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Series DC Arc Simulation of Photovoltaic System Based on Habedank Model

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Abstract: Despite the rapid development of photovoltaic (PV) industry, direct current (DC) fault arc remains a major threat to the safety of PV system and personnel. While extensive research on DC fault arc has been conducted, little attention has been paid to the long-time interactions between the PV system and DC arc. In this paper, a simulation system with an arc model and PV system model is built to overcome the inconvenience of the fault-arc experiments and understand the mechanism of these interactions. For this purpose, the characteristics of the series DC arc in a small grid-connected PV system are first investigated under uniform irradiance. Then, by comparing with different arc models, the Habedank model is selected to simulate the fault arc and a method to determine its parameters under DC arc condition is proposed. The trends of simulated arc waveforms are consistent with the measured data, whose fitting degree in adjusted R-squared is between 0.946 and 0.956. Finally, a phenomenon observed during the experiment, that the negative perturbation of the maximum power point tracking (MPPT) algorithm can reduce the arc current, is explained by the proposed model.

Keywords: PV arc fault; DC arc model; fault arc simulation; arc characteristics; renewable energy

1. Introduction

The direct current (DC) fault arc is essentially a gas discharging phenomenon. The huge amount of heat released by the burning arc can easily ignite the surrounding combustible materials [1], which leads to fire hazard and malfunction of the photovoltaic (PV) system. The earliest recorded fire hazard at a PV station caused by DC fault arc dates back to the 1990s [2]. With the rapid growth of PV installed capacity, DC fault arc becomes a potential danger that cannot be ignored. In 2011, an arc-fault interrupter was firstly required in PV systems above 80 V by the National Electrical Code (NEC) [3]. In the same year, the Underwriter Laboratories published UL 1699b, which specifies the test standards of arc-fault circuit interrupters; for example, the arcing time before the operation of interrupter should not exceed 2 s [4]. Since then, the DC fault arc in PV systems has attracted extensive attention from academia and industry.

The DC fault arcs in PV systems can be classified into series and parallel arcs (Figure 1). A series arc is usually formed by disconnection of a conductive circuit, while a parallel arc is caused by the failure of conductor insulation. The series arc can be extinguished by disconnecting the strings, and, in order to extinguish parallel arc, the strings affected by parallel arc should be shorted. In the past few years, the focus of academic research has been on detecting DC fault arcs in PV systems. The burning arc can generate sound, light, and electromagnetic wave which can be used as criteria to detect the arc [5,6]. On the other hand, when an arc is generated, it becomes a part of the PV system, which means...
it can affect the circuit signals of the PV system. The current and voltage signals of PV systems are used by most researchers to extract the arc characteristic signals. An important discovery that the arcing noise mainly exists in the 10–100 kHz frequency band was made by Sandia National Laboratories (SNL) [7]. In addition, because the methods used to extinguish series and parallel arcs are different, three ways to differentiate series and parallel arcs were proposed in [8]. Until now, many different DC arc detection methods have been proposed, including time-frequency domain detection [9–14], artificial intelligence [15–19], spread spectrum time domain reflectometry (SSTDR) [20], arc current entropy [21], and blind-source separation [22].

![Diagram of Direct current (DC) fault arc classifications in a photovoltaic (PV) system.](image)

Arc-fault detection mainly focuses on the changes of PV systems within 2 s after arc ignition according to the suggestion of UL 1699b, while the long-time response of PV systems addresses less attention of researchers. In fact, in order to have a profound understanding of the interactions between arc and PV system, both short- and long-time arc-caused reaction of PV systems should be well studied. Because of the inconvenience of arc-fault experiment and the difficulty of achieving specific experimental conditions such as temperature and irradiance, the influence of arc on the PV system under different conditions can be effectively analyzed through simulation. With the help of modern computer technology, the use of complex arc models has become possible. These arc models are based on fundamental physical equations, such as the conservation equations of mass, momentum and energy, and Maxwell’s equations [23]. The magnetohydrodynamic (MHD) model is one of the sophisticated arc models. The behaviors of arcs were studied in closed containers [24–26] and simple DC power system [27] by MHD modeling. When using MHD models, the focus is mainly on the basic physical characteristics of the arc, such as the movement of arc column, distribution of arc temperature, and particle velocity. However, when studying the interactions between the arc and external circuit, the focus is on the response of the circuit and the changes of the arc. Due to the complexity of the MHD model, some researchers chose simpler arc models to study how the arc and the circuit affect each other. In [28], the arc was simplified as a constant value resistor in the simulation, and the influences of the series and parallel arc on the PV system were analyzed. In [29], series DC arc faults were simulated in a DC microgrid. The arc was modeled as a resistor in parallel with a Gaussian noise source. This method enables the model to describe the randomness of the arc. In order to describe the general voltage–current (U–I) characteristics of the arc, some researchers chose dynamic arc models instead of resistors in simulation. In [30], the Heuristic model was applied to model three different types of series DC arcs in a low voltage microgrid without PV system. In [31], the PV system was simplified as a resistive system in simulation, and the Cassie model was chosen to simulate the series DC arc. In order to be close to reality, other researchers applied a complete PV system with PV array, maximum power point tracking (MPPT) function, and inverter in simulation. In [32], a modified Paukert model and pink noise were selected to simulate the voltage–current and noise features of series arc, respectively, in a PV system. The impact of PV system on arc was analyzed in frequency domain. In [33], a PV-based DC microgrid model containing arcs was built in MATLAB. In [34], 10 different arc models were used to model series arcs in a PV system. Unfortunately, both [33,34] only presented the fault signals within 2 s, because the purpose of the systems was to verify the proposed fault detection or arc location algorithm.
Therefore, a more suitable model should be proposed to study how the arc and PV system affect each other over a long time.

In summary, compared with the studies on arc-fault detection methods, there is limited research on DC arc simulation of PV systems. Thus, the objective of this article is to build a model that can simulate DC arc in a PV system, so that the long-time interactions between the arc and PV system can be studied more conveniently and deeply. In this paper, the long-time changes of arc current and voltage waveforms collected through experiments are first analyzed to study the variations of arc in PV system. Then, by comparing with other commonly used arc models, the Habedank arc model is selected to simulate the U–I feature of the arc. Moreover, the parameters determination process of Habedank model for long-time DC arc is introduced. Finally, the simulation is carried out by combining the arc model and a PV system model. Through the simulation results, the mechanism of interactions between the series arc and perturb & observation (P&O) MPPT algorithm is explained.

2. Experimental Setup

Because of its higher possibility of occurrence than parallel arc [10], series arc was chosen to study here. The experiment was conducted at a small grid-connected PV station. The topology of experimental circuit is shown in Figure 2. The PV array with a single string of 10 solar panels is connected to the grid with the help of a two-stage inverter. A two-stage inverter with boost circuit is usually used in small-scale PV station because the output voltage of PV array needs to be stepped up to meet the grid connection requirement. The series fault arc is generated at the DC bus, therefore, the arc current is equal to the DC bus current.

![Figure 2. The topology of experimental circuit and influence factors of arcing.](image)

The arc behavior is influenced by the properties of discharge gas and electrodes [35–37]. The discharge gas of fault arc is air, which means the gas components, ambient temperature, pressure, and chemical reactions are basically unchanged during the experiment. The electrodes used in the experiment were flat-tip copper columns, which are unified in shape and material. Hence, the airflow and other properties of electrodes, such as current, voltage, and gap width, are the major factors that determine the variations of arcs in the PV system. A flat-tip copper electrode was selected because it can reproduce the characteristics of devices such as connectors that often generate arcs in photovoltaic systems. In Figure 3, an arc-generating platform consisting of an arc-generating device and an acrylic glove box was built, so that the manipulability of experiment could be improved. The fault arcs were generated by separating the electrodes of the arc-generating device. Because the wind will cause the elongation of arc, resulting in a sudden change in the arc voltage [38], a glove box was used to isolate the arc from the outside atmosphere in order to obtain a smooth arc. In addition, the transparent acrylic glove box can provide good observation conditions while blocking splashing combustion. The type of solar panel, inverter, and measuring equipment used in the experiment are shown in Table 1. The parameters of solar panel are given in standard test conditions (1000 W/m² irradiance, 25 °C ambient temperature, and air mass 1.5). The experiments were conducted under uniform irradiance of around...
900 W/m². Besides, six years of operating time attenuates the output of PV array. Therefore, the measured arc current which is equal to the output current of PV array is less than 7.8 A.

3. Arc Fault Signals

The arc is equivalent to a load in the PV system, and its state is affected by the output of the PV array. In a PV system, the output power of PV array is maximized through MPPT. Thus, the state of the arc is mainly affected by the MPPT under certain environmental conditions (Figure 4). At \( t_0 \), the arc is generated by separating the two copper electrodes of the arc-generating device. \( t_0 \) is 0.2 s after the beginning of MPPT period I. The DC bus current which is equal to the arc current steps down to \( I_{arc_0} \), while the arc voltage steps up to \( U_{arc_0} \). From \( t_0 \) to \( t_m \), as the gap between the electrodes keeps growing, the arc current therefore continues to decrease, while the arc voltage continues to increase. During this period, the influence of MPPT on the arc is obscured by the intensified arc. At \( t_m \), the gap between the electrodes reaches the maximum. As a result, the arc current reaches the minimum value \( I_{arc_m} \), and the arc voltage reaches the maximum value \( U_{arc_m} \). During the MPPT period II, the current fluctuation around \( I_{arc_m} \) and the voltage fluctuation around \( U_{arc_m} \) after \( t_m \) are due to the irregular jumping of the arc.

![Figure 3. Arc generating platform.](image)

| Solar Panel Type | Maximum Power Point | Short-Circuit Current | Open-Circuit Voltage |
|------------------|---------------------|-----------------------|---------------------|
| JT240PLe         | (7.8 A, 30.8 V)     | 8.55 A                | 37.2 V              |
| Inverter         | Oscillator          | Current Probe         | Voltage Probe       |
| Zeverlution3000S | Tektronix           | Tektronix             | Sapphire            |
|                  | MSO2024             | TCP0030               | SI-9110             |

![Table 1. Experiment conditions.](image)

![Figure 4. Typical arc voltage and current waveform changes under the action of maximum power point tracking (MPPT) and reduced gap due to the thermal expansion of the electrodes.](image)
From MPPT period III, the arc current increases gradually to \( I_{\text{arc.fin}} \) in a stepped manner, and the arc voltage decreases gradually to \( U_{\text{arc.fin}} \). \( I_{\text{arc.fin}} \) is equal to the DC-link current before the arc occurs. The stair-step arc current waveform is caused by the MPPT action. The width of the step is 2 s, which is equal to the interval of MPPT action. Because the arc voltage is inversely proportional to arc current and proportional to arc length [39], when the arc current increases gradually, the arc voltage decreases correspondingly. Besides, a phenomenon of reduced gap occurs due to the thermal expansion of the electrodes, as shown at the bottom of Figure 4. The gap is photographed every 10 s from \( t_m \). Because of the isolation of the glove box, the arc length is approximately equal to the width of the gap. Thus, the arc length decreases as the gap decreases, which results in the decrease of the arc voltage. In summary, the reduction of the arc voltage is caused by increasing arc current and decreasing gap.

Especially if the gap is too small, the distance between the electrodes will decrease to zero due to the thermal expansion of the electrodes, which means a spontaneous arc-extinguishing situation occurs (Figure 5). The arc is generated at \( t_0 \). At \( t_1 \), the two electrodes are in contact because of thermal expansion, and the arc is extinguished. During \( t_1 \) and \( t_2 \), without the arc to produce heat, the electrodes gradually cool and contract. At \( t_2 \), the cooled electrodes separate from each other, and the arc reignites. At \( t_3 \), the two electrodes contact each other again, causing the arc to extinguish.

![Figure 5](image)

**Figure 5.** Spontaneous arc-extinguishing phenomenon due to thermal expansion of electrodes.

Sometimes, the lowest DC-link current is not caused by the series arc but the action of the MPPT (Figure 6). At \( t_m \), the gap between the electrodes reaches the maximum. The arc current should have reached its minimum value in MPPT period II. However, during MPPT period III, the arc current steps down to a lower level due to the negative perturbation of MPPT. In addition, due to the inverse relationship between the arc current and the arc voltage, the arc voltage reaches its maximum value in MPPT period III. The main difference between arc waveforms in Figures 4 and 6 is that the arc current in Figure 4 starts to increase from MPPT period III, while the arc current in Figure 6 continues to decrease. A complete explanation of this phenomenon is shown in Section 6 along with the simulation results.

![Figure 6](image)

**Figure 6.** Minimum arc current and maximum arc voltage caused by MPPT.
4. DC Fault Arc Model

Some variables that are crucial to the operation of the PV system are difficult or inconvenient to obtain during the arc-fault experiment, for example, the duty cycle of the boost circuit given by the MPPT algorithm. However, with the help of simulation, all those important variables can be monitored at the same time. The first step to establish an arc-fault PV system is to select an appropriate arc model.

4.1. U–I Arc Model

Since 20th century, many U–I arc models have been developed based on the characteristics of arc voltage, current, and length [39]. The earliest equation for arc modeling was proposed by Ayrton as [40]

\[ U_{\text{arc}} = A + BL + \frac{C + DL}{I_{\text{arc}}}, \]

where \( A \) is the voltage drop of electrodes, \( B \) is voltage gradient, \( C \) and \( D \) are empirical constants, \( L \) is arc length, and \( U_{\text{arc}} \) and \( I_{\text{arc}} \) are arc voltage and current, respectively.

Due to thermal expansion and ablation of electrodes caused by the arc, the variation of electrode gap is nonlinear. Therefore, for long-time arcs, it is difficult to obtain accurate gap width during arcing. In addition, the arc will bend because of the Lorentz force generated by itself [27], so the actual arc length cannot be obtained by simply measuring the electrode gap. As a result, the arc length \( L \) or gap width is the major factor that affects the accuracy of the long-time arc simulation using U–I arc models. Other U–I arc models such as Paukert model [41] and Stokes and Oppenlander model [42] also suffer from the same problem.

4.2. Physics-Based Arc Model

The physics-based arc model is also called the arc black box model, which is derived from the principle of energy balance. It has been widely used in simulation or calculation of arc-containing circuits, such as circuit breaker [43–45], railway traction system [46], and aircraft power system [47]. The Cassie [48] and Mayr [49] arc models are the most classic black box arc models and are suitable for the simulation of large current and small current arcs, respectively. In order to improve the applicable current range of the arc model, the Habedank arc model considers the arc to be composed of two parts in series, which are described by the Cassie and Mayr arc models, respectively [50]:

\[
\begin{align*}
\frac{1}{g_M} \frac{dI_M}{dt} &= \frac{1}{\tau_M} \left( P_0 - \frac{I^2}{2g_M} - 1 \right) \\
\frac{1}{g_C} \frac{dI_C}{dt} &= \frac{1}{\tau_C} \left( \frac{U^2}{2g_C} - 1 \right) \\
\frac{1}{g} &= \frac{1}{g_M} + \frac{1}{g_C},
\end{align*}
\]

where \( g \) is arc conductance, \( i \) is arc current, \( g_M \) and \( g_C \) are conductance described by the Mayr and Cassie arc models respectively, and \( \tau_M \) and \( \tau_C \) are Mayr and Cassie time constants, respectively, \( P_0 \) is power loss in Mayr arc model, and \( U_C \) is arc constant in Cassie arc model. The output current of the PV array is related to solar irradiance and the topology of PV array, meaning the output current varies in a large range. Thus, the Habedank arc model considers the arc to be composed of two parts in series, which are described by the Cassie and Mayr arc models, respectively [50]. After applying the method in Section 4.3 to Habedank model, only three parameters remain to be determined. And two of the three parameters are time constants \( \tau_M \) and \( \tau_C \). Therefore, it gives Habedank model the advantage in parameter determination over other arc black box models, such as Schavemaker model [51] and Schwarz model [52].
Comparisons between Habedank model and other types of models commonly used to simulate the arc are shown in Table 2. Although the arc models based on fundamental physical equations have the advantage of describing the chaotic behavior of the arc, they require high computing power. Approximations have been taken by researchers such as Lowke [53] to reduce the complexity of the physical equations of the arc. Based on simplified physical equations, these arc models can obtain the basic physical quantities of arc, while the complexity is moderate. However, changing arcing conditions, such as nonlinearly varying electrode gap and melting electrodes, make it difficult in determining the boundary conditions of physical equations. Compared with U–I arc models, the parameters of Habedank model do not contain arc length or gap width, which means simulation results will not be affected by inaccurate measurement of arc length and gap width. Therefore, the Habedank model can be selected to simulate long-time DC arc in PV system.

Table 2. Characteristics of different types of arc models.

| Model                                      | Advantage                                         | Computing Power Requirement |
|--------------------------------------------|---------------------------------------------------|----------------------------|
| U–I arc model                              | Easy to build the model                           | Low                        |
| Habedank model                             | No need to measure the arc length and gap width   | Low                        |
| Arc models based on simplified physical equations | The basic physical quantities of arc can be obtained, while the complexity is moderate. | Low to medium |
| Arc models based on fundamental physical equations | Describe the chaotic behavior of arc              | High                       |

4.3. Parameters Determination of Habedank Arc Model

Unlike alternating current (AC) arc, the current of the DC arc has no zero-crossings. After the DC arc is stable, its conductance is almost constant. Hence, except that $\tau_M$ and $\tau_C$ are empirical values, $P_0$ and $U_C$ cannot be determined by the method in [50]. Based on the assumption that $g_M$ is equal to $g_C$, a method to determine the parameters of Habedank arc model under steady state is proposed in [54]. However, this assumption is not always satisfied in reality. Thus, a modified method to determine $P_0$ and $U_C$ needs to be proposed for the DC arc in PV systems. Since the arc variation time is on the order of microseconds [55], its variation time is negligible compared to the time required for electrode expansion and interval of MPPT action. Therefore, if small variation caused by irregular jumping of arc is ignored, the change of arc can be regarded as a transient state, during which the conductance of the arc is constant. Thus, the conductance described in the Habedank arc model can be presented as the following equation:

$$ \begin{cases} \frac{dg_M}{dt} = 0 \\ \frac{dg_C}{dt} = 0 \end{cases} \tag{3} $$

By substituting (3) into (2), the following equation can be obtained:

$$ \begin{cases} i^2 = P_0 \cdot g_M \\ i = U_C \cdot g_C \end{cases} \tag{4} $$

By assuming $g_C = \alpha g_M$, where $\alpha$ is a positive constant, the following equation can be deduced:

$$ \begin{cases} g_M = \frac{1+\alpha}{1+\alpha} \cdot g \\ g_C = (1 + \alpha) \cdot g \end{cases} \tag{5} $$

Finally, by substituting (5) into (4), parameter $P_0$ and $U_C$ can be described by the following equation:

$$ \begin{cases} P_0 = \frac{\alpha}{1+\alpha} \cdot uu \\ U_C = \frac{1}{1+\alpha} \cdot u \end{cases} \tag{6} $$
where \( u \) is arc voltage. As a result, \( P_0 \) can be regarded as the function of \( \alpha \), \( u \), and \( i \). And \( U_C \) can be regarded as the function of \( \alpha \) and \( u \).

When calculating \( P_0 \) and \( U_C \) according to Equation (6), the variation of arc current \( i \) and voltage \( u \) is simplified as linear. Figure 4 is taken as an example to illustrate: From \( t_0 \) to \( t_m \), the arc current decreases linearly from \( I_{arc,0} \) to \( I_{arc,m} \), while the arc voltage increases from \( U_{arc,0} \) to \( U_{arc,m} \). From MPPT period III, the arc current increases linearly to \( I_{arc,fin} \), while the arc voltage decreases to \( U_{arc,fin} \). The advantage of this method is that only a few special moments of arc current and voltage values are required. Moreover, the process of determining parameters \( P_0 \) and \( U_C \) is simplified to determine the value of \( \alpha \).

After \( u \) and \( i \) are determined for calculation, different \( \alpha \) will result in different simulated arc currents and voltages (Figure 7). When \( \alpha = 1 \), the contribution of the Cassie and Mayr equation to the Habedank arc model are the same. As \( \alpha \) decreases, the simulated arc current increases, while the simulated arc voltage decreases, and the contribution of the Cassie equation increases. On the contrary, when \( \alpha \) increases, the contribution of the Mayr equation increases. Therefore, according to this relationship between \( \alpha \) and arc current and voltage, an appropriate value of \( \alpha \) can be obtained when the differences between simulation results and experimental data reach the minimum.

![Graph showing the influence of \( \alpha \) on simulated arc current and voltage when \( P_0 \) and \( U_C \) are constant.](image)

**Figure 7.** The influence of \( \alpha \) on the simulated arc current and arc voltage when \( P_0 \) and \( U_C \) are constant.

## 5. Model Validation

### 5.1. Simulation Setup

According to the experimental circuit, a simulation circuit including Habedank arc model and PV system was built in MATLAB/Simulink (Figure 8). In the boost circuit, the input capacitor \( C_1 \) and output capacitor \( C_2 \) are decoupling capacitors used for mitigating the power fluctuation effect at the PV-array side and balancing the power between DC side and AC side, respectively [56]. \( I_{pv} \) and \( U_{pv} \) are the output current of PV array and the voltage on the input side of boost circuit, respectively. \( D \) is the duty cycle of the boost circuit.

![Simulation circuit diagram](image)

**Figure 8.** Simulation circuit.
A variable-step-size MPPT based on the P&O algorithm was adapted in simulation to maintain the maximum output of the PV array [57]. The duty cycle $D$ is determined by the MPPT algorithm. Table 3 shows the arc model parameters setting of the arc waveforms in Figures 4 and 6. The mean values of arc current and voltage were used in simulation when calculating $P_0$ and $U_C$.

### Table 3. Habetdank arc model parameters setting.

| Figure 4 | $\tau_M$ | $\tau_C$ | $\alpha$ | $I_{arc_0}$ | $I_{arc_m}$ | $I_{arc_fin}$ | $U_{arc_0}$ | $U_{arc_m}$ | $U_{arc_fin}$ |
|----------|----------|----------|----------|-------------|-------------|-------------|-------------|-------------|-------------|
| $10^{-5}$ s | $10^{-5}$ s | 0.1 | 5.7 A | 4.1 A | 6.6 A | 15.5 V | 39.9 V | 24.1 V |

| Figure 6 | $\tau_M$ | $\tau_C$ | $\alpha$ | $I_{arc_0}$ | $I_{arc_m}$ | $I_{arc_fin}$ | $U_{arc_0}$ | $U_{arc_m}$ | $U_{arc_fin}$ |
|----------|----------|----------|----------|-------------|-------------|-------------|-------------|-------------|-------------|
| $10^{-5}$ s | $10^{-5}$ s | 0.1 | 5.7 A | 5.1 A | 6.8 A | 17.2 V | 32.3 V | 19.1 V |

#### 5.2. Simulation Results

The simulation results of experimental arc waveforms in Figures 4 and 6 are shown in Figures 9 and 10 respectively. Although the proposed model cannot describe chaotic variations of the arc current and voltage, the trends of all simulation waveforms are consistent with the experimental waveforms. The simulated arc current waveforms have the same step-like changes as the experimental waveforms after $t_m$.

![Figure 9. Simulation results of arc waveforms in Figure 4.](image_url)

![Figure 10. Simulation results of arc waveforms in Figure 6.](image_url)

Equations used to calculate the signed relative error (SRE) of the simulation results are shown as follows:

$$SRE_I = \frac{I_s - I_e}{I_e} \times 100\%, \quad (7)$$

$$SRE_U = \frac{U_s - U_e}{U_e} \times 100\%, \quad (8)$$
where $SRE_I$ and $SRE_U$ are SREs of the simulated arc current and the simulated arc voltage, respectively; $I_e$ and $I_s$ are measured and simulated arc currents, respectively; and $U_e$ and $U_s$ are arc voltages obtained by experiment and simulation, respectively. The positive or negative of SER reflects the position of the simulated waveforms relative to the experimental waveforms; that is, a positive SRE indicates that the simulated waveform is above the experimental waveform, while a negative SRE means the simulated waveform is below the experimental waveform. The SREs of simulation results are shown in Figure 11, where the SREs are calculated every 0.1 s.

Despite the impact of external airflow on the arc being minimized by the utilization of glove box, the arc still represented chaotic behaviors including elongation, shortening, and spot motion. These dynamic movements are mainly caused by Lorentz force generated by the arc and electrodes [58,59], resulting in the fluctuation of arc voltage. Thus, the experimental voltage waveforms fluctuate around the simulated voltage waveforms, which causes the positive and negative alternation of $SRE_U$. As the gap between the electrodes decreases after $t_m$, the variation of the arc length decreases relatively, the absolute value of $SRE_U$ therefore decreases correspondingly. Because of the inverse relationship between the arc current and arc voltage, $SRE_I$ and $SRE_U$ change in opposite directions, which can be better observed in MPPT period I, II, and III. Although the maximum mismatches of simulated arc current and voltage reach 14.8% and 18.6% respectively, there is good correlation between the simulation results and the measured ones with adjusted R-squared from 0.946 to 0.956. The adjusted R-squared is a statistics measure that represents the correlation between simulation results and experimental values. A comparison between the simulation results and the ones in other references is shown in Table 4. It shows that the proposed model is competitive to other models.

![Figure 11. Signed relative errors of simulation results: (a) relative error of simulated arc current in Figure 9; (b) relative error of simulated arc voltage in Figure 9; (c) relative error of simulated arc current in Figure 10; (d) relative error of simulated arc voltage in Figure 10.](image)

**Table 4.** Comparison between the simulation results and other references.

| Simulated Results or Reference | Adjusted R-square |
|-------------------------------|------------------|
| Figure 9                      | 0.946 (Arc current) 0.946 (Arc voltage) |
| Figure 10                     | 0.956 (Arc current) 0.948 (Arc voltage) |
| [60]                          | 0.952            |
| [61]                          | >0.9             |

6. Discussion

In the previous section, the validity of the proposed simulation system is verified. It is difficult to understand the interactions between the arc variation and MPPT action from the experimental data. However, these complicated interactions can be well analyzed with the help of simulation.
The main difference between the simulated arc waveforms in Figures 9 and 10 is that the arc current in Figure 10 drops to a lower level in MPPT period III, while the arc current in Figure 9 does not. Before further explanation, it is necessary to understand how MPPT maintains the maximum output of PV array (Figure 12a). The PV array can be simplified to a current source $I_{PA}$ connected to a variable resistance $R_{PA}$ in parallel, and the load is simplified as a constant resistance $R$. For a boost circuit, the following equations can be obtained:

$$U_0 = \frac{U_{pv}}{1 - D},$$  \hspace{1cm} (9)  

$$I_0 = (1 - D)I_{pv},$$  \hspace{1cm} (10)  

where $U_0$ and $I_0$ are the output voltage and output current of the boost circuit, respectively. Thus, the equivalent resistance of the external circuit without arc ($R_{\text{normal}}$) can be derived as follows:

$$R_{\text{normal}} = \frac{U_{pv}}{I_{pv}} = (1 - D)^2R.$$  \hspace{1cm} (11)  

![Simplified circuit of PV system with MPPT and changes of PV array operation point in arc-fault condition.](image)

*Figure 12.* (a) Simplified circuit of PV system with MPPT and (b) the changes of PV array operation point in arc-fault condition.

The output power of PV array ($P_{PA}$) can be obtained as:

$$P_{PA} = \left(\frac{I_{PA}R_{PA}}{R_{\text{eq}} + R_{PA}}\right)^2R_{\text{normal}}.$$  \hspace{1cm} (12)  

When $R_{\text{normal}}$ is equal to $R_{PA}$, the PV array has the maximum output power. Therefore, MPPT can achieve the maximum power point (MPP) of PV array by controlling $D$.

For a PV array under certain irradiance and temperature, its operation point (OP) is the intersection point of its U–I curve, and the line with a slope of $1/R_{\text{eq}}$, where $R_{\text{eq}}$ is the equivalent resistance of the external circuit (Figure 12b). In a nonfault condition, the OP$_1$ oscillates in a very small range around MPP. When an arc occurs at the DC bus, the OP jumps from OP$_1$ to OP$_2$, causing the voltage of PV array to step up. The equivalent resistance of the external circuit when arc happens ($R_{\text{faulted}}$) can be obtained as:

$$R_{\text{faulted}} = R_{\text{arc}} + (1 - D)^2R,$$  \hspace{1cm} (13)  

where the $R_{\text{arc}}$ is the arc resistance. As the gap between the electrodes increases, the $R_{\text{arc}}$ increases correspondingly; therefore, the OP gradually moves from OP$_2$ to OP$_3$. In order to move the OP from OP$_3$ to MPP, the duty cycle $D$ must be increased to reduce the $R_{\text{faulted}}$ to $R_{\text{normal}}$.

Since the increase and decrease of $D$ are controlled by MPPT algorithm, the variation of arc current in both experiment and simulation can be explained by the judgements of MPPT algorithm under arc-fault state. The flowchart of P&O algorithm used in the simulation is shown in Figure 13, where the $\Delta P_{\text{boost}}$ is the variation of the input power of the boost circuit, and $\Delta D$ is the variable step of the MPPT algorithm. The variable Flag has two values, 0 and 1, which refer to the negative and positive
perturbations of MPPT, respectively. A negative perturbation indicates a decrease in $D$, while a positive perturbation indicates an increase in $D$. When entering a new MPPT period, $I_{pv}$ and $U_{pv}$ will be first sampled, and then the MPPT algorithm will determine the variation of $D$ according to the sign of $\Delta P_{\text{boost}}$ and the value of $\text{Flag}$ in the previous MPPT period.

![Figure 13. Flowchart of the perturb & observation (P&O) algorithm.](image)

When P&O algorithm is selected as the MPPT algorithm, the variations of $D$ and $P_{\text{boost}}$ are shown in Figure 14. From $t_0$ to $t_m$, due to the intensifying arc, the $P_{\text{boost}}$ drops down gradually, leading to a negative $\Delta P_{\text{boost}}$. Thus, in MPPT periods II and III, the variation of $D$ is opposite to that of the previous MPPT period, according to Figure 13. As discussed above, in order to increase the output of PV array, $D$ must be increased. Hence, from MPPT period II, the decrease of $D$, which is a negative perturbation of MPPT, moves the OP further away from OP$_1$, resulting in the decrease of arc current, $P_{\text{boost}}$, and the output power of PV array. In Figure 14a, the P&O algorithm keeps $D$ increasing from MPPT period III, causing the OP to move towards OP$_2$ and the arc current to increase. The occurrence of negative perturbation is in the same MPPT period as the moment when the electrode gap reaches maximum. Therefore, the minimum value of the simulated arc current appears in MPPT period II. In Figure 14b, the negative perturbation of MPPT occurs in MPPT period III, causing the OP to move further away from OP$_1$. As a result, the arc current and $P_{\text{boost}}$ drop down to a lower level.

![Figure 14. When P&O is selected as the MPPT algorithm, the variations of simulated $D$ and $P_{\text{boost}}$ in (a) Figure 9 and (b) Figure 10.](image)

In summary, the influence of MPPT on the arc is that the arc current changes in a stair-step manner from MPPT period III. The arc can also affect the MPPT through negative perturbations. Under arc-fault condition, the negative perturbations of MPPT decrease the output power of the PV array, which is the opposite of the purpose of MPPT. Besides, the negative perturbation also affects the change of arc current. That is, if $\text{Flag}$ is equal to 0 at $t_m$, the arc current $I_{arc}$ will start to increase in the next MPPT period. On the contrary, if $\text{Flag}$ is equal to 1 at $t_m$, a lower $I_{arc}$ will appear in the next MPPT period due to the negative perturbation.
7. Conclusions

This paper has introduced a method to simulate the long-time-series DC arc in a PV system using MATLAB/Simulink software. The Habedank model was selected to simulate the U–I characteristics of the long-time DC arc, because it is not affected by the varying gap width, its parameters are simple to determine, and the computing power requirement is low. And the parameters determination process of Habedank model under the condition of long-time DC arc was introduced. Then, a PV system based on a P&O MPPT algorithm was combined with the Habedank model for long-time DC arc simulation under uniform irradiance. The simulation results show good correlation with the measured data. Finally, based on the simulation results, the interactions between the arc and MPPT were investigated. It shows that the arc can cause the P&O MPPT algorithm to reduce the output power of PV array through negative perturbation of MPPT, while the MPPT can influence the change of arc current.

In order to have a preliminary understanding of complex interactions between the arc and PV system, this study was conducted under uniform irradiance, which is the simplest situation. However, there are many complicated situations in reality. Therefore, the following research should be carried out in the future: (1) the interactions between DC arc and PV system under varying irradiance; (2) the impact of DC arc on advanced MPPT algorithms, such as global maximum power point tracking algorithms; (3) methods to enhance the robustness of MPPT algorithms under arc-fault conditions; (4) the impact of arcs of different types and locations on PV systems.

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