DESIGN AND IMPLEMENTATION OF 2.2KW FULL BRIDGE DC-DC CONVERTER BASED BATTERY CHARGER FOR LOCOMOTIVES

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ABSTRACT:
This paper illustrates about the design and implementation of 2.2 kW battery charger for electric locomotive using Texas controller with temperature sensing unit. The full bridge DC-DC converter approach of the battery charger caters mainly to high robustness, small size and low weight, low complexity, high efficiency and high conversion ratio. This topology is best suitable for handling high power, provides reduced Electromagnetic Interference (EMI) and known for reduced component stress. In this battery charger application, IGBTs are switched at 40 KHz for high efficiency and reduction in losses using Texas controller. The isolated buck topology is favoured for converter optimization and also helps in voltage regulation. The efficient variation of duty cycle in this proposed technique is used to regulate the output voltage at light loads. Also the presented DC-DC converter shows great conversion efficiency for large range of varying load conditions. The performance of the above DC-DC converter is evaluated via PSIM and hardware results are also been carried out.

Keywords: Battery charger, DC-DC converter, EMI, Locomotive, PSIM#

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1. INTRODUCTION

An electric locomotive is powered from overhead lines, a third rail or on-board energy storage such as battery or fuel cell. Hence, the major part of an electric locomotive is its battery. Generally in the development of a battery charger, the use of Isolated DC-DC converter is merely for safety purposes and also for voltage matching [1]. Due to the high operating switching frequencies of conductor switching devices; the size of all the magnetic components is reduced which result in smaller, lighter, and more economical power supplies but they require a wide range of frequency control, thus making the optimization of the filter components difficult. Hence, the resonant converters are emerged in which the converter’s capability of using circuit parasitic like leakage inductance of the transformer and intrinsic capacitance of the switch to create resonance and reduce switching losses has made it a must option for medium and high power applications [2-3].

The Bi-directional DC–DC power converter for solar photovoltaic energy application is presented in Figure 1. It largely contains of two half bridge converter circuits both located on every adjacent side of key high frequency transformer and inductance connected with the renewable resources, slight parallel capacitor for soft switching of the device [4-6]. When the electrical energy runs from the small voltage area to the high voltage area, the converter working in boost process is made to retain the high voltage side at an anticipated high value. In the new way of energy flow, the same converter is working in buck process mode to strengthen the small load from the renewable source [7-9]. The IGBT is designated as switching power devices that implement with high rating.

Generally in the development of a battery charger, the use of Isolated DC-DC converter is merely for safety purposes and also for voltage matching. Due to the high operating switching frequencies of conductor switching devices; the size of all the magnetic components is reduced which result in smaller, lighter, and more economical power supplies but they require a wide range of frequency control, thus making the optimization of the filter components difficult [10]. Hence, the resonant converters are emerged in which the converter’s capability of using circuit parasitic like leakage inductance of the transformer and intrinsic capacitance of the switch to create resonance and reduce switching losses has made it a must option for medium and high power applications (Figure 1).

From Figure 2 it is obvious that power converter signifies non-isolated DC-DC power converter along with asymmetrical transistor based bridge (for high-power alternatives, full bridge is better). The load is composed of pure resistive part, because it is predictable that objective application part is dispersed system architecture, thus other electronic components embodied by capacitive and resistive portions are associated at the output side. The outline of voltage at the parallel LC filter is to be clean sinusoidal waveform [11-12].
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Figure 2 DC-DC Resonant Converter [13]

<table>
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<tr>
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Table 1 Comparison of Converters

Table 1 shows the differences in various converters according to their power level, control circuitry for electric locomotive. The isolated DC-DC converters utilize a high frequency transformer to provide electrical isolation between the load and the input due to safety reasons mainly [14]. The isolated DC-DC converter topologies are derived from the basic non isolated DC-DC converter topologies[15-17].

The proposed topology has the accompanying appealing elements: off-state voltage on all switches in the circuit is just 50% of the voltage input; full information voltage is used on the heap for the entire working reach; three level output side waveform is accomplished, which essentially diminishes the necessities for the information and output channels; basic exchanging plan can be utilized to control the yield voltage in wide range. The converter can accomplish ZVS for all power switches in wide load go and even at light load condition; besides, less conduction loss is added to accomplish soft switching.

The paper is organized as follows: Section 2 deals with full bridge converter and its operation. In section 3 battery charging and in section 4 design of the proposed converter is discussed. Section 4 and section 5 presents the simulation and hardware results and section 6 concludes this paper.

2. FULL BRIDGE DC-DC CONVERTER

In the full bridge converter, switch pairs (Q₁ and Q₂, Q₃ and Q₄) work alternately with the same duty cycle, which results in the voltage level of $-V_{DC}$ or $+V_{DC}$ to the primary winding of transformer (Figure 3).
During the first half cycle, the switches $Q_1$ and $Q_4$ will conduct as long as the saw tooth signal is lower than the dc reference value. When it exceeds, the switch stops to conduct until the second half period takes place.

### 2.1. Modes of operation of full bridge DC-DC converter

**Figure 4** Operation of Full bridge Converter when $S_1$ and $S_2$ conducting

During the time interval $0 < t < DT_s$, switches $Q_1$ and $Q_2$ conduct, and the transformer primary voltage is $V_{dc}$. This voltage makes the magnetizing current to increase with a slope of $V_g/L_M$. The voltage at the secondary winding of the isolation transformer is $nV_{dc}$. Diode $D_1$ is forward biased $nV_{dc}$, and the output inductor current flows through it (Figure 4).

**Figure 5** Operation of Full Bridge Converter when all switches are off

For the second interval $DT_s < t < T_s$, all four switches are switched off, and hence the transformer voltage is Zero. Actually, the diode currents are functions of both the output inductor current and the transformer magnetizing current during this interval. Ideally, these
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currents should be equal in magnitude and the sum of the two diode currents is equal to the output current (Figure 5).

![Figure 6 Operation of Full bridge Converter when S3 and S4 conducting](image)

![Figure 7 Operation of Full Bridge Converter](image)

The next switching period, $T_s < t < 2T_s$, proceeds in a similar manner, except that the transformer is excited with voltage of the opposite polarity. During $t_s < t < (T_s + D)T_s$, transistors $S_3$ and $S_4$ and diode $D_2$ conducts (Figure 6). The applied transformer primary voltage which causes the magnetizing current to decrease. the voltage $V_p(t)$ is equal to $nV_{dc}$, and the output inductor current flows through diode $D_2$. Diodes $D_1$ and $D_2$ again both conducts during $(T_s + D)T_s < t < 2T_s$, with operation similar to subinterval (Figure 7).

By application of the principle of inductor volt-second balance to the magnetizing inductance, the average value of the transformer voltage must be zero when the converter operates in steady state. The net volts seconds, should be zero while the full bridge schemes causes this to be approximately true, in practice there exist imbalances such as small differences in the transistor forward voltage drops or in the transistor switching times. This increase can cause the transistor forward voltage drops to change such that small imbalances are compressed. However if the imbalances are too large then the magnetizing current becomes large enough to saturate the transformer.

The above said full bridge DC-DC Converter is not used usually for low power applications because of more switches. Since, there are 4 switches; there will be 4 driver circuits required which is not feasible for low power applications. Hence, this full bridge converter is typically used for power ratings more than 750Watts. At this higher power rating, the utilization of transformer is very efficient, especially the BH loop and core is utilized very effectively. Moreover, because of higher frequencies, the transformer and other filter
components size is also reduced. Because of the effective usage of transformer, the core loss is also limited. Hence, this configuration is preferred [20-21].

3. BLOCK DIAGRAM FOR BATTERY CHARGER

In this research paper the sensing unit also senses the single phase and three phase supply according to which the controller is designed. Battery charging modes also plays a crucial role in charging the battery i.e., boost and trickle mode. Figure 8 Shows the battery charging circuitry where Primary current across transformer, dc link voltage, input voltage been given to the controller as a feedback which senses the measured value accordingly.

![Battery Charging Circuit](image)

**Figure 8** Battery Charging Circuit

Here AC voltage is fed to the 3 phase bridge rectifier which is inverted through an Inverter further which is step down with a high frequency transformer and then the rectifier. Output voltage 24V, 80A is given to the battery and rest 320A is fed to the pantograph. Battery charger should withstand the temperature between +40°C to −40°C.

4. DESIGN:

The design of full bridge converter mainly incorporates the design of centre tapped transformer inductor capacitor and power switches. Based on these designs only we can implement the full bridge DC-DC converter in a proper manner [18-19]. The proposed full bridge converter specification is given below:

- Input three phase voltage
  \[ V_{\text{input\_max}} = 440 \text{ V} \]
  \[ V_{\text{input\_min}} = 350 \text{ V} \]

- Input single phase voltage
  \[ V_{\text{input\_max}} = 240 \text{ V} \]
  \[ V_{\text{input\_min}} = 200 \text{ V} \]

- DC bus maximum voltage
  \[ V_{\text{max}} = 650 \text{ V} \]
  \[ V_{\text{min}} = 370 \text{ V} \]
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Maximum voltage gain

\[ M_{VDC_{\text{min}}} = \frac{V_o}{V_{t_{\text{max}}}} = \frac{110}{650} = 0.16 \]  

(1)

Minimum voltage gain

\[ M_{VDC_{\text{max}}} = \frac{V_o}{V_{t_{\text{min}}}} = \frac{110}{370} = 0.29 \]  

(2)

Assume the converter efficiency of \( \eta = 90\% \) and the max duty cycle \( D_{\text{max}} = 0.4 < 0.5 \). The transformer turns ratio is

\[ N = \frac{2\eta D_{\text{max}}}{M_{VDC_{\text{max}}}} = \frac{2 \times 0.90 \times 0.4}{0.29} = 3.9 \text{ turns} \]  

(3)

Let \( n = 4 \) The minimum and maximum values of the duty cycle are

\[ D_{\text{min}} = \frac{n M_{VDC_{\text{min}}}}{2\eta} = \frac{4 \times 0.16}{2 \times 0.90} = 0.28 \]  

(4)

\[ D_{\text{max}} = \frac{n M_{VDC_{\text{max}}}}{2\eta} = \frac{4 \times 0.29}{2 \times 0.90} = 0.4 \]  

(5)

Assume the switching frequency \( f_s = 40 \text{ kHz} \). The minimum inductance required

\[ L_{\text{min}} = \frac{V_o (1 - D_{\text{min}})}{2 f_s L_{\text{min}}} = \frac{110 (1 - 0.28)}{2 \times 40 \text{kHz} \times 2.3} = 0.13 \text{mH} \]  

(6)

\[ C = \frac{1}{(2\pi f_s L_{\text{min}})^2} = 12 \mu \text{F} \]  

(7)

Assumed capacitor value \( C = 15000 \mu \text{F} \)

The maximum ripple of the inductor current is

\[ \Delta i_{L_{\text{max}}} = \frac{V_o (1 - D_{\text{min}})}{f_s L_{\text{min}}} = \frac{110 (1 - 0.28)}{40 \text{kHz} \times 0.13 \text{mH}} = 4.65 \text{ A} \]  

(8)

The ripple voltage is

\[ V_r = \frac{V_o}{100} = \frac{110}{100} = 1.1 \text{ V} \]  

(9)

The maximum ESR of the filter capacitor is

\[ R_{\text{c max}} = \frac{V_r}{\Delta i_{L_{\text{max}}}} = \frac{1.1 \text{ V}}{4.65 \text{ A}} = 0.23 \Omega \]  

(10)

Since \( i_s = \frac{i_{L_{\text{max}}}}{n} \), the maximum peak current through the ideal transformer primary winding is

\[ I_{L_{\text{max}}} = \frac{i_{L_{\text{max}}}}{n} + \frac{\Delta i_{L_{\text{max}}}}{2n} = \frac{23}{4} + \frac{4.65}{2 \times 4} = 6.33 \text{ A} \]  

(11)

Assume the maximum peak to peak value of the magnetizing current is less than 10% of \( I_{L_{\text{max}}} \). So, the maximum peak of the magnetizing inductance current is

\[ \Delta i_{L_{\text{m(max)}}} = 0.11 I_{L_{\text{max}}} = 0.2 \times 6.33 = 1.26 \text{ A} \]  

(12)

The minimum magnetizing inductance is

\[ L_{\text{m(min)}} = \frac{D_{\text{min}} V_{i_{L_{\text{max}}}}}{f_s \Delta i_{L_{\text{m(max)}}}} = \frac{0.283 \times 600}{40 \text{kHz} \times 1.26} = 3.4 \text{ mH} \]  

(13)
The stress across power MOSFETs are

\[ V_{SM_{\text{max}}} = V_{I_{\text{max}}} = 600 \, \text{V} \]

And

\[ I_{SM_{\text{max}}} = \frac{I_{0} \cdot D_{\text{max}}}{n} + \frac{\Delta I_{L_{\text{max}}}}{2n} = \frac{23 + 0.4}{4} \cdot \frac{4.65}{2 + 4} = 2.88 \, \text{A} \] (14)

### 4.1 TRANSFORMER

Max primary current

\[ I_{SM_{\text{max}}} = \frac{I_{0} \cdot D_{\text{max}}}{n} + \frac{\Delta I_{L_{\text{max}}}}{2n} = \frac{23 + 0.4}{4} \cdot \frac{4.65}{2 + 4} = 2.88 \, \text{A} \] (15)

Magnetizing current

\[ \Delta I_{L_{\text{mag}}} = 0.2 \cdot I_{\text{pmax}} = 1.266 \, \text{A} \] (16)

Minimum magnetizing inductance

\[ L_{\text{min}} = \frac{D_{\text{min}}}{n} \cdot \frac{V_{\text{inmax}}}{F_S + \Delta I_{L_{\text{mag}}}} = 3.3 \, \text{mH} \] (17)

### 4.2 IGBT LOSS CALCULATIONS- MITSUBISHI (CM100DY-24T)

Loss of energy during turn on \( E_{on} = 13\, \text{mJ} \)

Loss of energy during turn off \( E_{off} = 10\, \text{mJ} \)

Forward Voltage drop \( V_{ceo} = 1.75 \, \text{V} \)

Resistance \( R_{DS(\text{on})} = 0.25 \, \Omega \)

Load current \( I_0 = 23 \, \text{A} \)

Testing current \( I_{\text{test}} = 19 \, \text{A} \)

Max switch RMS current, \( I_{rms} = I_0 \cdot \sqrt{D_{\text{max}}} = 3.6 \, \text{A} \) (18)

Max average current, \( I_{avg} = I_0 \cdot \frac{D_{\text{max}}}{n} = 2.3 \, \text{A} \) (19)

Switching loss \( = P_{\text{switch}} = (E_{on} + E_{off}) \cdot \frac{I_{avg}}{I_{\text{test}}} \cdot F_S = 111.36 \, \text{W} \) (20)

Conduction loss \( = P_{\text{cond}} = (V_{ceo} \cdot I_{avg}) + (I_{rms})^2 \cdot R_{DS(\text{on})} = 5.715 \, \text{W} \) (21)

Total losses = Switching losses + Conduction losses = 117.075 \, \text{W}

### 5. RESULTS AND DISCUSSION:

The high frequency overshoot ringing on the diode voltage should be noted. This high frequency ringing sometimes can reach peaks large enough to cause failure of the rectifying diodes. The ringing is also transferred to the primary side of the transformer which could bring undesirable noise issues which result in glitches in the operation of the controller and the switching devices. Considering all the issues associated with the high frequency ringing, it is desirable that such issue be avoided. The combination of features and small size makes DCP02 series of devices suitable for wide range of application. Easy to use solution in application requiring signal path isolation. Dual high speed gate driver well suited for driving the latest IXYS MOSFET’s and IGBT’s. Eliminates current shoot-through and cross conduction.

### 5.1. SIMULATIONS RESULTS

The simulation work is carried out in the PSIM simulation environment and related waveforms are given in this section. The output voltage and output current waveforms of DC-DC full bridge converter is presented in Figure 9 and Figure 10. The DC link voltage waveform is given in Figure 11. In the isolation transformer voltage existing on primary and secondary side of the transformer is shown the Figure 12 and Figure 13 respectively.
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Figure 9 Output voltage waveform for full bridge DC-DC converter

Figure 10 Output current waveform for full bridge DC-DC converter

Figure 11 DC Link voltage waveform for full bridge DC-DC converter

Figure 12 Voltage waveform across Primary winding

Figure 13 Voltage waveform across Secondary winding

5.2. HARDWARE RESULTS
The results obtained from the prototype model are presented in this section. The primary side output voltage of the transformer is presented in Figure 14 and Figure 15 under no load and load condition respectively. The gate pulses generated to power switching IGBT’s (S1-S4) are shown in Figure 16 and Figure 17 respectively. The output voltage and current obtained from the converter is presented in Figure 18. The test setup for battery charger shown in Figure 19
**Figure 14** Transformer primary voltage with no load

**Figure 15** Transformer primary voltage with load

**Figure 16** Gate Pulse for $S_1$ and $S_4$ IGBTs

**Figure 17** Gate Pulse for $S_2$ and $S_3$ IGBTs

**Figure 18** Output Voltage and Output Current Waveform
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6. CONCLUSION
Battery Charger achieved highest efficiency 91.6% with 40 kHz frequency for 110V, 2.2 kW Output power. Silicon carbide switches can also considered which makes our charger more and more efficient. 2.2 kW battery charger has driver IC IX3120 which has its own driver and opto coupler in it which makes it more compact. Reverse polarity protection, over voltage, over current protection also been tested on 2.2 kW battery charger which also is convenient for 10 kW or much higher power level. The presented control technique advances the overall efficiency of the battery charger up to 3.5% during light load environments than the traditional control technique without any additional hardware circuits. The future research will be on optimizing the conduction losses, and core losses to attain best system efficiency over an extensive range of output side voltage. Also researchers may focus on expanding the power of the charger to a higher level.

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Figure 19 Test setup with power on Diesel locomotive Battery Charger


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