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Design and simulation of three phase bi-directional dc-dc converter for battery charging-discharging application

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ABSTRACT

This paper describes three phase bi-directional battery charger widely used in Energy storage application. The full bridge scheme is widely used for the high power application. The high-frequency transformer is used for the isolation purpose. This paper describes the design and simulation of a 7.75-kW, full-bridge, bi-directional isolated dc-dc converter with active front-end converter (AFC). The AFC is connected with the 3-phase ac system, which provides 650 to 700 dc voltage to dc-dc converter with lower value of THD (according to IEEE- 915) and improve power factor at input side. The dc-dc converter converts 310V from 650V for charging the battery. Software tool PSIM is used to obtain the simulation result of the converter. The closed loop system is simulated to achieved voltage and current ripple at output side less than 1% rms of rated voltage.

Introduction

The bi-directional dc-dc converters allow the transfer of power between two dc sources in either direction. They are increasingly used in applications such as dc uninterruptible power supplies, battery chargers, multiplexed-battery systems, computer systems, aerospace systems, dc motor drives circuits and electric vehicles [1].

Possible implementation of bi-directional converters using resonant soft switching and hard switching PWM has been implemented earlier. But, these topologies may often lead to an increase in component ratings, circuit complexity a conduction losses in resonant mode implementations, high output current ripple and loss of soft switching at light loads for soft-switched circuits, and lack of galvanic isolation in integrated topologies.

In general circuit diagram for energy storage system employing a line-frequency (50- or 60-Hz) transformer, a PWM converter, a bi-directional chopper, and an energy storage device such as super capacitors or lithium-ion batteries. The transformer is necessary for some applications, where voltage matching and/or galvanic isolation between the utility grid and the energy storage device is required. [2-7].

Voltage ratings for energy storage systems connected close to the user end should be low to ensure user safety matching and meeting high safety regulations is required. Existing energy storage systems have heavy and costly line-frequency transformers of 50/60 Hz for voltage matching and galvanic isolation to the ac mains. Combining high-frequency switching devices with a high-frequency transformer in a single-phase full-bridge bi-directional isolated dc-dc converter can reduce the weight, size, and cost of the energy storage systems [3-7].

There are many topologies to design the dc-dc converter but most efficient method is using the full-bridge topology. The two-stage dc-dc full bridge converter is proposed in this paper to achieve the required specification. The main objective is to reach a high efficiency, high power density and cheap topology in simple structure. In older days resistor was used to discharge the battery. So the total energy wasted in the form of I^2R losses. In the proposed topology, during the discharge mode of operation the battery power will flow in the reverse direction and it will feed to the supply grid

The bi-directional isolated dc-dc converter

There are mainly four sections of proposed topology. (A) The bi-directional ac-dc converter (B) Primary side Full bridge converter (C) High frequency Transformer (D) Secondary side Full bridge converter.

The bi-directional ac-dc converter

During the battery charging mode, the ac current first goes through a filter which helps remove unwanted frequency components. Next the ac current is rectified into dc current as it passes through the bi-directional ac-dc converter. Since the ac-dc converter output voltage might not match the require voltage of the dc energy storage system, so the output of the ac-dc converter is applied to the dc-dc converter.

Primary side full bridge converter

The second stage is a pulse width modulated dc-dc isolated converter. During charging mode of operation this bridge is working as a phase shifted full bridge inverter. During discharging mode of operation, this bridge is working as a full bridge diode rectifier.

High frequency Transformer

HF transformer step-down the voltages during charging mode of operation and steps-up the voltages during discharging mode of operation. It is also providing isolation between primary and secondary. The turns-ratio is same during both charging and discharging mode of operation.

Secondary side full bridge converter

There are mainly four sections of proposed topology. (A) The bi-directional ac-dc converter (B) Primary side Full bridge converter (C) High frequency Transformer (D) Secondary side

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Full bridge converter.

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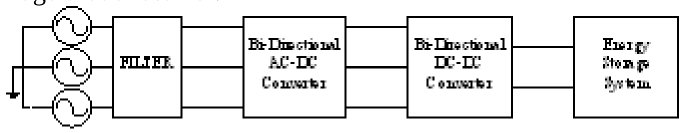


Fig.1. Basic block diagram of bi-directional dc-dc converter

High frequency Transformer

HF transformer step-down the voltages during charging mode of operation and steps-up the voltages during discharging mode of operation. It is also providing isolation between primary and secondary. The turns-ratio is same during both charging and discharging mode of operation.

Secondary side full bridge converter

The fourth stage is a pulse width modulated dc-dc isolated converter to provide the desired output power. During charging mode of operation, this bridge is working as a full bridge diode rectifier. During discharging mode this bridge is working as a Phase shifted full bridge inverter.

Circuit description of AFC section

The three phase full-bridge converter is made of decoupling inductor, grid inductor, high-frequency filter capacitor and six IGBTs with internal diodes. The decoupling inductor and grid inductor is also a part of the filter, so with combination of capacitor it is L-C-L filter. The purpose of these two inductor is to boost up the voltage for grid to ac-dc converter and also remove the dc components when feed from ac-dc converter to grid.

During the battery charging mode, the switches of AFC section (Q1-Q6) as shown in Fig.2 can be switched in such a way so works as a PWM rectifier. While operating in battery discharge mode, it works as a PWM inverter. The grid inductor and decoupling inductor are used to boost-up the line voltage. The output voltage of AFC section is 650 to 700 volt, so to boost-up the 3-phase line voltage from (415*1.414= 586 volt) to 650 volt this two inductors are required.

The high frequency filter capacitor contains damping resistor and damping inductor in series with it. The purpose of damping resistor is to avoid oscillation condition at resonance frequency. So the value selected for damping resistor is not to be so high to reduce the efficiency. To reduce the wattage capacity of the damping resistor, the damping inductor has been incorporated in parallel with the damping resistor.

Voltage drop across the total inductor is find by,

$$\frac{V_S}{I_S} * (\%Vol.drop) = 2 * \pi * f * L_T \quad (1)$$

Take the voltage drop equals 10% of supply voltage and frequency is 50Hz.

For the better attenuation L_g equals 83% of L_T and L_d equals 17% of L_T, where L_g is grid inductor and L_d is decoupling inductor.

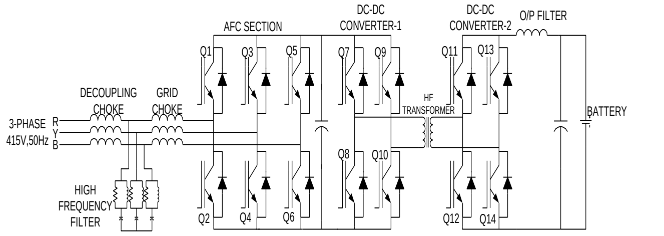


Fig.2. Basic circuit diagram of bi-directional DC-DC system

$$C = 10\% * \frac{P_{rated}}{3 * 2 * \pi * f_{line} * V_{rated}^2}$$

P_{rated} is calculated 8611VA, and V_{rated} is take 240 Volt.

The resonance frequency can be finding by following equation

$$f_r = \frac{1}{2\pi} \sqrt{\frac{L_g + L}{L * L_g * C_f}}$$

By putting the values in above eq. (1) to (3) the selected value of components shown in TABLE-I.

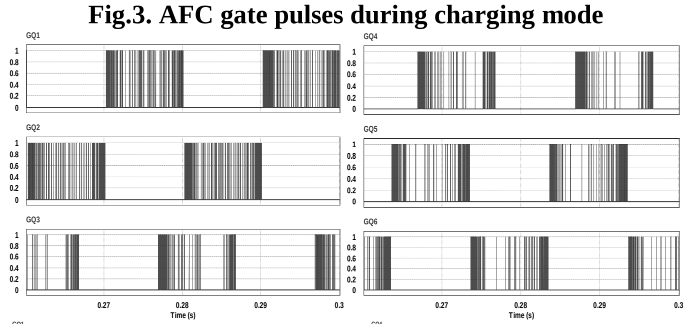
Fig.3 and Fig.4 shows the gate pulses (Q1-Q6) during charging mode and discharging mode of operation.

Table I

Parameters FOR L-C-L filter

Parameter	Selected Value
Total inductor (L_T)	6.35mH
Grid inductor (L_g)	5.3mH
Decoupling inductor (L_d)	1.0mH
Filter capacitor (C)	15uf
Resonance frequency	1.4kHz

Fig.3. AFC gate pulses during charging mode



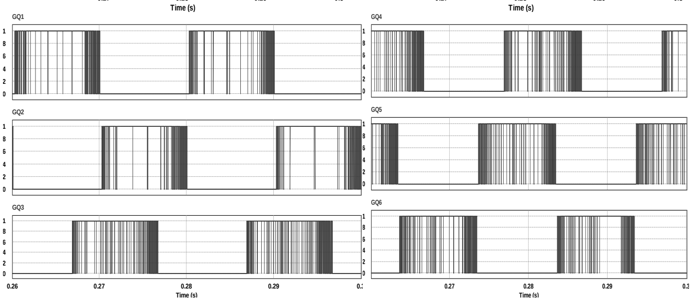


Fig.4. AFC gate pulses during discharging mode

Bi- directional DC-DC converter

The main two topologies for PWM generation are (1) The conventional full bridge PWM converter (2) The phase shifted full bridge PWM converter. The phase shifted full bridge PWM topology is used in this paper. Circuit parameters are mentioned in Table II Fig.2 shows the basic circuit diagram to simulate the Bi-directional dc-dc converter in PSIM 9.0 software tool.

Table III
Circuit parameters of dc-dc converter

Switching Device	**IGBT**
Input Voltage	650-700 volt (D.C)
Output Voltage	310 volt (D.C)
Output Current	25 Amp
Output Power	7.75 Kw
Switching Frequency	8 kHz
Transformer turns ratio	1:0.5846
Leakage Inductance	1uH
Magnetizing Inductance	14mH

Charging Mode

In the charging mode of operation, the AFC section provides 650 to 700 volt, to the converter-1 as shown in Fig.5. The output of the converter-1 is applied to the high-frequency transformer, which gives the square wave ac pulse. During the charging mode transformer steps-down the voltage from 645 volt to 380 volt. The transformer secondary voltage is applied to the converter-2, during charging mode gate pulses are not given to the IGBT so it works as a rectifier and converts ac square wave pulse from transformer to the dc pulse and further feed to the L-C filter section. The L-C filter removes the ac components from rectifier output and dc current is feed to the battery for charging purpose.

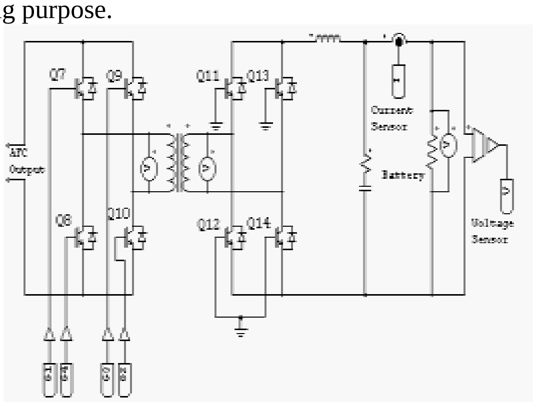


Fig.5. Simulation circuit of dc-dc converter during charging mode

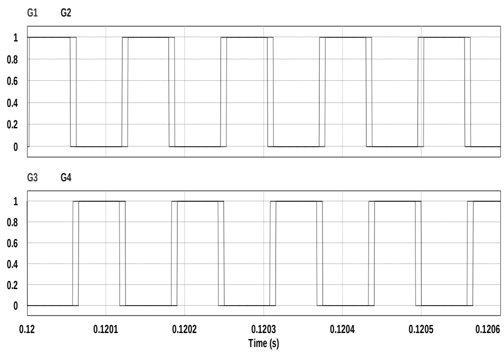


Fig 6 Gate pulses across switches Q7 to Q10

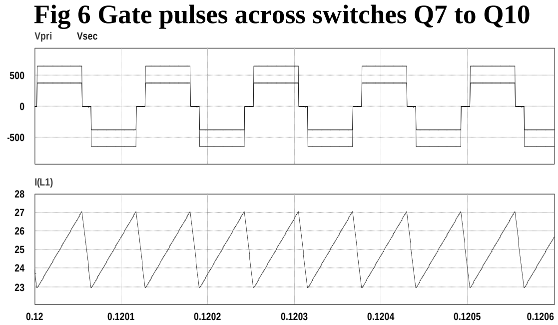


Fig 7 Voltage across transformer voltage and inductor current

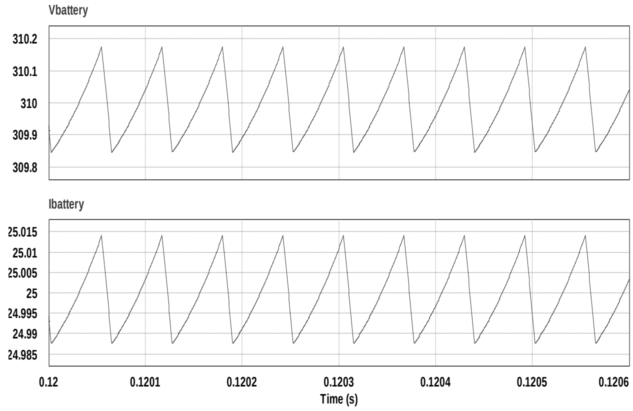


Fig 8 output voltage and current

As shown in Fig.6 the switches Q7 and Q8 are complementary switches, similarly Q9 and Q10 are complementary switches. These complementary switches have 3.2us dead time in their switching.

When the switches Q7 and Q10 both are ON, means during the overlap of their switching period transformer provides positive voltage. Same way when the switches Q8 and Q9 both are ON, transformer provides negative voltage. During the period of zero voltage across transformer switches Q7 and Q9 or Q8 and Q10 are ON.

As shown in Fig.7 inductor stores the energy when transformer provides positive or negative voltage. During the zero voltage period across the transformer inductor release energy to the load to maintain constant voltage and current across battery. As shown in Fig.8 the battery charges with continuously 310 volt and 25 amps.

Discharging Mode

In the discharging mode of operation, the battery provides 310 volt and gradually decreases up to 60 volt. Fig.9 shows the simulation circuit for discharging mode of operation. Fig. 10 shows gate pulses of switches Q11 to Q14. The switch Q11 controls the switches Q12 and Q14 same way switch Q13 controls the switches Q12 and Q14. It means when switch Q11 is on during that period Q12 and Q14 are switched on one after another.To maintain 650volt at output of converter-1 the voltage must be boost-up at battery side only because transformer ratio can’t be changed. So to boost-up the voltage at battery side switches Q11 and Q12 shorts for some period of the positive half cycle. Similarly Q13 and Q14 also short for some period of the negative half cycle as shown in Fig.11. But care should be taken that inductor should not saturate during this period.

During the short period of the Q11 and Q12 inductor stores the energy. After some period when Q11and Q14 are on then total voltage will be battery voltage plus inductor boosted voltage. In this way boost-up of voltage is done before the voltage feed to transformer.

As shown in Fig.12 when transformer provides positive or negative voltage at same time inductor release the energy to boost transformer voltage as in the boost converter. During the transformer voltage is zero position inductor stores the energy. The voltage and current feed to AFC is shown in Fig. 13 for battery voltage of 310 Vdc. same way for battery voltage 60-volt, the output voltage and current maintain same as shown in Fig. 14.

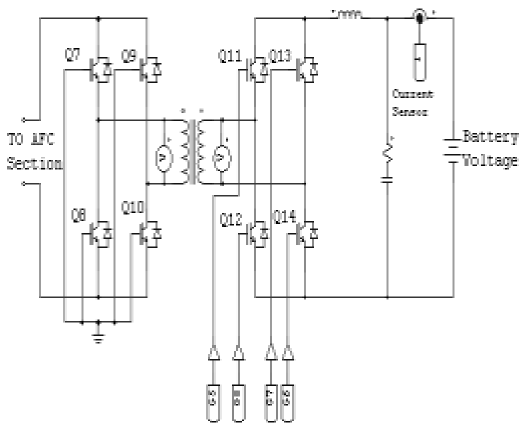


Fig 9 Simulation circuit of dc-dc converter during discharging mode

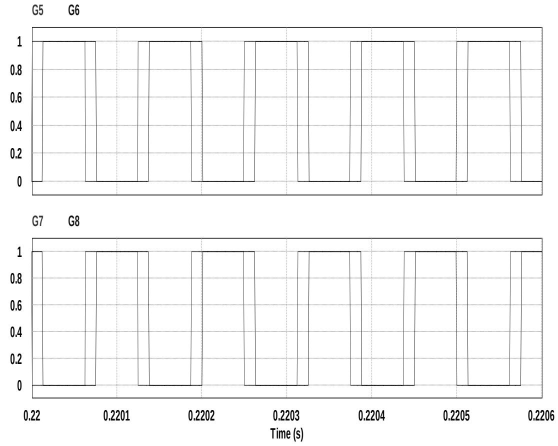


Fig 10 Gate pulses across switches Q11 to Q14

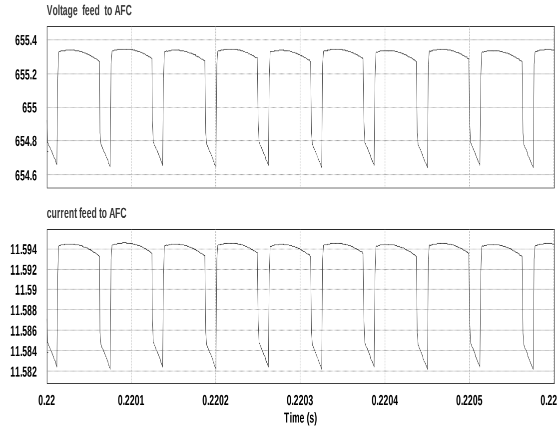


Fig 11 Short period during same leg switches are short

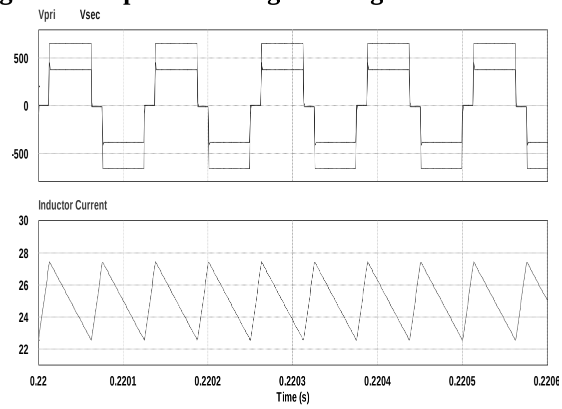


Fig 12 Voltage across transformer and inductor current when battery voltage is 310 volt

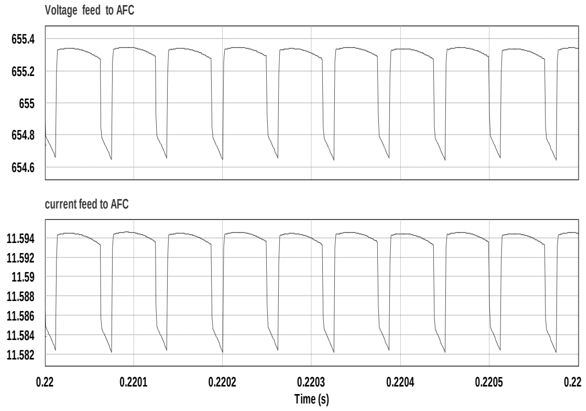


Fig 13 Voltage and current feed to AFC when battery voltage is 310 volt

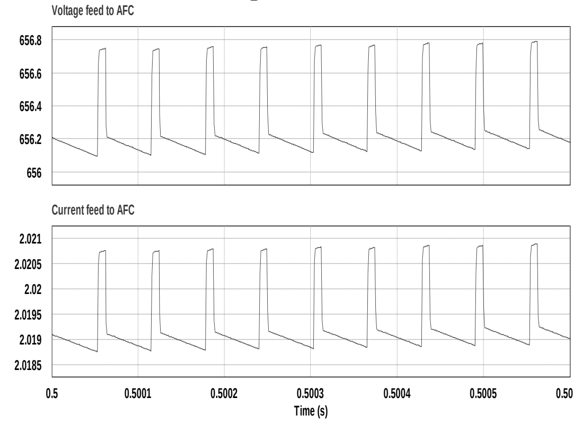


Fig 14 Voltage and current feed to AFC when battery voltage is 60 volt

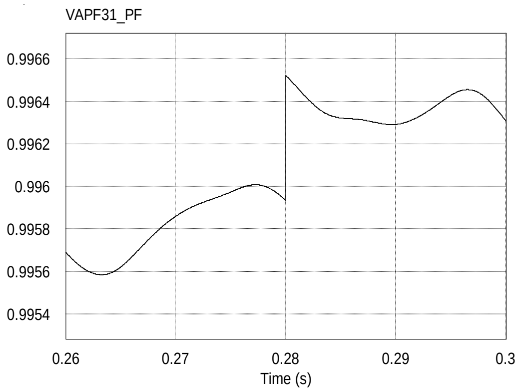


Fig 15 Power factor at the grid side during discharge mode

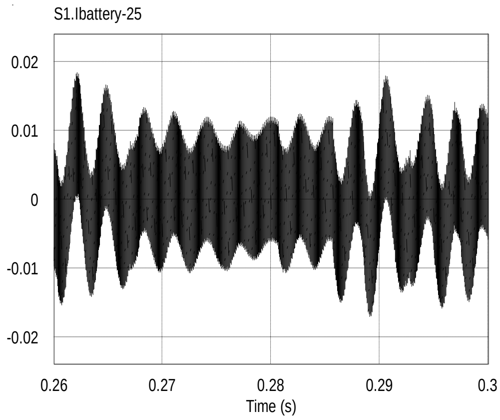


Fig 16 Ripple current at battery during charging mode

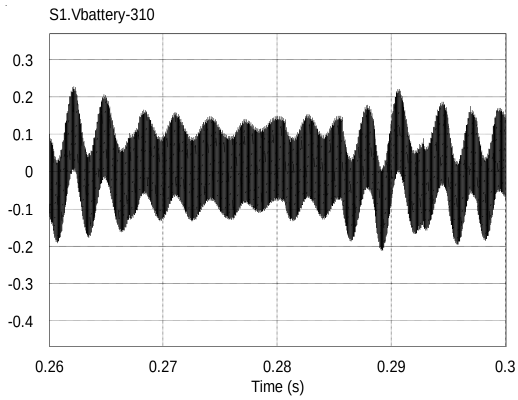


Fig 17 Ripple current at battery during charging mode

Conclusion

In this paper, circuit topologies of the dc-dc converter with bi- directional power flow control and conversion capability and with electrical isolation between the two sides through a single HF transformer is evaluated for battery charging and discharging application. In charging mode of operation, minimum output current and voltage ripple is achieved shown in Fig. 18 and 19. As shown in Fig. 17 power factor is achieved up to 0.9965. With this topology by using the minimum switching devices the result is achieved. In the discharging mode by connecting the active front-end converter (AFC) the output dc power can converted to three phase ac and feed to the grid .so the overall efficiency is increased and also saving of energy.

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