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Modelling and Analysis of LLC Resonant Converter for LEV Applications

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Abstract:

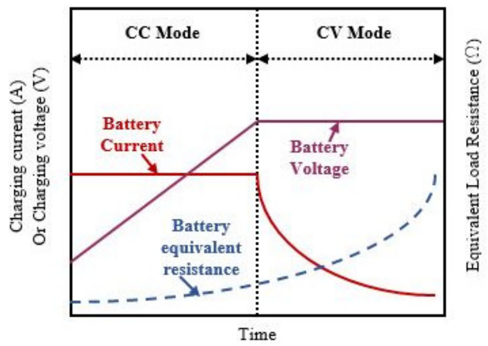
In DC-DC converters, resonant converters are becoming popular in the electric vehicle industry. There are various topologies of resonant converters but each has its own limitations. To avoid limitations under light load conditions and large load variations hybrid of series and parallel topology is proposed. Out of all the constructions LLC resonant converter has advantages of soft switching, high efficiency etc. LLC resonant converters are prevalent in employing CC charging technique as well as CV charging technique. This article focuses on the scheme of LLC resonant converter for light electric vehicles. A MATLAB simulation was done of 360 W to study and evaluate the performance. The corresponding results demonstrate that the battery can be charged with the given LLC converter when 6 A of constant current and 60 V of constant voltage is applied.

Keywords— LLC, converters, switching loss, zero voltage switching, electric vehicle.

I. Introduction

The world's rapid temperature rise has made it necessary to cut back on fossil fuel use and the pollutants that go along with it. Improving electricity-generating technology, has caused a shift toward renewable energy sources and reduced costs. By 2030, India promises to reduce its GHG emissions intensity by 33% to 35% from 2005 levels [1]. In the automotive industry, an electric vehicle is seizing its place swiftly. A light electric vehicle (LEVs) is an electric vehicle with two or four wheels that are powered by a battery, hydrogen cell, or a system consisting of both battery and hydrogen cell. LEVs include battery powered wheelchairs, electric scooters, and bicycles. They don't emit gases [5]. Therefore, EVs and LEVs contribute to clean air. In comparison to diesel or gasoline vehicles. Additionally, they offer the benefit of requiring low upkeep and producing less noise. In spite of booming in the industry, people have become reluctant to buy electric vehicles due to their charging issues[6-7].

Though LEVs give an average of 90-100 km, it takes a lot of time to charge the battery. With this much amount of time, chargers can also lead to heating issues and become inefficient [8]. Therefore, technology is focusing nowadays more on fast charging techniques, for which switching with high frequency is done by using techniques of ZVS (Zero Voltage switching) or ZCS (Zero Current Switching) because of which size of the system also reduces. Because of significant features like less switching losses, high power density, high efficiency and inexpensive, the LLC resonant full bridge converter is broadly used in different types of applications and industries [9]. The block illustration of the EV Charger using an LLC resonant converter is provided in Fig 2. The AC input voltage used to power the EV charger ranges from 170-300 V. EMI Filter is used to filtering out all the harmonic distortion from the AC supply and bridge rectifier, which converts that supply to DC.



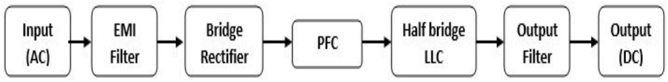


Fig. 1. CC CV Charging profile

The PFC step up the voltage to 400 V for LLC input which LLC converts to 60 V. After filtering out all the ripples through the output filter, we get 60 V voltage and 6 A current as output [10].

Fig. 2. Block diagram of EV charger using LLC resonant converter

Chargers with LLC resonant converter topology are tested to be more efficient and charge faster than any other charger. Fast charging of batteries depends on CC, CV and CC-CV modes [11]. A CV is a constant voltage mode in which same voltage is maintained while charging the battery. If there is a large voltage difference, a large amount of current will flow that is why a current limiter is used to limit that large current. In a CC mode, a constant current is given to the battery from the start to the end of charging. The battery can get damaged if charging current and time are not controlled simultaneously which will lead to overcharging. [2][3].

To lessen switch dissipation, some research employ synchronous rectifiers at the converters' output stages [13]–[15]. But unlike battery charging applications, which need a wide range of output voltage variation, the majority of these applications are made to function at a constant output voltage or within a small input voltage range. Considering CC-CV mode, a battery is first charged in a CC mode and then slowly charging mode is shifted to CV mode. In the beginning, maximum static current is applied to the battery while voltage increases till the SOC reaches 80~90%, after that, current starts decreasing and constant voltage is maintained till the SOC reaches 100% of the charging [2-4].

In [12], discussed the design process of an efficient DC electric vehicle (EV) fast charger, achieving a peak efficiency of 99.5%, is outlined alongside adherence to applicable UL standards regarding conducted harmonics and leakage current.

II. Working of LLC Resonant Converter

The LLC is a member of a much bigger family with topologies for resonating converters, all based on resonant tanks. Circuit with inductors and capacitor form resonant tanks, which oscillates at a pre-determined frequency known as the resonant frequency. An LLC resonant converter comprises four blocks, i.e., a square wave voltage generator, a resonant tank, a transformer, and a diode rectifier. Firstly, the phase difference between MOSFETs Q_1 and Q_2 in 180 degrees in such a way to provide square voltage wave V_{sq} at very high frequency at primary side of the transformer. Now the resonant tank circuit convert the square wave into oscillatory sine wave.

There are two types of current flow at primary side, load current which flows from transformer primary (oscillatory current) and magnetising current which flows through parallel inductor (L_m). Q_1 and Q_2 must have substantial dead time in order to avoid cross conduction. Due to inductor behaviour the magnetising current never stops flowing during the operation, even during the dead time. Thus, even when Q_1 is off, magnetising current still flows through its internal capacitance, the conduction from magnetising inductance L_m happens in such a manner that internal capacitance of Q_1 is fully charged and internal capacitance of Q_2 is discharged completely that creates zero voltage condition at switch Q_2 hence, it creates ZVS condition for Q_2. Similarly, we create ZVS switching for Q_1 for next cycle. It is mentioned that the dead time needs to be sufficient to guarantee ZVS condition. The primary load current transferred to secondary side rectifier through a high frequency transformer which scale the voltage up and down according to output requirement.

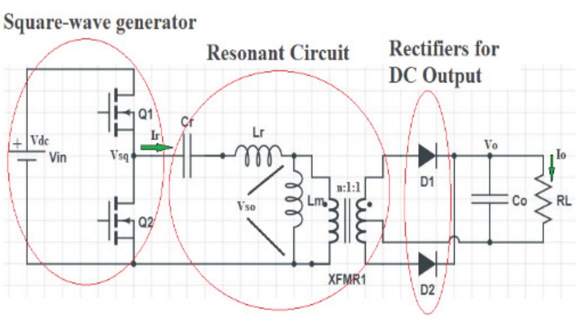


Fig. 3. A typical configuration of LLC resonant converter

A. Modes

As frequency modulation is responsible for gain of the LLC network, there are three modes in which the operation of the converter is done. It depends on the voltage which is given as input and current which is passing through the load.

i. Below resonant frequency operation, fs<fr.

ii. At resonant frequency operation, fs=fr

iii. Above resonant frequency operation, fs>fr.

Below is the resonant frequency operation (fs<fr).

There is a power delivery operation in each half of the switching cycle after the resonant inductor current reaches the magnetizing current and the resonant half cycle is finished. Conduction losses in the primary side grow as a result of the freewheeling operation, which begins and continues until the end of the switching half cycle. When a boost operation or a step gain is needed in this mode, lower ivoltage is applied at the input for the operation of the converter.

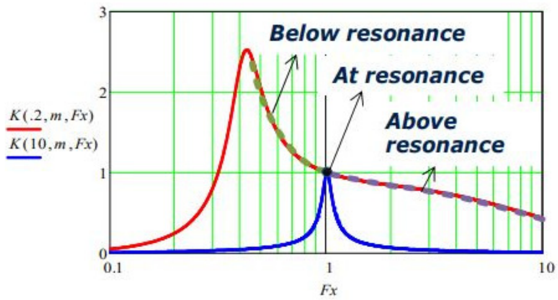


Fig. 4. LLC Network gain at different frequencies

At resonant frequency operation (fs=fr). During half cycle of switching, resonance half cycle is completed and, in this condition, for each of the switching cycles there is a complete power delivery operation. When half cycle of switching is ended, the resonant inductor current reaches the magnetizing current, and the rectifier current reaches zero. At the resonant frequency, the resonant gain is unity and has the best-improved process and efficiency. To operate the converter at nominal input and nominal output voltage the transformer turns ratio is calculated.

Above resonant frequency operation (fs>fr). A partial power delivery action, similar to the resonant frequency operation, is present in each half of the switching cycle. Even yet, it is different in that the switching cycle's other half begins before the resonant half cycle is finished. As a result, secondary rectifier diodes have difficult communication and primary-side MOSFETs have enhanced turn-off. In this mode, the converter operates at a higher input voltage, necessitating the use of a step-down gain or buck operation.

III. 3 Design Objectives of LLC Resonant Converter

Designing a high-efficiency LLC resonant converter with a broad voltage range at the output requires achieving two goals:

1. To reduce RMS current, the magnetising inductance should be as high as possible, and
2. Under various loading situations, a peak gain that is roughly 1.5 times the nominal voltage should be designed.

Below equations are used to design the LLC resonant converter:

$$Q = \frac{\sqrt{L_r/C_r}}{n^2 r} \quad (1)$$

$$f_o = \frac{1}{2\pi\sqrt{L_r C_r}} \quad (2)$$

$$k = \frac{L_m}{L_r} \quad (3)$$

From (1), (2), and (3), quality factor is denoted as Q which is the ratio of the characteristic impedance and the equivalent load resistance, f_o are the LLC converter's resonant switching frequency and *n* is the transformer turns ratio. k is defined as the magnetizing inductance divided by resonant inductance. The relation between these equations helps in creating the LLC resonant tank circuit. As is well known, the resonant converter functions at resonance under typical operating circumstances. Therefore, to ensure high-efficiency operation, at this operating region, it is crucial to reduce switching and conduction losses on both the primary and secondary sides. Conduction loss is evaluated with the help of magnetizing inductance, and the RMS current is related to the inductance, which is described in equations (4) and (5) as:

$$I_{rms\_tank} = \frac{1}{8}\frac{V_o}{nR_{load}}\sqrt{\frac{2n^4 R_{Load}^2 T^2}{L_m^2} + 8\pi^2} \quad (4)$$

$$I_{rms\_secondary} = \frac{1}{4}\frac{V_o}{nR_{load}}\sqrt{\frac{5\pi^2 - 48}{12\pi^2}\frac{n^4 R_{load} T^2}{L_m^2} + 1} \quad (5)$$

Meanwhile, to ensure ZVS condition, the magnetizing inductance of the transformer should be small enough and also large enough to produce a smaller turn-off current at the primary side current MOSFETs Q_1 and Q_2 to achieve minimum switching loss, the MOSFET junction capacitors should be discharged within the desired dead time by the peak magnetizing inductor current. We can calculate the magnetizing inductance from equations (1), (2), and (3) as:

$$L_m = \frac{2\pi f_o k Q}{n^2 R_{load}} \quad (6)$$

The correlation between *k* and *Q* and the magnetising inductance is shown in equation (6). The improved magnetising inductance value can be used to compute the *k* for a given *Q* value. At resonance, the resonant capacitors and inductors are tuned to have gain at unity. To attain maximum efficiency, the impedance has to be very low, which happens only at resonance conditions. Therefore, operation must be at the tank circuit's resonance frequency. Despite the fact that the input voltage from the PFC is regulated by the LLC resonant converter due to the existence of AC line frequency ripple, the converter still needs to control the input voltage. That is why the range of the switching frequency should be minimum. However, with large value of k, design of resonant inductor becomes easy. The optimal value of *k* and *Q* can be used to determine the resonant components, L_r and C_r, while taking into account the trade-off in design between converter size and efficiency. Calculations can be made to determine the converter's likely target efficiency, which is 96% by:

$$P_{in} = \frac{P_o}{e_{ff}} \quad (7)$$

he approximate transformer ratio is:

$$n = \frac{n_p}{n_s}\frac{V_{nominal}}{V_o + V_f} \quad (8)$$

Where V_f is the voltage drop on the secondary side of rectifier diode. Although the input is regulated by the constant PFC output, the input voltage will be dropped during the hold-up time. Considering the hold-up time T_{HOLD_TIME}, the minimum input voltage is:

$$V_{in}^{min} = \sqrt{V_{PFC_{Out}}^2 - \frac{2P_{in}T_{HOLD_{TIME}}}{C_{DC_{Link}}}} \quad (9)$$

Where $V_{PFC_{Out}}$ is the PFC output and $C_{DC_{Link}}$ is the DC link capacitor. The maximum gain of converter is calculated by equation (10) and minimum gain of the LLC resonant converter is calculated by equation (11) as:

$$M^{min} = \sqrt{\frac{k}{k-1}}\,2n\frac{V_o + V_f}{V_{in}^{max}} \quad (10)$$

$$M^{max} = \frac{V_{in}^{max}}{V_{in}^{min}}M_{min} = 2n\frac{(V_o + V_f)}{V_{in}^{min}} \quad (11)$$

Where turns ratio is denoted by n and k=L_p/L_r. V_o is the voltage at the output and V_f is the voltage drop at the secondary side of the rectifier. We can calculate equivalent load resistance by taking 6 as the value of k by the equation:

$$R_{ac} = \frac{8n^2}{\pi^2}\frac{V_o^2}{P_o} \quad (12)$$

To ensure ZVS, little change under loading, and optimum performance, a relative 95% Q value is selected from the highest Q_{max} attainable, Equation (13), which describes how the LLC converter functions at its maximum resonant converter gain, M_{max} provides the formula for Q_{max} To obtain the Q value suggested by the equation, the resonant network's values are as follows:

$$Q = 0.95Q_{max} = \frac{0.95}{k * M^{max}}\sqrt{\left(k + \frac{(M^{max})^2}{(M^{max})^2 - 1}\right)} \quad (13)$$

We can calculate the resonant components as:

$$C_r = \frac{1}{2\pi Q f_o R_o} \quad (14)$$

$$L_r = \frac{Q}{2\pi}\frac{R_{ac}}{f_o} \quad (15)$$

The minimum frequency in concern can be calculates as follow:

$$f_{min} = \frac{f_o}{\sqrt{\left(1 + k\left(1 - \frac{1}{(M^{\max})^2}\right)\right)}} \quad (16)$$

The minimun number of turns which is present in the primary side of the transformer is given by the equation:

$$n_{p\_min} = \frac{n_{real}\left(V_o + V_f\right) * 10^3}{2f_{min} * \Delta B * A_e} \quad (17)$$

where A_e is the transformer core's cross-sectional area in metres squared and ΔB is the maximum flux density swing in Tesla. N_s selected such that the resulting N_p is greater than N_{p_min}:

$$N_p = nN_s > N_{p\_min} \quad (18)$$

Table 1 lists the design criteria that this work has established.

Table 1. Design Specifications

Design parameter of the proposed LLC Resonant Converter			
Specifications		**Variables**	**ValueS**
Input voltage range		$V_{in}^{min} - V_{in}^{max}$	330-420 V
Nominal input voltage		$V_{in\_nominal}$	400 V
Output voltage range		$V_{out}^{min} - V_{out}^{max}$	56-71.4 V
Nominal output voltage		$V_{out\_nominal}$	60 V
Switching frequency		$f_{min} - f_{max}$	146-150 KHz
Turns ratio of transformer		n	3:1
Magnetising inductor		L_m	200 μH
Resonant	Inductor	L_r	33 μH
	Capacitor	C_r	35 nH
	Frequency	f_o	148.0 KHz

IV. LLC Resonant Converter Result discussion

Fig.5 displays a software simulation of the LLC resonant converter of 360 W to validate design specifications. According to the results, with 6 A of constant current and 60 V of constant voltage, a battery of LEV can be recharged. The nominal voltage of the converter is 59.7 V. Fig. 6 shows the output result of the LLC resonant current when 400 V is given as input.

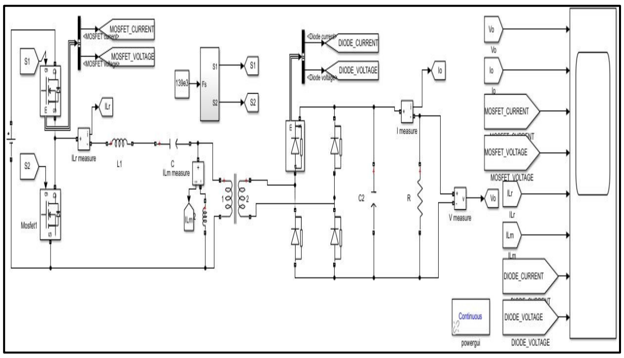


Fig. 5. MATLAB Simulation of LLC Resonant Converter

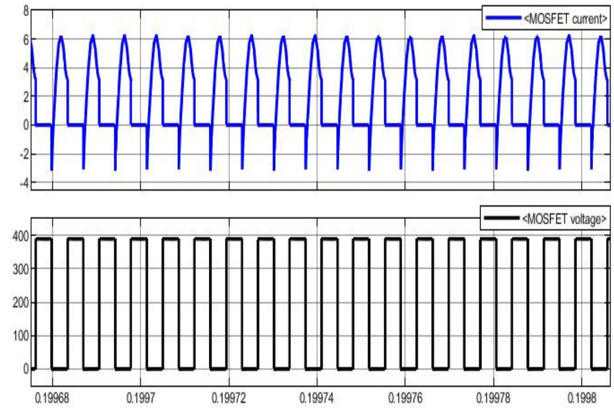


Fig. 6. Waveform result of output voltage and output current

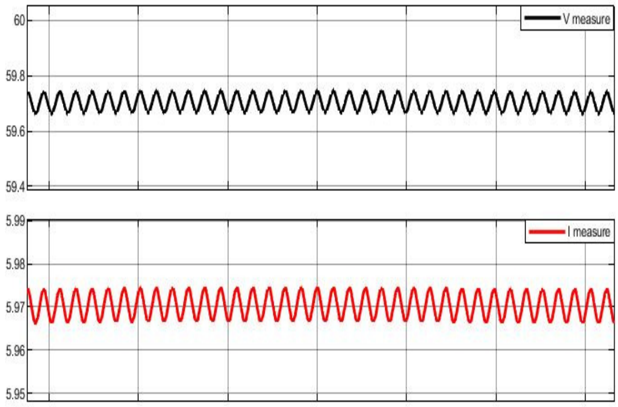


Fig. 7. Waveform result of MOSFET Voltage and MOSFET Current

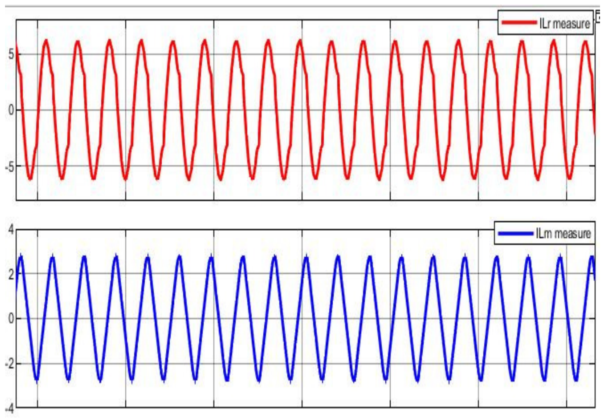


Fig. 8. Waveform result of inductor resonant current and magnetising current

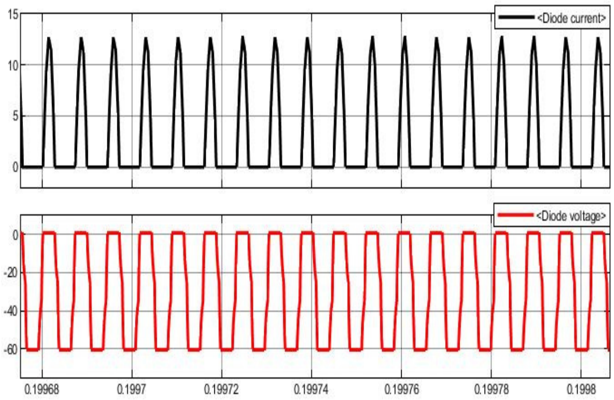


Fig. 9. Waveform result of Diode current and diode voltage

The maximum and minimum value of current is 5.965 to 5.975 A. Fig 7 shows the voltage and current value from the MOSFET connected in the input side of the LLC resonant converter. Fig 8 illustrate the resonant current value and magnetizing current value from the resonant inductor and magnetizing inductor connected in LLC topology. Fig 9 demonstrate the diode current and diode voltage from the diodes connected to the output of the step-down transformer.

V. CONCLUSION

In this article, the design methodology of LLC resonant converter topology and its simulation are shown for light electric vehicles (LEV). Despite the fact that resonant LLC converters provide a variety of advantageous qualities, including high efficiency, low EMI, and high power density, designing one is more difficult than designing a PWM converter, and it takes more time and effort to optimize. We can use LLC resonant converter for high-power and high-efficiency applications. It is possible to develop the converter efficiency to its maximum potential by determining the appropriate magnetising inductance. An effective design process for the LLC converter can also be achieved by cautiously selecting the parameters k and Q from the DC gain curves.

As we can see from the results, using an LLC Resonant converter in the charger makes the charger more efficient. There are fewer switching losses in comparison with other topologies, because of which the heating problem also becomes trivial. Its resonant nature enables it to sustain great efficiency also at high power. Due to LLC converters' resonant nature, gentle switching is possible on both the primary and secondary sides, boosting efficiency by lowering switching losses.

References

1. Fisher, T.M.; Farley, K.B.; Gao, Y.; Bai, H.; Tse, Z.T.H. Electric vehicle wireless charging technology: A state-of-the-art review of magnetic coupling systems. Wirel. Power Transf. 2014, 1, 87–96.
2. Bao, K.; Li, S.; Zheng, H. Battery charge and discharge control for energy management in EV and utility integration. In Proceedings of the 2012 IEEE Power and Energy Society General Meeting, San Diego, CA, USA, 22–26 July 2012.
3. Huang, S.J.; Huang, B.G.; Pai, F.S. Fast charge strategy based on the characterization and evaluation of LiFePO4 batteries. IEEE Trans. Power Electron. 2013, 28, 1555–1562
4. Xerxex Dan Gumera, Aileen Caberos, Shu-Chuan Huang, "Design and Implementation of a High Efficiency Cost Effective EV Charger Using LLC Resonant Converter"; 978-1-5386-0971-2/17/2017 IEEE
5. A. Dixit The" Server Access Pattern Analysis" Based on Different" Weblogs, Application of Advance Techniques in Power and Energy Systems: Select Proceedings of International Conference.
6. L. R. Chen, "A Design of an Optimal Battery Pulse Charge System by Frequency-Varied Technique," IEEE Transactions on Industrial Electronics, Vol. 54, No. 1, February 2007, pp.398
7. Junjun Deng, Siqi Li, Sideng Hu, Chunting Chris Mi, Ruiqing Ma, "Design Methodology of LLC Resonant Converters for Electric Vehicle Battery Chargers" 0018-9545, 2013 IEEE
8. M. Yilmaz and P. T. Krein, "Review of Battery Charger Topologies, Charging Power Levels, and Infrastructure for Plug-In Electric and Hybrid Vehicles," in IEEE Transactions on Power Electronics, vol. 28, no. 5, pp. 2151-2169, May 2013.
9. Wang, H.; Dusmez, S.; Khaligh, A. Design and Analysis of a Full-Bridge LLC-Based PEV Charger Optimized forWide Battery Voltage Range. IEEE Trans. Veh. Technol. 2014, 63, 1603–1613
10. P.N.,WPT System for Bidirectional On-Board Electric Vehicle Charging-A Review, 2024 IEEE 3rd International Conference on Electrical Power and Energy Systems (ICEPES)
11. L. R. Chen, "Design of duty-varied voltage pulse charger for improving Li-ion battery-charging response," IEEE Trans. Ind. Electron., vol. 56, no. 2, Feb. 2009, pp. 480–487.
12. Tiwari P. N, Analysis of Microgrids Electric Vehicles Charging Stations with Hybrid Energy Storage System Algorithm with AI, International Conference on Computational Intelligence And Smart Technologies In Electrical Engineering
13. D. Fu, Y. Liu, F. C. Lee, and M. Xu, "A novel driving scheme for syn-chronous rectifiers in LLC resonant converters," IEEE Trans. Power Elec-tron., vol. 24, no. 5, pp. 1321–1329, May 2009
14. Mudiyanselage, G. A., Pradhan, R., Kozielski, K., Zhou, L., Pietrini, G., Nayak, P., & Emadi, A. (2024). Phase-Shift and Duty-Ratio Control Optimization of a 6 kW Three-Port Resonant DC-DC Converter for Dual Auxiliary Voltage EV Applications. IEEE Transactions on Power Electronics.
15. Yin, M., & Luo, Q. (2024). Stepwise Multi-Objective Parameter Optimization Design of LLC Resonant DC-DC Converter. Energies, 17(8), 1919.
16. Tiwari. K ,Thakre. K, Tiwari P. N., (2022) Performance Analysis of PV Fed DC-DC Converter for Simultaneous Buck-Boost Operation, IEEE International Conference on Current.
17. Zhaksylyk, A., Rasool, H., Abramushkina, E., Chakraborty, S., Geury, T., El Baghdadi, M., & Hegazy, O. (2023). Review of active front-end rectifiers in ev dc charging applications. Batteries, 9(3), 150.
18. Pal. S., Gupta, S. K Solar and Wind Energy-Based Charging Station Designing for EV with Hybrid Storage Systems Having Power Flow Optimization Using F_MS_GA Algorithm, International Conference on Computational Intelligence And Smart Technologies In Electrical Engineering.
19. Sideng Hu11, Junjun Deng1, Chris Mi1, "LLC Resonant Converters for PHEV Battery Chargers", 978-1-4673-4355-8/13/$31.00 2013 IEEE

20. A. Dixit Pattern and Prediction Analysis by Using Different Data Mining Techniques, Application of Advance Techniques in Power and Energy Systems: Select Proceedings of International Conference, CISTEE 2023.
21. S. Schilling, "Ensuring Lead-Acid Battery Performance with Pulse Technology", 1100 South Kimball Avenue, South Lake Texas, 1999.
22. Kumar. A. Renewable Energy Sources Integration with Flywheel Energy Storage System based on Wind and Solar Energy. International Conference on Current Development in Engineering and Technology (CCET).