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PV Based Electric Vehicle Charger Using LLC Resonant Converter

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ABSTRACT

Twitter Today, Electric Vehicles are gaining much popularity and provides a clean and smooth means for transport. Need for Electric vehicle charging stations are significant, due to increased number of electric vehicles. Electric vehicle charging stations incorporated with renewable energy sources offers significant reduction of global pollutant emission. In Photovoltaic fed EV charger, surface temperature and solar irradiance can affect the output voltage and performance. For maximum power extraction from the PV panel maximum power point tracking with simple P&O algorithm is selected. The variable dc voltage from the PV panel is extracted and boosted by the LLC based resonant converter. The resonant action provides maximum power extraction and voltage regulation capability, dual controlling action is provided with the help of MPPT and voltage mode control. Depending up on the input voltage range (24-45V), output voltage can vary from 230-430V. A 350W model is designed as the prototype for the LLC resonant EV charging station. MATLAB/Simulink results and waveforms are presented in the paper.

Keywords: *Photo Voltaic, Electric Vehicle, LLC Compensation*

1. INTRODUCTION

The use of Electric Vehicle (EV) started back in 19th century. Now the govt policies are mainly focused on reducing the carbon emission by promoting the use of EVs. Rather than powering directly from grid, electric vehicles can be powered from renewable energy sources. In the renewable energy sources, Photo voltaic (PV) system is one of the dependable and cost-effective system used worldwide. This system has increased life, reduced upkeep cost and is pollution free. Photo-voltaic system can be setup as a standalone system or as a grid tied system. Active research works are going on in PV field, so leads to reduced cost and marks as a competitive source for EV charging station applications. Fuel and labor cost are reduced in PV fed system due to reduced maintenance. PV applications are advanced due to the increased research interest in power converter technologies.

Recently different resonant topologies for EV battery charging applications put forward and these topologies mainly focuses on reducing the switching losses by incorporating zero voltage and zero current switching and thus improving the overall efficiency of the battery charger. Though resonant topologies increase the overall efficiency, it is noted that losses associated with other components must be reduced along with implementing simple control strategy. Conventional resonant converters consist of different combination of inductor and capacitor such as LC, LCL, LCC, LCLC, LLC and many more. In all this resonant topologies [2-6] losses associated with them vary depending up on components and its combinations. Even though resonant converters are capable of high frequency operation, it is noted that most of the converters are sensitive to variation of its circuit parameters. This variation reduces the overall efficiency due to the changes in the resonant frequency. To eliminate this problem, converter should follow the resonant frequency and track its variation regardless of the load conditions.

Due to the design complexity and control problems, fifth order resonant converters capable of extending switching frequency are limited to below its second resonance frequency. switching frequency regulation is mainly due to wide extension of resonance frequency and its non operational area of resonant curve [2]. On comparing fifth order circuit with fourth order resonant topology, forth order LCLC is also capable of extending the switching frequency beyond its second resonance frequency but LCLC does not take into accound the transformer secondary leakage inductance which leades to less accurate regulation capability due to inaccurate steady state analysis[6]. Third order resonant converters LCC, LCL are derived from LCLC topology. LCC and LCL have the capability to attain high voltages for battery charger application[4-5]. LCL is suitable for telecom applications and LCC for both low voltage and high voltage applications. Topologies mentioned above responds to variations of input voltage and works satisfactory under maximum power point tracking (MPPT) but lacks to attain required voltage gain, so not suitable for specific application.

LLC is one of the most common resonant converter topology. LLC comprises of three reactive elements. which can generate two resonant frequencies, series resonant frequency and a parallel resonant frequency. One of the limitation by using LLC topology is existence of diode junction capacitance, which creates limitation for the operating frequency range and input output voltage regulation capability. This limitation can be overcome by a suitable control architecture in which a dual control action is carried out. In the initial state a variable frequency control is carried out with the help of MPPT based control and then a fixed frequency voltage control is carried out. A voltage control

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oscillator (VCO) facilitates this dual control action with the help of a selector switch.

Photo voltaic fed EV charging stations consist of roof top PV panel which is fed to an inverter section followed by a resonant converter and rectifier section. The rectifier output is stored in the battery bank. In the case of PV fed battery chargeable system, the regulation challenges are severe. It requires constant tracking of the PV output and also estimating the battery state of charge. Depending up on the control variables a suitable control algorithm is made for controlling the battery charger [1]. Since the forth order resonant circuit is much complex for control action. It uses magnetic integration for the resonant components. The resonant circuit switching frequency is varied over a large range and design equations are complex while compared to simple LLC resonant network. Resonant network used in PV fed EV charger is of third order, consist of two inductors and one capacitor (LLC). Even though resonant network is of third order, the system uses magnetic integration thus uses magnetization inductance of the transformer as one of the resonant component. so even though network is third order it is seen as a second order system. So by using LLC converter, overall size and cost can be reduced also control action is much simpler.

Fig.1 PV Based EV Charging Station.

In solar powered battery charger, the output of PV panel is a variable dc supply due to the unpredictable changes in the ambient temperature and irradiation level [7]. In such cases the control strategy is very complex and which is only possible with a constant tracking of the resonant frequency with the help of a control oscillator. Two types of control actions are incorporated, MPPT and a voltage mode control. Since the resonant converter having inherent short circuit protection, current mode control is not required. The control action starts with constant power mode and changes to constant voltage mode to keep output voltage in the floating state. A 350W prototype of Photo voltaic fed Electric vehicle charger is designed and simulation results and waveforms are presented.

2. BLOCK DIAGRAM

The block diagram of the PV based EV energy station is shown in Fig 2. It is comprises of a power source (Photo Voltaic) and a DC/AC inverter supplying to the resonance converter. Resonant converter composed of a ferrite core transformer for stepping up the voltage and for providing isolation. The output from the resonant section is fed to the diode rectifier followed by a tuning capacitor and battery bank. The PV panel is placed in the rooftop and battery bank in the ground section. A feedback control section monitors the battery states and PV output power. The control action is provided with the help of frequency control oscillator and a selector switch which switches between two control modes - constant power mode and constant voltage mode. So the control oscillator produces switching pulses, according to the requirements to switch the inverter. Thus energy flowing through the transformer is controlled to maintain the required level of output power.

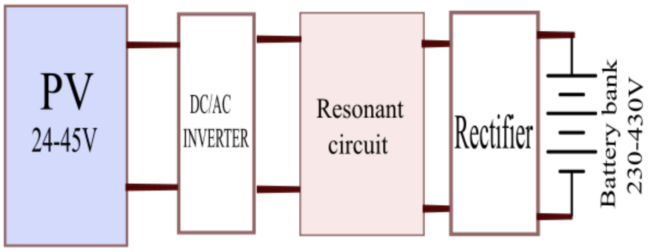

Fig.2 Block Diagram of Typical Resonant Converter.

3. SYSTEM CONFIGURATION

PV fed resonant converter EV charging station consist of power source, which is a Photo-voltaic panel. It is followed by an inverter section which energises resonant network accompanied by a diode rectifier and storage system.

3.1 PHOTO-VOLTAIC SYSTEM

Power extracted from a photo-voltaic system mainly depends up on ambient temperature and irradiance level. PV panel produces a variable DC supply. Due to the variation of output power from the PV, it must be constantly followed to extract maximum power. The conventional equations for the PV modules are chosen for understanding the working with respect to different weather conditions.

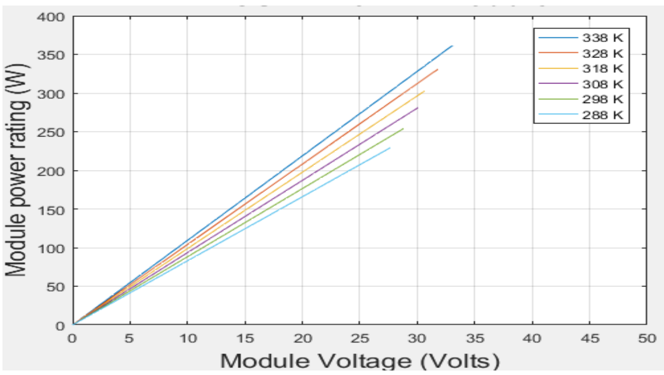

Fig.3 PV Module Depends on Different Temperature.

From Fig. 3, it is evident that as the temperature is low the performance is satisfactory, optimum temperature of $ 25˚C is chosen as the reference value for the calculations and simulations.

Variation of irradiance levels are applied such as 1000, 800, 600, 400 & 200 w/m^2 and accordingly PV curve

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is plotted in Fig. 4. It is evident that the output power of the PV panel is maximum when the irradiation level is at its maximum value of 1000 w/m^2. So this maximum irradiation level is chosen as the optimum value for the calculations.

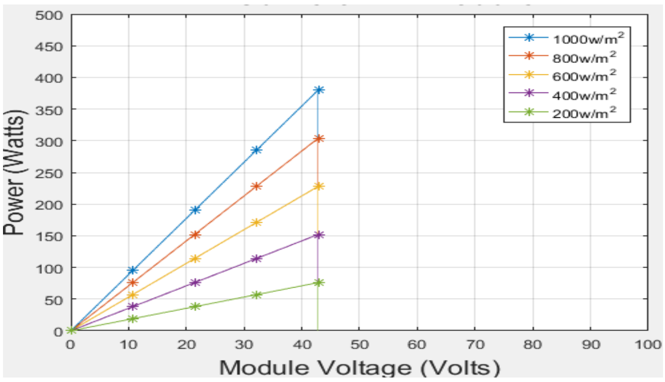

Fig.4 PV module depends on different irradiance.

A 350W PV panel is selected as the input power source for the resonant converter, which is having output voltage range from 24-45V, depending up on the irradiance level. This output is fed to the converter section, which is having wide voltage regulation capability.

3.2 LLC RESONANCE CONVERTER

The resonant circuit presented here for EV charging station is of third order. From the AC equivalent circuit of the transformer and resonance converter, it is possible to obtain the resonance model. An external resonant inductor is placed at the primary side of the isolation transformer. Transformer Magnetizing inductance is chosen as the second resonant component. A capacitor is also allotted at the primary side combined to form a LLC resonant network.

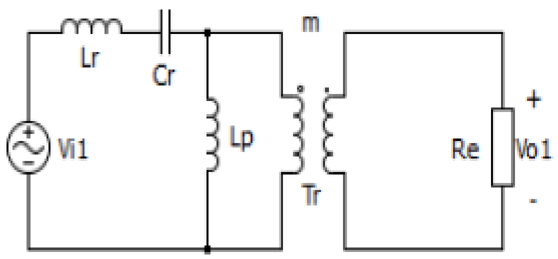

Fig.5 AC Equivalent Circuit of LLC Converter.

LLC resonant converter has the capability to restrict output current, so that it can avoid short circuit and over current problems, while providing constant charging current. In the over current condition, inductor acts loading to the inverter switches. So that sudden changes in current is limited and thus provide safety at any operating frequency.

3.3 ENERGY STORAGE SYSTEM

In the beginning era of the Electric Vehicle, lead acid batteries were in practice, but due to its lack of performance, power density and poor temperature characteristics, it is not recommended for EV purpose. Now a days Li-Ion batteries are gaining popularity due to higher power density, good temperature characteristics, fast charge capability, low self-discharge rate and long cycle life. Li-Ion battery is chosen as the energy storage system. Li-Ion battery has the capability to with-stand over charge for a short duration. Due to its high thermal stability during fully charged condition, ease of handling is also improved.

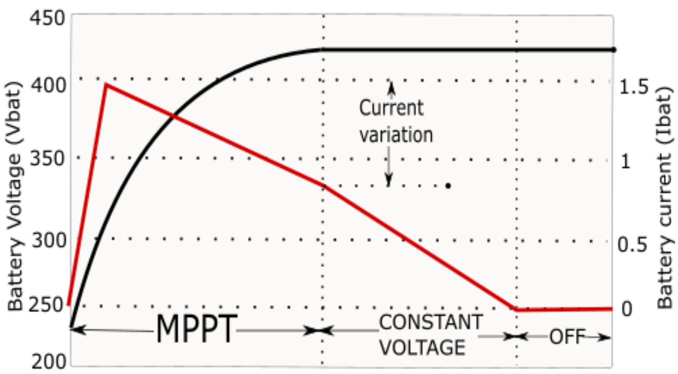

Fig.6 Battery Charging Cycle Considering MPPT and Voltage Mode.

Fig.6 shows the battery states for EV charger application. In which battery powered in constant power mode during starting and as the voltage level reaches to the floating value, charging transferred to constant voltage mode.

4. SYSTEM DESIGN

Fig.7 shows the complete circuit diagram of PV fed EV energizing system. LLC resonant converter gained its popularity in moderate and large power operation, due to its high efficiency and high power density. LLC can achieve zero voltage switching and provides high competence in different load conditions. For battery charging applications that must satisfy certain constraints such as charging according to battery SOC (state of charge), also charging profile is factored according to some charging algorithm. Due to low ripple and high efficiency LLC is the optimum choice for this operation.

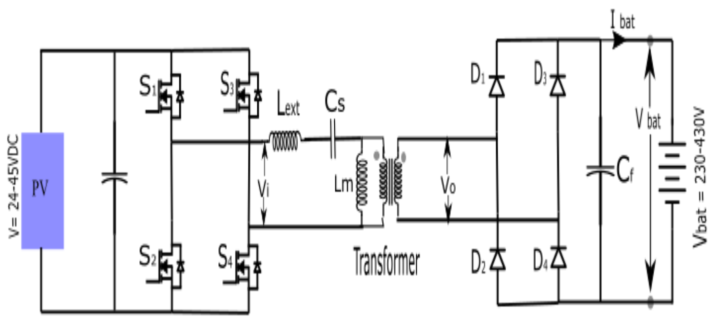

Fig.7 Photo Voltaic Fed LLC Battery Charger.

The system described consists of a square wave inverter, followed by a resonant network and a rectifier section. Shown in Fig.7, Lm is the magnetizing inductance of the resonant network. Lext and Cs are the resonant inductor and capacitor respectively. Resonant circuit is operated in constant power mode and constant voltage mode.

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5. DESIGN OBJECTIVES

The objective is to design a PV based charging station for EV application using LLC resonant converter. Electric Vehicle charger of 350W is designed for an output voltage range from 230-430V. There are two design objectives to be met, while designing high efficiency LLC converter.
four significant weather events and three weather services that are all based in the United States as identified below.

- The peak voltage gain under different loading condition must be approximate to 1.5 times the nominal voltage.
- The value of magnetizing inductance should be high to limit RMS current value.

LLC converter acts as a current source to the load section, as that of a series resonant converter. Thus by applying First Harmonic Approximation (FHA) analysis to LLC, we can obtain input voltage, output voltage, equivalent resistance. FHA model of the LLC converter is shown in Fig.5.

$$V_i = \frac{4V_{in}}{\pi} * \sin(\omega_s t) \qquad 1$$

$$V_o = \frac{4V_{in}}{\pi} * \sin(\omega_s t - \varphi_v) \qquad 2$$

$$R_e = \frac{V_o}{I_o} = \frac{8}{\pi^2} * R \qquad 3$$

Important equations define the LLC converter are:

$$f_o = \frac{1}{2\pi\sqrt{L_{ext} * C_s}} \qquad 4$$

$$Q = \frac{\sqrt{L_{ext}/C_s}}{n^2 * R} \qquad 5$$

$$K = \frac{L_m}{L_{ext}} \qquad 6$$

$$x = \frac{f_s}{f_o} \qquad 7$$

Where f_o is the converter resonance frequency and Q is quality factor, which is the ratio between characteristic impedance of the network and equivalent load resistance. 'n' is the transformer turns ratio. The ratio between magnetizing and resonant inductance is taken as value K. 'x' is the ratio between switching frequency and resonance frequency. From equations (4),(5), & (6) magnetizing inductance value can be calculated as

$$L_m = \frac{2\pi f_o K Q}{n^2 * R} \qquad 8$$

From the ac equivalent circuit of the LLC, after taking First Harmonic Approximation (FHA) normalized gain can be calculated as

$$G = \frac{1}{n\sqrt{[1 + \frac{1}{K} * \left(1 - \frac{1}{x^2}\right)]^2 + [Q\left(x - \frac{1}{x^2}\right)]}} \qquad 9$$

Taking equation (9) as reference, DC Gain vs normalized frequency graph has been plotted as shown in Fig. 8. As per the design constraints, the converter should operate in ZVS region ie zone 1. In zone 2 the converter works in discontinuous mode, ZVS switch ON of inverter switches and ZCS turnoff of diodes can be achieved. So switching loss on both sides are reduced. To make sure soft switching operation, input impedance is limited to the inductive region.

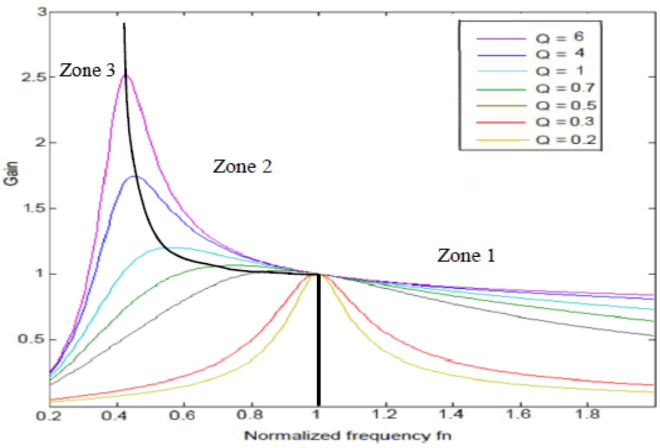

Fig.8 DC Gain characteristics of LLC

6. LLC CONTROL STRATEGY

The control approach for PV to battery charging for LLC converter includes two modes of operation, constant power mode and constant voltage mode. EV charging station is accomplished according to charging approach described. In constant power mode, the charging is done with maximum current up to voltage reaches to its floating voltage of 430V and floating limit of about 3%. Due to the limitation of PV power level, the charging current is limited in PV powered EV charger applications. Usually in the charging station applications the charging power is of few KW, so fast charging is possible. But in PV powered systems, the charger power level is limited to few Watts. Li-ion battery allows slow charging with longer charge duration. In the first stage by keeping output power constant, voltage increases from its minimum level to its floating value. In the second stage voltage is kept at floating value. So during first stage charging current is at maximum of about 1.5A and it decreases to 0.8A, during floating stage until battery is fully charged.

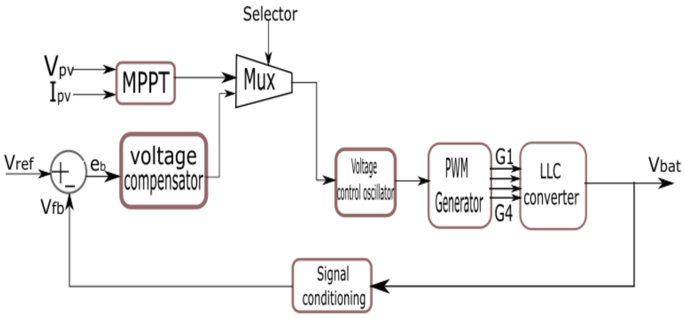

Fig.9 Controller for LLC battery charger.

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The control action starts with taking the sample output voltage from the battery. It is compared with a reference voltage. This error signal after compensation is available. The selector switch provided selects between MPPT and voltage mode control, depending up on suitable control action required. The signal from the selector switch is available at the voltage control oscillator, which produces frequency corresponding to the control action required and gives to PWM generator for control pulse generation.

- In the beginning LLC converter switching frequency set at maximum value. During this condition converter operates at no load condition. Output voltage at this stage is less than 230V. Switching frequency reduces as the battery voltage reaches 230V.
- At 230V the MPPT algorithm starts and controlling starts with reduced switching frequency by extracting maximum power from the PV supply.
- According to battery state of charge, it has different voltage and current height and behaves similar to a variable resistor. So voltage rises from 230 to 430V and current reduces from 1.5 to 0.8A.
- When the output voltage reaches 430V, the control action changes to constant voltage mode. In constant voltage mode the voltage is regulated at the float value until the battery is fully charged.

7. SIMULATION RESULTS AND ANALYSIS

Simulated for the PV fed EV charger using LLC converter using MATLAB/SIMULINK. The simulation parameters are given in table I. The controller action is executed with MPPT and voltage mode control with the help of selector switch. The waveforms corresponding to both controllers are also shown.

TABLE 1
Design parameters of LLC converter

Parameter	Value
Input voltage	24-45V DC
Output battery voltage	230-430V DC
Power rating	350W
Maximum output current	1.5A
Transformer ratio	0.24
Resonant frequency	150KHz
Switching frequency	180KHz
Resonant inductor (L_{ext})	4.5µH
Resonant capacitor(C_s)	36nF
Magnetizing inductor(L_m)	27µH

In the table L_{ext} and C_s are resonant inductor and capacitor respectively. L_m is the magnetizing inductance of the transformer. Resonant frequency is set at 150 kHz and switching frequency at 180 kHz.

The waveform showing the MPPT control scheme, in which the control action starts with MPPT mode until the output voltage reaches to its floating limit. Fig.10 shows the voltage and current waveforms of the resonant network, before catching resonant frequency. Maximum power extraction is not possible, when the resonance condition not achieved. The desired output voltage and current levels are not possible under this condition. Fig.11 shows the resonant network voltage and current, after catching resonant frequency with MPPT mode of control. The maximum power extraction is possible in resonance condition with MPPT mode. The charging action starts with desired output voltage and power level. ZVS is achieved in this resonance condition so that switching losses are limited. Fig.12 shows the resonant voltage and current waves in constant voltage mode during resonant condition. Resonant action provides to stabilize the voltage at the floating limit at the charging side. During the transient state of the converter phase between voltage and current are not equal and voltage control oscillator starts building up the switching frequency until the converter picks up the resonant frequency.

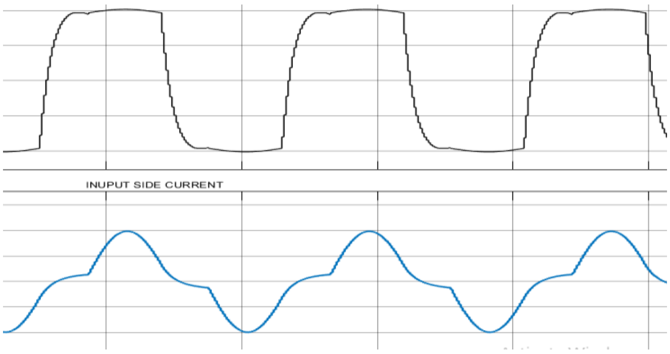

Fig.10 Resonant tank circuit voltage and current waves previously reaching resonant frequency with MPPT control.

when the converter picks up the resonant frequency, converter operates at steady state and zero voltage and zero current switching are achieved.

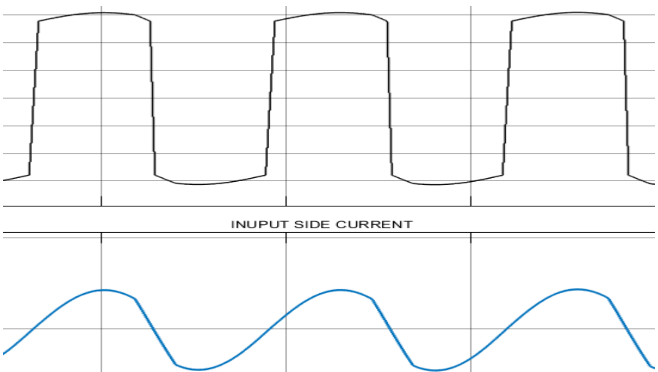

Fig.11 Resonant tank voltage and current thereafter reaching resonance frequency with MPPT control.

On comparing LLC converter with voltage mode control and LLC converter with dual mode of control. Dual mode control with MPPT algorithm and voltage mode control, more effective in controlling the resonant converter. Table II describes a comparison of the two control modes. Overall efficiency of dual mode control of LLC converter is 94.5% in constant voltage mode of operation. For the single mode of control, overall efficiency is limited to 88% due to the increased switching loss and conventional control mode.

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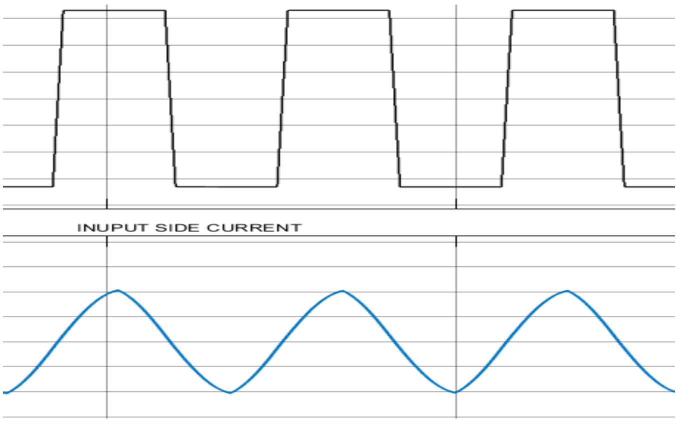

Fig.12 Resonance tank voltage and current thereafter reaching resonance frequency with voltage mode control.

TABLE 2
Comparison of two control strategies for LLC converter.

	Dual mode control	Conventional single mode control
Switching frequency	Within a limited range	Wide variation
Switching loss	Reduced	More
Switching ON of the primary switches	ZVS mode	ZVS mode
Switching OFF of the primary switches	Nearly ZCS	High turnoff loss
Circulating current	Small	Large
Reverse recovery loss of rectifier diodes	Small	Large

8. CONCLUSION

PV fed EV charger using LLC converter with dual mode closed loop control technique is presented in this paper. The main advantage of the described system is, its ability to control the resonance action according to the variation in the resonant parameter. Parameters for the design of the EV charger are described along with the design equations. Simulation for the 230-430V battery powered EV charger is depicted along with waveforms. From the results it is presumed that circuit provides soft switching along with battery charge management. Soft switching is achieved with the help of VCO by tracking the resonant frequency conditions. Charging system is slow but reliable with high conversion rate for wide output voltage range.

REFERENCES

[1] Navid Shafiei, Martin Ordonez, Mohammad Ali Saket Tokaldani, Seyed Ali Arefifar. ``PV Battery Charger Using an L3C Resonant Converter for Electric Vehicle Applications" IEEE Transactions on Transportation Electrification 2018, vol-4.

[2] Navid Shafiei,Martin Ordonez. ``Improving the Regulation Range of EV Battery Chargers With L3C2 Resonant Converters" IEEE Transactions on power electronics 2016,vol-30.

[3] Xerxex Dan Gumera, Aileen Caberos, Shu-Chuan Huang. ``Design and Im-plementation of a High Efficiency Cost Effective EV Charger Using LLC Resonant Converter" Asian Conference on Energy, Power and Transportation (ACEPT) 2017.

[4] Weihan Li,Chunting Chris Mi,Siqi Li,Junjun Deng, Tianze Kan. ``Integrated LCC Compensation Topology for Wireless Charger in Electric and Plug-in Electric Vehicles" IEEE Transactions on industrial electronics 2015, vol-62.

[5] Jikun Zhou, Fugang Wu, Rong Zhang,Xin Dai. ``Design and Analysis of the LCL Resonant Convertor in Inductive Power Transfer System" International Power Electronics and Application Conference and Exposition 2014.

[6] Y. A. Ang, C. M. Bingham, M. P. Foster, D. A. Stone and D. Howe. ``Design oriented analysis of fourth-order LCLC converters with capacitive output filter" Inst. Elect. Eng. Electric Power Applications, vol. 152, no. 2, pp. 310-322, Mar. 2005.

[7] HaoyuWang, Zhiqing Li. ``A PWM LLC Type Resonant Converter Adapted to Wide Output Range in PEV Charging Applications" IEEE Transactions on Power Electronics 2018, vol-33.

[8] Ray-Lee Lin, Chiao-Wen Lin. ``Design Criteria for Resonant Tank of LLC DC-DC Resonant Converter" 36th Annual Conference on IEEE Industrial Electronics Society IECON 2010.

[9] Junjun Deng, Siqi Li, Sideng Hu, Chunting Chris Mi. ``Design Methodology of LLC Resonant Converters for Electric Vehicle Battery Chargers" IEEE Transactions on vehicular technology, vol. 63, no.4, may 2014.

[10] Haoyu Wang, Serkan Dusmez, Alireza Khaligh. ``Design and Analysis of a Full Bridge LLC Based PEV Charger Optimized for Wide Battery Voltage Range" IEEE Transactions on Vehicular Technology 2014, vol-63.

[11] Debashish Mohapatra, Subhransu Padhee, Jhansirani ``Design of Solar Powered Battery Charger: An Experimental Verification" IEEE International Students Conference on Electrical, Electronics and Computer Science (SCEECS) 2018.

[12] Fariborz Musavi, Marian Craciun, Deepak S. Gautam, Wilson Eberle. ``Control Strategies for Wide Output Voltage Range LLC Resonant DCDC

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Converters in Battery Chargers" IEEE Transactions on Vehicular Technology 2014.

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