches. *IEEE Transactions on Industrial Electronics*, 62(5):2795–2806, May 2015.

[114] P. Dananjayan, V. ShRam, and C. Chellamuthu. A flyback constant frequency zcs-zvs quasi-resonant converter. *Microelectronics Journal*, 29(8):495–504, August 1998.

[115] Long Xiao, Liang Wu, Jun Zhao, and Guozhu Chen. Virtual prototype and gan hemt based high frequency llc converter design. *The Journal of Engineering*, 2019(7):4672–4674, April 2019.

[116] Reza Beiranvand, Bizhan Rashidian, Mohammad Reza Zolghadri, and Seyed Mohammad Hossein Alavi. Using llc resonant converter for designing wide-range voltage source. *IEEE Transactions on Industrial Electronics*, 58(5):1746–1756, May 2011.

[117] Yuqi Wei, Quanming Luo, Zhiqing Wang, and Homer Alan Mantooth. A complete step-by-step optimal design for llc resonant converter. *IEEE Transactions on Power Electronics*, 36(4):3674–3691, April 2021.

[118] Estiko Rijanto, Asep Nugroho, and Pekik A. Dahono. A dynamical model of full bridge llc resonant converter which incorporates power loss coefficients for controller design. In *2018 International Conference on Sustainable Energy Engineering and Application (ICSEEA)*, page 101–105. IEEE, November 2018.

[119] Rahul Pandey and Bhim Singh. A cuk converter and resonant llc converter based e-bike charger for wide output voltage variations. *IEEE Transactions on Industry Applications*, 57(3):2682–2691, 2021.

[120] Aman Jha and Bhim Singh. A bridgeless boost pfc converter fed led driver for high power factor and low thd. In *2018 IEEMA Engineer Infinite Conference (eTechNxT)*, volume 1, page 1–6. IEEE, March 2018.

[121] Xiaoyong Ren, Zhi-Wei Xu, Zhiliang Zhang, Haoran Li, Mingxie He, Jiachen Tang, and Qianhong Chen. A 1-kv input sic llc converter with split resonant tanks and matrix transformers. *IEEE Transactions on Power Electronics*, 34(11):10446–10457, November 2019.

[122] K. Sudheer Reddy, G. Partha Saradhi Varma, and S. Sai Satyanarayana Reddy. Understanding the scope of web usage mining applications of web data usage patterns. In *2012 International Conference on Computing, Communication and Applications*, pages 1–5, 2012.

[123] H. L. Tian, J. F. Liu, and J. Zeng. A bridgeless electrolytic capacitor-free led driver based on series-resonant converter with constant frequency control. In *2017 7th International Conference on Power Electronics Systems and Applications - Smart Mobility, Power Transfer & Security (PESA)*, volume pp, page 1–5. IEEE, December 2017.

[124] Nikhil Kumar and M P R Prasad. A comparative analysis of different topologies of on-board charger (obc) with an approach of interfacing it with mcb. In *2021 6th International Conference for Convergence in Technology (I2CT)*, volume 56, page 1–6. IEEE, April 2021.

[125] Yuqi Wei, Quanming Luo, and Alan Mantooth. A hybrid half-bridge llc resonant converter and phase shifted full-bridge converter for high step-up application. In *2020 IEEE Workshop on Wide Bandgap Power Devices and Applications in Asia (WiPDA Asia)*. IEEE, September 2020.

[126] Andrii Chub, Abualkasim Bakeer, and Dmitri Vinnikov. Step-up series-resonant dc-dc converter with switched mode rectifier operating at fixed switching frequency. In *2020 IEEE 11th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, page 597–601. IEEE, September 2020.

[127] Ch Naga Santhosh Kumar and K.S. Reddy. Effective data analytics on opinion mining. *International Journal of Innovative Technology and Exploring Engineering*, 8(10):2073–2080, August 2019.