Optimal free-burning AC arc model selection for electromagnetic transients in power systems

A S Brilinskiy1, G A Evdokunin2 and A D Petrova2,*

1 Electrical Power Systems Design and Development Department, JSC «Scientific and Technical Centre of Unified Power System», 1 lit A Kurchatov Str., St.Petersburg, 194223, Russia
2 Electrical Power Systems and Networks Department, Institute of Energy and Transport Systems, Peter the Great St.Petersburg Polytechnic University (SPbPU), 29 Polytechnicheskaya Str., St.Petersburg, 195251, Russia

* E-mail: petrova4anna@gmail.com

Abstract. This paper provides a review of two different mathematical arc models. The first one is based on the arc diameter variation, the second one is defined as cylindrically-symmetric channel model of a vertical arc with a variable radius. The arc model based on the arc diameter was introduced for high current setup, while the channel model was implemented in software for low current experiment. Both models performed well, and the simulated curves matched with the experimental data taken as a basis. However, the model considering the arc diameter impact on its conductance requires additional parameters that should be estimated using measured data. In contrast, the channel model does not impose the use of such parameters, which makes it more flexible.

1. Introduction
There are a lot of papers that observe different ways of dynamic arc modelling to evaluate the breaker parameters [1-5]. In the conventional arc models, the arc diameter is considered to be constant being an implicit parameter in arc model constants. In case of decreasing arc diameter along with the arc extinction, the arc voltage decreases as well. Consequently, the arc diameter can be represented as a function of current that is taken into account in the mathematical model. At this rate the arc voltage behavior during the simulation better coincides with the measured values.

This paper covers comparison between two mathematical open-flame alternating-current arc model methods. In the former case the improved electrical arc model based on its geometric features variation (arc diameter alteration) was used for transient analysis. The second mathematical model was based on the channel model of a cylindrically symmetrical upright arc stabilized by rising convective gas flow. The model also had an option of alternating arc diameter consideration.

2. The electric drive on the basis of RFC with constant sign DC-link (LCCD)

2.1. Model specification
In [6] the arc cross section dependence on the current is outlined. Hence, the arc diameter is defined as follows
\[ d_i = b \cdot \sqrt{|i|} \]  

where \( b \) is a constant parameter and the current dimension is Ampere.

Since the dependency of the arc diameter on the current can be a function of additional effects and corresponding diameter variation, it is proposed in [7] to implement numerical parameters \( b \) and \( q \):

\[ d_i = b \cdot \sqrt{|i|} \]  

where \( q \) has dimensionless value and \( m \cdot \text{A}^{-q} \) is \( b \) dimension.

In the conventional arc models the arc diameter is factored into such parameters as the dissipation power and the arc time constant. However, in [8] they suggested the way how to integrate arc diameter directly as a parameter in a model, that covered the low- and high-current range:

\[ d_i = b \cdot \sqrt{|i|} \]  

Here \( g \) denotes the arc conductance, \( u \) and \( i \) are time-dependent values of the arc voltage and current, \( \tau \) represents the arc time constant, \( U_{\text{arc}} \) is the average arc voltage. The arc diameter \( d_k \) is calculated from equations (1), (2) \((k=1 \text{ or } 2)\), \( a \) and \( c \) – additional adjustment factors, defined from the experiment. Choosing the values of the factors the arc voltage for high and low current can be found.

2.2. Experimental design

2.2.1. Experimental setup. The power source applied in the experiment consisted of capacitors, inductances, charging and control units that gave the possibility to realize current waveforms of different shapes. In the experiment mentioned sinusoidal (50 Hz) current was used. The capacitors charging voltages were equal to 2 kV.

The geometric configuration of the electrodes in operation was known. W-Cu electrodes with a diameter of 10 mm surrounded by ceramic nozzles were used. The experiment itself was examined by a high-speed camera.

For the ignition of the arc, a thin copper wire was placed between the electrodes. In addition to the electrode arrangement, there was a spark gap to trigger the discharge process.

Thereby, comparison between model estimated values and experimental data from [8] was made. Figure 1 displays a schematic representation of the experimental arrangement implemented in software ATPDraw [9].

![Figure 1. A free-burning AC arc test circuit configuration.](image-url)

2.2.2. Model code. ATP (Alternative Transients Program) is the universal program for digital simulation of electric power systems. ATPDraw is a graphical, mouse-driven pre-processor to the ATP, which along with the standard internal components provides users opportunity to create their unique components by using so called MODELS-objects with its code written as a text file [10]. Hence, with the help of the program mentioned it is possible to realize any mathematical model.

The input signals of the mathematical model under consideration are current passing through the arc and the voltage over the arc. The output variable of the model is the arc resistance calculated by
the model equations at each timestep. The computed value of the arc resistance is sent to the MODEL-controlled resistance representing the arc itself. The size of the resistance gives size to the arc voltage. The MODEL-unit code based on the equations (2), (3) is provided in Figure 2.

Figure 2. The MODEL simulation code.

```
MODEL arcdi
  DATA Uarc, tau, b, q, a, c
  INPUT curr, volt1, volt2
  OUTPUT res
  VAR g, res, dg, volt, d
  HISTORY g (dfilt:1e-3)
  INIT
    g:=1e-3
    res:=1/g
  ENDINIT
  EXEC
    volt:=volt1-volt2
    d:=b*abs(curr)**q
    dg:=g*(volt*curr/(Uarc*abs(curr)*abs(curr)+a*d**c)-1)/tau
    laplace(g/dg):=1.110/((111)
    res:=abs(recip(g))
  ENDEXEC
ENDMODEL
```

The parameters used in the script are defined as follows:

- $U_{arc}$ – the average arc voltage in the high-current range;
- $\tau$ – the arc time constant;
- $b, q, a, c$ – additional coefficients;
- $curr$ – time-dependent value of the arc current;
- $volt1$ – time-dependent value of the voltage on the equivalent arc resistance input pole;
- $volt2$ – time-dependent value of the voltage on the equivalent arc resistance output pole;
- $volt$ – the arc voltage;
- $res$ – the arc resistance;
- $g$ – the conductance of the electric arc;
- $d$ – the arc diameter.

Numerical values of the parameters $U_{arc}, \tau, b, q, a, c$ are taken from [8] and represented in Table 1.

| $U_{arc}$ [V] | $\tau$ [μs] | $b$ | $q$  | $a$ | $c$  |
|---------------|-------------|-----|-----|-----|-----|
| 53            | 95          | 2.85·10^{-5} | 0.8 | 1.2 | 0.04 |

2.3. Results

Figure 3 shows the estimated arc current and voltage curves.

Figure 3. Simulated arc current and voltage.
The numerical computation conducted in ATPDraw proves that the model under consideration provides better prediction of the arc voltage behavior in comparison with the experimental data available. The average arc voltage differs by 2% from the value given in [8] and equals to 52 V.
At the same time there is divergence of the results. Corresponding with the experimental curves during the first half-period of the arc current, in the periods following the estimated average arc voltage remains constant (52 V), while the experiment shows that it tended to decrease (20% less in the fourth half-period).
Hereafter figure 4 depicts the arc diameter alteration.

![Figure 4. The arc diameter.](image)

The arc diameter at maximum current is about 9.7 mm. As soon as the arc current becomes zero the arc extinguishes, after its reignition the arc diameter at the peak current during the half-period decreases by 23%.

3. Channel model of the arc

3.1. Model specification
While investigating ways of open-flame arc modeling another simulation model was examined. For transients analysis the mathematical model of a free-burning arc realized in ATPDraw on the basis of the algorithm mentioned in [11] was used. The channel model of a cylindrically symmetrical upright arc stabilized by rising convective gas flow accounted for the simulation. The arc channel was defined as cylindrically symmetrical, electrode sheaths were ignored. Plasma was supposed to be quasi-isothermal and quasi-neutral. Pressure was considered to be constant and equal to atmosphere one. Magnetic effects, viscosity, radial convective gas flows and emission were neglected due to its insignificance. After assumptions implementation mathematical formulation of the burning arc processes was reduced to dynamic second-order partial temperature dependent energy equation proposed in [12]. The criterion of the arc extinguishment which equation was solved simultaneously with the external network transient equations was conductivity loss of the whole arc column.

3.2. Experimental design
The experiment used as a basis during the simulation was outlined in [13]. A free-burning arc was initiated between two parallel horizontal Cu-Zn electrodes with a diameter of 10 mm for currents exceeding value of 50 A. A fuse wire with a diameter of 0.1 mm maximum was placed between the electrodes for the arc ignition, so once it burned out an open-flame arc emerged. During the modelling the circuit was accepted as an inductive one represented by an AC source 4530 V with inductance of 158 mH due to the fact of current limiting coils presence on the low voltage side of the experimental network.
3.3. Results

The open-flame arc mathematical model was also run in ATPDraw software program by means of embedded element MODELS. The arc ignition timepoint during simulation was \( t = 95 \) ms. Figures 5, 6 display the estimated arc current and voltage curves and the arc diameter alteration.

![Figure 5. Simulated arc current and voltage.](image)

![Figure 6. The arc diameter.](image)

The peak current during the short circuit reached the value of 90 A. As soon as the arcing started the peak current dropped to the level of 65 A. The results show that the arc extinguished in 100 ms since the ignition timepoint due to introduction of arc extension that influences its resistance significantly. The maximum arc voltage was equal to 4 kV. Importantly, the arc model based on the arc diameter did not take influence of arc extension on arc conductance into account. In addition, it should be mentioned that unlike in the experiment from section 1 here the arc was stable (the arc channel diameter did not become zero until the moment of extinction).

4. Conclusions

In this paper, comparison of two free-burning arc modeling techniques are proposed. Both methods are adequately accurate which is confirmed by the fact that the curves simulated are qualitatively similar to the experimental ones.

Nonetheless, the arc model based on its diameter has a flaw. The equivalent arc resistance computed according to the algorithm provided significantly depends on additional parameters obtained from the experiment. This implies that without experimental data such arc modeling is impossible.

Whereas, the channel arc model does not rely on parameters calculated from the empirical data. Evidently, this model is versatile since it allows to consider such physical parameters of plasma as
temperature, density, etc. However, the channel arc model from [11] is designed only for low current arc modeling.

It is viable to improve the channel arc model for researches connected with arcing during high currents interruption by implementing previously unaccounted attributes such as voltage drops at cathode and anode regions, emission, etc. As a result, a general arc model independent of experimental data and applicable for a wide range of currents is to be realized.

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