Design Considerations of Power Distribution Control Unit for Electric Buses and Increasing Reliability of the High Voltage Components

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***Abstract*—The use of electric buses is gradually increasing worldwide. The weight and sizes of these vehicles implies the use of high voltage levels up to 750 V. High voltage is used in powertrain to answer high power demand, charging process and other related applications.**

"High Voltage Control Box (HVCB)" or "Power Distribution Control Unit (PDCU)" is responsible for distribution of high voltage to all components in electric vehicles. Also, the status of electrical components and precharge process are controlled by this system. The entire switching operations can be made with high voltage contactors but as they are operating mechanically, their lifespan and reliability level are not enough for automotive applications.

There is no particular study about design parameters of high voltage control unit for electric buses in literature. In this paper, the design and development process of HV control unit is implemented for electric buses and the power inputs of components are controlled by DC (Direct Current) contactors with solid-state switches. Also, the simulation results are shown. In summary, a new approach about PDCU design for electric buses was proposed in this paper.

Keywords—high voltage control unit, electric buses, automotive, IGBT (Insulated Gate Bipolar Transistor) modules, solid-state switching, PCB (Printed Circuit Board)

I. INTRODUCTION

The efficiency and reliability issues of high voltage components always continue to be relevant. This actuality prompts to Electric Vehicle (EV) manufacturer to focus on designing new high voltage control units. If there is one thing mostly of manufacturers agree on, it's that the usage of solid-state switches make the high voltage systems more reliable and long-lasting. These solid-state switches will be mounted in PCB (Printed Circuit Board) to accelereate the production rate and increase the reliability of the control unit. When designing a PCB, the EMC (Electromagnetic Compability) issues may occur because of the switching components. To avoid EMC issues, PCB design must be made very attentively. The integration technology can be one of the leading solution to make control system more applicative.

Unremarkably, the power distribution control units are produced with railway contactors in existing electric buses which are too big to fit in one electric distribution panel. In addition to mounting problems, these contactors can cause the safety problems as well. The huge components obstruct to design of power control system**.**

The majority of studies in literature includes power semiconductor packaging for automotive system, lifetime expectations of IGBT (Insulated Gate Bipolar Transistor) modules for EV applications, design procedures of integrated PDCU for hybrid electric vehicles (HEVs) and different topologies for integrated power units of electrical vehicle. The main overemphasized objective is integrating all related high voltage power distribution unit components such as DC-DC converter, electric motor, on-board battery charger and measurement devices in an one unit. The principal purpose of this approach is making more compact, light-weight and cost effective control unit [2] [3].

Other studies in literature includes the packaging and modelling of power modules for automotive applications because not only for the EVs but also for HEVs, power IGBT modules are crucial component that affecting the reliability, temperature, performance, cost, weight and volume issues [4]. Nowadays, lifetime of IGBT modules, design of high power density modules for high speed switching are discussed by the leading automotive manufacturers [6] [7] [8].

Also, the patents related with power distribution control unit was reviewed and a patent provided an insight to us which is called as "High voltage DC relays" in point of arc suppression [5]. The another patent which was taken as reference relates to a hybrid DC electromagnetic contactor. In the same manner, this patent give an idea for our design about arc prevention [13]. Distinctively from these patents, our new design consists of precharge processes and voltage&current measurement functions.

However, there is no particular study about design parameters of power distribution control unit for electric buses. In this paper, the development process of power distribution control unit is implemented for electric buses and the power inputs of components are controlled by DC contactors with solid-state switches. Also, the solid-state switches individually controlled by a control unit.

In electric buses, main contactor distributes the high voltage to the whole electrical system. During this process, switching applications must be occur and this processes may cause the adhesion of contacts. The precharge process must be done for inhibiting the inrush currents during the DC link capacitor charging.

Due to these reasons, the main purpose of this study is determined as preventing the adhesion of main contactor during switching by using semiconductor switches. In addition to this, safety of HV components and humans will be increased with new design.

The new designed HVCB (High Voltage Control Boxis consist of DC contactors, solid-state switches, IGBT drivers, precharge circuit, power varistor and fuses. In Figure 1, the block diagram of HVCB is depicted.

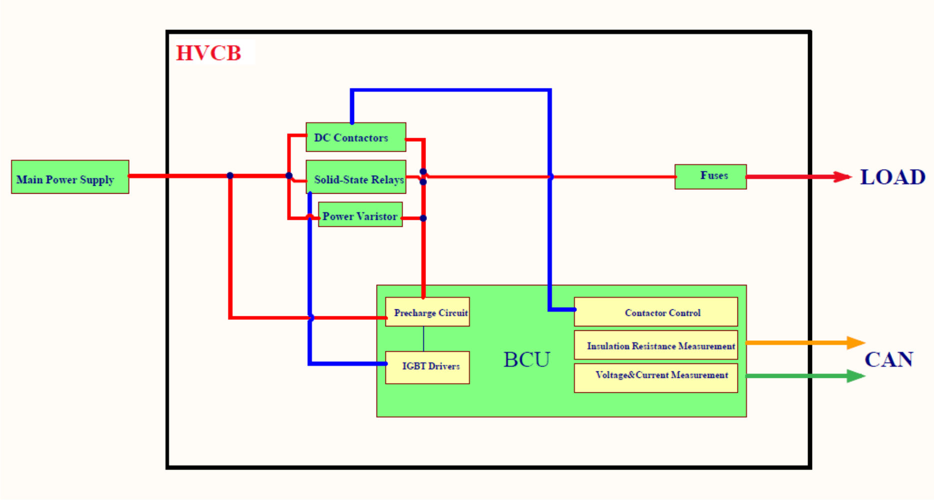

Fig. 1. Block diagram of the HVCB

IGBT drivers are controlled by BMS (Battery Management System) via I/O (Input/Output) line. BMS reads the message which is sent from vehicle body controller via CAN (Controller Area Network) communication protocol and determines the starting or ending times of the high voltage switching operations. Also, BMS communicate with other components of vehicle via CANBUS. The CANBUS is a vehicle bus standard designed to allow microcontrollers and devices to communicate with each other in applications without a host computer. It is a message-based protocol, designed originally for electrical wiring within automobiles, but is also used in many other contexts [1]. Also, the power level of module is suitable for low voltage (24 V) system which are complies with CAN protocols. Our entire vehicle system consists of solid-state relays, BCU (Battery Control Unit), IGBT drivers, power varistor, fuses and BMS.

II. DESIGN CONCEPT

In our design, the adhesion problem of contactors shall be solved with connecting a parallel semiconductor component before the main contactor. Thus, the all arc and stress in the system can be absorbed by this semiconductor element namely IGBT. The safety and reliability of the system can be increased with IGBT modules and the difference of our design based on this approach. In this way, the low and high voltage systems shall be completely separated and isolated from each other. Also, high voltage components are isolated from other components of electric vehicle.

The more active control system can be established with our new integrated design. With this new approach, automotive-grade products will be used for the system. The dimension of automotive-grade components are smaller than other industrial components. Thus, the layout will takes up less space and mounting problems will be removed, so the safety functions will be more active.

The electric buses requires more power than other electric vehicles because of their size and weight, so power distribution control unit design for its is fairly different from other vehicles. In this paper, the focus point is design of PDCU for electric buses and increase the reliability of the high voltage electrical components.

A. Steps of Design Procedure

Mechanical DC contactors are mostly adheres when it is releasing under high current. In case of need, the power must be separated from power line immediately for safety procedure. It is considered that the arc can be suppressed by the operation of semiconductor relays which is connected parallel with the DC contactors immediately before switching moment. In this way, a hybrid solution has been applied for this problem. Also, precharge process will be implemented via semiconductor relays as a result of this solution. With this study, not only protect DC relays but also both user and other components by way of reading current and voltages through connectors and connecting terminals. Thus, some situations will be observed such as whether the charge connector is energized or not and the distribution unit is open or not considering the status of contactors. The new control algorithms will be developed for controlling all situations.

B. System Structure

In Figure 2, the schematic demonstration of aforementioned hybrid design is given. Positive and negative high voltages are indicated with respectively number 1 and 17. Also, precharge components such as precharge resistor and precharge IGBT module are pointed out number 2 and 5. The other important components namely main contactor and arc preventive IGBT module are represented with respectively number 7 and 6. The current of IGBT which is numbered with 6 is measured by number 3 current sensor. The related current information is transmit to the controller. The existence of positive high voltage is sensed with number 4 voltage sensor and the presence of voltage on load side is controlled with number 9 voltage sensor.

Also, the all components that are responsible for charge process are indicated in the figure. The charge relay is denoted with number 11 and charge socket is pointed out number 14. The existence of voltage in the charge socket can be determined with number 15 voltage sensor. The concerned voltage informations are transmit the controller which is indicated with number 10 and these informations are evaluated by this controller. The LED group which is indicated with number 12 is used for determining the existence of voltage in related sensors. The load current is continuously measured by number 16 current sensor. The result of measurement are sent to controller.

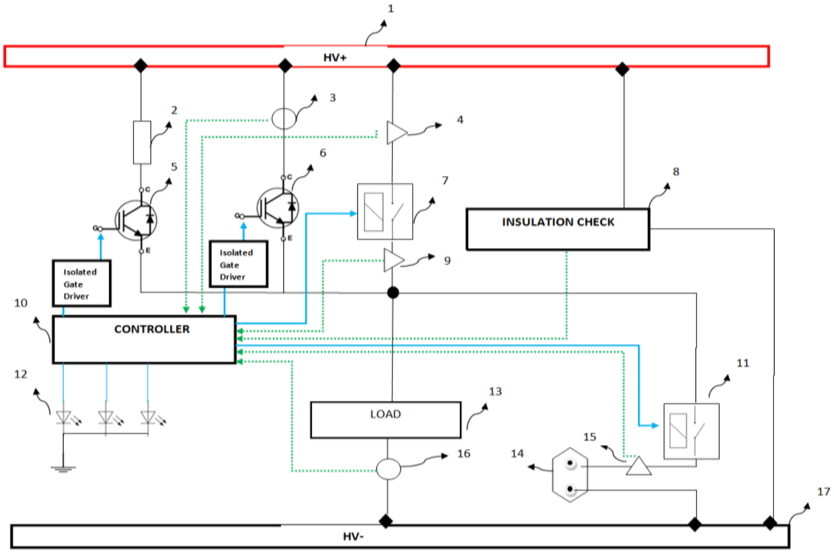

Fig. 2. Schematic demonstration of aforementioned hybrid design

C. Operation Principle of System

When the ignition contact is closed, controller activates the IGBT by sending a signal to gate pin of IGBT. In this way, precharge process is started. When the load voltage becomes stabil, gate signal of IGBT is interrupted by controller and the arc preventive IGBT is activated by sending a signal to its gate pin simultaneously. After the IGBT closed and current is observed in the number 3 current sensor, the main relay is closed by activating the its coil.

In order to determine the current flow through the main relay, the difference of values of number 16 and 3 current sensor measurements must be evaluated. The gate signal of arc preventive IGBT is interrupted and it becomes disabled after the controller senses the current on the main relay.

When the ignition contact is opened, gate signal of arc preventive IGBT is activated again. After the sensing of current in number 3 current sensor, the signal of main relay coil is interrupted and thus main relay contact is separated. During this separation, arc preventive IGBT is operates so, the arc limitations function is implemented by this IGBT module. This function provides reliable switching for HV applications.

Besides, the isolation resistance between HV conductor and vehicle chassis is continuously measured by number 8 isolation test circuit. The measurement signal is transferred to controller. In case of the measured isolation resistance value is lower than predefined reference value, main relay contactor is separated by arc preventive IGBT as mentioned above.

D. Selection Criterias of Electronic Equipments

- **Precharge Circuit Components:** The precharge circuit consists of number 2 PTC resistor and number 5 Precharge IGBT module. The value of each PTC resistor is equal to 100 ohm and it includes two parallel resistors. As a result, totally 50 ohm resistance value is provided and precharge current value is thereabout 15 A. The rates of relevant PTC resistor is given in below Table I:

TABLE I. THE RATES OF PTC RESISTOR

V_{max}	R_R	T_{ref}	$I_{pulsemax}$
800 V	100 ohm	130°C	20 A

In order to calculate how many PTC resistor can be connect parallel for the reliable power distribution control unit, the following formula has been used :

$$\boxed{N \geq ((C*V^2) / (2*C_{th} * (T_{ref} - T_{A,max})))} \quad (1)$$

Where **N, C, V, C_{th}, T_{ref} and $T_{A,max}$** represents the number of required PTC thermistors connected in parallel, the capacitance of DC link capacitor in F, the charging voltage of capacitor in V, heat capacity in J/K, reference temperature of PTC in °C and expected maximum ambient temperature in °C.

For our system, the choosen values for precharge components are like this : DC link capacitor is 100uF, charging voltage of capacitor is 640 V, heat capacity is 2 J/K, reference temperature of PTC is 130°C and expected maximum ambient temperature is 40°C. After the determination of values, the number of required PTC thermistors connected in parallel is evaluated with help of Equation 1. For given values, N was evaluated as "1,13" after calculations. As mentioned at earlier, the other component of precharge circuit is number 5 IGBT module. The concerned electrical parameters are given in Table II.

TABLE II. ELECTRICAL PARAMETERS OF PRECHARGE IGBT MODULE

V_{CE} max	1200.0 V
I_C (@ 100°C) max	33.0 A
I_C (@ 25°C) max	57.0 A
P_{tot} max	200.0 W
$V_{CE(sat)}$ max	1.7 V

The electrical parameters are shown with their abbreviations in Table II namely $V_{CE,}$ I_C and $P_{tot.}$. These parameters are represent respectively Collector-to-Emitter Voltage, Continuous Collector Current and Total Power Dissipation. This IGBT module was chosen in compliance with automotive industry applications. The maximum amount of collector-to-emitter voltage was chosen as 1200 V to not affected from voltage fluctuation.

The most important features of this IGBT is that enduring up to 33 A at 100°C temperature. Thus, the component will effortlessly promote precharge current even in high temperatures. The precharge IGBT is driven with isolated gate driver. Thus, the isolation was provided between vehicle chassis and high voltage components.

- **DC Relay Protection Device:** This semiconductor relay is necessary for protecting the number 6 arc-preventive IGBT module. The function of protection is preventing DC relay arc occurence by operating immediately before rising and releasing of DC relay. The maximum rated values of IGBT is given below where $\mathbf{T_{vj}}$, $\mathbf{T_c}$ and $\mathbf{t_P}$ refers to operating temperature, collector temperature and pulse time respectively.

TABLE III. MAXIMUM RATED VALUES OF IGBT, INVERTER

Collector-Emitter Voltage - V_{CES} (Tvj=25°C)	1200 V
Continuous DC Collector Current - $I_C$nom (Tc=80°C,Tvj=25°C)	800 A
Repetitive Peak Collector Current - I_{CRM} (t_P=1 ms)	1600 A
Total Power Dissipation - Ptot (Tc=25°C,Tvj max=25°C)	3550 W
Gate-Emitter Peak Voltage (V_{GES})	+/- 20 V

The DC relay has been selected at 1200 V level to withstand the high voltages during arc occurence. In addition to this, the current level was selected as 800 A, since it must withstand the load current even at full load. Although the power consumption of IGBT seems high, actually power consumption will be very low since this IGBT will be active for a very short time. The IGBT is driven by an isolated gate driver. Thus, the vehicle chassis can be isolated from high voltage components.

- **Power Varistor Device:** The varistor limits the voltage across the IGBT modules. The varistor clamps the voltage to about 1000 V during dissipation and it is able to protect the IGBT modules against over-voltages. The maximum voltage of IGBT should not be exceeded, otherwise IGBT will be damaged [15]. The B40K550 EPCOS(TDK) varistor devices are chosen for our HVCB design to dissipate the energy.

Fig. 3. B40K550 Varistor device

- **Current Measurement Devices:** For current measurement LEM DHAB series automotive grade current transducers were used. These tranducers has two channels namely "Channel 1" and "Channel 2". Channel 1 can measures the current value -75 to 75 A, and Channel 2 can measures -750 to 750 A.

Fig. 4. LEM DHAB Current sensor

- **Voltage Measurement Devices:** The voltage measurement made by circuit shown below.

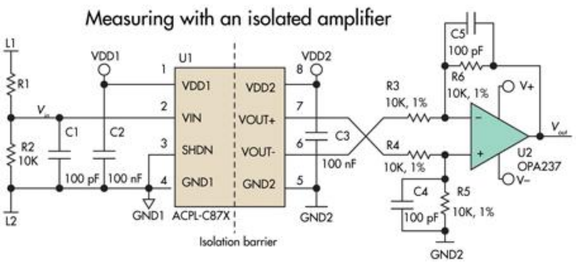

Fig. 5. Voltage measurement circuit with an isolated amplifier [14]

The circuit with an isolated amplifier has two sections as "HV Section" and "Signal Section". In HV section 3.6M high voltage resistor and 10K resistor used to divide HV voltage (0 to 720 V max) to get 0 to 2 V input signal and sensed by isolation amplifier. The galvanically isolated differential output voltage ($V_{OUT+} - V_{OUT-}$) is proportional to the input voltage. The OPA237, configured as a difference amplifier, converts the differential signal to a single-ended output. Then the output was send to battery management system to read and determined which led indicator will be ON.

- **Insulation Check:** The IMD device is used to ensure there is no leakage between HV conductors and Vehicle Battery Chassis. This device works at 0 to 1000 Vdc range and continously measures the insulation resistance and send signals to Battery Management System to stop vehicle and shut down the power.

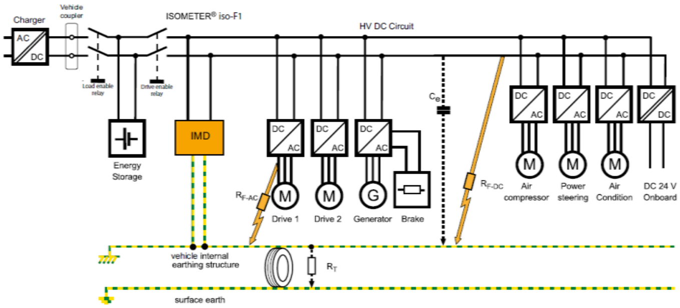

Fig. 6. Typical application of IMD [11]

E. *Methods are Used for Modelling the PDCU*

The new design PDCU system was modelled with MATLAB simulation program. MATLAB is very powerful programming environment with a lot of toolboxes and libraries from different scientific areas. Also, the graphical analysis can be made with MATLAB very efficiently. Having all these in mind, MATLAB is the best choice for modelling our system.

In Figure 7, the generated arc during release of DC relay under high current was shown. When t = 0.80 sec, an arc is generated and the voltage is increase very rapidly up to 1200 V level. This situation can caused damages on the other high voltage components and humans. The new design PDCU system aims to prevent this arc during opening of DC contactor under high currents. The simulation model which has arc-preventive function is given in Figure 7.

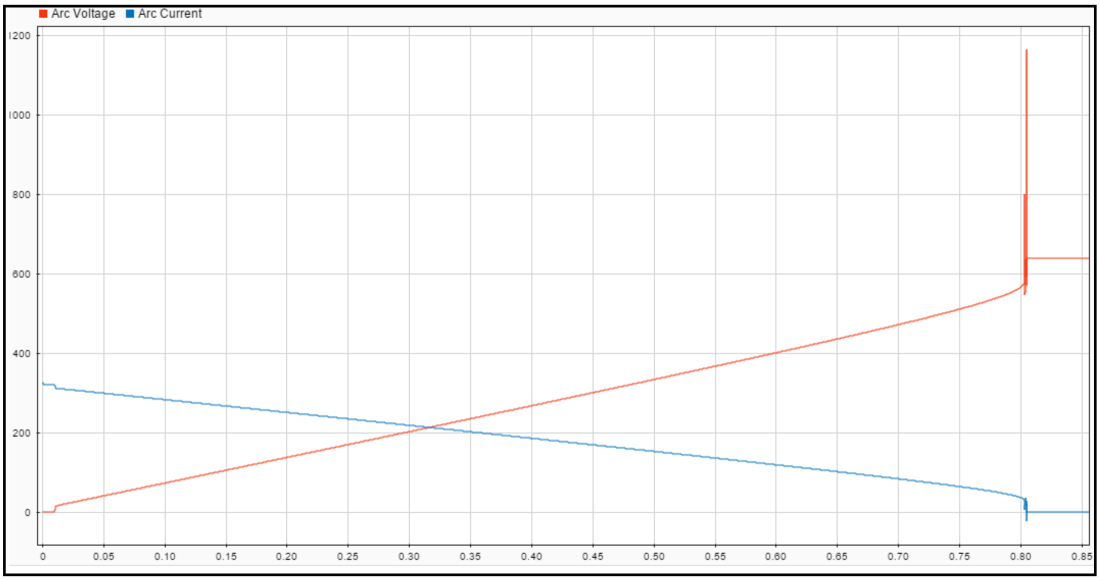

Fig. 7. Generated arc under high current during release of DC relay (Voltage vs. time graphic)

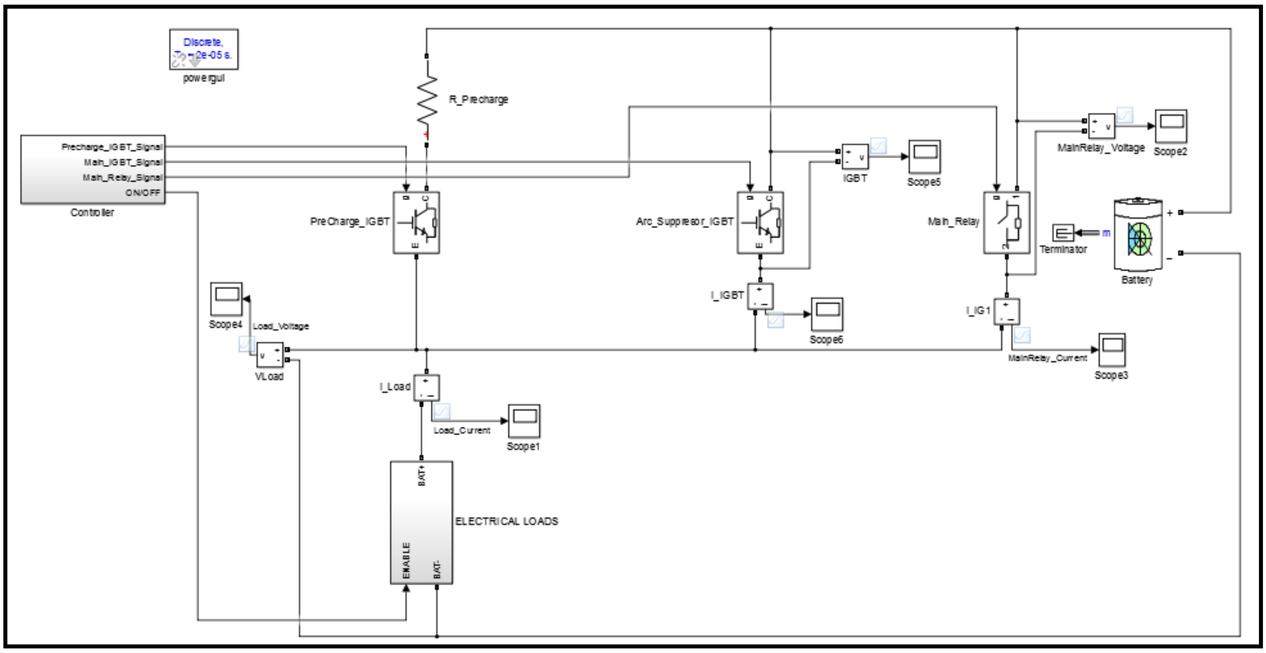

Fig. 8. The arc-preventive simulation model

In Figure 8, the main components of arc-preventive simulation model is shown. The MATLAB simulation model comprise of controller circuit, precharge circuit which is consists of precharge resistor and precharge IGBT, main relay, arc suppressor IGBT and an electrical load. The graphical output of this model is given in following section and the results of analysis are discussed.

III. RESULTS AND DISCUSSION

In Figure 9, the graphical output of our arc-preventive solution model is given. When t=0.01 sec, the switching process is begin but the voltage is never changed until the switching is implemented. As it is seen in the Figure 8, the switching is implemented at t=0.8 sec, at this time the voltage is increase up to approximately 650 V but arc generation is not observed. Also, there is no change in current during switching, so safety is provided for high voltage components.

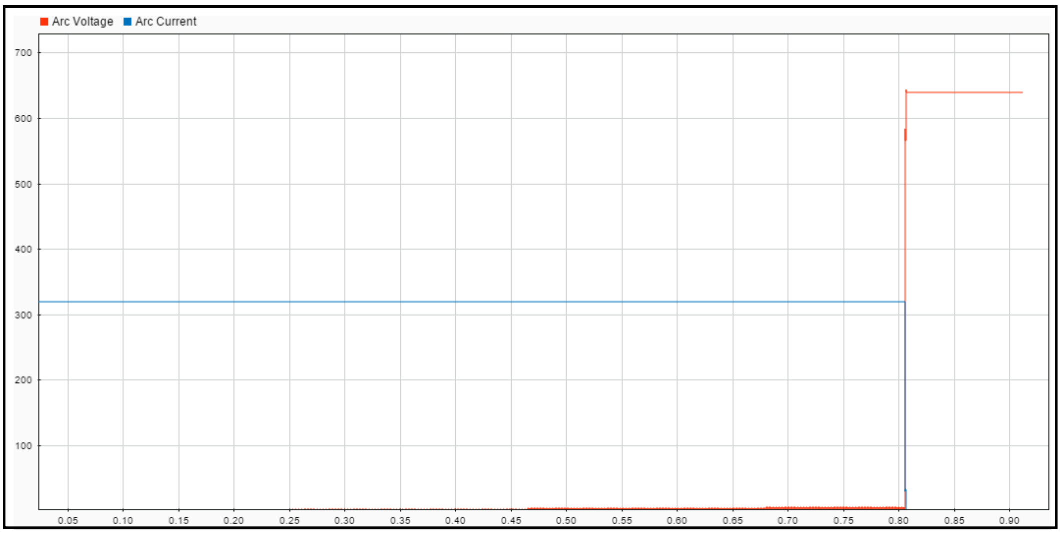

Fig. 9. The graphical output of arc-preventive simulation model (Voltage vs. time graphic)

The main objectives of new design are preventing the adhesion of main relay and precharge contactor. Non-occurrence of arc leads us to the conclusion that the inhibiting contactor adhesion during switching under high current. When considering these facts and the modelling analysis results, we can contentedly say that the our new approach to design of PDCU was succeeded.

IV. CONCLUSION

In this paper, the commercial type of PDCU design for electric buses is underlined. The major contribution of the paper is the detailed explanation of commercial power distribution control unit design and increasing the safety and reliability of high voltage components for electric buses.

Contributions of this study are summarized below:

- Preventing the adhesion of main contactor
- Preventing the adhesion of precharge contactor
- Providing safety for high voltage components and humans
- Developing a new approach for power distribution of electric buses
- Increasing the reliability of high voltage components

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Nomenclature

- **F :** Farad
- **V :** Volt
- **J/K :** Joules per Kelvin
- **DC :** Direct Current
- **EV :** Electric Vehicle
- **HV :** High Voltage
- **PCB :** Printed Circuit Board
- **EMC :** Electromagnetic Compability
- **I/O :** Input/Output
- **HVCU :** High Voltage Control Unit
- **PDCU :** Power Distribution Control Unit
- **CAN :** Controller Area Network
- **BMS :** Battery Management System
- **IGBT :** Insulated Gate Bipolar Transistor
- **PTC :** Positive Temperature Coefficient
- **IMD :** Insulation Monitoring Device

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