Pre/Post Charge Control using IGBT for Relay Contact Protection in Electric Vehicle

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Abstract: - This paper focuses on solving the problem of relay contact arc in an electric vehicle by using IGBT. When a relay opens, interacting high current, an arc is produced across the relay contacts. The arc may melt and destroy the contacts. The IGBT is used to limit the inrush current from the battery to the capacitor in the inverter when the system is turned ON. To shutdown the system, the IGBT is also used to gradually reduce the current to zero. This is achieved by controlling IGBT's gate voltage which in turn controls current flowing through the IGBT. The simulation responses of the proposed system and the convention system that uses a pre-charge relay in series with a resistor were compared and analysed. With the proposed control system inrush currents are significantly reduced, solving the arc problem. A prototype of the proposed system was built and tested, the test results proved that the proposed method gives the satisfactory response.

Key-Words: - pre charge, post charge, inductive load, capacitive load, contact arc, inrush current, surge voltage

1 Introduction

The most important components in a pure electric vehicle include batteries used as energy source, traction motors used for propulsion, auxiliary loads such as air conditioning unit, air compressor, and steering pump, auxiliary load unit used to supply power to the auxiliary loads, inverters used to control motors, and very important switching devices called power relays. Power relays are used to turn ON the system (connecting the battery to the load) and to shut it down (disconnecting the battery from the load).

A protective mechanism is needed to prevent electric arc across relay contacts when the relay closes or opens. Conventionally, in an electric vehicle, a pre-charge relay is connected in series with a resistor to limit inrush current to the capacitor in the inverter. When the system is turned on, the pre-charge relay and negative relay are energized to pre-charge the capacitor until the inrush current subsides. Then, the positive relay is energized and the pre-charge relay is de-energized [1]. But, if inverters are not OFF, the conventional method cannot limit the inrush current when turn ON the system. To shutdown the system, all inverters must be turned OFF first. However, even if the inverters are OFF but, some inductive loads are still running, shutting down the system may result to a surge voltage across relay contact which will cause arc and damage at the contacts. The arc can melt relay contacts and cause a permanent close, that is, the contacts cannot be opened electrically.

This paper presents a solution to the relay contacts arc problem in high voltage systems by using IGBT transistor to limit inrush current when turning ON and limit the surge voltage when turning OFF a system.

2 IGBT transistor modeling

The IGBT model is shown in Fig .1, when the voltage is applied at the gate pin, drain current (I_d) of the MOSFET transistor equals the base current (I_b) of the BJT transistor given by Equation (1). The current I_c through the IGBT is given by Equation (2), the value for k is obtained under saturation condition using Equation (3). Thus Equation (2) can be rewritten as in Equation (5) [2].

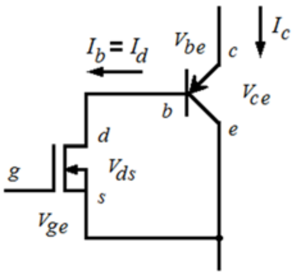

Fig.1 IGBT Model

$$I_d = I_b = \frac{1}{2}k\left(V_{ge} - V_{th}\right)^2 \quad (1)$$

$$I_c = \frac{1}{2}k\left(\beta + 1\right)\left(V_{ge} - V_{th}\right)^2 \quad (2)$$

$$k = \frac{I_{bs}}{\left(V_{ge} - V_{th}\right)\left(V_{bes} + V_{ces}\right) - \frac{\left(V_{bes} + V_{ces}\right)^2}{2}} \quad (3)$$

$$K = \frac{I_{ces}}{2\left(V_{ges} - V_{th}\right)\left(V_{bes} + V_{ces}\right) - \left(V_{bes} + V_{ces}\right)^2} \quad (4)$$

$$I_c = K\left(V_{ge} - V_{th}\right)^2 \quad (5)$$

3 System Design

The proposed system is shown in Fig.2. The IGBT is connected in parallel with the negative relay to limit inrush current during turning ON and limit the surge voltage when shutting down the system.

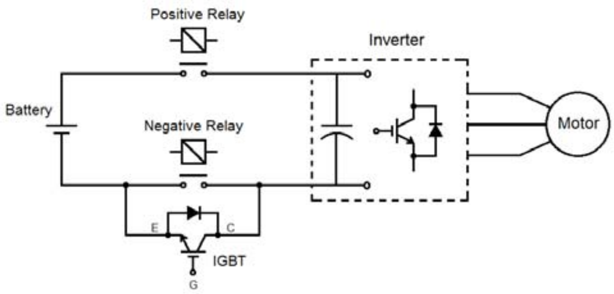

Fig.2 Pre/Post charge control Structure

To turn ON the system, the positive relay is turned ON first while the negative relay and the IGBT are OFF. Then, the IGBT is partially turned ON to limit the current flowing into the capacitor which is in the inverter. The voltage at the IGBT gate is then gradually increased to fully turn ON the IGBT (reducing voltage drop between collector and emitter) allowing full load current to flow. Then the negative relay is turned ON and the IGBT is turned OFF. Thus, the system runs with IGBT OFF, positive and negative relays ON.

To shutdown the system, the IGBT is turned fully ON, and then the negative relay is turned OFF. The voltage at the IGBT gate is then gradually decreased (to decrease current flow) until the transistor is fully OFF. When the IGBT is OFF, the positive relay is then turned OFF.

3.1 Pre Charging

The circuit shown in Fig.3 is used to control the IGBT gate voltage, enabling turning ON the system. When the voltage V_1 is applied across the capacitor C_1, the IGBT transistor is partially turned ON (IGBT gate voltage is limited) limiting current flowing through it. This enables limiting load current when turning ON the system.

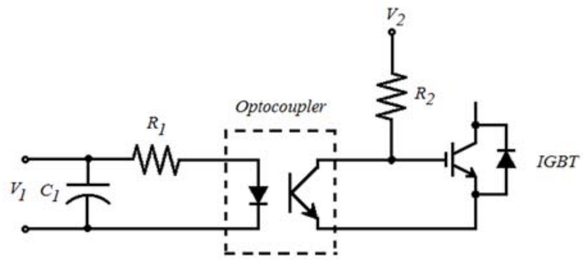

Fig.3 IGBT gate voltage control turning ON circuit

The procedure starts by applying the voltage V_1 first and then the voltage V_2. The voltage V_1 determines voltage drop across the optocoupler, thus determining gate voltage V_{ge} of the IGBT which in turn determines current flowing through the IGBT.

From the IGBT control circuit shown in Fig.3, the voltage drop across the output of the optocoupler can be obtained from equation (6), the input current (I_F) and the output current (I_C) through the optocoupler is given by Equation (7) and equation (10) respectively. Thus the gate voltage (V_{ge}) can be obtained from Equation (9). The gate voltage V_{ge} from Equation (5) equals Equation (9). Thus the relationship between the voltage V_1 and current I_c is given by Equation (11). The minimum value of resistor R_2 is used [3], to determine the worst case scenario under the operation conditions.

$$V_{ce} = V_{ge} = V_2 - I_C R_2 \quad (6)$$

$$I_F = \frac{V_1 - V_F}{R_1} \quad (7)$$

$$I_C = \left(\frac{CTR}{100}\right) I_F \quad (8)$$

$$V_{ge} = V_2 - \left(\frac{CTR}{100}\right)\left(\frac{R_2}{R_1}\right)(V_1 - V_F) \quad (9)$$

$$\sqrt{\frac{I_c}{K}} + V_{th} = V_2 - \left(\frac{CTR}{100}\right)\left(\frac{R_2}{R_1}\right)(V_1 - V_F) \quad (10)$$

$$V_1 = \frac{\left(V_2 - \sqrt{\frac{I_c}{K}} - V_{th}\right)}{\left(\frac{CTR}{100}\right)}\left(\frac{R_1}{R_2}\right) + V_F \quad (11)$$

The voltage across the capacitor in the inverter is given by Equation (12). From Equation (11) the capacitor in the inverter charging by the constant current, thus time determines how long the IGBT should remain partially ON by Equation (13).

$$V_C = \frac{1}{C}\int_0^t I_c(t)\,dt \quad (12)$$

$$t_1 = \frac{CV_C}{I_c} \quad (13)$$

The next step procedure is turning OFF the voltage V_1 and still voltage V_2. The voltage V_{C_1} determines the voltage drop across the optocoupler. The voltage V_{C_1} can be obtained from Equation (14) and Equation (15). Thus the current I_c can be obtained by Equation (19).

$$V_{C_1} = V_1 e^{-t/R_1C_1} \quad (14)$$

$$V_{C_1} = I_F R_1 + V_F \quad (15)$$

$$V_1 e^{-t/R_1C_1} = I_F R_1 + V_F \quad (16)$$

$$I_F = \frac{V_1 e^{-t/R_1C_1} - V_F}{R_1} \quad (17)$$

$$V_{ge} = V_{ce} = V_2 - \left(\frac{CTR}{100}\right)\left(\frac{V_1 e^{-t/R_1C_1} - V_F}{R_1}\right) R_2 \quad (18)$$

$$I_c = K\left(V_2 - \left(\frac{CTR}{100}\right)\left(\frac{V_1 e^{-t/R_1C_1} - V_F}{R_1}\right) R_2 - V_{th}\right)^2 \quad (19)$$

The value of capacitor C_1 can be obtained from Equation (20). The charging time is 5 times time constant (τ_1), thus the values of the resistor R_1 and capacitor C_1 determine the time to turn ON the negative relay according to the Equation (21).

$$C_1 = \frac{\tau_1}{R_1} \quad (20)$$

$$t_2 = 5R_1C_1 \quad (21)$$

3.2 Post Charging

To shutdown the system, only V_3 is applied to fully turn on the IGBT and then the IGBT control circuit is de-energized, as the capacitor C_2 discharges, the IGBT gate voltage gradually decreases. Further explanations are given in the following subsections.

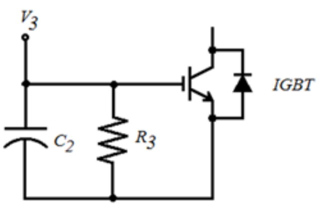

Fig.4 IGBT gate voltage control turning OFF circuit

The shutdown procedure starts by the IGBT is turned ON to bypass the current. This is done by applying voltage V_3, as the capacitor C_2 charges, the gate voltage (V_{ge}) of the IGBT increases to fully turn ON the IGBT. When the IGBT is fully ON, the negative relay is de-energized. And then the IGBT controlling circuit is de-energized, as the capacitor C_2 discharges, V_{ge} decreases, when the voltage V_{ge} becomes less than the threshold voltage (V_{th}) the IGBT is fully turned OFF. Finally, the positive relay is de-energized. As the capacitor C_2 discharges, the voltage V_{ge} will decrease according to the Equation (22). The capacitance of the capacitor C_2 will determine by Equation (23). Thus the values of the resistor R_3 and capacitor C_2 determine the time to turn OFF the positive relay according to the Equation (24). Designing the IGBT cooling system is used [4].

$$V_{ge} = V_{C_2} = V_3 e^{-t/R_3C_2} \quad (22)$$

$$C_2 = \frac{\tau_2}{R_3} \quad (23)$$

$$t_{off} = 5R_3C_2 \quad (24)$$

4 Simulation and Experimental Result

A conventional system (Fig.5) and the proposed system (Fig.9) were both simulated using MATLAB/Simulink, and the results are compared. Simulation parameters were taken from an electric bus called PEA Ze-Bus that was recently developed in Thailand. The bus has 650 V, 300 Ah Li-ion battery, 495 μF no-load capacitance (C_0), 0.11MΩ no-load resistance (R_0), 0.08mH no-load inductance (L_0), 40Ω on-load resistance (R_1), and 1.2H on-load inductance (L_1). Arc power model to simulation is used [5].

4.1 Conventional System

A conventional system that uses a pre-charge relay in series with a current limiting resistor is shown in Fig.5. As previously mentioned, parameters for the battery, C_0, L_0, R_0, L_1, and R_1 were taken from the PEA Ze-Bus. The pre-charge relay is connected in series with a 120Ω resistor.

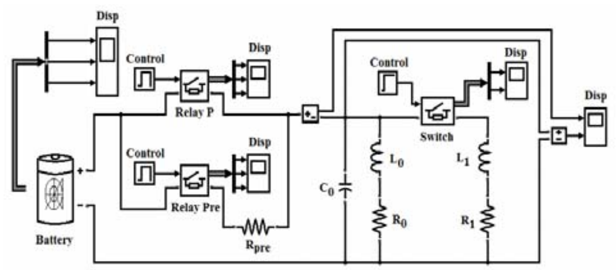

Fig.5 Conventional control system

When the system is turned ON and OFF on load, the responses in the positive relay, pre-charged relay and load are shown in Fig.6 through Fig.8. Maximum current through the positive relay is 18 kA and the maximum arc power is 2.68 kW which is very high, as shown in Fig.6. Maximum current through the pre-charge relay is 6.33A, and the maximum arc power is 800 W with a surge during the shut-off as illustrated in Fig.7.

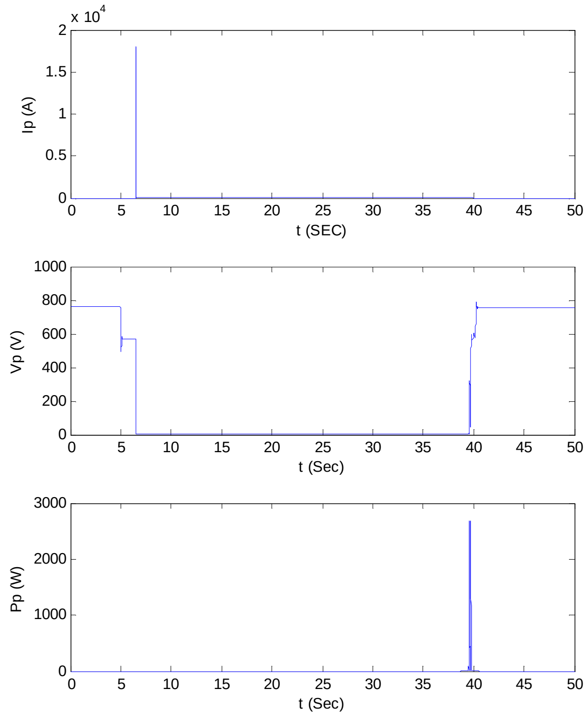

Fig.6 Response in the positive relay by conventional control

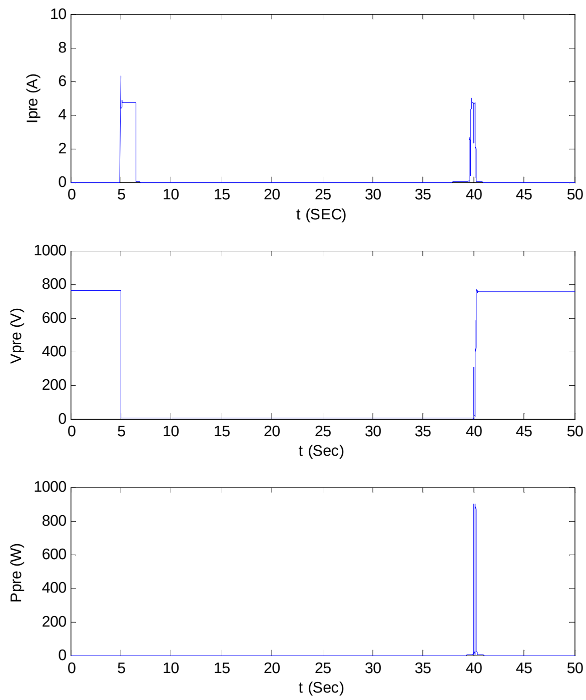

Fig.7 Response in the pre-charge relay by conventional control

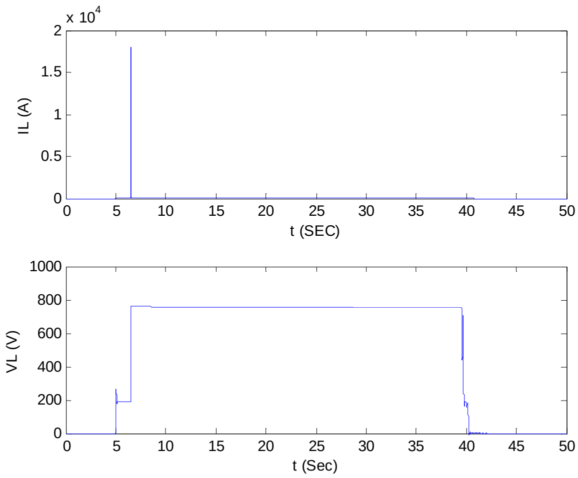

Fig.8 Response to load by conventional control

4.2 Proposed System

The simulated proposed system that uses IGBT to limit inrush current is shown in Fig.9. The profile of the IGBT gate voltage V_{ge} is shown in Fig.10.

With load connected, the maximum current through the positive relay is 18.97A and the maximum arc power is about 0.45W as shown in Fig.11. Load current and voltage profiles are shown in Fig.12. The load current rises to 22.53 A, when the positive relay starts and stops.

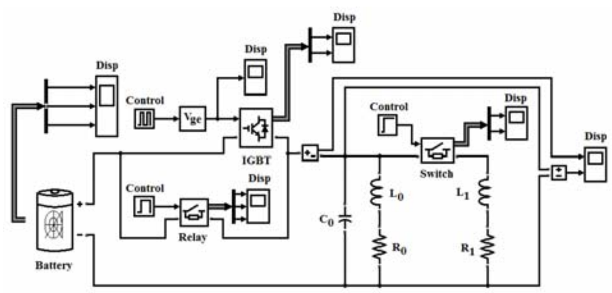

Fig.9 Pre/Post charge control by IGBT

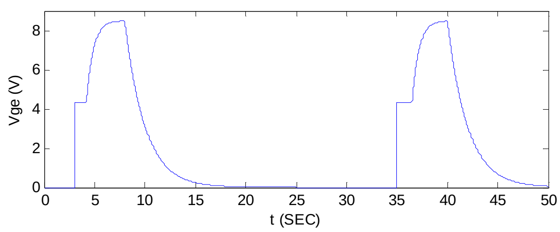

Fig.10 Gate voltage response of the IGBT

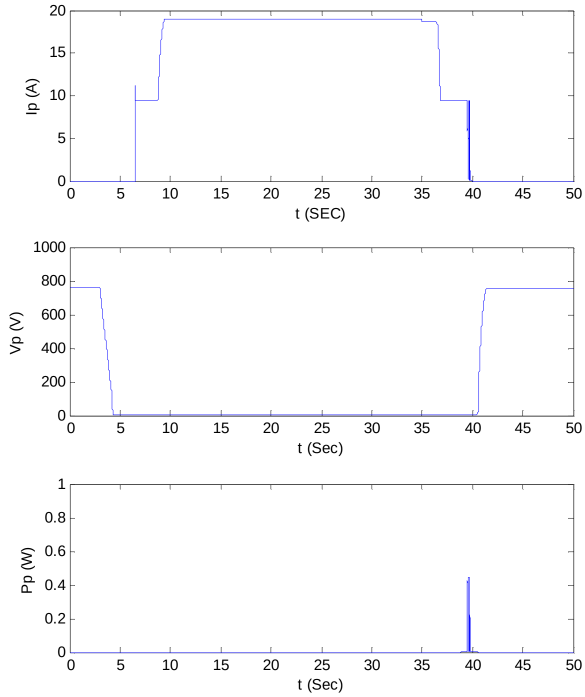

Fig.11 Response in the positive relay by IGBT control

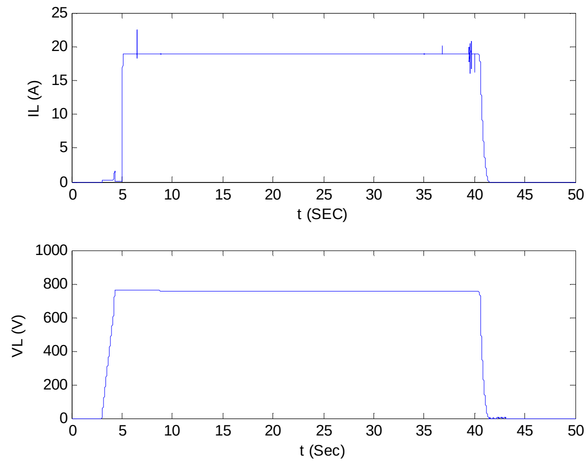

Fig.12 Response to load by IGBT control

4.3 Experimental Setup and Test Result

This section presents test results of the proposed system prototype. The prototype was built using IGBT number GT60M303 which has a maximum current of 60A, the saturation voltage V_{ces} of 900V and, the gate voltage V_{ges} of $\pm$25V, is used [6], 50V DC power supply, 30,000 uF load capacitance, 12 Ω load resistance and 1H load inductance. Our circuit are compose of optocoupler number TLP251 [7], R_1 of 9.4 kΩ, R_2 and R_3 of 10 kΩ, C_1 and

C_2 of 470 μF, V_1, V_2 and V_3 of 15 VDC. The built prototype is shown in Fig.13. A controlled V_{ge} voltage used to control IGBT transistor is shown in Fig.14. Load current and voltage profiles are shown in Fig.15 from which it can be seen that, load current gradually increases when the system is turned ON, and gradually decreases when the system is turned OFF, without any surge. Thus, electric arc across relay contacts is eliminated. The oscilloscope could not be used to measure the voltage across the relay contact because the probes would get very hot and melt.

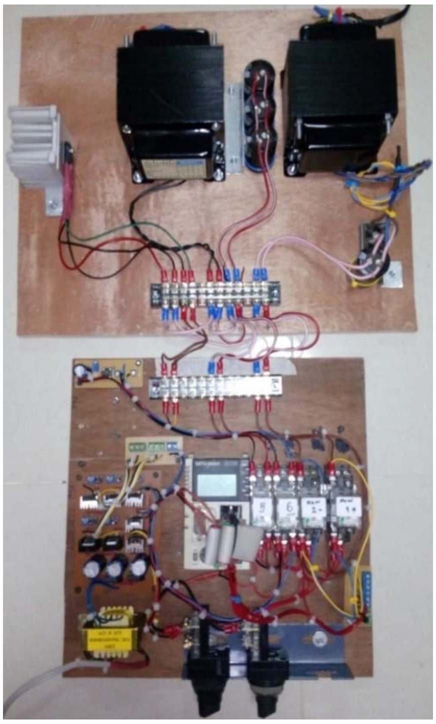

Fig.13 Control system

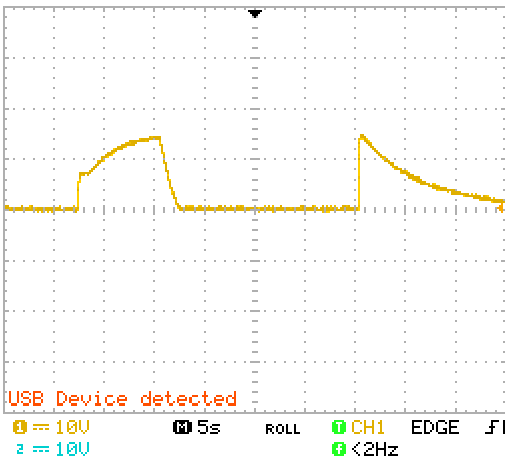

Fig.14 Gate voltage to control the IGBT

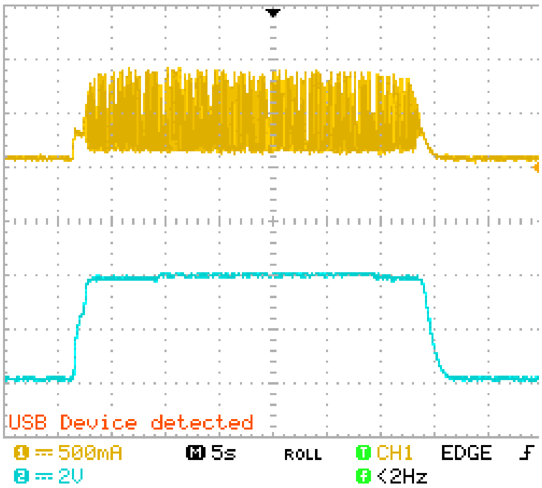

Fig.15 Response to the load by implementation

5 Conclusion

The paper presents a solution to the relay contacts arc problem in electric vehicles by using IGBT to limit inrush current when turning ON and OFF a system. Simulated in MATLAB/Simulink, the proposed system was found to give satisfactory results compared to the conventional system that uses a pre-charge relay in series with a resistor. A prototype of the proposed system was built and tested, the tested results also showed that the proposed system gives satisfactory results.

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