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Design and Implementation of IGBT based Constant Voltage Battery Charger for Railway Coaches

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Abstract – **This paper presents a 6.5kW IGBT based DSP controlled constant voltage battery charger designed and implemented for Railway Coaches. The proposed battery charger comprises of a three phase uncontrolled bridge rectifier at the front end and an IGBT based full bridge DC-DC converter at the output end. The rectifier circuit converts the three phase 415V AC supply to DC. The rectified DC output is given as input to the full bridge DC-DC converter. The converter then generates a regulated and isolated DC voltage which is used to charge the battery. A complete analysis of full bridge DC-DC converter, design considerations and validation of simulation results are discussed in this paper.**

Keywords – DSP, constant voltage battery charger, three phase uncontrolled bridge rectifier, full bridge DC-DC converter, isolated DC output.

I. INTRODUCTION

Modern locomotives have various electrical & electronic equipment, such as lighting, heating and communication systems. They must continue to work even in case of power failures. Hence, the battery packs are a critical part of the on-board safety equipment. Valve regulated lead acid (VRLA) batteries are widely being used in passenger coaches of Indian Railways. These batteries are capable of operating under extreme temperatures, highly humid and dusty atmosphere and can withstand vibrations. Nine 12V batteries are connected in series to form an 110V battery of 70Ah capacity. It is essential to charge these batteries efficiently in order to prolong the battery life and so a battery charger plays a very important role.

In recent times, several high efficiency, high-power density AC-DC switched mode power supply topologies have been proposed for charging the battery [1]. Amongst various topologies, a diode based bridge rectifier coupled with a full bridge DC-DC converter is presented in this paper. A full-wave rectifier produces a DC voltage from a three phase 415V±15%, 50 Hz AC source, and a full bridge DC-DC converter reduces the rectified DC voltage to an appropriate level suitable for the application. A full bridge DC-DC converter is chosen because of its high power handling capability and stability [3, 4].

The proposed battery charger is operated in Constant Voltage Mode with the help of a DSP controller (TMS320F28027). In constant voltage mode, irrespective of the battery's state of charge, the charger maintains nearly the same voltage input to the battery throughout the charging process.

Digital controllers are more beneficial than analog controllers as they have the following advantages: Reduced noise levels, programmable compensator, high reliability and high speed. TMS320F28027 has advanced on-chip control peripherals like PWM modules, analog comparators with digital analog converter (DAC), slope compensation hardware and 12-bit high speed ADCs coupled with an efficient 32-bit CPU.

II. PROPOSED CONVERTER TOPOLOGY

The basic block diagram representation of the proposed battery charger circuit is as shown in Fig. 1.

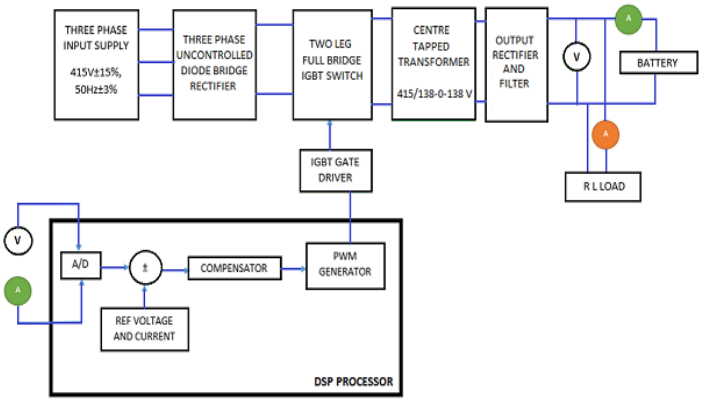

Fig 1. Block Diagram Representation of Battery Charger

The core part of the proposed battery charger circuit is the full bridge DC-DC converter which consists of 4 IGBTs connected in a bridge formation feeding power to a high frequency transformer which provides galvanic isolation between input and output. The secondary side of the high frequency transformer is connected to an output rectifier and LC filter circuit.

A. Analysis of full bridge DC-DC converter

The circuit diagram of a full bridge DC-DC converter is as shown in Fig 2:

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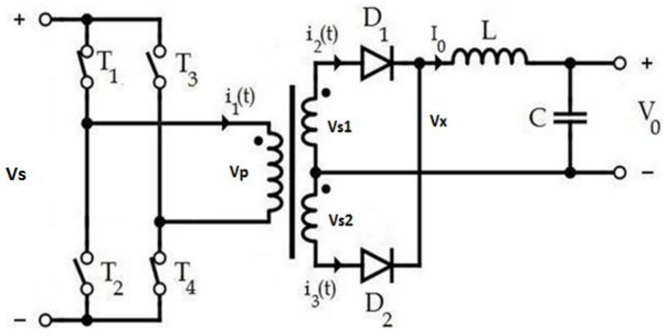

Fig 2. Full Bridge DC-DC Converter

The switching topology used for the full-bridge converter is the bipolar voltage switching, where the transistors are switched in pairs. Transistors T1 and T4 are considered as one switch pair and transistors T2 and T3 are considered as the other switch pair. The switching sequence is as shown in Fig 3:

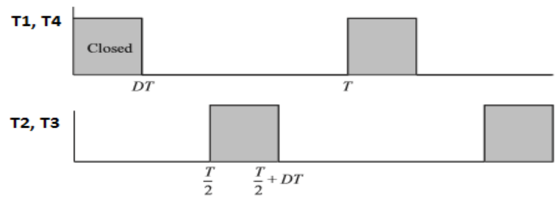

Fig 3. Switching sequence

When T1 and T4 are closed, the voltage across the transformer primary is Vs. When T2 and T3 are closed, the transformer primary voltage is – Vs. For an ideal transformer, having all switches open will make $Vp = 0$. Diodes D1 and D2 on the transformer secondary, rectify this waveform to produce the voltage Vx as shown in Fig 4:

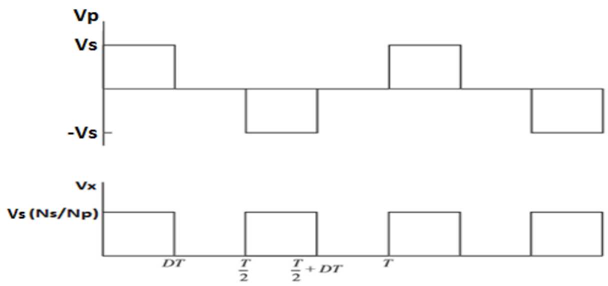

Fig 4. Voltage Vx

Mode 1: Transistors T1 and T4 are closed

- Transformer primary voltage, $Vp = Vs$
- Diode D1 is forward biased and diode D2 is reverse biased.
- Therefore, $Vx = Vs1 = Vs\left(\frac{Ns}{Np}\right)$

Voltage across the filter inductor $= Vx - Vo = Vs\left(\frac{Ns}{Np}\right) - Vo$

Assuming a constant output voltage Vo, the voltage across L is a constant, resulting in a linearly increasing current in L. In the interval when T1 and T4 are closed, the change in current in L is,

$$\Delta IL = \left[\frac{Vs\left(\frac{Ns}{Np}\right) - Vo}{L}\right] DT \quad (1)$$

Mode 2: Transistors T2 and T3 are closed

- Transformer primary voltage, $Vp = -Vs$
- Diode D2 is forward biased and diode D1 is reverse biased.
- Therefore, $Vx = -Vs2 = Vs\left(\frac{Ns}{Np}\right)$

Voltage across the filter inductor $= Vx - Vo = Vs\left(\frac{Ns}{Np}\right) - Vo$

Transistors T2 and T3 are also switched ON for a period of DT. Therefore,

$$\Delta IL = \left[\frac{Vs\left(\frac{Ns}{Np}\right) - Vo}{L}\right] DT \quad (2)$$

Mode 3: When all the transistors are switched open

- Transformer primary voltage, $Vp = 0$
- Transformer secondary voltages, $Vs1 = Vs2 = 0$
- Therefore, $Vx = 0$

With both switches open, the current in each of the primary windings is zero. The current in the filter inductor L must maintain continuity, resulting in both D1 and D2 becoming forward-biased. Inductor current divides evenly between the transformer secondary windings.

Voltage across the filter inductor $= -Vo$.

The change in inductor current is given by,

$$\Delta IL = \frac{-Vo}{L}\left(\frac{T}{2} - DT\right) \quad (3)$$

Since, average voltage across inductor is assumed to be zero, net change in inductor current over one period is zero. Therefore,

$$\left[\frac{Vs\left(\frac{Ns}{Np}\right) - Vo}{L}\right] DT + \frac{-Vo}{L}\left(\frac{T}{2} - DT\right) = 0$$

$$\left[\frac{Vs\left(\frac{Ns}{Np}\right) - Vo}{L}\right] DT = \frac{Vo}{L}\left(\frac{T}{2} - DT\right)$$

$$DVs\left(\frac{Ns}{Np}\right) - DVo = \frac{Vo}{2} - DVo$$

$$\boldsymbol{Vo = 2DVs\left(\frac{Ns}{Np}\right)} \quad (4)$$

The waveform of current through the filter inductor is as show in Fig 5:

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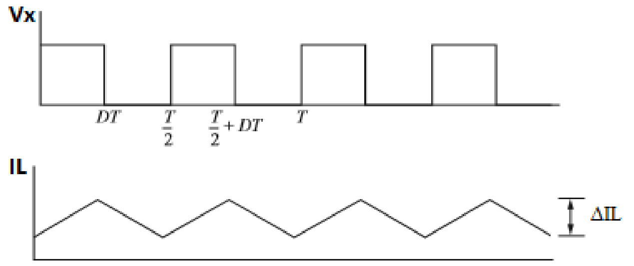

Fig 5. Inductor current waveform

The waveforms of current through the filter capacitor and output voltage ripple are as shown in Fig 6:

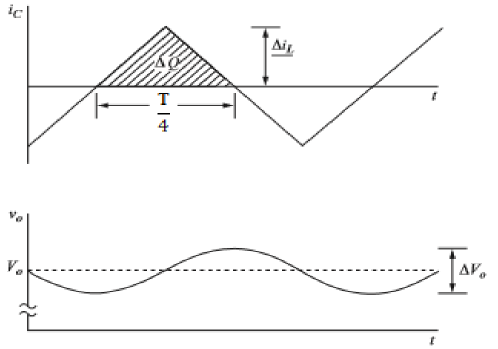

Fig 6. Capacitor current and Output voltage ripple waveforms

The output voltage ripple of the full bridge converter is given by,

$$\frac{\Delta Vo}{Vo} = \frac{1-2D}{32LCf^2} \quad (5)$$

B. System Requirements

SL. No.	Parameter	Specifications
1	Operating Mode	Constant voltage
2	Input: • Nominal Voltage • Operating Range	 415V AC (3 phase, 3 wire system) 415 volts ± 15%, 50Hz, 3 phase
3	Output: • DC output voltage • Output Current DC • Battery Charging Current • Other loads	 110 V 50A 20A 30A
4	Power Output	6.5kVA
4	Efficiency	Not less than 92% at full load
5	Ripple Factor • Output voltage ripple • Output current ripple	 Less than 2% of output voltage Less than 3% of output current
6	Output Regulation	2% over input range

C. Design Considerations

The circuit is designed for critical value of input supply voltage.
Three phase input supply line voltage = 415 – 15% = 350V
Peak Line Voltage = 350 x $\sqrt{2}$ = 494.97V
Phase Voltage (Star Connected Source) = 350 / $\sqrt{3}$ = 202.07V
Peak Phase Voltage (Vm) = 202.07 x $\sqrt{2}$ = 285.77V

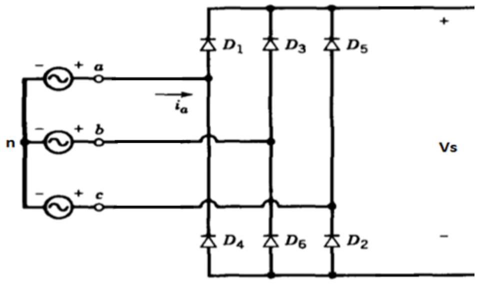

Fig 7. Three Phase Uncontrolled Bridge Rectifier

Output voltage of three phase uncontrolled bridge rectifier = $\frac{3\sqrt{3}Vm}{\pi}$ = 472.66V

This rectified voltage is given as input to the full bridge DC-DC converter. Therefore, the supply voltage to full bridge DC-DC converter is Vs = 472.66V

Calculation of Duty Ratio (D)

Required Output Voltage, Vo = 110V
Ideally, when a switch is ON, the voltage drop across the switch is zero. However it is not true in practical cases. Considering the forward voltage drops of the switch and diode, the output voltage equation of the full bridge DC-DC converter is,

$$Vo = \left[2\left(Vs - (2\,Vsw)\right)\left(\frac{Ns}{Np}\right) - Vd\right]D \quad (6)$$

Transformation ratio of the high frequency transformer,
$\frac{Ns}{Np} = \frac{138}{415}$
IGBT (IGW40T120) forward voltage drop (Vsw) = 1.7V
Diode (DSI 30-16A) forward voltage drop (Vd) = 1.6V
Therefore, D (max) = 35.4 %

The switching frequency of the IGBT (Fsw) is chosen to be 8 kHz, considering the associated losses and efficiency of the converter.

Calculation of Filter Inductor Value (L)

Output Current of battery charger circuit = 50A
According to the system requirements, current ripple should be less than 3% of output current
Δ IL < 3% of 50 A < 1.5A

Value of Filter Inductor is given by,

$$L = \frac{Vo\left(\frac{1}{2} - D\right)}{\Delta IL\,.\,Fsw} \quad (7)$$

Taking Δ IL =1.5A, L = 1.33mH
Therefore, choose L = 3mH

Calculation of Filter Capacitor Value (C)

According to system requirements, output voltage ripple should be less than 2% of output voltage

$$\frac{\Delta Vo}{Vo} < 2\% < 0.02$$

In a Full bridge DC-DC converter, $\frac{\Delta Vo}{Vo} = \frac{1-2D}{32LCf^2}$

Value of filter capacitor,

$$C = \frac{1-(2\,X\,0.354)}{32\,X\,3\,X\,10^{-3}\,X\,0.02\,X\,(8\,X\,10^{3})^{2}} = 2.376\mu F$$

Therefore, choose C = 4700μF

D. Feedback System

Voltage Sensing Element

The output voltage of the battery charger is sensed and fed to the ADC of the DSP Processor (TMS320F28027) so that the output voltage is maintained constant even when there is a variation in the input supply voltage by changing the duty ratio of PWM pulses correspondingly. In order to provide a convenient analog input range to the embedded analog-to-digital converter, a voltage sensing element (AMC1100) from TI is chosen. Fig 8 shows how the voltage sensing element is connected to the battery charger circuit.

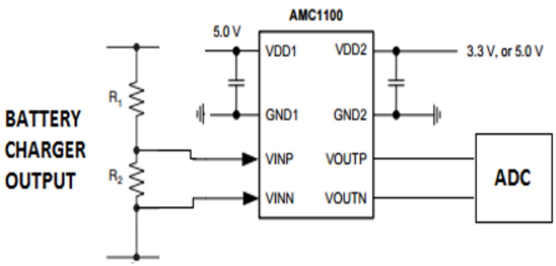

Fig 8. Output Voltage Sensing

A voltage divider circuit (R1 & R2) is connected across the battery charger output. Values of R1 and R2 are chosen such that the differential analog input range, (VINP) – (VINN), is ±250 mV with a maximum of ±320 mV before clipping occurs. Once the VDD1 and VDD2 power is applied to the AMC1100, the analog output is available with a fixed gain of 8. Therefore, with an input voltage of ±250 mV, the nominal output is ±2.0 V.

IGBT Gate Driver

The PWM pulses generated by the DSP processor do not have the brute drive capability required for switching the IGBT. Therefore, an IGBT gate driver IC (UCC27324) from TI is chosen. UCC27324 is capable of delivering 4 A of current to an IGBT gate. It also helps in reducing the effect of high-frequency switching noise. Fig 9 shows the typical connection of IGBT Gate Driver IC.

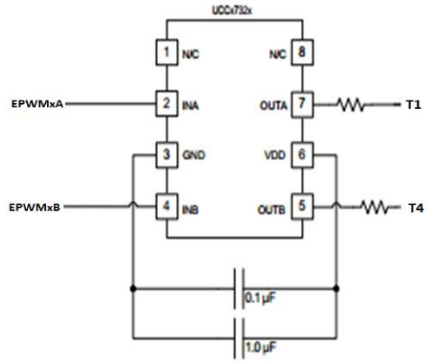

Fig 9. IGBT Gate Driver

III. SIMULATION AND RESULTS

The proposed battery charger circuit is simulated using MATLAB SIMULINK to validate the design. It has been simulated in two parts. Fig 10 shows the SIMULINK model of three phase uncontrolled bridge rectifier and Fig 12 shows the SIMULINK model of full bridge DC-DC converter. Corresponding waveforms are as shown in Fig 11, Fig 13, Fig 14, Fig 15 and Fig 16. The simulation results are in agreement with the theoretical calculations.

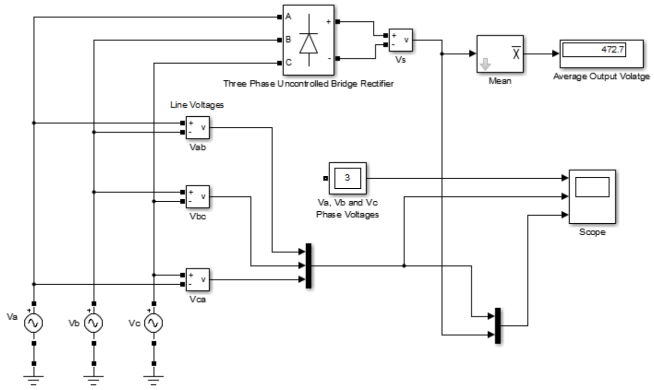

Fig 10. Simulink model of Three Phase Uncontrolled Bridge Rectifier

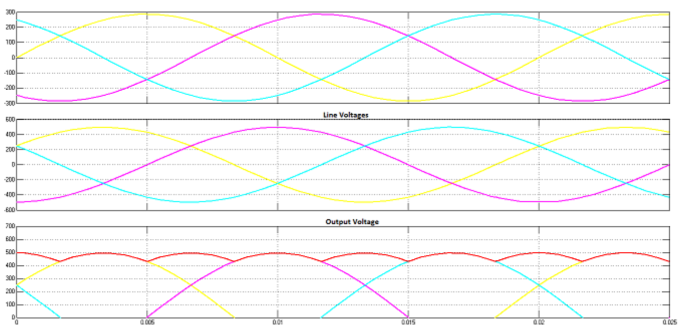

Fig 11. Phase and line voltages of three phase input and output voltage waveforms

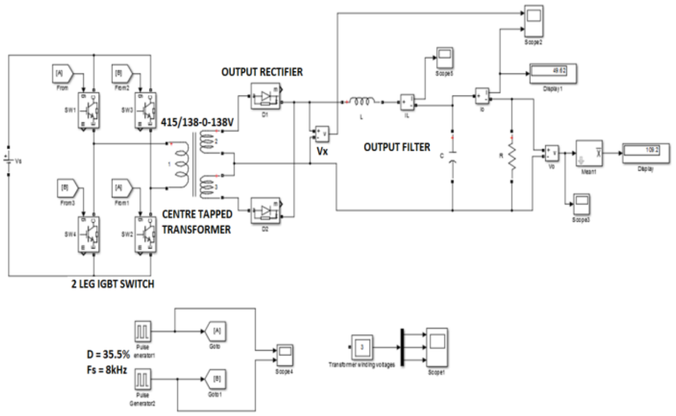

Fig 12. Simulink Model of Full Bridge DC-DC Converter

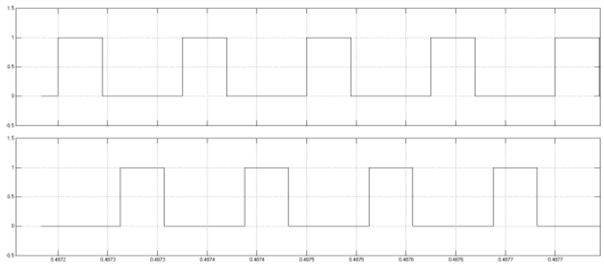

Fig 13. PWM pulses to (T1&T4) and (T2&T4)

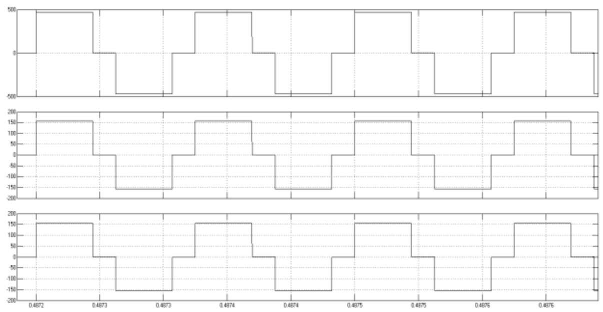

Fig 14. Transformer Primary and Secondary Voltages

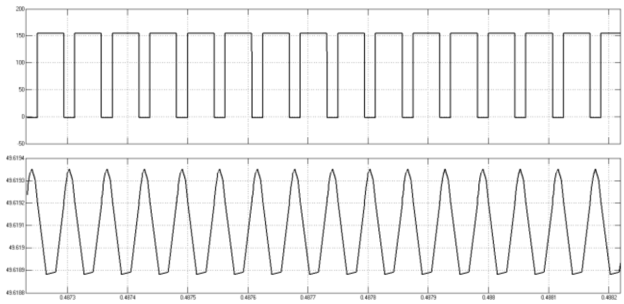

Fig 15. Voltage Vx and Inductor Current Waveforms

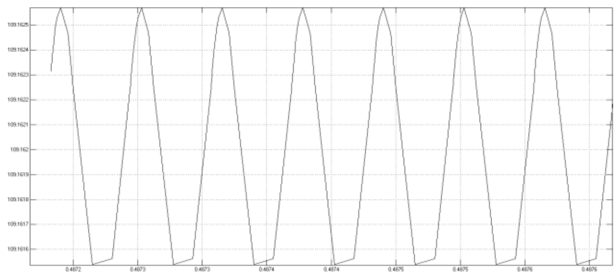

Fig 16. Output Voltage Waveform

The results are tabulated as shown in Table 1.

TABLE 1: SIMULATION RESULTS

PARAMETER	VALUE
Output Voltage Ripple	0.001%
Output Current Ripple	1.33%
Efficiency	95%
Regulation	Less than 2%

The hardware implementation of the battery charger circuit is as shown in Fig 17.

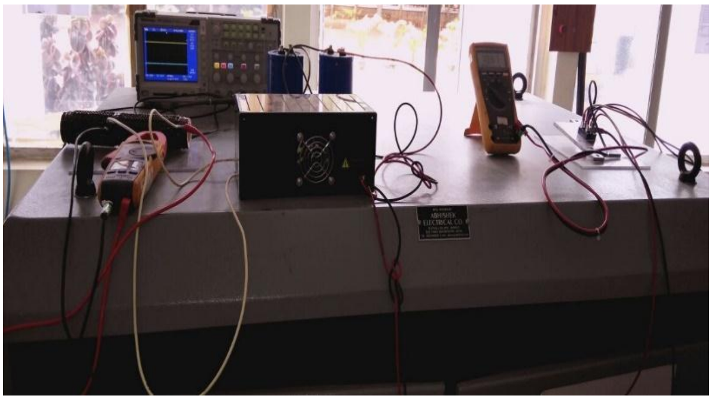

Fig 17. Hardware Setup

IV. CONCLUSION

An IGBT based constant voltage battery charger circuit was designed and validated. The DSP controller enabled the circuit to be free of human intervention. The desired efficiency and output regulation was achieved.

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