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 an 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 contacts 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, the drain current \( I_{d} \) of the MOSFET transistor equals the base current \( I_{s} \) of the BJT transistor given by Equation (1). The current \( I_{s} \) 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].
\[ \begin{align*}
I_d &= I_b = \frac{1}{2} k (V_{ge} - V_{th})^2 \\
I_c &= \frac{1}{2} k (\beta + 1) (V_{ge} - V_{th})^2 \\
k &= \frac{I_{bc}}{(V_{ge} - V_{th})(V_{ces} + V_{vs}) - \left(\frac{V_{ces} + V_{vs}}{2}\right)^2} \\
K &= \frac{I_{ces}}{2 (V_{ge} - V_{th})(V_{ces} + V_{vs}) - \left(\frac{V_{ces} + V_{vs}}{2}\right)^2} \\
I_c &= K (V_{ge} - V_{th})^2
\end{align*} \]

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.

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.

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 \( I_p \) 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.
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).

\[
V_c = \frac{1}{C} \int_0^{t_1} I_c(t) \, dt \\
t_1 = CV_c \frac{I_c}{I_e} 
\]

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.

![IGBT gate voltage control turning OFF circuit](image)

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 \( R_j \) 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].

\[
V_{ge} = V_{C1} = V_c e^{-\frac{t}{\tau_c}} 
\]
\[ C_2 = \frac{r_2}{R_1} \]  
\[ t_{\text{off}} = 5R_2C_2 \]  

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 \( \mu \)F no-load capacitance (\( C_0 \)), 0.11M \( \Omega \) no-load resistance (\( R_0 \)), 0.08mH no-load inductance (\( L_0 \)), 40\( \Omega \) 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 120\( \Omega \) resistor.

![Fig.5 Conventional control system](image)

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 8.3 A, 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](image)

![Fig.7 Response in the pre-charge relay by conventional control](image)
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.

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 $\Omega$ load resistance and 1H load inductance. Our circuit are compose of optocoupler number TLP251 [7], $R_1$ of 9.4 k$\Omega$, $R_2$ and $R_3$ of 10 k$\Omega$, $C_1$ and
$C_2$ of 470 $\mu$F, $V_1$, $V_2$ 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.

References: