Power converter for battery charger of electric vehicle with controllable charging current

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ABSTRACT

Research on electric vehicle chargers primarily focuses on improving charging technology to enhance the convenience, quality, efficiency, and affordability of charging electric vehicles. This paper discusses a different AC-DC power converter topology proposed as a potential candidate for electric vehicle battery charger. Using the proposed converter circuit, the charging process of electric vehicle battery can be simply adjusted to meet the battery requirement, and even for increasing the charging speed while avoiding overcharging of battery. During the charging process, if the voltage of battery approaches to the targeted battery voltage level, the charging current can be reduced gradually to zero. Hence it will prevent the battery from overcharging condition. Moreover, the ability of working at high power factor operation, low distortion of alternating current (AC) input current, and low direct current (DC) output current ripple are other features of the proposed charger circuits. Some test results of the proposed power converter were presented. The test results revealed potential features of the converter for battery charger of electric vehicle with power factor 0.9996, total harmonic distortion (THD) of AC current 2.73%, and low charging current ripple, i.e. 3.91%. Therefore, it minimizes the negative effects caused by ripples of charging current especially for lithium-ion batteries widely used in electric vehicles.

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1. INTRODUCTION

Concerns about air pollution and the environmental impact of fossil fuels prompted renewed interest in electric vehicles (EV). As society becomes increasingly focused on sustainability and reducing carbon emissions, electric vehicles are likely to play a significant role in shaping the future of transportation [1]–[3]. Many governments worldwide began offering incentives to promote electric vehicle adoption. These included tax credits, rebates, and reduced registration fees to encourage consumers to switch to electric cars. Additionally, various countries implemented stricter emission regulations, which pushed automakers to invest in electric vehicle development. In recent years, electric vehicles have entered the mainstream automotive market. Major automakers began producing affordable electric cars with reasonable ranges, making electric mobility more accessible to the general public [4]–[6]. To address the challenge of limited charging infrastructure, governments, businesses, and electric utilities invested in building charging stations to support electric vehicle owners. Public charging networks and home charging solutions became more prevalent, further boosting the appeal of electric cars. Various governments and private companies invested in research and development of electric car technology, aiming to improve overall performance [7]–[10].

Ongoing research and development have led to continuous improvements in electric vehicle technology, including more efficient batteries, faster charging times, higher quality battery charger, and enhanced driving ranges [11]–[13]. Research on electric vehicle chargers primarily focuses on improving charging technology to enhance the convenience, quality, efficiency, and affordability of charging electric vehicles. One of the main challenges with EV charging is reducing charging times [14]–[17]. Researchers are exploring ways to increase charging speeds without compromising battery health. This involves studying new battery chemistries, cooling techniques, and charging protocols to enable faster and more efficient charging. Moreover, developing high-power charging stations is crucial for enabling long-distance travel and reducing range anxiety [18], [19].

On-board and off-board electric vehicle battery chargers refer to the location of the charging system in relation to the electric vehicle itself. An on-board charger is integrated directly into the electric vehicle and is part of the vehicle's power electronics system. It is typically located inside the vehicle, close to the battery pack. Having the charger on-board means that the EV owner does not need to carry an external charger or connect, and disconnect it each time the vehicle is charged. Making it easy to charge at various locations with compatible charging infrastructure [20]–[24]. An off-board charger, also known as a portable charger or external charger, is a separate device that is not integrated into the electric vehicle. Instead, it is a stand-alone unit that can be plugged into a power outlet and connected to the EV to charge its battery. Off-board chargers can be used for multiple EVs, making them versatile and suitable for households or locations with multiple electric vehicles [25], [26].

Moreover, integrating EV charging with the power grid intelligently is crucial for optimizing energy usage and minimizing strain on the grid. Efficient battery management is vital for maximizing battery life and performance. Advanced battery management systems (BMS) that monitor battery health, control charging rates, and implement thermal management strategies to ensure safe and reliable charging [27]–[29]. Furthermore, integrating renewable energy sources, such as solar and wind power, into charging infrastructure is become interesting issue to increase the use of renewable energy sources. This includes investigating energy storage solutions to store excess renewable energy for use during peak charging periods [30], [31]. The research on electric vehicle chargers is dynamic and continuously evolving as the technology landscape advances, and as electric vehicles become more prevalent in the transportation ecosystem. The goal is to create a robust and efficient charging infrastructure that can support the widespread adoption of electric vehicles and contribute to a more sustainable future.

Lithium-ion batteries currently have become the dominant energy storage technology for electric vehicles due to their high energy density, relatively low weight, and excellent performance characteristics. Lithium-ion batteries are capable of accepting high charging currents, allowing for faster charging times. However, lithium-ion battery storage issues and charging issues have yet to be sorted out. In charging process, electric current ripple in a lithium-ion battery refers to the fluctuation of the current flowing in the battery. This ripple effect is caused by various factors, including the characteristics of the charger, electrical components, and battery itself. Excessive or uncontrolled ripple can have several effects on the lithium-ion battery. High current ripple leads to increased heat generation within the battery, especially during charging and discharging [32]–[34]. Elevated temperatures can accelerate the degradation of the battery's internal components, including the electrode materials and the electrolyte. Heat is a significant factor in shortening the lifespan of lithium-ion batteries. High current ripple may lead to decreased charging efficiency, as some of the electrical energy is lost as heat or in side reactions rather than being effectively stored in the battery. High-quality power electronics chargers with low ripple output are essential for maintaining the health and safety of lithium-ion batteries during charging and use [35]–[37].

The front-end AC-DC converter is an important part of the EV battery charger system. A single-phase diode bridge rectifier with and without power factor correction (PFC) circuits is shown in Figure 1. Figure 1(a) is a simple and commonly used for low power AC-DC converter, and even for low quality battery chargers, particularly for slow and low-power charging applications, i.e. level 1 charging. Level 1 charging is commonly used in residential settings and some public charging stations where the charging time is less critical. This converter converts alternating current (AC) from the grid into direct current (DC) to charge the EV's battery. However, a disadvantage of using a single-phase diode rectifier is its low power factor. It also draws current in short pulses, causing higher harmonic distortion [38], [39]. Therefore, incorporating a power factor correction circuit (PFC) in this diode rectifier as shown in Figure 1(b) is crucial for ensuring higher efficiency, reducing harmonic distortion, complying with regulations, and optimizing the overall performance of the charging system. Some circuit topologies and control methods have been created for the PFC application [40]–[42]. However, because of low frequency ripples in the output current, only lead acid batteries are chargeable. The circuit configuration of Figure 1(b) is not suitable for lithium-ion battery charger because of its detrimental current ripple effect. In consequence, the front-end PFC section is then equipped by a DC-DC converter section to meet the requirement of the charger system especially for lithium-ion batteries. In this paper, a different circuit of diode bridge rectifier with power factor correction power converter, and controllable charging current for battery charger of electric vehicle is proposed and discussed. The difference of the proposed topology compared to the others is the adding of additional DC-DC converter with controllable DC output current, and its possible application for battery charger. Some basic operation principles of power converter circuits are explained. Moreover, some test results are presented and discussed to verify the power converter system.

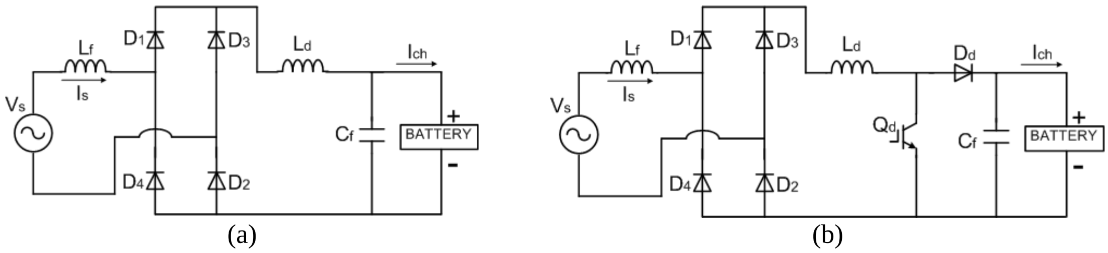


Figure 1. Single phase diode bridge rectifier: (a) conventional diode bridge rectifier and (b) diode bridge rectifier with power factor correction

2. PROPOSED CONVERTER CIRCUITS

Figure 2 shows a simplified block diagram of a common two-stage power converter charger utilized for lithium-ion batteries of electric vehicles. Figure 3 presents circuits of the proposed converter system for electric battery charging. Mainly the circuits composed by the rectifier with power factor correction circuit, and charger circuits. The rectifier consists of diode bridge rectifier D_1, D_2, D_3 and D_4 with input filter L_f to filter the harmonics components of AC current drawn from AC power source V_{ac}. The inductor L_d, insulated-gate bipolar transistor (IGBT) switch Q_d, diode D_d, and capacitor C_d construct the power factor correction circuit of AC input power. This circuit will also improve quality of the drawn AC current.

Controller of the power factor circuit is shown in Figure 4(a). The parameters of AC input voltage V_{ac}, and current I_{Ld} flowing thru inductor L_d were measured as input of controller as shown in this figure. In this figure, K was the gain of the AC voltage sensor. The error will be the input of proportional-integral (PI) controller. Moreover, the output of PI controller will be modulated with triangular carrier signal in the comparator circuit to generate control signal to operate the power IGBT switch Q_d. The waveform signals of V_{ac} and I_{Ld} will be utilized to correct the power factor value of AC power source to be closer to 1. Figure 4(b) is the controller of the charger circuit. The charging current I_{ch} is adjusted by detecting the current I_{Lch} and control the reference charging current. The reference current is notified as I_{ref}. The error between I_{Lch} and I_{ref} will be the input of the PI controller. The output of the PI controller is modulated by a triangular carrier signal in the comparator circuit to generate control gating signal of power switch Q_{ch}.

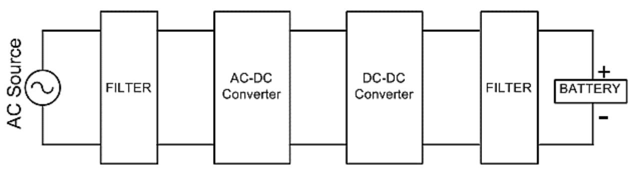


Figure 2. Block diagram of battery charger

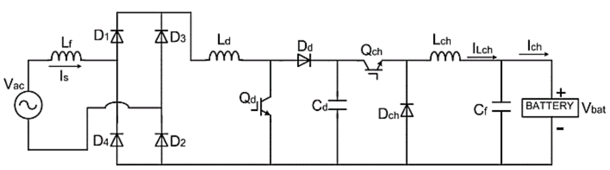
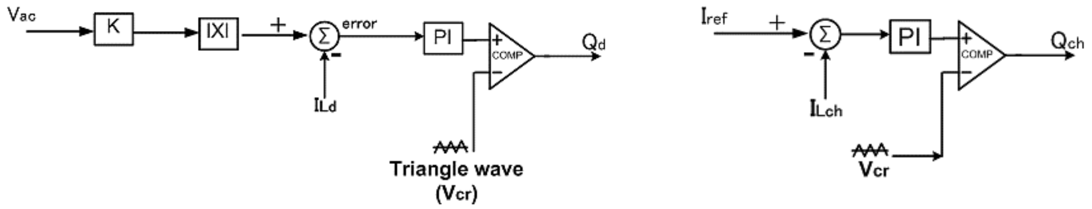


Figure 3. Proposed battery charging system



(a) (b)

Figure 4. Control system: (a) controller of power factor circuits and (b) controller of charging circuits

Moreover, the IGBT switch Q_{ch}, diode D_{ch}, inductor L_{ch}, and capacitor C_f construct the charger circuit of batteries as front-end circuits. Figure 5 shows the operation modes of inductor charging current for continuous operation mode. V_g is the driving signal of IGBT switch Q_{ch}. The ON-OFF cycles of IGBT switch Q_{ch}, adjust the current I_{Lch}. In order to ensure continuous current mode of charging current the minimum inductor size of L_{ch_min} can be determined as (1):

$$L_{ch\_min} = \frac{(1-D).R_{bat}}{2f_s} \quad (1)$$

Where D is the duty cycle of IGBT Q_d, f_s is the switching frequency of IGBT Q_{ch}, and R_{bat} is the equivalent internal resistance of battery. The diode D_{ch} works to keep current path of inductor current I_{Lch}. Some features are obtained by the proposed topology such as the ability to adjust the charging current to meet the battery charging requirement. It can also minimize the ripple of charging current. Hence, it will lengthen battery life time. Furthermore, the charging time depends on the battery capacity, and magnitude of charging current as expressed in (2).

$$t_{ch} = \frac{C_{bat}}{I_{ch}} \quad (2)$$

Where t_{ch} is the charging time, C_{bat} is the battery capacity and I_{ch} is the charging current. A faster charging time needs higher charging current, and vise versa.

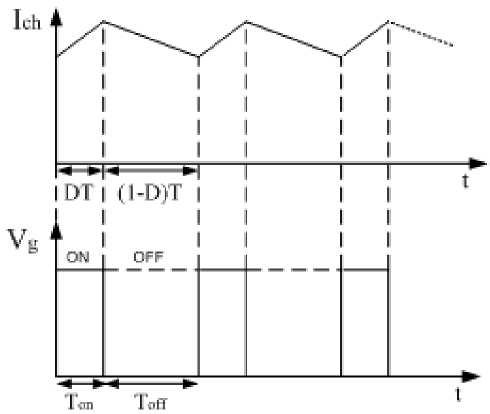


Figure 5. Continuous current operation mode of inductor charging current I_{ch}

3. RESULTS AND DISCUSSION

To explore and validate the principle operation of the circuits, the proposed battery charger converter was tested and evaluated using computer simulation of PSIM software. Table 1 presents the test parameters of the proposed circuits. The rms value of AC input voltage was 220 V with frequency 50 Hz which is the residential voltage system in Indonesia. The inductor input filter L_f was chosen as 1 mH to filter the harmonics of input AC current. The inductor size of power factor circuit was 0.1 mH in order to minimize the inductor size. While the capacitor value of PFC circuits and filter of charger circuits was the same as 10 µF. The inductor of charger circuit was selected as 5 mH referred to (1) to obtain low ripple continuous charging current of battery. In order to simulate the charging process, the battery was modelled by a capacitor 100 mF connected in series with resistor 1 mΩ as internal resistance of battery.

Figure 6 shows AC voltage power source (V_{ac}), and AC input current (I_s) waveforms drawn by the power converter circuits. The AC input current was a sinusoidal current wave with low distortion, i.e. THD value 2.73%. This result was much lower than the standard of maximum THD value current, i.e. 5%. The measured power factor was also high close to unity power factor, i.e. 0.9996. Figure 7 presents the fast fourier transform (FFT) analysis of low frequency harmonics components of the AC input current with frequency range from 0 Hz to 2000 Hz. The amplitude of all of low harmonics orders were less than 0.1% making low distortion of current waveform. The PFC circuits worked well improving the drawn AC current, and its power factor compared with conventional diode rectifier circuits. Moreover, current waveforms flowing through inductor L_d, switch IGBT Q_d, and diode D_d of PFC circuits are shown in Figure 8. The inductor current I_{Ld} was the rectified waveform of input AC current I_s. Whilst the current of switch IGBT Q_d, and diode D_d were PWM currents, where their sum was equal to the inductor current I_{Ld}.

Figure 9 depicts the enlarged gating signal of IGBT switches Q_d and Q_{ch} of the proposed power converter. The signals were PWM waveforms generated by each controller of circuits. Moreover, the current waveforms flowing thru the charger inductor L_{ch}, IGBT switch of charger circuit Q_{ch}, and diode of charger circuits are depicted in Figure 10. As can be observed in the figure, the charging current I_{Lch} has very small ripple current. The measured ripple of charging current in this test was 3.91 %. This feature will become a great advantage when it is applied as charging current of battery, especially for lithium-ion battery to minimize the temperature increase during charging process. Hence it will avoid fast battery degradation, and lengthen the battery life. Another feature of the proposed charger circuits is shown in Figure 11. Using the proposed power converter, the charging current of the battery can be controlled well to meet the charging requirement of battery. The figure shows that at first the charging current (I_{ch}) was set at highest level of battery charging current capability, and reduced gradually according to the rise of battery voltage level (V_{bat}). When the battery charge was almost full, the charging current was adjusted by lowering the current level till the battery is fully charged, and finally the charging current was set as zero. The charging time will be determined by charging current and capacity of the battery. A faster charging time needs higher charging current, and vise versa as previously described in (2). Moreover, if the proposed power converter was realized using power MOSFETs IXFH 26N60, power diodes RURG3060, and power inductors with resistance 1mΩ, the maximum efficiency of a 7 kW battery charger was achieved at 95.75%.

Table 1. Test parameters

Parameters	Values
Power voltage source, V_{ac}	220 V (RMS)
Frequency of power source, f_s	50 Hz
Input filter inductor, L_f	1 mH
Inductor of PFC circuits, L_d	0.1 mH
Inductor of charging circuit, L_{ch}	5 mH
Capacitance of PFC circuits, C_d	10 µF
Capacitance of charging circuits, C_f	10 µF
Triangle signal frequency, f_{cr}	20 kHz

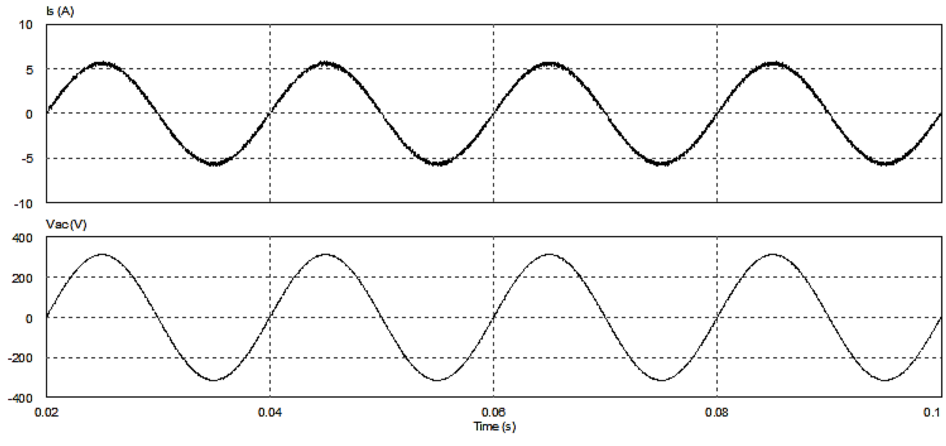


Figure 6. AC input current (I_s) and voltage (V_{ac}) waveforms (THD I_s = 2.73%, PF=0.9996)

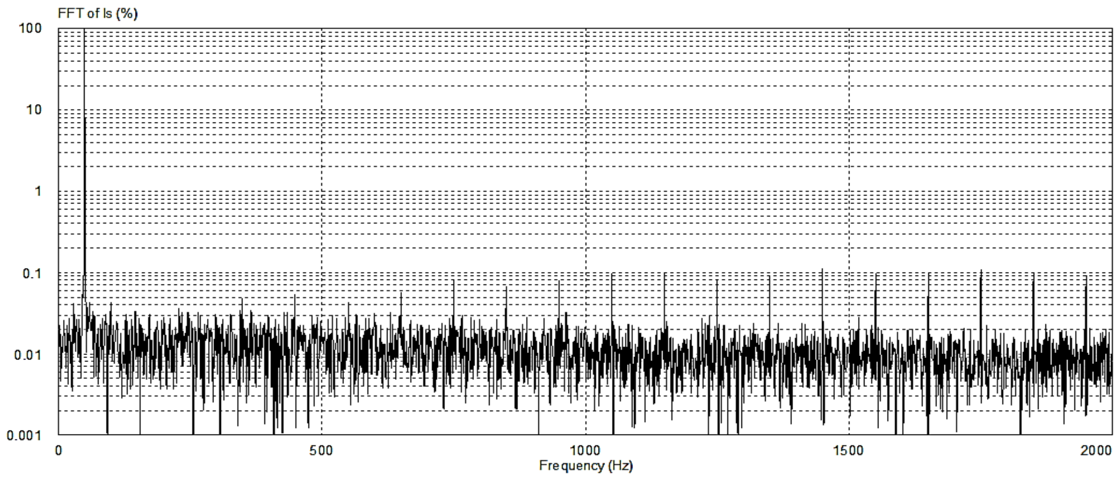


Figure 7. Low frequency harmonics components of AC input current (I_s)

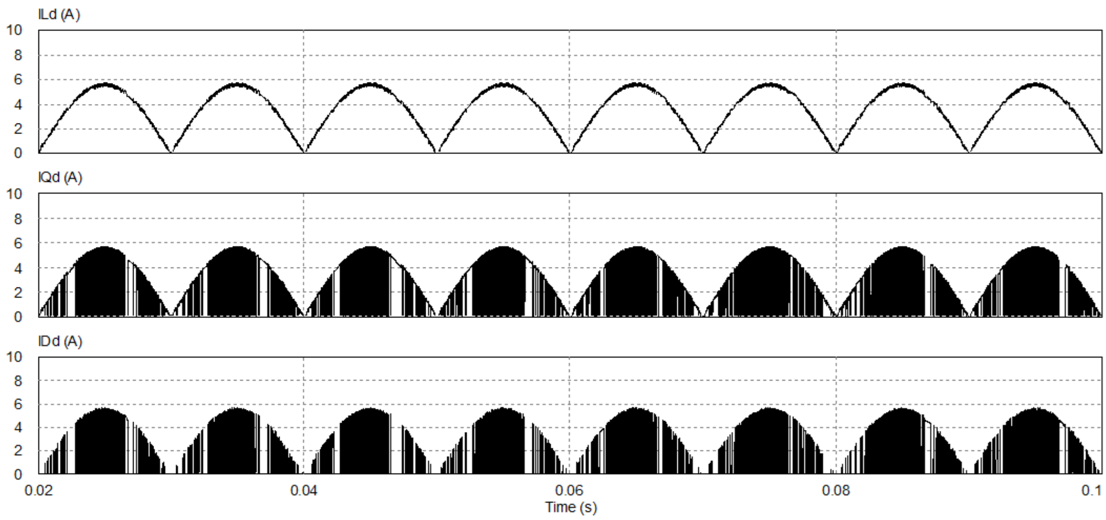


Figure 8. Current waveforms flowing through inductor (I_{Ld}), IGBT (I_{Qd}), and diode (I_{Dd}) of PFC circuits.

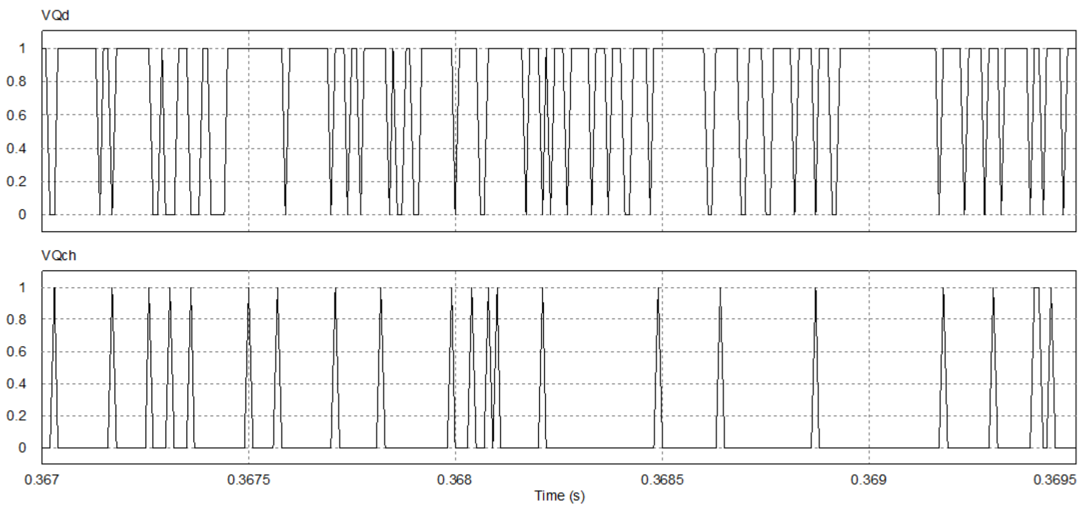


Figure 9. Enlarged gating signals of IGBTs Q_d (V_{Qd}) and Q_{ch} (V_{Qch})

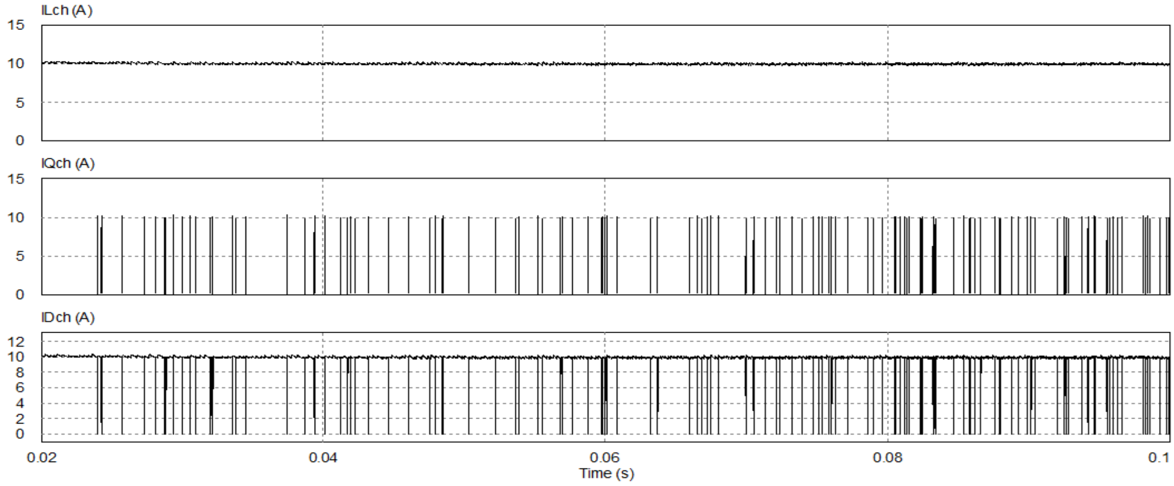


Figure 10. Current waveforms flowing through inductor (I_{Lch}), IGBT (I_{Qch}), and diode (I_{Dch}) of charging circuits

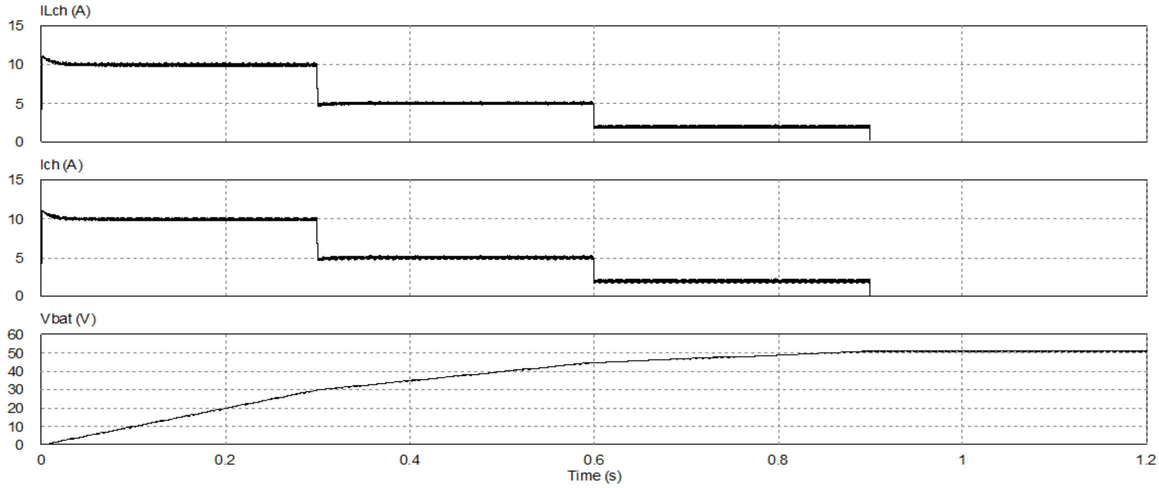


Figure 11. Inductor current (I_{Lch}), charging current (I_{ch}), and battery voltage (V_{bat}) during charging with different charging current values

4. CONCLUSION

Different configuration of a power converter proposed for battery charger of electric vehicle was proposed and presented in the paper. The proposed converter generated low THD value of the AC input current drawn from the AC power source which was less than 5%. The power factor operation of the proposed power converter was close to unity power factor. It complies the standard requirement of electric vehicle battery charger. Another feature of the proposed charger converter is its low ripple of charging current. Moreover, the charging current can be controlled to meet requirement of battery.

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