AC-DC PFC-CUK FED ONE-SWITCH RESONANT CONVERTER WITH BMS FOR E-BIKE BATTERY CHARGING SYSTEM

Shashank Varshney
Dept. of Electrical Engineering
NIT Warangal
Warangal, Telangana, India
svee20102@student.nitw.ac.in

B.L. Narasimharaju
Dept. of Electrical Engineering
NIT Warangal
Warangal, Telangana, India
blnraju@nitw.ac.in

Sambhani Madhu Babu
Dept. of Electrical Engineering
NIT Warangal
Warangal, Telangana, India
sam1729@student.nitw.ac.in

Ashok Kumar Kanithi
Dept. of Electrical Engineering
NIT Warangal
Warangal, Telangana, India
akk0107_jrf@nitw.ac.in

2021 IEEE Transportation Electrification Conference (ITEC-India) | 978-1-6654-2146-1/21/$31.00 ©2021 IEEE | DOI: 10.1109/ITEC-INDIA53713.2021.9932531

***Abstract*—Nowadays, electric bikes are substituting conventional bikes due to economic and environmental advantages. This paper presents an improved converter for battery charging of E-bikes. PFC-CUK converter is used as primary stage to achieve near unity power factor (UPF). In the secondary stage, efficient one-switch resonant converter is utilized. The second stage converter process the power with the help of resonance circuit formed by leakage inductor and capacitor. The detailed operation of the proposed topology is explained followed by the simulation results. A lithium-ion battery pack of 36V, 7650 mAh is charged by incorporating different protection schemes. Simulation results evident that the proposed converter provides near UPF and reduced THD of 4.28%, which is below IEEE standard limit of 5%.**

Keywords—Power factor corrected (PFC); Unity power factor (UPF); Continuous Conduction mode (CCM); Discontinuous Conduction mode (DCM); Total harmonic distortion (THD)

I. INTRODUCTION

Automobiles used for transportation system are releasing lethal emissions due to extensive fossil fuel consumption that results in environmental pollution [1]. To address these issues, eco-friendly electrical vehicles (EV) are the only alternative to meet transportation needs. However, the exponential growth of EVs require an establishment of domestic charging system with a number of power ranges [2]. Distribution transformers are heavily burdened because of harmonics present in the current which is due to the capacitive behaviour of batteries [3, 4]. Converters that can improve the power factor at the source end and reduce current THD must be used. This helps in improving efficiency of the system & increases the real power extracted from mains. Conventional boost converter topology is supreme over available topologies for PFC. In [5], an extensive survey of different topologies of boost-converter for hybrid electric vehicle charging system is presented. However, these topologies get affected due to high inrush current. In [2], the author has presented front-end AC–DC converter topologies standards. In [6], electric vehicles charger used in CCM based on one-stage CUK converter is presented. However, DC voltage having ripples in it, charges the EV battery. High-ripple voltage consequence over the life of Li-ion battery required to be evaluated [7]. In [8], the author has proposed a wireless charger for e-bikes that has SEPIC converter with bridgeless topology operating in DCM. But the system is not highly efficient. Based upon the capability of PFC converters to handle the power, following modes of operation are present (a) CCM, (b) DCM (c) critical conduction mode (CRM) [9]. In CCM, two control loops results in ramification of the system. In DCM, voltage-follower approach that requires complex electromagnetic interference filtering is used to achieve current shaping. At the borderline of DCM and CCM, CRM operates. In second stage, one-switch isolated converter without RCD snubber [11] used in the proposed work.

II. PROPOSED CONVERTER WORKING PRINCIPLE

The proposed converter model is shown in Fig. 1., which has two power conversion stages. The first stage contains PFC-CUK converter with front end bridge rectifier and second stage is an isolated one-switch PWM resonant converter. The detailed explanation of the proposed converter is provided as follows.

A. Working of the first stage converter

The two modes of operation of the first-stage CUK converter is shown in Fig. 2. and is briefly discussed below-

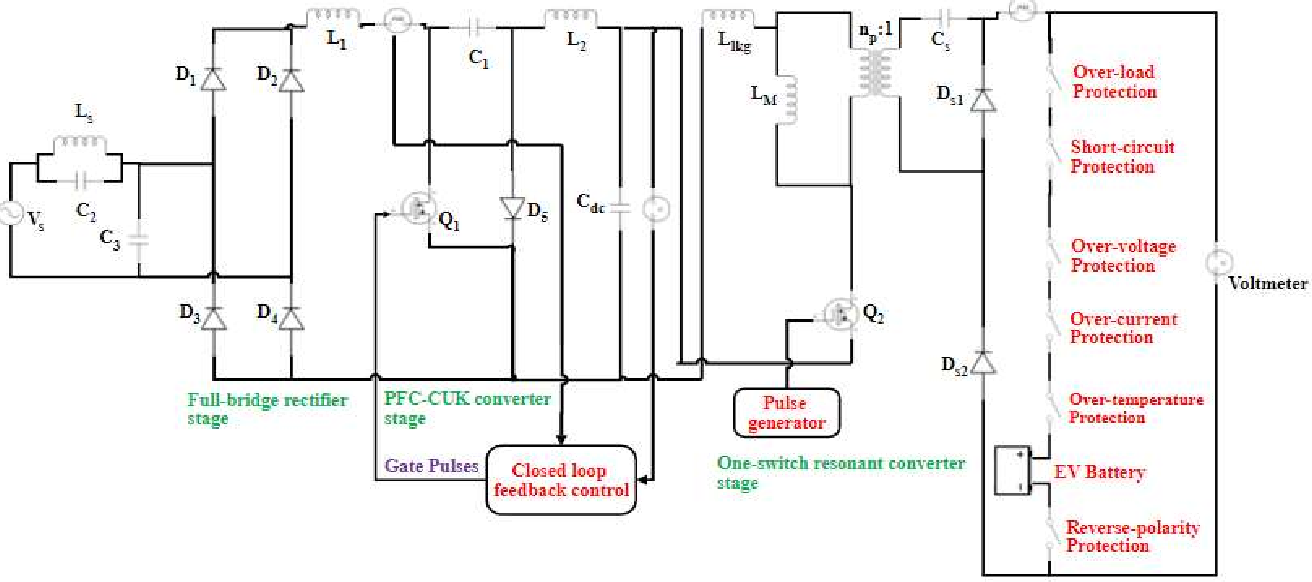
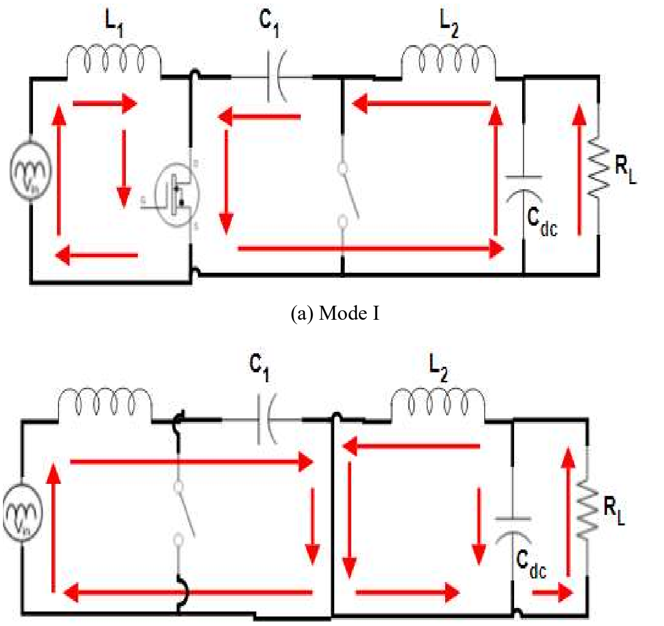


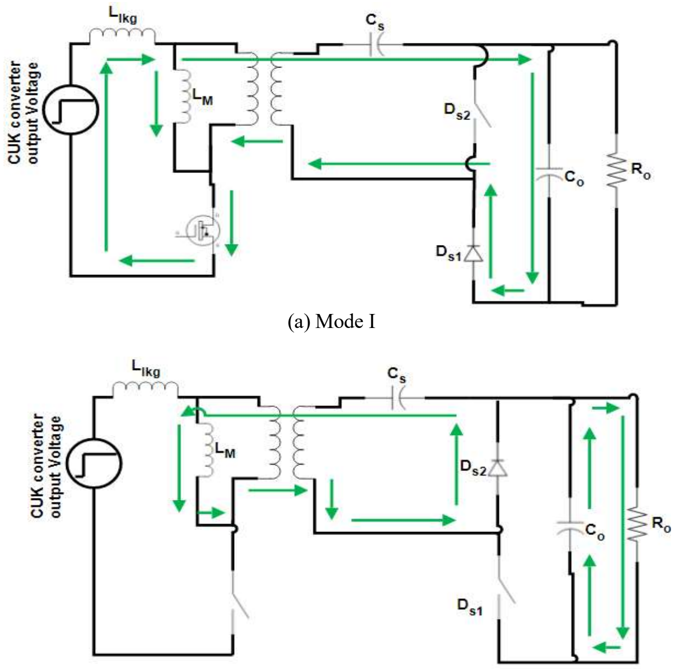
Fig. 1. Proposed PFC-CUK fed PWM resonant one-switch converter with BMS for E-bike charging.



(a) Mode I

(b) Mode II

Fig. 2. PFC-CUK converter modes of operation



(a) Mode I

(b) Mode II

Fig. 3. One-switch resonant converter modes of operation

Mode I: Switch Q_1 is ON in this mode while diode D_5 is reverse biased. L_1 stores energy from source while C_1 transfers its stored energy to L_2 & C_{dc}. Common way for current to flow through two different meshes is provided by Q_1, as shown in Fig. 2(a).

Mode II: With the start of this mode, Q_1 is switched OFF, and diode D_5 is forward biased as shown in Fig. 2(b). During this time period, L_1 starts discharging its stored energy to C_1 and the load is supplied by the already charged L_2 & C_{dc}. Diode D_5 provides the common path for the current through two different meshes.

B. Working of the second stage converter

Operation of second stage resonant converter is shown in Fig. 3. The resonance period of the circuit with L_{lkg} & C_S is expressed in (1). The converter can be operated in two regions i.e., above resonant region ($T_R/2 > DT_S$) & below resonant region ($T_R/2 < DT_S$) [11].

$$T_R = 2\pi \sqrt{(L_{lkg} * C_S)} / n_p \qquad (1)$$

III. Proposed Control Scheme

Various configurations for an E-bike battery are available in the market, among them a ten series connected cell & three parallel-connected cell of Lithium-ion battery with 7650 mAh capacity & battery pack voltage of 36 V, battery pack cut-off voltage of 27.5V & battery pack charging voltage of 41.8 V is considered. Standard pack charging current is 3 A, standard pack charging temperature is 45°C, standard pack charging time is 60 mA or 3 Hrs whichever is earlier. The following are three common methods of charging an EV battery:

(I) Constant Voltage method

(II) Constant Current method

(III) Constant Voltage-Constant Current method

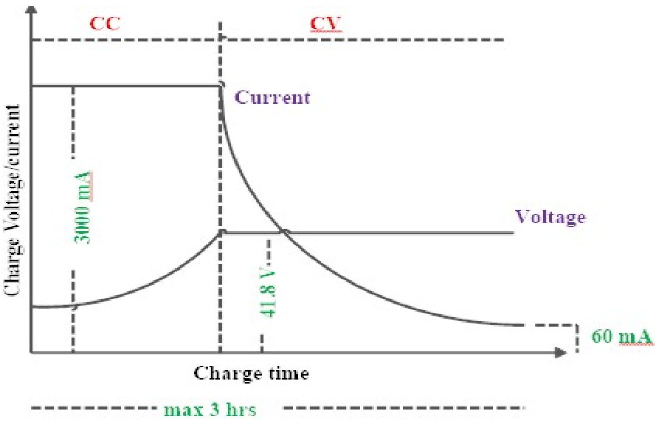


Fig. 4. CV-CC EV battery charging modes

Fig. 4., demonstrate the battery charging method. In CV – CC method of EV battery charging, until the battery attains a pre-set voltage level, the charger will limit the amount of current to pre-set level. As battery becomes fully charged, current reduces. This method helps in fast charging without over-charging & is suitable for Lithium-ion batteries. PFC-CUK converter as shown in Fig. 1., feeds the PWM resonant one-switch isolated converter. The CUK converter input and output inductors (L_1 and L_2) are operated in CCM. C_1 is set for continuous voltage over a switching period. V_{dc} of the CUK converter appears across C_{dc}, which is fed to the one-switch isolated converter. Two loops with different motives are utilized by CUK PFC converter. Input line current is shaped to sinusoidal by the inner current loop whereas DC-link voltage is maintained by the outer voltage loop. We get error voltage V_e on comparison of V_{dc} with reference voltage V^*_{dc}. V_e is handled by a voltage PI controller to provide a DC reference i^*_{L1}. Input Inductor i_{L1} current is compared with the DC reference current i^*_{L1} and it generates the gating pulse for the switch. Parallel input resonant filter is used to achieve reduced THD of source current and improved power factor. For input parallel resonant filter, equivalent impedance n^{th} harmonic component is given by

$$Z_n = [n * X_{Ls} * (X_{C2} / n)] / [jnX_{Ls} - j(X_{C2} / n)] \tag{2}$$

where, X_{Ls} represents impedance of input resonant inductor L_s & X_{C2} represents impedance of input resonant capacitor C_2 both at fundamental frequency. Theoretically, the third harmonic impedance of the input resonant filter will be infinity. Therefore, $(3 * X_{Ls}) = (X_{C2} / 3)$ & $L_s = 1 / (9\omega^2 C_2)$, accordingly C_2 & L_s can be designed. The value of C_3 is chosen in this way that at the rated output power, the input power factor reaches its peak value.

IV. Results And Discussion

The proposed converter is simulated for an output power of 133.08W using MATLAB/Simulink. The specifications and design parameters of the proposed converter is given in TABLE I.

TABLE I. Specification And Design Parameters

Parameters	Values
V_{AC}	220V (RMS)
f_{supply}	50Hz
$V_o = V_{Bat}$	41.8V (DC)
Switching frequency of resonant converter	75KHz
L_s	11mH
C_2	2mF
C_3	20mF
L_1	10mH
L_2	10mH
C_1	0.5μF
C_{dc}	30μF
L_{lkg}	8.3μH
L_M	3mH
C_S	8μF
C_O	10mF

With the help of parallel resonant input filter applied at the source end, THD of source current is reduced up to IEEE recommendation, which is less than 5% as shown in Fig. 5. Fig. 6. represents the output voltage of CUK converter and the output current of CUK converter. As closed loop feedback control is applied to the PFC converter, we can see its output voltage is approximately constant in nature. Since output voltage polarity of CUK converter is inverted when compared to input voltage polarity of CUK converter, thus, second stage one-switch converter is connected as shown in Fig. 1. Output of CUK converter is given as input to PWM resonant single switch isolated converter. Switching frequency for second stage converter is kept at 75 kHz. SIMULATION is performed in above resonant region (i.e. $(T_R / 2) > DT_s$) by properly selecting value of T_R as shown in Fig. 7.

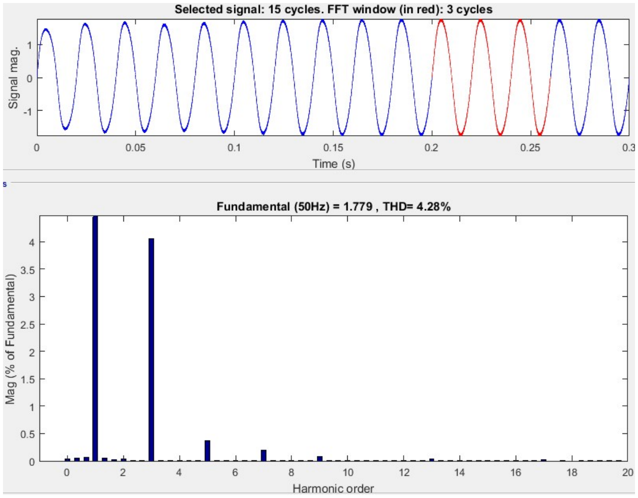


Fig. 5. FFT analysis of source current

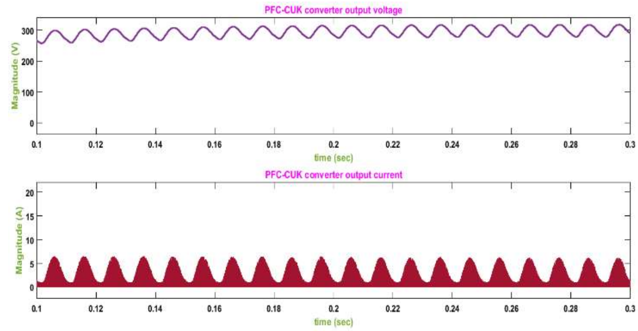


Figure 6. PFC-CUK converter output voltage & output

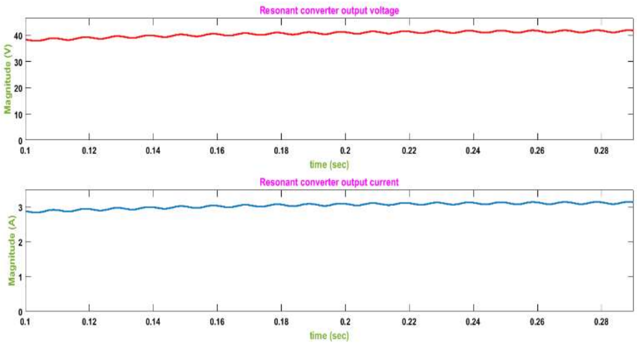


Fig. 7. Resonant converter output voltage & output current

Fig.7. shows the simulation waveforms for second stage one-switch isolated resonant converter with 300 V_{dc} input voltage. The resonance circuit components L_{lkg} and C_S are designed at this point, to satisfy $T_R/2 = DT_S$ condition. It can be observed that the value of I_{lkg} at turn-off instant is small, thus provides reduced turn-off switching loss.

Output of second stage converter acts as input for the EV battery. Simulation waveforms of EV battery is shown in Fig. 8. The voltage and current waveforms of the devices (Q_1) and (Q_2) performances are shown in Fig. 9. (a) and (b) respectively.

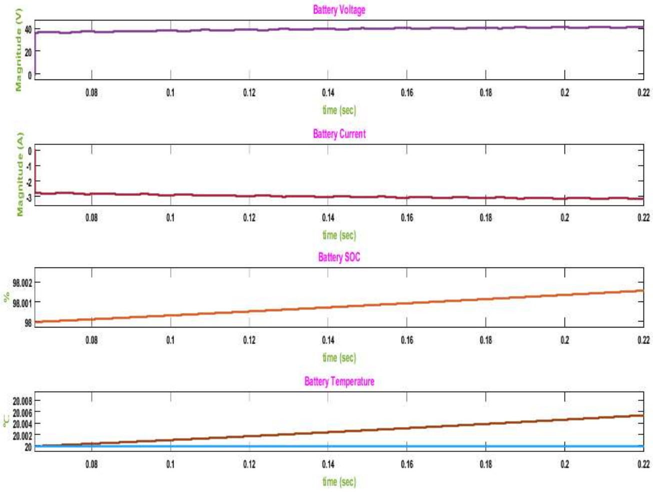
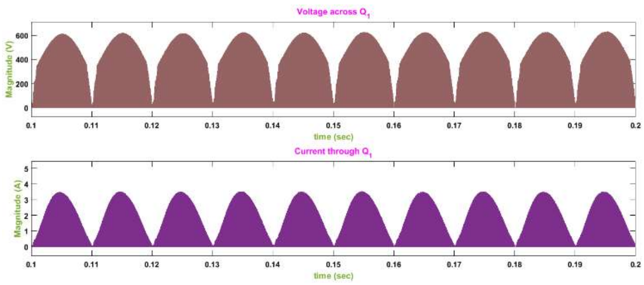
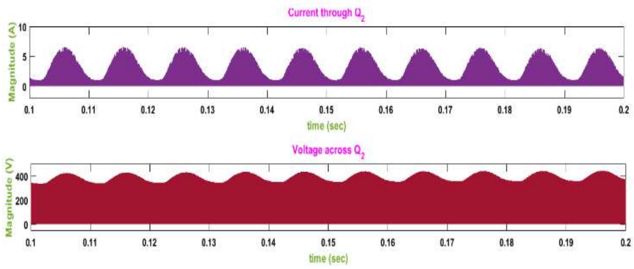


Fig. 8. Battery voltage, current, SOC & temperature



(a)



(b)

Fig. 9. (a) Device (Q_1) waveforms (b) Device (Q_2) waveforms

As can be seen from Fig. 1., various types of protection schemes like overload protection, short-circuit protection, over-voltage protection, over-current protection, over-temperature protection & reverse polarity protection are provided to the EV battery. Output voltage V_O needs to maintain between 41 V to 43 V. Similarly, output current must be less than 3.2 A, temperature at which EV battery is getting charged must be less than 47°C, & the load at the output of second stage converter should not exceed 133.08 W, otherwise respective switches will get opened.

Fig. 10. shows the simulation waveform for source voltage & source current which is evident for UPF. TABLE II presents performance of the proposed converter, which is evident that the

THD, voltage stress, current stress and switch count are reduced as compared to the converter presented in [10]. Moreover, the proposed converter is assisted with battery protection system.

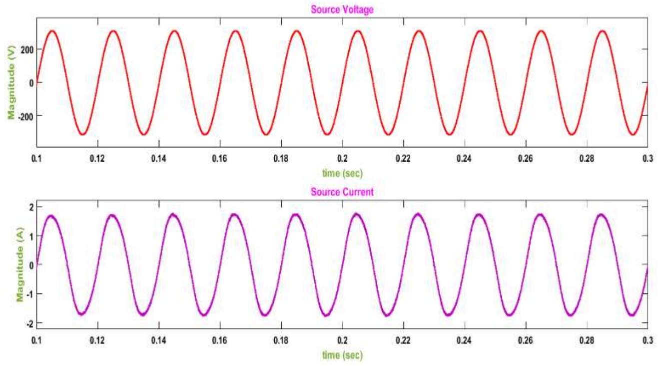


Fig. 10. Source voltage & source current waveforms

TABLE II. PERFORMANCE COMPARISION OF PROPOSED CONVERTER WITH THE CONVERTER IN [10]

Parameters	**Proposed Converter**	**Converter in [10]**
%THD of source current	4.28%	5.6%
Switch Q_1 voltage stress	632.3V	700V
Switch Q_1 current stress	5A	10A
Switch count	8	10
Battery protection	Yes, but need 6 relay switches	No battery protection

V. CONCLUSION

The Enhanced power quality charger for E-bikes is proposed. In addition, second stage one-switch converter makes use of L_{lkg} and C_s as a resonant tank to extract power, instead of a large filter inductor. Moreover, the proposed converter provides near UPF, lower THD of 4.28% for source current which well below the IEEE standard limit. Also, it provides low switch current stress, low switch voltage stress, less switch count in power stage, and battery protection system.

ACKNOWLEDGEMENT

This research work is supported under IMPRINT-IIC.1 project funded by SERB, Govt. of India with file no IMP/2019/000295.

REFERENCES

[1.] B. Bilgin et al., "Making the Case for Electrified Transportation," in IEEE Transactions on Transportation electrification, vol. 1, no. 1, pp. 4-17, June 2015, doi: 10.1109/TTE.2015.2437338.

[2.] SS Williamson, AK Rathore, F Musavi, "Industrial Electronics for Electric Transportation: Current State-of-the-Art and Future Challenges," in IEEE Transactions on Industrial Electronics, vol. 62, no. 5, pp. 3021-3032, 2015

[3.] R. Liu, L. Dow and E. Liu, "A survey of PEV impacts on electric utilities," ISGT 2011, 2011, pp. 1-8, doi: 10.1109/ISGT.2011.5759171.

[4.] GA Putrus, P Suwanapingkarl, D Johnston, E C. Bentley and M. Narayana, "Impact of electric vehicles on power distribution networks," IEEE Vehicle Power and Propulsion Conference, 2009, pp. 827–831.

[5.] F Musavi, M Edington, W Eberle, WG Dunford, "Evaluation and Efficiency Comparison of Front-End AC-DC Plug-in Hybrid Charger Topologies," in IEEE Transactions on Smart Grid, vol. 3, no. 1, pp. 413-421, 2012

[6.] BR Ananthapadmanabha, R Maurya and S R Arya, "Improved Power Quality Switched Inductor Cuk Converter for Battery Charging Applications", IEEE Transactions on Power Electronics, vol. 33, no. 11, pp. 9412-9423.

[7.] R Hou, A Emadi, "A Primary Full-Integrated Active Filter Auxiliary Power Module in Electrified Vehicles with Single-Phase Onboard Chargers," in IEEE Transactions on Power Electronics, vol. 32, no. 11, pp. 8393-8405.

[8.] Han Zhao, Wenbin Shu, Desong Li and Siqi Li, "A novel wireless power charging system for electric bike application," IEEE PELS Workshop on Emerging Technologies: Wireless Power (2015 WoW), 2015, pp. 1-5

[9.] SF Lim, AM Khambadkone, "A Simple Digital DCM Control Scheme for Boost PFC Operating in Both CCM and DCM," in IEEE Transactions on Industry Applications, vol. 47, no. 4, pp. 1802-1812, July-Aug. 2011.

[10.] Rahul Pandey, Bhim Singh, "PFC-SEPIC converter-fed half-bridge LLC resonant converter for e-bike charging applications" in IET Electrical Systems in Transportation, 2020, Vol.10, Iss. 3, pp. 225-233.

[11.] K. Park, C. Kim, G. Moon and M. Youn, "PWM Resonant Single-Switch Isolated Converter," in IEEE Transactions on Power Electronics, vol. 24, no. 8, pp. 1876-1886, Aug. 2009