

# Development and Analysis of a DC Arc Diagnostic Device for 1000V-Class Electric Vehicle Systems

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This paper presents the development and analysis of a DC arc fault diagnostic device tailored for 1000V-class electric vehicle (EV) systems. As the voltage levels in EV batteries increase from 400V to 1000V to improve charging efficiency and extend driving range, the risk of DC arc faults also rises. Unlike AC systems, DC systems lack current zero-crossing points, making arc extinguishing challenging and heightening fire risks. Through experimental testing using a 1000V, 400A DC power system, this study investigates arc voltage and power characteristics under various load and electrode configurations. The arc behavior was measured at low current levels and predicted at high current levels using the Paukert V-I equation. Results indicate that arc faults must be diagnosed or interrupted within 0.16 seconds to prevent excessive arc energy exceeding 750J, as prescribed by UL1699B standards. The findings provide a foundation for developing a real-time arc fault detection device for high-voltage EV systems.

**Index Terms**—Arc Fault Detector, DC arc fault, Diagnosis, High-Voltage Electric Vehicles

## I. INTRODUCTION

ENHANCING the driving range and reducing the charging time of electric vehicles (EVs) are critical goals in increasing consumer acceptance [1]. One approach to achieve this involves raising EV battery voltages from the traditional 300–400V to 800–1000V [2]. While higher voltage levels enable faster charging and improved efficiency, they also pose significant challenges, particularly in terms of safety.

As the system voltage increases, the probability of DC arc faults rises, presenting a greater fire risk compared to AC systems, where current zero-crossing aids in extinguishing arcs. In high-voltage DC systems such as solar power installations, arc fault detectors (AFDs) are mandated by UL1699B for voltages exceeding 80V [2]. However, similar regulatory standards for EV systems have yet to be established, despite the critical safety risks posed by DC arcs.

To address these challenges, this study focuses on developing and analyzing a DC arc diagnostic device for 1000V-class EV systems. By investigating arc characteristics under real-world conditions, key parameters necessary for arc detection and interruption were identified, providing a basis for reliable arc fault detection in high-voltage EV environments.

## II. DC ARC CHARACTERISTIC TEST

### A. Experimental setup for DC arc characteristic test

To evaluate the characteristics of DC arc characteristic, an experimental setup was designed to simulate arc faults under real operating conditions. The system, depicted in Fig. 1, comprises a DC power supply constructed by connecting 80 units of 12V, 200Ah batteries in series, resulting in an output voltage exceeding 1000V and a total capacity of 400Ah. A DC relay rated at 1500V and 400A serves as a primary switching device to control the power supply output and ensure circuit protection during testing. Additionally, a high-power resistive load with a maximum capacity of 400kW is used to regulate the current across a wide range (2–400A).

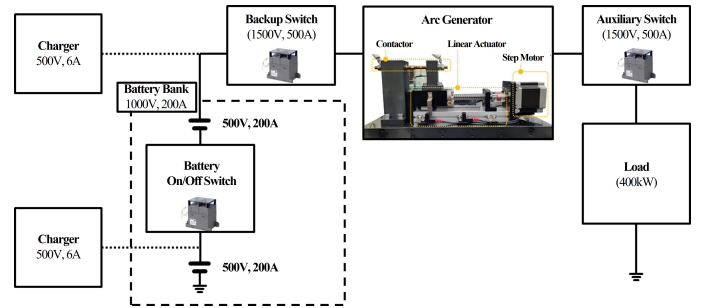


Fig. 1. Configuration of experimental test for DC arc fault

An arc generator was custom-built according to UL1699B specifications. The generator includes adjustable electrodes that can be positioned at specific distances and moved at controlled speeds to simulate various arc fault conditions. This configuration allows for accurate control over key parameters such as electrode gap and opening speed, ensuring reproducibility of the test conditions.

### B. Condition of dc arc detection

The UL1699B standard defines three operational regions (Regions A, B, and C) for arc fault detection and interruption devices, as shown in Fig. 2. The device must diagnose or interrupt the arc when either of the following conditions is met first:

- Arc generation time: 2.5 seconds
- Arc energy: 750J ( $V_{arc} \times I_{arc} \times t_{arc}$ )

If neither condition is satisfied, the device operation is considered non-compliant (Region C). Therefore, an arc fault diagnostic device must ensure that arc faults are detected and interrupted before exceeding either 2.5 seconds of duration or 750 J of energy. This dual criterion necessitates precise monitoring of both arc voltage and current to evaluate arc energy in real time.

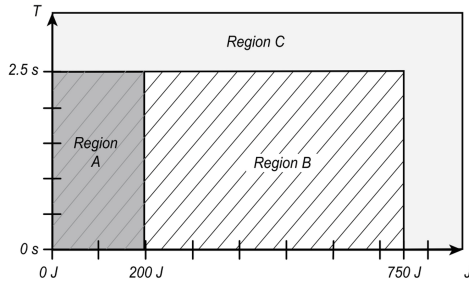


Fig. 2. Arc energy regions (UL1699B)

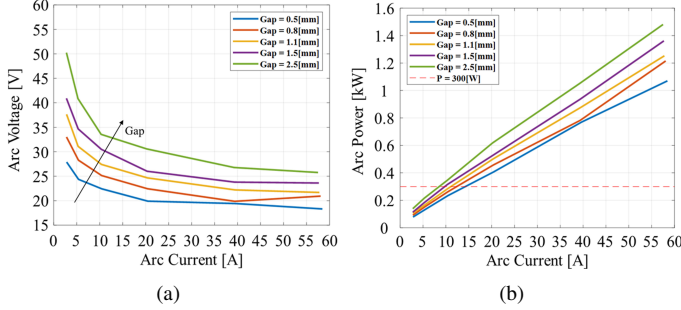


Fig. 3. Measured arc characteristics. (a) Arc voltage v.s arc current, (b) Arc power v.s arc current

### C. Analysis of arc characteristics

The arc characteristics were analyzed under varying load conditions and electrode distances to identify critical factors influencing arc behavior. The test conditions are summarized in Table I. The measured results of arc voltage and arc power as functions of arc current are illustrated in Fig. 3. It was observed that the arc voltage increases proportionally with the electrode distance but stabilizes at higher current levels. Additionally, approximately 2200 J of arc energy was generated under the condition of a 60 A arc current, 0.5 mm electrode gap, and 2 seconds of arc duration. This result highlights the importance of controlling both the arc generation time and electrode movement speed to simulate arc faults under realistic conditions that adhere to the 750 J energy threshold.

Unlike DC arcs in solar power systems, where load levels are relatively low, EV systems involve higher power levels, making it necessary to refine arc testing procedures. In particular, the large load current in EV systems requires careful adjustment of the arc duration and electrode speed to maintain the arc energy within prescribed limits for compliance with UL1699B.

### III. DETERMINATION OF ARC DETECTION TIME

Since the arc should be diagnosed or interrupted before the arc energy reaches 750 J, it is necessary to determine the arc duration by measuring or predicting the magnitude of the arc voltage at 400 A. In this study, the arc duration required to prevent excessive energy accumulation was evaluated by measuring and predicting the arc voltage and power characteristics at different current levels. The arc voltage and power characteristics were predicted using the Paukert V-I equation, which relates arc voltage to current and electrode gap, as shown

TABLE I  
ARC CHARACTERISTICS TEST CONDITIONS

| Items                   | Unit   | Values                            |
|-------------------------|--------|-----------------------------------|
| Input Voltage           | [V]    | 1000                              |
| Resistance Load         | [Ω]    | 12.5, 16.6, 25, 50, 100, 200, 400 |
| Electrode Opening Speed | [mm/s] | 2.5                               |
| Electrode Distance      | [mm]   | 0.5, 0.8, 1.1, 1.5, 2.5           |
| Arc Duration            | [s]    | 2                                 |

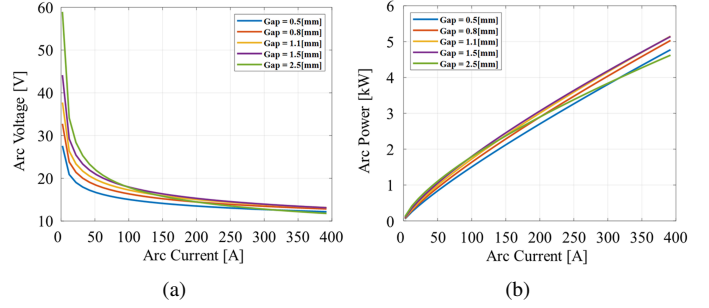


Fig. 4. Calculated arc characteristics. (a) Arc voltage v.s. arc current, (b) Arc power v.s. arc current

in (1) [3]. Fig. 4 shows the predicted arc voltage and arc power characteristics, which is obtained by calculating the parameters of the Paukert V-I equation based on the V-I characteristic curve measured up to 60A.

$$V_{arc} = \frac{a + cL_{gap}}{I_{arc} + dL_{gap}} = \frac{20.19 + 21.05L_{gap}}{I_{arc} + 0.1174 + 0.0075L_{gap}} \quad (1)$$

It is confirmed that an arc power is about 4.5 kW under the conditions of arc current of 400 A and an electrode distance of 0.5 mm. It is figured out that the arc generation time should be set to about 0.16 seconds or less to satisfy the arc energy of 750 J. As a result, the time required to diagnose or interrupt the arc should be at least about 0.16 seconds or less.

### IV. CONCLUSIONS

This study analyzed arc characteristics in a 1000 V, 400 A-class EV system, with measurements up to 60 A and predictions up to 400 A using the Paukert V-I equation. It was determined that arc faults must be diagnosed or interrupted within 0.16 seconds to limit arc energy to 750 J. These findings serve as a foundation for developing an arc fault diagnostic device for high-voltage EV systems. Future work will focus on implementing an arc detection algorithm and validating the device's performance under various operating conditions.

### REFERENCES

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