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REGULAR ARTICLE

Performance Investigation of LLC Resonant Converter for Electric Vehicle Application

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The purpose of this study is to use an LLC resonant tank to extend battery life. The design of LLC tanks and their practical evaluation in an LLC multi-resonant converter are examined in this paper. Battery life is increased by the LLC multi-resonant DC-DC converter by reducing frequency current ripples. To increase the power factor, a bridgeless Cuk converter is also used. To increase power factor and reduce conduction losses, the Cuk converter uses discontinuous conduction mode (DCM). Applications involving battery charging are best suited for the suggested model. The system produces a 42 – 24 V controlled DC voltage output. A power rating of 650 W is supported. Switching losses are decreased with the incorporation of LLC topology. High efficiency is guaranteed by the converter design. The output is stabilized via frequency modulation techniques. The method improves battery longevity and performance. The study sheds light on resonant power conversion methods. The system provides dependable and effective battery charging, the LLC and Cuk converters guarantee less electromagnetic interference and the suggested design reduces strain on power devices. The design contributes to improved overall power conversion efficiency. The experimental validation validates the efficacy of the topology; and future research will concentrate on additional optimization for electric vehicle applications.

Keywords: LLC multi-resonant converter, Bridgeless Cuk converter, Discontinuous conduction mode (DCM), Frequency current ripple, Power factor.

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1. INTRODUCTION

A built-in re-chargeable charging battery powers the electric motor that propels the electric vehicle (EV) [1- 2]. The need for typical battery storage system availabilities is normally increasing enormously. Despite advancements in battery technology, the system needs a very high current and high voltage to power such types of batteries. Because of advancements in charging algorithms, the smart charger battery charging technique has become extremely complicated [3]. Because of increasing disturbances in rapid fast charging of battery packs with enormous potential, smart chargers that produce minimum interference are necessary. As shown in Fig. 1, the proposed system of the architectural block contains a bridgeless type cuk converter preceded by the use of a resonant converter that denies a high-frequency transformer is used to charge a ripple current recharging energy storage, such as a battery [4-5]. The soft-switching properties of resonant converter topologies at extreme frequencies have led to their widespread application in power processing systems [6-7]. High-frequency functioning, along with the passive components' reduced size and weight, are the benefits of this architecture.

In this study, two converters are proposed and compared [8-9]. By using zero voltage switching, the LLC and LCC resonant converters increase efficiency and lower switching losses. Over a broad load range, the operation can be accomplished even with a narrow frequency variation [10-11]. Fig. 1 displays the resonant converter's generalized circuit diagram. This can be transformed into a resonant converter with a different topology. A resonant converter with an LCC topology has an extra capacitor connected in series with the resonant inductor. In a series resonant converter with an LLC type topology, the resonant capacitor is coupled

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in parallel with an extra inductor. Resonant power converters with several energy storage elements are another name for this kind of converter. Low efficiency results from large switching losses caused by the high frequency. Resonant converters have been utilized extensively in the power industry because of their ZVS or ZCS function, which lowers switching losses [12-13].

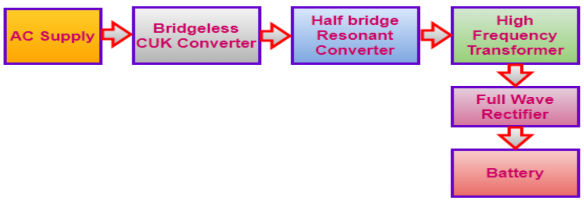

Fig. 1 – Block representation of proposed converter

The first section of this proposed study discusses the functioning of a bridgeless Cuk converter in DCM architecture. Natural safeguard against excessive current, simplicity of transformer isolation design, and reduced interference with electromagnetic waves are all criteria for choosing discontinuous conduction mode architecture. The second section discusses a half-bridge multi-resonant DC-DC chopper [14-15]. Fig. 2 represents the EV's battery for LLC Resonant Converter. However, the rechargeable batteries vast voltage output standards are exceedingly difficult and variable in comparison to the applications present in telecommunication that work under a restricted range. The voltage output of a DC-DC converter battery ranges between 36 and 72 volts [16-18]. As a result, the specification design parameters for selecting the bridgeless Cuk converter and LLC elements differ from those for telecom applications requiring continuous voltage. To achieve the requirements, an LLC resonant converter must be used.

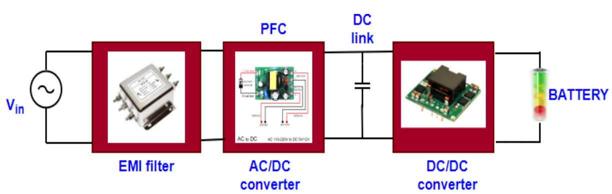

Fig. 2 – EV's battery for LLC resonant converter

The resonant harmonic tank is designed to function across a large range of input side voltage to obtain a high switching frequency and improved efficiency. Over the entire operational range having zero voltage, as well as zero current switching's, are made possible. Section 2 explains how a bridgeless Cuk converter operates. Section 3 describes the proposed DC-DC converter and LLC multi-resonant converter designs. The proposed simulation findings are explained in Section 4. Section 5 dis-cusses the hardware outcomes. The conclusion is provided in Section 6.

2. CUK BRIDGELESS DC-DC CONVERTER

2.1 Operation of the Analysis of the Proposed DC-DC Converter

The proposed converter's operation, as shown in Fig. 3, is discussed. To achieve power factor correction (PFC), the output inductor current and the inductors namely i_{Lo1} and iLo2 maintain discontinuously, whereas the voltage between intermediary capacitors and the input inductor current (i_{L1} and i_{L2}) remains to be continuous

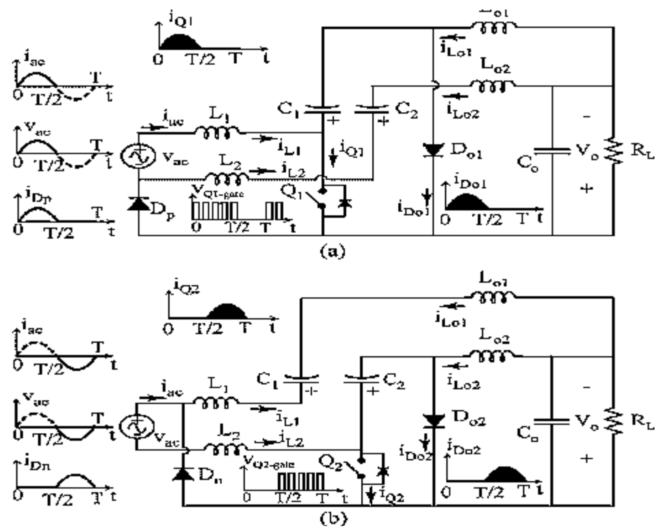

Fig. 3 – Bridgeless CUK converter

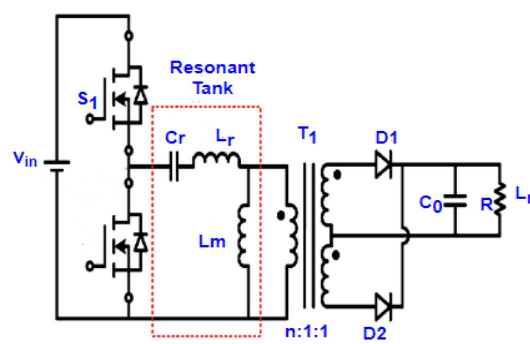

Fig. 4 – Schematic circuit diagram of the proposed method

The operating principle of the converter is depicted in Fig. 4 including both alternating current sources having half-cycles. S1 is in conduction between i_{L1} and D_p during the positive portion of the AC voltage V_{ac}. C_1 is a capacitor that transmits energy across L_{01} and D_{01}. Similarly, during the (-ve) phase of the AC voltage cycle, the S_2 is having conducting across i_{L2} and Dn. Mode I describes the many operation modes of the DC-DC cuk converter during the +ve half cycle. While S_1 is in ON condition, the L_{01} first stores the energy occupied via the D_p diode, causing the i_{L1} current in the course of the inductor to increase. The accumulated energy in C_1, the current intermediately capacitor, is drained to C_0, the

DC link capacitor, and L_{01}, the inductor output.

Mode II: Whenever S_1 is in OFF condition, the i_{L1} inductor current dissipates from the capacitor C_1 via the diodes of D_1 and D_p. In addition, the stored energy in the L_{01} inductor is transmitted to the C_0 capacitor through the DC-link. The currents across the inductors such as i_{L1} and $iL01$ continue to drop, though the voltage crossways the C_0 DC-link and C_1 capacitor started to increase. As a consequence, i_{L01} and V_{dc}, the voltage throughout the DC-link increase, while V_{C1}, the voltage generated in the capacitor providing positive control and starts to decreases, and i_{L1} current automatically increase. However, the C_0 capacitor pre-sent across the DC-link gives the required energy, so V_{dc} voltage seems to decrease in the operation of mode III.

3. COVERTER DESIGN

3.1 Bridgeless Cuk Converter Design

The converter's design is based on specific mathematical assumptions. A DCM's operation is obtained under the following conditions:

$$Ke < Ke_{crit} = \frac{1}{2(\mathrm{M}+\sin(\omega t))^2} \tag{1}$$

Ke is a dimensionless conduction factor as follows:

$$Ke = \frac{2\mathrm{Le}}{\mathrm{R_L\,Ts}} \tag{2}$$

$$K_{\mathrm{e-cr-min}} = \frac{1}{2(\mathrm{M}+1)^2} \text{ and } K_{\mathrm{e-crit-min}} \frac{1}{2(\mathrm{M})^2} \tag{3}$$

$$\Delta\, i_{L1} < 10\%\ I_{L1} \text{ and } \Delta V_{c1} < 5\% \tag{4}$$

$$\Delta\, I_{L1} = \frac{\mathrm{D.Vin}}{\mathrm{F_S.L1}} \tag{5}$$

$$\Delta\, I_{L2} = \frac{(1-\mathrm{D}).\mathrm{Vo}}{\mathrm{F_S.L2}} \tag{6}$$

$$\Delta\, V_{C1} = \frac{\mathrm{D.V_d.I_d}}{\mathrm{V.C.F_S}} \tag{7}$$

The inductances and capacitances values are deter-mined by the Eq. (5), (6), and (7):

$L_1 = L_2 = 300$ mH, $L_{01} = L_{02} = 1$ mH, $C_1 = C_2 = 2200$ µF, $C_{out} = 2200$ µF.

The DC link voltage of the PFC converter is as follows:

$$V_o = V_{ac}\frac{\mathrm{D}}{(1-\mathrm{D})} \tag{8}$$

V_{ac} represents the output of a rectifier for a specified V_s. V_{ac} and V_s are connected as follows:

$$V_{ac} = 2\sqrt{2}\frac{\mathrm{Vs}}{\pi} \tag{9}$$

3.2 Resonant Converter Design

The parameters necessary for the converter's design must be provided. Maximum power output, maxi-mum input voltage limit, resonance harmonic frequency, and voltage output are all must be mentioned. The converter input voltage is calculated at the DC link capacitor through the power factor correction (PFC) bus. The converter output voltage is between 24 V and 43 V. For a maximum output power of 650 W, the present voltage output of 43 V is given. Fig. 5 depicts the LLC resonant equivalent circuit.

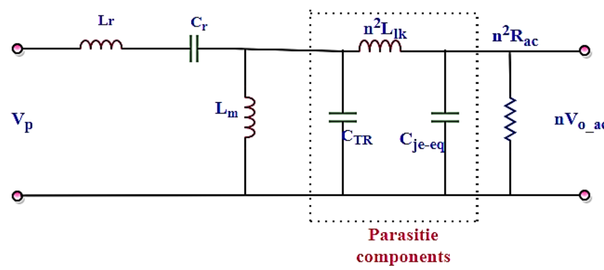

Fig. 5 – LLC resonant converter – equivalent circuit

Fig. 6 depicts the Proposed Converter's entire MATLAB Simulation circuit. The resonant frequency of TTR is computed by using Eq. 10 at unity gain, where V_d represents the rectifier's diode output voltage drop.

$$N_n = \frac{V_i(n)}{2(V_o(m)+V_d)} \tag{10}$$

Eq. 11 determines the minimal inductance.

$$L_{r(scc)} = \frac{N_n.V_{in(nom)}.V_{o(nom)}}{8.f_{s\_max}.P_o} \tag{11}$$

As once resonant inductor value has been found, the resonant capacitor value may be computed by using Eq. 12.

$$C_{r(res)} = \frac{1}{(2\pi f_o)2L_r(s)} \tag{12}$$

Eq. 13 requires the maximal magnetizing inductance, L_m(ZVS). Eq. 14 gives the greatest gain at the smallest switching frequency, denoted L_m(max).

$$L_{m(ZVS)} = \frac{\mathrm{t_{dead}}\cdot\mathrm{N_n}\cdot\mathrm{V_{o(min)}}\cdot\left(\frac{1}{4\mathrm{f_{smax}}} - \frac{\mathrm{t_{dead}}}{2}\right)}{\mathrm{C_{HB}V_{in(max)}}} \tag{13}$$

$$L_{m(max)} = \mathrm{L_{r(scc)}}\frac{\pi^2}{4}\frac{\frac{\mathrm{f_o}}{\mathrm{f_{s\_min}}}-1}{1-\frac{1}{\mathrm{M_{dc\_max}}}} \tag{14}$$

Therefore, using Eqs. 15 and 16, the value of the total inductance should fulfill the storage of the energy stability requirement present in the half-bridge overall capacitance.

$$\frac{1}{2}\left(\mathrm{L_{m(min)}} + \mathrm{L_{r(scc)}}\right)\mathrm{I^2_{m-pk}} > \frac{1}{2}\mathrm{C_{HB}}\ \mathrm{V^2_{in(max)}} \tag{15}$$

$$\mathrm{I_{m\_pk}} = \frac{\mathrm{N_n}\cdot\mathrm{V_{o(min)}T_o}}{4\mathrm{L_m}} \tag{16}$$

4. RESULTS AND ITS DEISCUSSION

In the MATLAB platform, the proposed DC-DC converter is simulated and tested. The performance is discussed, including power factor and overall harmonics distortion. The potential of LLC resonant converters to function at higher frequencies with reduced switching losses makes them highly valuable. With the help of two inductors and a single capacitor, the converter can control the output voltage throughout a broad range of line and load variations. Unlike LCC resonant converters, soft switching can be accomplished across the whole operating range. In Fig. 5, the LLC resonant converter's resonant tank is displayed. Figs. 6 to 12 display the performance parameters, which include output voltage ripple, output voltage, and output current, that are calculated using MATLAB/Simulink.

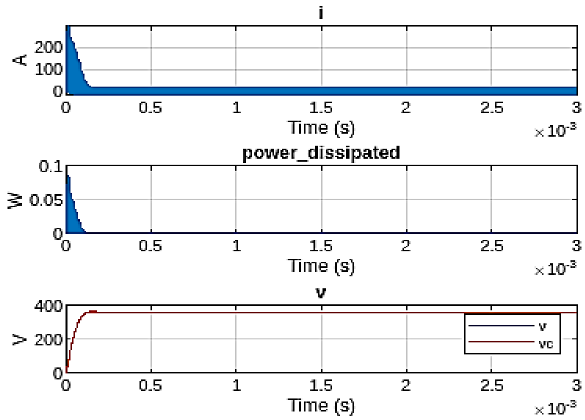

Fig. 6 – Performance parameter of capacitor

The performance parameter of capacitor such as current, power dissipated and voltage is analyzed for the proposed design. The current amplitude is 200 A in the starting then it is settle down at 12 A. The power dissipation is high only in the starting after 0.1 sec it is settle down at less values and the voltage across the capacitor settled at 0.1 sec as depicted in Fig. 6.

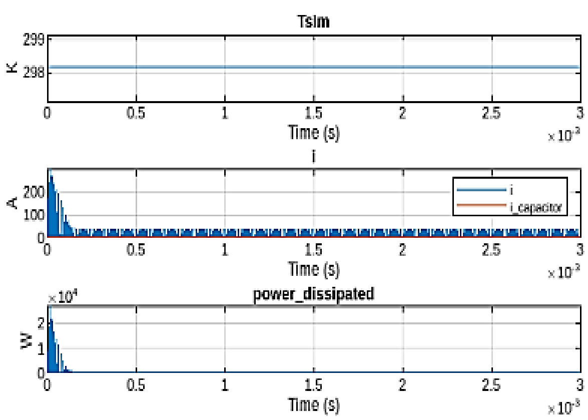

Fig. 7 – Performance parameter of diode

The performance parameter of diode such as Temperature, current and power dissipated is analyzed for the proposed design. The current amplitude is 200 A in the starting then it is settled down at 12 A. The power dissipation is high only in the starting after 0.1 sec it is settled down at less values as depicted in Fig. 7.

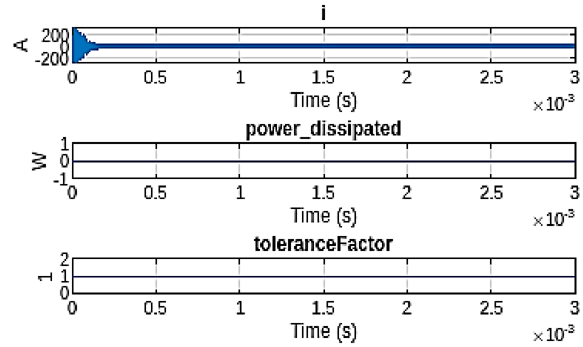

Fig. 8 – Performance Parameter of Cr

The performance parameter of Cr such as current, power dissipated and tolerance factor is analyzed for the proposed design. The current amplitude is + 200 A to – 200 A in the starting then it is settle down at 13 A. The tolerance factor is 1 as depicted in Fig. 8.

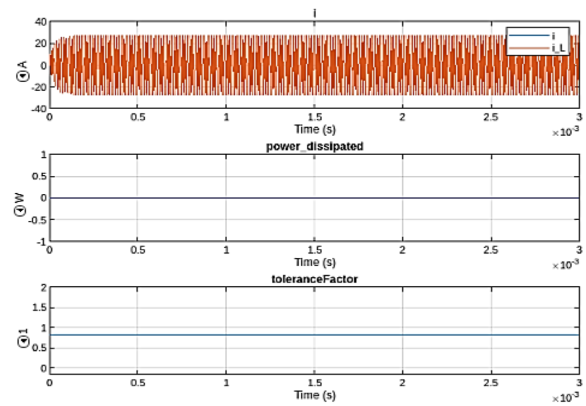

Fig. 9 – Performance Parameter of Inductor

The performance parameter of inductor such as current, power dissipated and tolerance factor is analyzed for the proposed design. The current amplitude is + 20 A to – 20 A. The tolerance factor is 0.7 as depicted in Fig. 9.

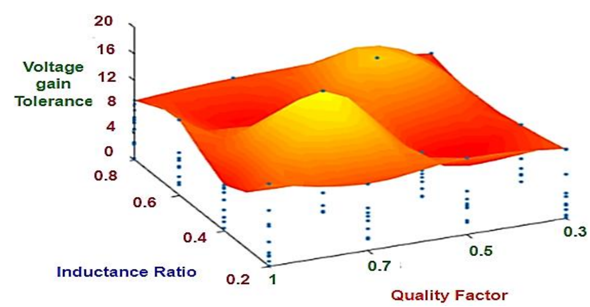

Fig. 10 – Maximum gain tolerance

The maximum gain tolerance is analyzed for the proposed design. The voltage gain tolerance with quality factor is analyzed as depicted in Fig. 10. This graph illustrates the relationship between "Voltage Gain Tolerance" and "Inductance Ratio" and "Quality Factor," providing important information for enhancing circuit performance. The curve shows a distinct tolerance peak, indicating that the best results are obtained when the Inductance Ratio is in the moderate range of roughly 0.6 – 0.8 and the Quality Factor is higher, around 0.6 – 0.7. There is a sweet spot where the system operates at its finest, according to these findings, and neither too low nor too high values of these parameters produce the optimum outcomes. When developing and fine-tuning electronic circuits, like LC filters or oscillators, where attaining high voltage stability and tolerance is essential, this analysis is especially valuable.

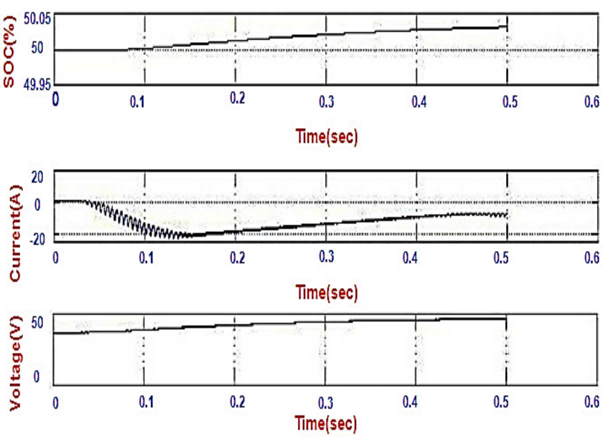

Fig. 11 – Voltage output of the battery V_0 = 46 V, output current I_0 = 17 A, and SOC's of battery = 50 %

The proposed system technique outperforms the conventional method in terms of performance. The power factor has gradually increased by 0.9288 and the harmonics distortion has decreased by 4.0700 percent. Fig. 11 depicts the characteristics of battery charging. The battery's SOC is 50 % charged, and it charges at a voltage output of 42 V and a current of 16 A. Fig. 12 depicts a hardware prototype of the proposed system converter that includes a Bridgeless CUK converter, an LLC Resonant converter, and a pulse-producing circuit.

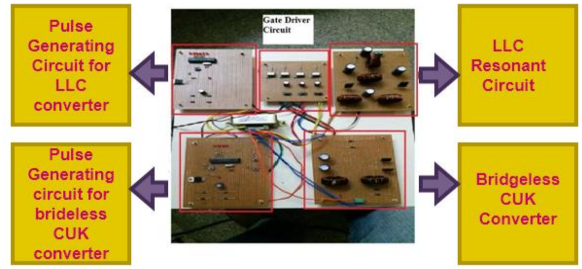

Fig. 12 – Hardware Setup

Table 1 – Comparison table based on performance

Parameter specification	Traditional system	Proposed system
Power Factor	0.9222	0.98888
THD – Input current	46.266 %	4.0700 %
Output Voltage (V)	8.7	12
Output Current (A)	3	5.8
Voltage gain	0.1733	0.754

A novel resonant converter with the combination LLC resonant converter is proposed to enhance the DC-DC converter's effectiveness for massive range of voltage applications. The resultant voltage as well as current gain were higher than those of the single topology LCC resonant converter. The performance of proposed LLC resonant converter is compared with the conventional method in terms of power factor and THD. The proposed method has improved power factor as 0.99 compared to the conventional. The total harmonics distortion has reduced in the proposed method such as 4.07 percent compared to the conventional method as depicted in Table 1.

5. CONCLUSION

To maximize the life of the battery and broad voltage output range of multi-resonant LLC tank the research design and practical system design evaluation are imparted. The current ripples are minimized in electric vehicles (EV) by utilizing a multi-resonant LLC dc-dc converter. Bridgeless CUK converter is employed to achieve unity power factor, and power factor is enhanced by 0.99. The modeling for the battery charging application produces an output voltage range of 24 – 42 V for 672 Watts.

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Дослідження працездатності резонансного перетворювача LLC для застосування в електромобілях

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Метою даного дослідження є використання резонансного резервуара LLC для подовження терміну служби акумулятора. У статті розглядається конструкція резервуарів LLC та їх практична оцінка в багаторезонансному перетворювачі LLC. Термін служби акумулятора збільшується за допомогою багаторезонансного перетворювача постійного струму LLC шляхом зменшення пульсацій частотного струму. Для збільшення коефіцієнта потужності також використовується безмостовий перетворювач Cuk. Для збільшення коефіцієнта потужності та зменшення втрат провідності перетворювач Cuk використовує режим переривчастої провідності (DCM). Застосування, пов'язані зі заряджанням акумулятора, найкраще підходять для запропонованої моделі. Система виробляє керований вихід постійної напруги 42–24 В. Підтримується номінальна потужність 650 Вт. Втрати на перемикання зменшуються завдяки впровадженню топології LLC. Висока ефективність гарантується конструкцією перетворювача. Вихід стабілізується за допомогою методів частотної модуляції. Цей метод покращує термін служби та продуктивність акумулятора. Дослідження проливає світло на методи резонансного перетворення потужності. Система забезпечує надійне та ефективне заряджання акумулятора, перетворювачі LLC та Cuk гарантують менше електромагнітних перешкод, а запропонована конструкція зменшує навантаження на силові пристрої. Конструкція сприяє підвищенню загальної ефективності перетворення потужності. Експериментальна перевірка підтверджує ефективність топології; а майбутні дослідження будуть зосереджені на додатковій оптимізації для застосувань в електромобілях.

Ключові слова: Багаторезонансний перетворювач LLC, Безмостовий перетворювач Cuk, Режим переривчастої провідності (DCM), Пульсації струму частоти, Коефіцієнт потужності.