Pulse Charging Method for Electric Vehicles and Renewable Energy Applications

M.Ejas Ahamed
PG Scholar-Department of EEE, Bannari Amman Institute of Technology, Sathyamangalam, India.

R.Ramya
PG Scholar-Department of EEE, Bannari Amman Institute of Technology, Sathyamangalam, India.

K.Indirajith
PG Scholar-Department of EEE, Bannari Amman Institute of Technology[3], Sathyamangalam, India.

Abstract – High Capacity Li-ion and Pub-acid batteries are broadly used in present Renewable Energy and EV applications. Consequently, charging these batteries in a minimum amount of time while maintaining efficiency is crucial. The need for fast charging has carried up the method of Pulse Charging. However, present pulse charging method which involves hard-switching, pose difficulties due to switching losses in the semiconductor devices. This paper represents a Fast Pulse Charging mechanism for High Capacity Pub-acid and Li-ion Batteries which minimize switching losses by Soft Switching. The operation of the methodology is concentrated on the Fully Clamped Quasi-resonant DC Link Converter which usefully generates current pulses to charge the battery in both between Constant Current (CC) and Constant Voltage (CV) phases. Switching losses are minimized by manipulating Zero Current Switching (ZCS), and the simulated results show that this can be achieved for higher switching frequencies further minimizing the circuit size.

Experiments were conceded out by the research group for both conventional CC-CV method and for current pulse charging method. The results declared that proposed methodology reduces the charging time of Pub-acid batteries by 14.01% in comparison to the conventional CC-CV charging method.

Index Terms – Fully Clamped Quasi-resonant DC Link Converter, Pulse charging, Renewable Energy Applications, Zero Current Switching.

1. INTRODUCTION

High capacity Battery Storage Units such as Li-ion, Pub- acid and NiMH are broadly used in Renewable Energy Applications and Electric Vehicles (EVs) [1] [2]. These energy storage units are necessary in storing electricity produced by renewable sources, and therefore meet the energy demand of the grid whilst adding flexibility to the system [3].

Pb-acid batteries have been the preferred choice for large scale energy storage over the years, mainly owed to its reliability and low cost. On the other hand, Li-ion batteries with their high energy density, control the Electric Vehicle industry-where the weight of the battery pack has a major effect on the vehicle dynamics[4][5]. Additionally, in many countries, Li-Ion batteries are currently united with wind turbines and photovoltaic applications as a storage device.

Regardless of the battery type, there should be a simple and efficient charging mechanism to charge the batteries integrated to these renewable energy applications. Efficient charging plays a vital role in renewable energy applications, where the energy output of the renewable energy source is constantly subjected to fluctuations due to the varying environmental conditions [6][7]. Hence, capturing and storing the produced energy in an effective manner has become a requirement of importance.

Ensuring efficient charging alone is not sufficient - the chargers involved should be capable of charging the batteries in a least amount of time. Fast charging carries a wide advantage when it comes to electric vehicle industry where the charging time consumed by an EV has a major consequence on the market dominancy of the vehicle. Generally, both Pb-acid and Li-Ion batteries are charged using Constant Current- Constant Voltage (CC-CV) charging [6] [8] method. In the constant current phase, a constant current stream is fed to the battery till the rated voltage of the battery is reached to its limit. However, use of continuous current charging circuits- involving semiconductor devices worked in active region; cause an active device loss during the charging process. Evidently, this loss is considerably high for large scale batteries.

It is also not desirable to increase the charging current above the suggested limits of the battery to reduce the charging time. High currents may cause unwanted chemical reactions inside the battery, causing the battery to heat up, and ultimately limitation the lifespan of battery lifetime [4][9][10]. Then again, maintaining the charging current below that limit will also increase the charging time.

Current pulse charging is the desired fast charging mechanism for both Pb-acid and Li-Ion batteries. In this method, a current pulse stream is fed to the battery instead of a constant continuous current, in the CC phase, to charge the battery within limit [11]. Recent studies have presented that using a current pulse stream to charge high capacity Li-Ion batteries not only reduces the charging time, but also expands the lifespan of the battery[11][12].

However, in order to generate the necessary current pulses, a topology which involves continuous switching of power semiconductor devices should be employed [14]. Most of the old-fashioned pulse-charging methods use hard switching to facilitate this requirement. Although this method decreases charging time. Although the switching losses are quite small for low voltage applications, they are quite important in renewable energy applications and Electric vehicles which employ high currents in the battery charging process.

This is disadvantageous in charging large scale batteries connected to renewable sources where the limited energy output of the source needs to be fully used. As an instance, an electric vehicle charged using this method would cause a considerable amount of loss of electricity, which may have been produced using fossil fuels such as coal, petrol, diesel etc. Therefore, when it comes to the final carbon credit calculation for an electric vehicle [15], the anticipated advantage over a conventional vehicle can't be achieved. Hence, wasting a huge amount of energy to minimize the charging time of an Electric Vehicle challenges the purpose of replacing conventional vehicles with EVs [15].

The proposed methodology in this paper implements a fast charging mechanism for high capacity batteries while significantly reducing the above-mentioned switching losses. Switching losses are reducing through a Fully Clamped Quasi-resonant DC Link Converter [18], which allows Zero Current Switching (ZCS) [19], hence permitting fast charging capability while maintaining efficiency. Charging time can be further minimized by varying the frequency of the current pulse stream depending on the battery type. The charger can be used in both renewable energy applications and Electric Vehicles.

2. METHODOLOGY

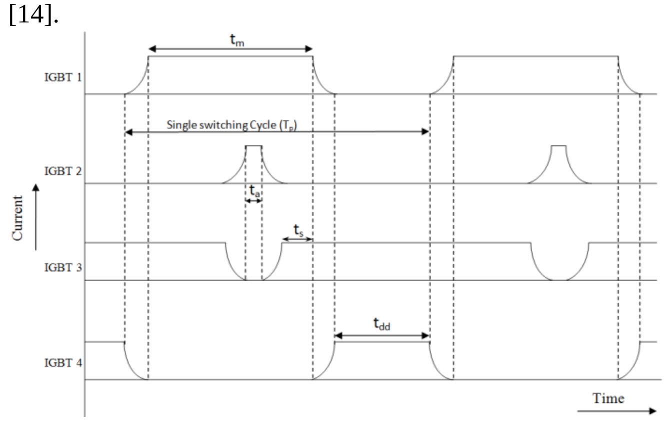
In the formulated methodology, a current pulse stream is applied to charge the battery in both the Constant Current and Constant Voltage phases. The Fully Clamped Quasi-resonant DC Link Converter [16] implemented in this topology produces the required current pulse stream through a zero current switching mechanism [17]. The current pulse stream of absolute magnitude and pulse width is supplied to the battery until the rated value of battery terminal voltage is reached. Then the charger changes to the Constant Voltage phase. In this phase the battery terminal voltage is kept at its rated value by regulating the current pulse height of the output current pulse stream of the Quasi-resonant Fully

It should be highlighted that the proposed method uses the same circuit topology for both CC and CV phases, thus eliminating the need for an additional circuitry for the CV phase. However, the pre-defined magnitude of the current pulses in the stream continues to drop as the battery reaches the charged level.

The design of the proposed Li-Ion/Pb -acid battery charger contains of three major sub circuits. They can be known as, boost converter to obtain the required DC voltage [14], Fully Clamped Quasi -resonant DC L ink converter to obtain the fast charging pulse method [16], and the Control Unit to handle the complete charging process. The power flow of the charging method is shown in Fig. 2.

The functioning of the sub circuits can be explained as discussed below. The function of the Boost converter is conventional in the sense of operation and the topology affords almost a unity power factor condition [14] [18] [19]. The necessity of the diode rectifier bridge depends on the voltage waveform generated by the renewable energy source. In the case where the battery of an EV is charged, the "Renewable Energy Source" block is swapped with a 110- 220 V_{AC} input. The PI controller implemented with the boost converter (Shown in Fi g.5) confirms that the voltage at the boost converter output is maintained as required by the Battery bank attached [18] [19]. The thyristor bridge (behaves as a controlled voltage source) acts as the boundary between the boost converter output and the input of the Fully Clamped Quasi-resonant DC Link Converter. Additionally, it is possible to swap the thyristor bridge by an H-Bridge isolation unit joined with a Diode-Bridge unit if isolation is required [14] [20]. In any case the input to the DC link converter can be concentrated to a form of a controlled voltage source [16].

The Fully Clamped Quasi-resonant DC Link converter takes input power from the controlled voltage source and performs a path switching process which generates a periodic stream of current pulses at its output. In addition, the selection of high frequency operation is advantageous in the sense that it allows the circuit size reduction circuit magnetics and capacitances, [14].



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A. Principle of Operation of the Fully Clamped Quasi-resonant DC Link Converter

As shown in Fig. 3, the DC-DC topology consists of four IGBTs, which are switched in a definite order to generate the current pulse stream. Note that the output IGBT-Diode combination makes sure that the power flow from the battery to the charger is continuously blocked [14]. The inductor L_0 (comparatively smaller compared to L_d) and the capacitor C_0 act as the resonant tank which enables the task of soft switching (ZCS) the DC link IGBTs [16][17].

In Fig. 3, E represents the controlled voltage source output, which performances as the input to the DC Link Converter. If the boost converter output is denoted by V_{dc}, then E would take either V_{dc} or $-V_{dc}$ upon the calculated firing of the Thyristor Bridge.

The current handling capability of the depends upon the inductor L_d which performances as the current source. The current through the inductor, I_d, can be kept about equal to a dc reference current level due to the high-frequency switching in the DC link converter. After few switching cycles the amplitude I_d will differ from the reference value. By changing the controlled voltage source output (E) it is possible to take the amplitude of I_d back to its reference value [16][21]. However, change of I_d from its average value for few switching cycles can be rejected due to the high switching frequency as discussed below.

$$v_{Ld} = L_d * \frac{di_d}{dt} \qquad (1)$$

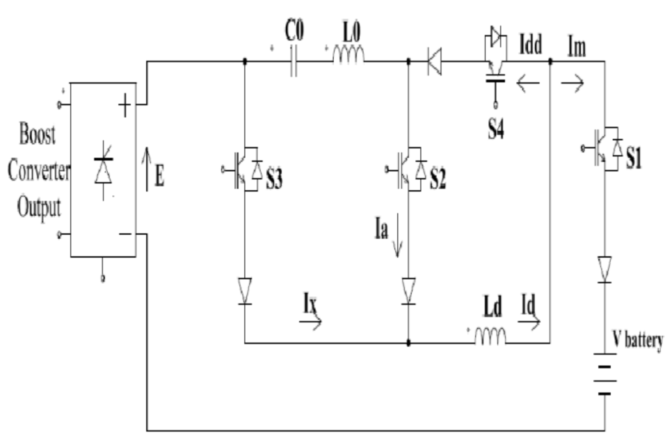


Figure 4. Fully Clamped Quasi-resonant DC Link Converter with the battery

Change in $i_d = di_d = \frac{vL_d}{L_d} * dt \qquad (2)$

Here V_{Ld} indicates the voltage across the inductor L_d. It is obvious that due to high frequency switching operation, dt is much small, hence the change in I_d is not considerable. In fact, for few switching cycles it can be assumed that I_d remains constant [16].

The DC link mechanism guides I_d through the load only for a specified amount of time (t_m) within a single switching cycle of the whole converter (T_p), hence periodic pulses of current passages through the load. This is shown in Fig. 4. The width of the current pulse is ruled by the individual switching times of the four IGBT switches in the DC link topology. In fact, the frequency of the output current pulse stream depends on the switching frequency of the complete converter.

Generation of current pulses can be conceived using the Modes of Operation of the Fully Clamped Quasi-resonant DC link Converter as mentioned in [16].

After each complete switching cycle, the link current I_d through inductor $L_d$is compared with the instantaneous

Reference current value needed by the application. And if the difference is significant between these two currents, the voltage of the controlled voltage source E is change consequently, and the new value is kept constant for the next switching cycle. This procedure is carried for each switching cycle, so that the current I_d is maintained approximately at the necessary reference value.

B. Control Implementation if CC and CV Phases

The overall control of the charger circuit is illustrated in Fig 5 the control operation for the circuit can be explained as follows.

Consider the constant current phase. V_{ref} (determines the boost converter output) and Id_{ref} values depend upon the load specifications and are adjustable through the control unit. Id_{ref} is set according to the average current needed by the battery and is kept constant for the constant current phase. Note that Id_{ref} represents the peak value of the current pulse stream fed to the battery. For example, Id_{ref} would be twice the value of average current needed by the battery for a pulse stream with 50% duty. The current source current I_d is compared with this Id_{ref} value and is kept approximately equal to Id_{ref} throughout the constant current phase. If the link current I_d becomes less than its reference value the thyristor bridge is fired such that $E=V_{dc}$ and the link current is brought up again to its reference value. If the link current goes beyond its reference value the thyristor bridge is fired such that $E= -V_{dc}$ and the link current is minimized back again to its reference value[16].

In constant voltage phase the voltage across the battery should be kept constant at the value specified by the battery ratings. As shown in Fig. 6 terminal voltage of the battery is detected and passed to the control unit.

Evidently, the average current supplied to the battery should be minimized with time in this phase in order to keep the terminal voltage at a constant value, as illustrated in Fig. 1. Therefore, the control circuit implements methods to minimize the value of Id_{ref} accordingly with time. This reduces the average current fed to the battery in such a way that the terminal voltage of the battery does not exceed its rated value. Additionally, the V_{ref} value is also adjusted by the control unit in this phase in order to maintain constant voltage V_{dc} at a higher value than the battery terminal voltage.

The overall charging process of the circuit's output is monitored by an onboard Battery Monitoring System (BMS) [22]. The battery monitoring system measures the voltage across and current through the battery bank

As well as the temperature, and controls the charging process consequently. Furthermore, voltages and currents at each stage of the circuit are also measured to confirm that the charger is operating in desired value.

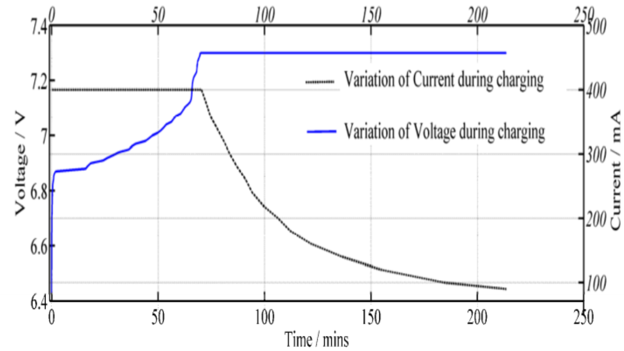


Figure 10. Charging curve for conventional CC-CV charging

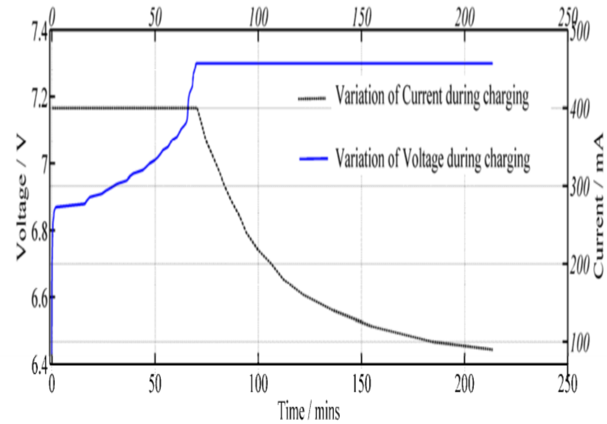


Figure 11. Charging curve for current pulse charging

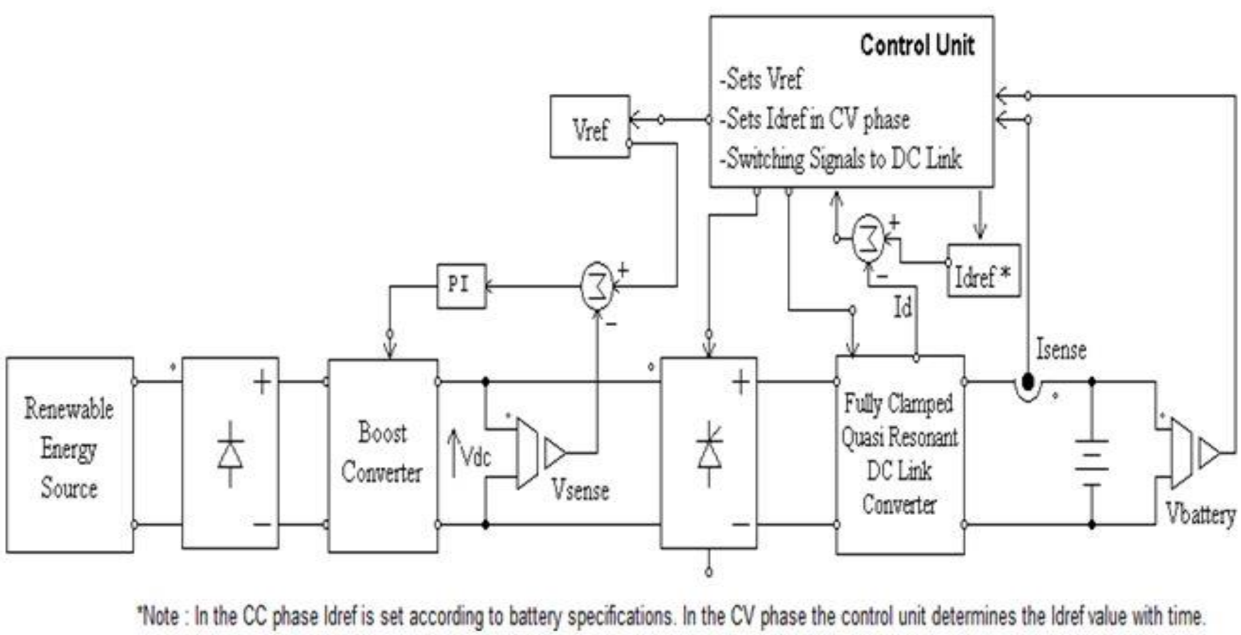


Figure 4. Control Topology for CC and CV phases

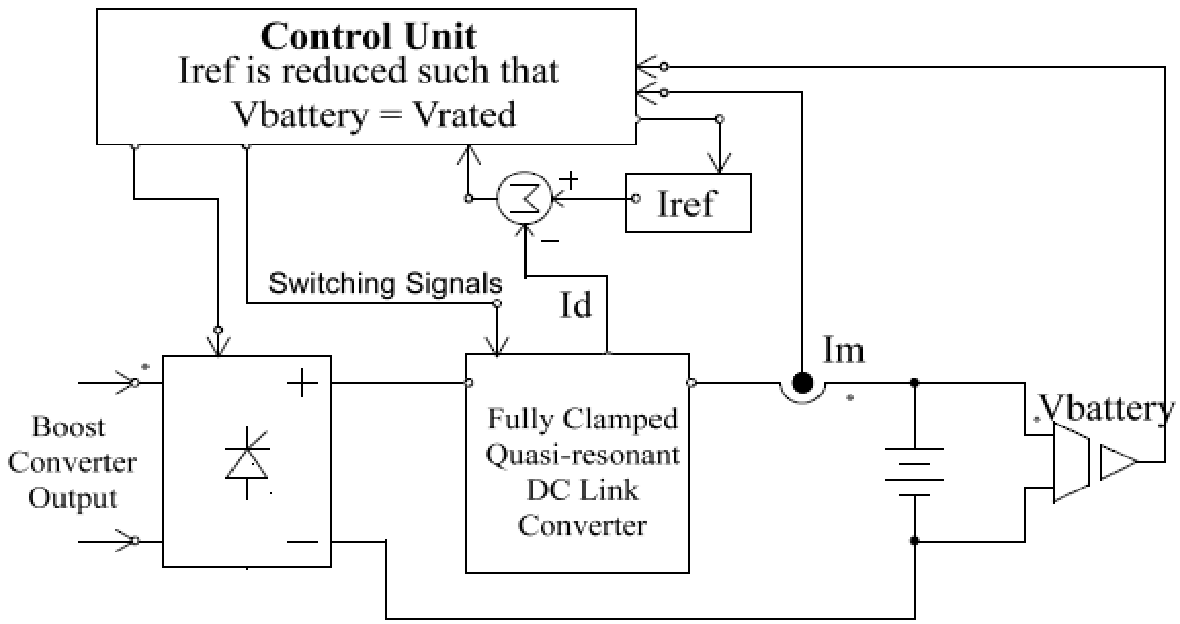


Figure 6. Control topology in the CV phase

3. RESULTS

A. Simulation and Hardware Results

Results obtained through PSIM Version 9.0 for theQuasi-resonant Fully Clamped DC Link Converter is shown in Fig.7. Zero Current Switching of the IGBTs ensures efficiency while producing a current pulse stream of preferred magnitude, pulse width and frequency at the Fully Clamped Quasi-resonant DC Link converter output. The on time (t_m) of the output current I_m of the DC Link converter, can be controlled as explained in Section II. Fig. 8 represents the output current waveform of the implemented hardware prototype for a resistive load. Note that the peak-to-peak current value for the resistive load is 1.5A.

Fig.9 represents the zero current switching situations for $IGBT_1$ where the turn off signal is set only when the current through $IGBT_1$ has reached zero. It is also apparent here, that the current I'_m brought to zero in accordance to the resonant manner of current transfers, between the operating modes topology.

The simulations results obtained for the control topology implemented for the CC and CV phases is shown in Fig.10.

As shown in Fig.10 DC link current-I_d can be controlled by adjusting the Id_{ref} value as decided by the control unit.

B. Current Pulse Charging Experiments

Experiments were carried out using a 6V, 4.5 Ah Pb-acid battery to identify the effects of pulse charging on the charging time of the battery. A current pulse stream with a frequency of 5 kHz (with a 50% duty ratio) was applied to charge the battery, in this case. The results obtained shown that the proposed methodology reduced the charging time by approximately 14 %. Fig.11 and Fig.12 shows the charging curves obtained from the experiments for the two types of charging.

C. Specifications- Hardware Prototype

Following parameters are based on the conditions on which the preliminary tests were carried out.

Supply Voltage	: 70V
Output current pulse rating I_{p-p}	: 2A
Operational Frequency	: 500Hz 5 kHz

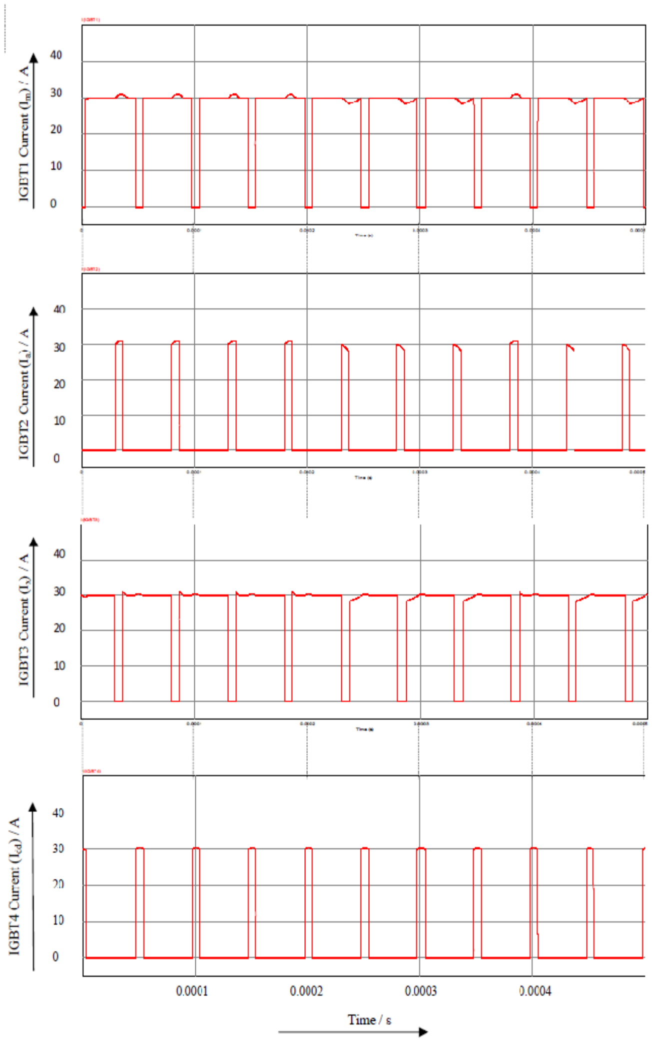
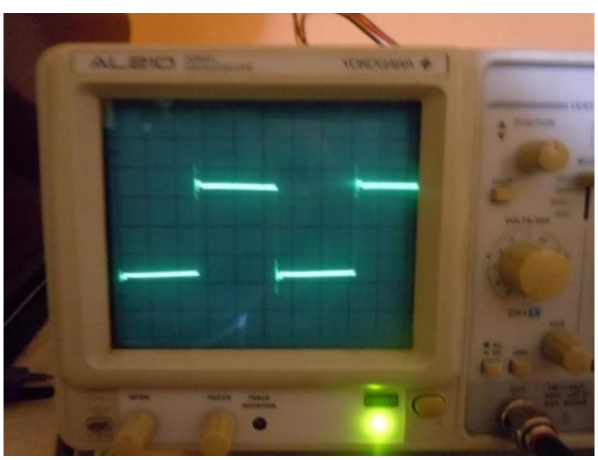


Figure.7 Currents through individual IGBTs for few switching cycles



4. Figure 8. Output current waveform of the hardware prototype

4. CONCLUSION

Fast and efficient charging of batteries used in automotive and renewable energy applications is of complete importance. The proposed charging methodology generates a current pulse stream with the help of the Fully Clamped Quasi-resonant DC Link Converter, to charge the battery. The resonant behavior of the charger circuit enables Zero Current Switching, hence eliminating the switching losses included in current pulse generation. The charging system services current pulse charging in both Constant Current and Constant Voltage phases, eliminating the necessity for any extra circuitry for the constant voltage phase. Additionally, high frequency switching, reduces the size of circuit magnetics and capacitances paving the way to a compact charger circuit. Experiments carried out using this methodology showed that the proposed charging methodology reduced the charging time of a Pb-acid battery by 14.01%.

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