Q. Cao, Z. Li, and H. Wang*, "Wide voltage gain range LLC dc/dc topologies: state-of-the-art," in Proc. International Power Electronics Conference (ECCE Asia), Niigata, Japan, May 2018, pp. 100-107.

Wide Voltage Gain Range LLC DC/DC Topologies: State-of-the-Art

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Abstract— **LLC resonant converter is a prevalent isolated dc/dc topology due to its high efficiency, high power density, and simple structure. However, it is challenging to optimize the design of conventional LLC converter in wide gain range applications. Therefore, modifications either on the circuit structure or control strategy are necessary to improve its voltage regulation performance. This paper presents a comprehensive overview of recent evolvements of LLC topology in wide voltage gain applications. The broad applications of wide gain LLC converters, which include hold-up operation, wide input voltage range, and wide output voltage range, are investigated. State-of-the-art wide gain LLC solutions are reviewed and classified into four categories. Benefits and constraints of different solutions are addressed in detail. Finally, the circuit selection principles for different application backgrounds are summarized with a comparative study of different configurations.**

Index Terms—LLC topology, review, wide voltage range.

I. Introduction

Dc/dc converters with wide voltage gain capability are widely used in different power conversion applications. Typically, those applications are featured with one of those characteristics: 1) hold-up operation, 2) wide input voltage range, and 3) wide output voltage range.

Hold-up operation is required in applications with demanding requirements on power supply continuity and reliability, such as sever power supply and telecommunication systems [1]–[3]. When a short duration of grid blackout occurs, the dc bus voltage between the ac/dc power-factor-correction stage and the front-end dc/dc stage drops substantially [4]. However, the dc/dc converter is expected to maintain a stable output voltage to ensure the proper function of the equipment [5]. Therefore, the dc/dc converter needs to fit the wide input voltage range. The hold-up operation lasts about 20 milliseconds [6]–[8]; hence, the converter mainly operates in normal mode, while the high gain mode rarely occurs [9], [10]. In those scenarios, research is mainly focused on maintaining high efficiency in normal mode. Thus, relatively low priority is assigned to the efficiency performance at high voltage gain mode for hold-up operation.

Wide input range applications regularly require a wide gain range to maintain a constant output under different input voltages. The most common scenario is the photovoltaic systems, where a dc/dc converter is required to couple the renewable sources with the grid [11]. Renewable energy sources such as solar panels usually have a wide terminal voltage range and low output power (below 500 W) [12], [13]. In those scenarios, researches are mainly focused on optimizing the efficiency over the entire input voltage range.

For wide output voltage applications, the input voltage is usually constant, while the output voltage varies in a wide range. The efficiency optimization over entire output range must be considered. For example, in battery-charging systems, constant current (CC) stage and constant voltage (CV) stage are enforced in the charging profile [14], [15]. In CC stage, battery pack's terminal voltage demonstrates a wide variation range [16]. The dc/dc stage of the battery charger needs to match its output voltage with the battery pack terminal voltage [17].

Frequency modulated LLC resonant converter is a prevalent isolated dc/dc topology and has attracted wide research focus in recent years [18]–[22]. This is mainly due to its appealing merits: 1) high efficiency,2) wide zero-voltage-switching (ZVS) and zero-current-switching(ZCS) range, 3) simple circuit structure, and 4) high power density [23]. How to design conventional LLC topology to fit the wide gain range applications has been explored in the literatures [15], [24]–[26]. However, when the conventional LLC topology is deployed in wide gain range applications, switching frequency range will be extra wide. This leads to several drawbacks: 1) constrained ZVS and ZCS range, 2) increased core size determined by lowest f_s , and 3) limited light-load regulation ability, especially considering secondary-side equivalent parasitic capacitance [5], [9], [19]. To overcome these drawbacks, researchers have proposed various modifications and corresponding design considerations to the conventional LLC structure. The main purpose is to make the LLC-based converter achieve a wide voltage range and meanwhile to maintain a high overall efficiency.

This paper presents a comprehensive overview of the recent evolvements of the LLC type topologies adapted to wide gain range applications. Section II analyzes the conventional LLC structure. Section III reviews the modified LLC topologies and proposed control strategies. A comparison of these solutions and summary of topology selection principles for different applications are given in Section IV. Conclusion is drawn in Section V.

II. Conventional LLC Resonant Converter

Fig. 1 shows the block diagram of a typical LLC resonant converter. It consists of four parts: 1) a primary-side switch network, 2) a resonant tank, 3) a high-frequency transformer (Tx), and 4) a secondary-side rectifier. The primary-side switch network is either a full-bridge (FB) or half-bridge (HB) inverter. A square wave is generated and fed into the resonant tank. The resonant tank consists a resonant capacitor C_r, resonant inductor L_r and magnetizing inductor L_m. The high-frequency

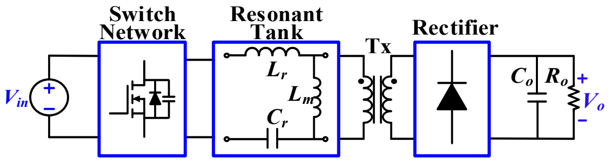

Fig. 1. Block diagram of typical LLC resonant converter.

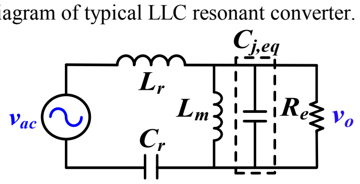

Fig. 2. Ac equivalent circuit model of conventional LLC resonant converter.

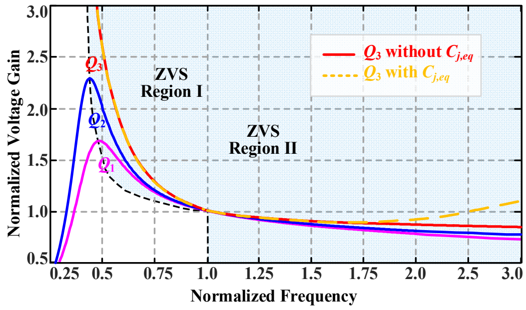

Fig. 3. DC gain curves of conventional LLC resonant converter.

transformer promises electrical isolation and delivers energy to the output. The secondary-side rectifier could be a FB rectifier or a center-tapped synchronous rectifier (SR).

Among mainstream isolated dc/dc topologies, LLC topology distinguishes itself with its good circuit performance. In LLC topology, ZVS for primary-side switches and ZCS for diodes can be maintained in a wide load range. The soft switching feature enables a high switching frequency, which facilitates a compact transformer [23]. Thus, high power density can be achieved. Besides, on the primary side, L_r and L_m can be integrated into one single magnetic core; while on the secondary side, only one capacitor filter is required. Hence, the circuit complexity is reduced [27].

To design and analyze an LLC resonant converter, a voltage transfer function should be determined. The widely used first harmonic approximation (FHA) method approximates the square wave with its fundamental harmonic while ignoring the higher order components. Fig. 2 shows the ac equivalent circuit model, where v_{ac} is the output of primary side switch network and R_e is the equivalent load resistance. $C_{j,eq}$ is the equivalent junction capacitor of secondary side rectifier and transformer parasitic capacitor. The FHA method provides acceptable accuracy if f_s is at the vicinity of f_r, since the first harmonic part of the resonant current dominates. Ignoring $C_{j,\mathrm{eq}}$, the normalized voltage gain function can be determined as

$$M_g = \frac{nV_o}{V_{in}} = \left| \frac{L_n \cdot f_n^2}{\left[(L_n+1) f_n^2 - 1\right] + j\left[\left(f_n^2 - 1\right) \cdot f_n \cdot Q_e \cdot L_n\right]} \right| \quad (1)$$

where $f_n = f_s / f_r$ is normalized frequency, $L_n = L_m / L_r$ is inductance ratio, Q_e is the quality factor, which is defined as

$$Q_e = \sqrt{L_r / C_r} / R_e \quad (2)$$

and n is the turns ratio of Tx. The output voltage can be regulated by frequency modulation (FM) since M_g varies with f_s.

Meanwhile, either decreasing L_n or Q_e results in a larger peak gain. The gain curves are plotted in Fig. 3. As shown, there always exists a combination of L_n and Q_e to fulfill the design requirements. However, there are some critical issues and restrictions, especially in wide gain range applications. As shown in Fig. 3, the regulation ability of FM degrades when f_s is beyond f_r, especially in light load condition [28]–[30]. In light load condition, the influence of $C_{j,eq}$ increases the voltage gain when f_s is above 2-2.5 times of f_r [31]. This phenomenon is also illustrated in Fig. 3. The efficiency with a wide frequency range degrades as well since the optimal operation point only occurs in the vicinity of f_r [32], [33]. When f_s deviates beyond f_r, the secondary-side diodes lose ZCS, and the MOSFET turning-off current increases [34]. This leads to increased switching loss and the diodes' recovery issues [35]. When f_s deviates below f_r, the circulating power increases. This leads to increased conduction loss and current stresses.

Moreover, a wide switching frequency range leads to a large transformer core, high core loss, and low power density [9], [36]. Also, a high peak gain requires a small L_n, which results in increased circulating power and degraded efficiency [10]. Besides, the accuracy of FHA method will also be undermined [11]. Therefore, the conventional LLC structure is not an optimal solution for wide voltage range applications.

III. Modified LLC Topologies for Wide Voltage Range

This section provides a comprehensive review of recent research efforts to narrow down the f_s range of LLC topology. According to the specific stage where the circuit modification is enforced, the solutions for LLC topology extension are classified into four categories.

A. Reconfiguration of Resonant Tank

This kind of modification mainly reconfigures the structure of resonant tank (C_r, L_r, and L_m) and transformer's turns ratio n. The equivalent value of those parameters can be tuned by either mode transition or switching frequency variation. Therefore, the voltage gain can be extended to a wide range with narrow frequency window. Typically, the control strategy is simple, while the parameter design is more complicated.

Several modifications are proposed to change L_m. In conventional LLC structure, the trade-off between wide voltage range and small circulating current needs to be addressed when designing L_m. Thus, a variable L_m is beneficial to extend the gain range with improved overall efficiency. The modification includes linking an extra transformer, adding an auxiliary transformer as a variable L_m and auxiliary LC structures [2], [5], [10], [11]. Figures 4-7 shows the topologies. The first method changes L_m by controlling a bi-directional switch, which endures overshoot problem during mode transition. Besides, an extra FB rectifier increases its volume. The second method changes the equivalent L_m by controlling dc current bias of auxiliary transformer. In the third method, equivalent L_m can be changed adaptively with frequency.

Taking the LCLC structure proposed in [2] as the example, the equivalent L_m can be expressed as,

$$L_{m\_eq}(f_s) = L_p - \frac{1}{(2\pi f_s)^2 C_p} \quad (3)$$

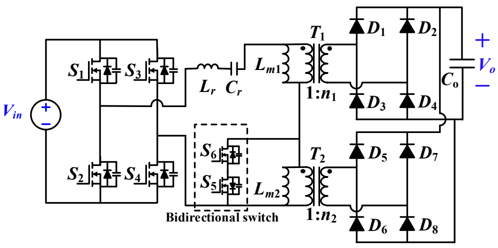

Fig. 4. Two-transformer LLC converter [11].

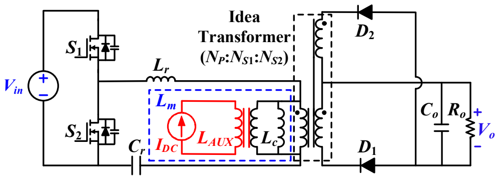

Fig. 5. Modified LLC converter with variable inductance [10].

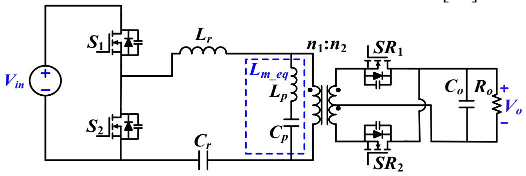

Fig. 6. Topology of LCLC converter [2].

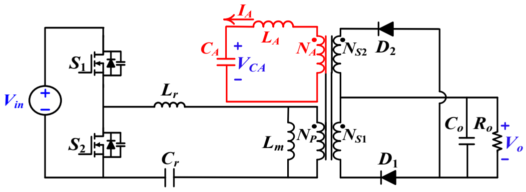

Fig. 7. Modified LLC converter with auxiliary LC circuit [5].

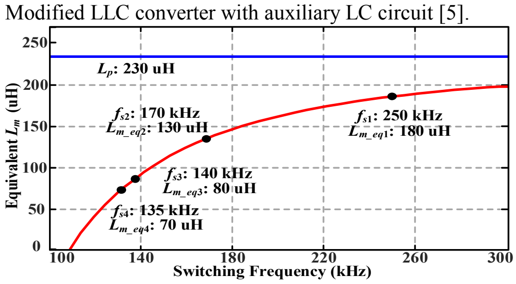

Fig. 8. Equivalent L_m varies with switching frequency [2].

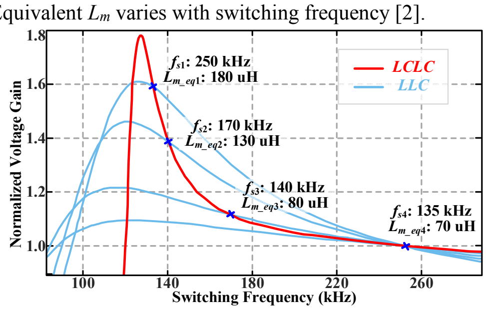

Fig. 9. Gain curves of LCLC and equivalent LLC [2].

Figures 8-9 illustrates operation principles in [2], where L_p = 230 uH and C_p = 9.4 nF. The circuit reliability can be enhanced since there is no need for extra control circuits. Moreover, the abrupt mode transition is avoided; hence, the overshoot problem no longer exists.

Alternatively, in [1], equivalent C_r can be changed by paralleling an extra capacitor. In [17], [37], transformer's turns ratio can be tuned by connecting extra coils or switching between series and parallel connected structure of two

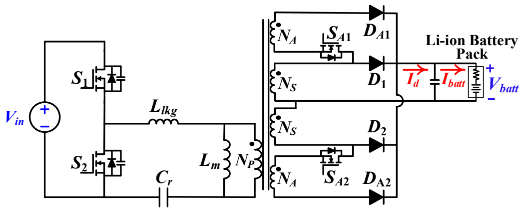

Fig. 10. Reconfigured LLC converter with adaptive turns ratio [17].

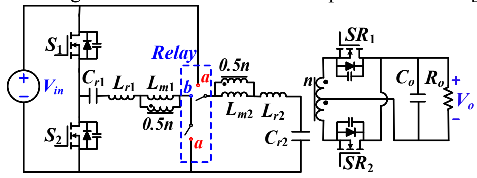

Fig. 11. Reconfigured LLC converter with adaptive turns ratio [37].

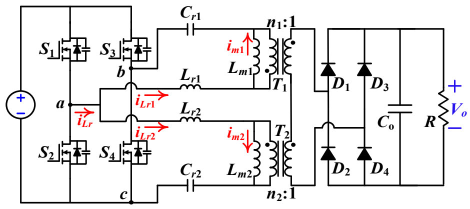

Fig. 12. Modified LLC converter with two split resonant tank [38].

primary-side coils. Figures 10-11 shows the circuit structures.

As shown in Fig. 12, , an extra resonant tank is added in [38]., Smooth mode transition between HB/FB can be realized by different PWM pattern of $S_{1\text{-}4}$. This method restrains the overshoot problem.

B. Modification on Primary-side Switch Network

The modifications on the primary-side switch network mainly follow those principles: 1) regulation of equivalent input voltage of the resonant tank, and 2) modification for specific control strategies.

The primary-side switch network generates an ac voltage (v_{ac}) to feed the resonant tank. Regulating the amplitude and pulse width of v_{ac} changes its root-mean-square (RMS) voltage. This improves regulation ability of the voltage gain. Moreover, the design procedure of resonant parameters can be simplified. However, this method usually requires some extra switches, which increases switching loss, complexity of control strategy, and the volume of converter.

The modifications include fixed frequency dual bridge structure, variable frequency multiplier (VFX) with three-level structure, three-level full-bridge structure, buck-boost cascaded structure, and Interleaved Boost-Integrated LLC (IBI-LLC) [23], [35], [39]–[42]. Figures 13-16 shows their topologies.

The first structure realizes v_{ac} regulation by transition between HB and FB mode in primary side. The second and third structures generate various waveforms of v_{ac} by controlling duty cycles and phase-shift (PS) angles of primary-side switches. In the third structure, the v_{ac} waveforms in three modes are shown in Fig. 17, where α, β, and γ are control variables. In this structure, lower voltage-rating devices can be used since the voltage stress on each MOSFET is reduced. The last two structures combine a buck-boost or interleaved boost stage with LLC stage. The equivalent input voltage V_{CLINK} can be regulated by duty cycle control. However, its non-symmetric operation results to dc offset current and a larger size of transformer.

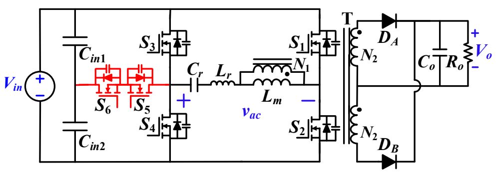

Fig. 13. Dual bridge LLC converter [41].

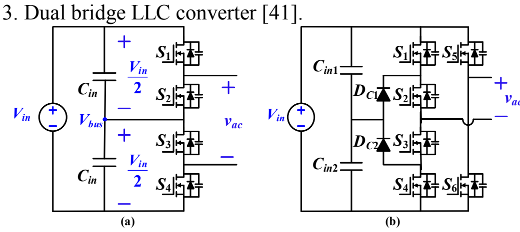

Fig. 14. Topology of modified primary-side inverter. (a) Three-level bridge structure [23]. (b) Three-level full-bridge structure [35].

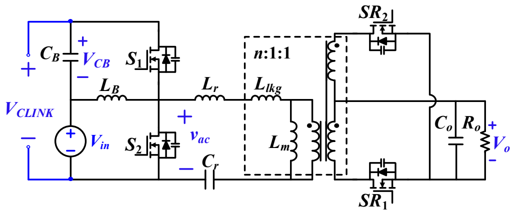

Fig. 15. Buck-boost + LLC cascaded converter [39].

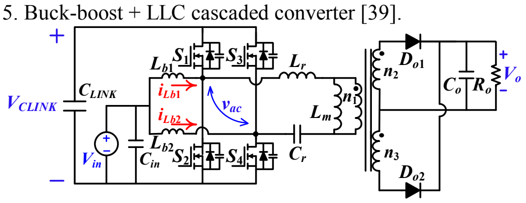

Fig. 16. Interleaved Boost-Integrated LLC (IBI-LLC) converter [42].

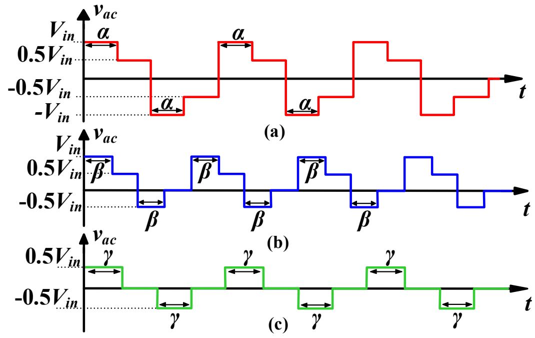

Fig. 17. Waveforms of v_{ac} proposed in [40]. (a) HG mode. (b) MG mode. (c) LG mode.

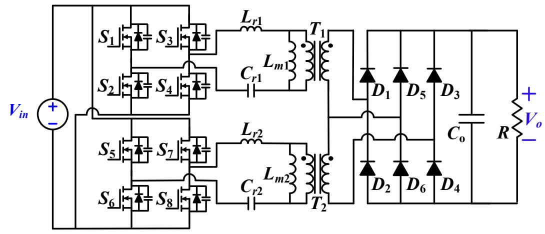

Fig. 18. Topology of interleaved LLC converter [44].

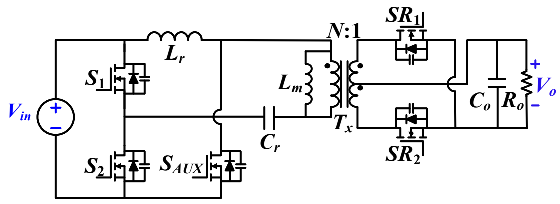

Fig. 19. Modified LLC converter with primary-side auxiliary switch [45].

Differently, the main purpose of modification proposed in [43] and [44] is to realize their unique control strategies that work complementarily with FM to squeezes the f_s range. The structure proposed in [43] combines an identical structure shown in Fig. 14(a) and a secondary-side SR. The input voltage range is extended by PS control between primary-side and secondary-side switches. The structure proposed in [44] is shown in Fig. 18. Once $f_s > f_r$, voltage gain can be further extended by controlling PS angle between two resonant tanks.

In [45], a different method to extend the voltage range is proposed by injecting more energy into resonant tank by controlling ON time of S_{AUX} in each switching cycle. Fig. 19 illustrates this topology.

C. *Modification on control strategies*

Instead of topological modifications, customizing the control strategies is also considered as a feasible solution to extend the gain range of LLC converter. Reported works are mainly based on those two principles: 1) modifying the control strategies on the primary-side switch network, and 2) regulating the dc link voltage.

The first type solutions include fixed frequency phase shift (FFPS) approach, HB/FB transition, and asymmetric (APWM) control of HB inverter [46]–[48]. In [46], the HB/FB transition is proposed based on a FB inverter. Nevertheless, this abrupt mode transition leads to a severe overshoot issues. In [47], APWM control works as a supplement to FM, which can further increase the voltage gain by adjusting the duty ratio of the HB. The asymmetric operation introduces offset current, which leads to saturation problem of magnetic component. Typically, the size of transformer will be increased to avoid saturation. However, its volume decreases due to a squeezed frequency range. Conclusively, the low conduction loss and high power density are also retained.

For the second principle, since an isolated battery charger typically consists a front-end ac/dc stage for power factor correction (PFC) and a second dc/dc stage for voltage regulation, the variable dc link strategy can be realized by the modulation of the PFC stage [49]–[51]. The control methods in these three papers are similar, which can be summarized as, 1) to ensure the power factor, and 2) to regulate the dc-link voltage following battery voltage. This strategy can keep the LLC converter always operating at f_r with symmetric operation of primary-side switches, thus the switching and conduction losses are decreased. However, the PFC stage has a limited range of voltage variation.

D. *Modification on Secondary-side Rectifier*

Regarding the modifications on the secondary-side rectifier, the variable-structure voltage multipliers are typically adopted in [31], [33], [52], [53].

In [31], [53], the secondary side can be switched between a FB rectifier and a voltage-doubler rectifier (VDR). In [52], it can operate as a VDR or a voltage-quadrupler rectifier, which is called semi-active variable-structure rectifier (SA-VSR). Fig. 20 shows their structures. However, these three methods require mode transition between two structures, which ensures that the maximum voltage gain should be at least twice of minimum voltage gain. Hence, the complexity of parameter design increases.

Applying the same concept shown in Fig. 20(b), PWM control is applied on the extra switch [33]. Thus, the circuit could always operate at f_r and output voltage could be regulated by duty cycle. Meanwhile, it can further widen voltage gain range by PWM+FM hybrid control.

In [9], one leg of diode bridge is replaced by synchronous switches. Fig. 21 shows the secondary-side circuit and critical operation mode. During this mode, large amount of energy is stored in L_r when the secondary side is shorted. The principle is similar to that in [45].

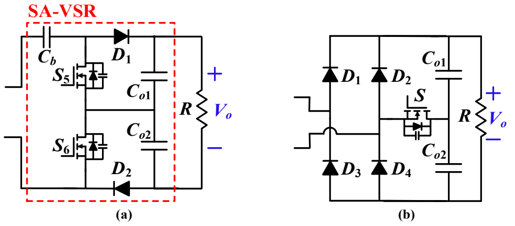

Fig. 20. Topology of modified secondary-side rectifier. (a) SA-VSR structure [52]. (b) Modified voltage doubler structure [31].

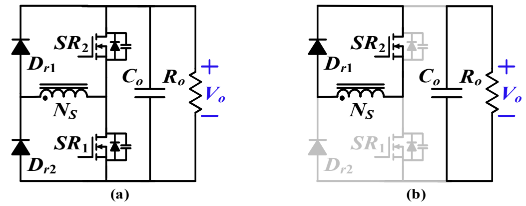

Fig. 21. (a) Modified secondary-side rectifier proposed in [9] (b) Its critical operation mode.

IV. Comparison and Summary of Modification Principles Based on Different Applications

In this section, Table I shows the comparisons of the various solutions for different applications. Modification, control strategies, and performance of various topologies are listed. Then, some circuit selection principles are summarized for different applications.

A. Hold-up operation

The hold-up operation rarely occurs and lasts for a short time duration. Thus, improving the efficiency during normal mode is more important. Typically, normal mode and extra hold-up compensation mode are designed. To design the hold-up compensation mode, less extra components and simpler control strategies are preferred. As shown in Table I, modification of the resonant tank is a popular method. The extra operation mode can be simply implemented by an extra resonant component and a switch for mode transition [1], [9], [10], [45]. Some topologies even realize automatic mode transition without switch control [2], [5].

Moreover, relatively low efficiency in hold-up compensation mode is acceptable. For example, the asymmetric PWM control in [47] results in a large current stress and transformer dc offset current, which increases core loss and is not preferable for high power cases [2], [5]. The solutions proposed in [9], [45] increase the current stress on primary-side components. However, the server power supply and telecommunication system usually have a relatively low rated power under 500 W [2], [10], [45]. Thus, the increased current stress is acceptable during the short hold-up operation.

B. Wide Input Voltage Applications

Solar energy system is a typical example of wide input voltage applications, which features a wide output voltage range and large current ripple [42], [54]. Therefore, high efficiency over the entire input voltage range is required, which is different from the hold-up operation.

Mode transition with extra resonant components is no longer an optimal choice, since frequent mode transitions damage the overall efficiency and slow down the transient response. Moreover, in some structures such as [10], [11], [45], the abrupt mode transition leads to current overshoot problem. However, applying the smooth mode transition technique can be a better solution, the solution proposed in [38] is an example.

Among the modifications reviewed in section III, most solutions are suitable for this application by regulating the RMS voltage of v_{ac} [23], [38]–[42]. These methods have three advantages: 1) the voltage variation in resonant tank is repressed, so the switching frequency range is narrow and may even be fixed at f_r, 2) with the squeezed frequency range, parameter design of resonant components is easier and 3) L_m can be larger so the primary-side circulating current is reduced.

Besides, for this application, that realized by cascading a buck-boost or an interleaved boost stage with LLC are also preferable methods [39], [42]. First, wide input voltage range is realized, meanwhile sudden mode transition is avoided. Secondly, the cascaded buck-boost or interleaved boost stage can effectively reduce input current ripple. However, these two methods apply PWM control on primary-side switches, which requires non-symmetric operation. This results in a dc offset current and leads to a larger size of transformer.

Generally, the structure modifications and control strategies for this application are usually more complex or contain more extra switches to realize the v_{ac} regulation.

C. Wide Output Voltage Applications

For wide output voltage applications, variable structure on secondary side are suitable than those on primary side. When the voltage gain is regulated on the secondary side, it's easier to optimize resonant parameters and to reduce circulating current. Besides, among the modifications on primary-side, regulating the RMS value of v_{ac} or the dc-link voltage are feasible [35], [48], [50], [51]. Resonant tank has a small variation, which is helpful to reduce circulating currents. The dc-link voltage regulation can also reduce the switching and conduction loss of LLC stage. However, it can't be applied to renewable energy applications such as PV or fuel cell systems.

Battery charger is a common example of this kind of application. The ripple-free output current is necessary for this case since it provides a high-quality charging current and reliable operation of battery management system. For example, in [48], the proposed FFPS technique provides a ripple-free charging current to eliminate burst mode oscillation. The control algorithm in dc-link voltage regulation methods can also suppress the output current ripple [50], [51].

TABLE I
COMPARISON OF MODIFICATIONS FOR DIFFERENT APPLICATIONS

MODIFICATION		CONTROL		PERFORMANCE			
STRUCTURE	TYPE & COMPLEXITY	MODULATION	OPERATION MODE	RATED POWER	VOLTAGE RANGE	RANGE OF SWITCHING FREQ.	RESONANT FREQ. f_r
Modifications for Hold-up Operation							
Auxiliary LC Circuit [5]	Resonant Tank, Simple	FM	-	56 V/350 W	330-390 V	60- ~110 kHz	100 kHz
LCLC Structure [2]	Resonant Tank, Simple	FM	-	12 V/500 W	250-400 V	135-250 kHz	250 kHz
Auxiliary Capacitor [1]	Resonant Tank, Simple	FM	Mode Transition	56 V/350 W	325-385 V	34-106 kHz	90 kHz
Auxiliary Switch [45]	Resonant Tank, Simple	FM + PWM	Hybrid Modulation + Mode Transition	12 V/300 W	250-400 V	150-260 kHz	260 kHz
Variable Inductance [10]	Resonant Tank, Medium	FM	Mode Transition	56 V/350 W	290-405 V	~75-110 kHz	110 kHz
Two secondary-side SR [9]	Secondary-side, Simple	FM + PS	Hybrid Modulation	200 V/300 W	250-400V	35-75 kHz	75 kHz
APWM Approach [47]	No modification on topology	FM + APWM	Mode Transition	18.5 V/85 W	300-400 V	61-100 kHz	100 kHz
Modifications for Wide Input Voltage Range							
FB/HB Switch [46]	No modification on topology	FM	Mode Transition	500 V/2 kW	125-550 V	40-120 kHz	60 kHz
Dual-Bridge LLC [41]	Primary-side, Medium	PWM	-	24 V/480 W	120-240 V	Fixed @ f_r	100 kHz
Buck-boost + LLC [39]	Primary-side, Medium	FM + APWM	Hybrid Modulation	15 V/300 W	36-72 V	Range: ~20 kHz	100 kHz
Interleaved Boost+LLC [42]	Primary-side, Medium	PWM	-	24 V/600 W	120-240 V	Fixed @ f_r	100 kHz
Three-level Bridge with VFX [23]	Primary-side, Complex	FM	Mode Transition	20 V/50 W	85-340 V	~240-~500 kHz	500 kHz
Three-level Full Bridge [40]	Primary-side, Complex	PWM + PS	Hybrid Modulation + Mode Transition	30-60 V/1 kW	240-480 V	Fixed @ f_r	100 kHz
Three-level Bridge [43]	Primary-side, Complex	FM + PS	Hybrid Modulation	48 V/1 kW	200-400 V	Around f_r	~43 kHz
Two Split Resonant Tank [38]	Resonant Tank, Complex	FM	Mode Transition by PWM	400 V/1 kW	80-200 V	80-160 kHz	140 kHz
Auxiliary Tx, Serial Connected [11]	Resonant Tank, Medium	FM	Mode Transition	210 V/250 W	22-65 V	80-140 kHz	140 kHz
Modifications for Wide Output Voltage Range							
FFPS Approach [48]	No modification on topology	FM + PS	Mode Transition	400 V/3 kW	120-180 V	100-200 kHz	122 kHz
Variable DC-link [50]	No modification on topology	FM	-	269-352 V/ 1 kW	320-420 V	Around f_r	200 kHz
Variable DC-link [51]	No modification on topology	FM	-	500-800 V/ 6.6 kW	250-420 V	Around f_r	500 kHz
Three-level Full-bridge [35]	Primary-side, Complex	PS + PWM	Hybrid Modulation + Mode Transition	385 V/6.6 kW	225-378 V	Fixed @90 kHz	78 kHz
Adaptive Turns Ratio [17]	Resonant Tank, Medium	FM	Mode Transition	311 V/300 W	25-42 V	~53-130 kHz	130 kHz
Interleaved LLC [44]	Two Resonant Tank, Complex	FM + PS	Mode Transition	400 V/3.5 kW	150-500 V	~45-100 kHz	100 kHz
SA-VSR [52]	Secondary-side, Medium	FM + PWM	Hybrid Modulation + Mode Transition	400 V/1.5 kW	100-500 V	70-150 kHz	100 kHz
Modified Voltage Doubler [31]	Secondary-side, Medium	FM	Mode Transition	400 V/1.5 kW	100-420 V	94.37-236.6 kHz	170 kHz
Modified Voltage Doubler [33]	Secondary-side, Medium	PWM	PWM+FM hybrid control is available	390 V/1 kW	250-420 V	Fixed @ f_r	100 kHz

V. CONCLUSIONS

In this paper, a comprehensive overview of LLC type topologies suitable for wide gain range applications are presented. The state-of-the-art wide gain LLC solutions based on conventional structure mainly aim to squeeze f_s range. The modifications are analyzed and classified into four categories based on circuit structure: modification on the resonant tank, primary-side switch network, control strategies and secondary-side rectifier. The first type usually adds extra resonant components. It features a simple control strategy. However, the parameter design of resonant components is challenging. The second type utilizes more extra switches on primary-side to realize v_{ac} regulation. Nonetheless, the control of switch patterns is complicated and some might cause extra switching losses. The third type modifications apply various control strategies without extra components, while they may introduce some problems like circuit imbalance and dc bias current through L_m. The last type distinguishes itself with variable rectifier structure; hence, the control and design is simple. However, mode transition problem, extra switches and conduction losses are introduced.

Besides, the comparison of reviewed topologies for different applications from modification, control, and performance is conducted. For hold-up operation, since it rarely occurs and time duration is short, introducing an extra compensation mode is preferred, which features high efficiency in normal mode and simple control [1], [2], [5], [10], [45], [47]. For wide input voltage applications, overall high efficiency is required, input current ripple should be suppressed, and sudden mode transition should be avoided. v_{ac} regulation is one of the suitable solution [23], [38]–[42]. For wide output voltage applications, overall high efficiency and restrained output current ripple are necessary. Variable-structure on secondary side is widely adopted for this application [31], [33], [52].

As described, the requirements of various applications are different. The review and comparison in this paper give a design reference for different LLC-based wide gain applications. Besides, it can bring some insights to the further improvements of LLC resonant converter.

ACKNOWLEDGEMENT

This work was supported in part by the National Natural Science Foundation of China under Grant 51607113, and in part by the Shanghai Sailing Program under Grant 16YF1407600.

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