Simulation Study of the Influence of Wall Ablation on Arc Behavior in a Low-Voltage Circuit Breaker

Qiang Ma, Mingzhe Rong, Member, IEEE, Anthony B. Murphy, Yi Wu, and Tiejun Xu

Abstract—This paper focuses on the numerical research of the influence of polymer (polyoxymethylene) on the arc behavior during arcing motion process. The mathematical model of 3-D air–arc plasma considering the ablation of sidewalls is built based on magnetic hydrodynamics. The mass-fraction equation is introduced to the model on the basis of traditional mass, momentum, and energy-balance equations. The influence of wall ablation on the thermodynamic and transport properties of air–polymer mixtures is considered in this paper. The distributions of temperature field, pressure field, and mass fraction in the arc chamber are calculated. The simulation results indicate that the vapor concentration behind the arc column is higher than that in front of the arc column because of the existence of “vortex” in the arc chamber. The use of polymers could accelerate arc movement and reduce the probability of occurrence of back-striking. Using polymers can also increase arc voltage, which can be explained by the change of electrical conductivity for air–polymer vapor mixtures.

Index Terms—Arc behavior, arc simulation, low-voltage breaker, wall ablation.

I. INTRODUCTION

LOW-VOLTAGE circuit breakers are used to protect the power supply to electrical machines and to protect humans and electrical equipment against fault currents. When a low-voltage breaker interrupts a fault current in the electrical circuit, arc plasma is established between the contacts of the breaker, and its behavior largely impacts the performance of the arc chamber. Investigations into arc behavior are significant for the design of new switching devices.

Modern low-voltage circuit breakers utilize the ablation of polymers such as polyoxymethylene (POM) and polyamide 6 (PA6) to produce suitable conditions for arc quenching. The polymer is usually bonded to the sidewalls of the circuit breaker. During the arcing period, the polymer is ablated by the high-temperature arc plasma, and the resulting gas diffuses into the arc chamber. Wall ablation is thought to improve the performance of a low-voltage circuit breaker in three ways.

First, the ablated polymer vapor, which is generated by strong arc radiation, changes the thermodynamic and transport properties of air and polymer mixture and, consequently, modifies the arcing environment. Second, the ablated polymer vapor usually contains $\text{H}_2$, which is with high thermal conductivity, and can cool arc effectively. Third, the ablated vapor produced by the wall material elevates the pressure difference between the arc chamber and the outside space, changing the gas flow in the arc chamber. Because of the very high pressure and fast gas flow in the arc chamber, the arc can be extinguished more easily.

A lot of approaches have been used to determine and predict arc behavior and the various characteristic quantities in the arc chamber of low-voltage circuit breaker: the experimental way [1]–[6] and the simulation approach [7]–[10]. Although many researchers have contributed to these studies over these years, a comprehensive model of the arc in the low-voltage circuit breaker does not yet exist due to the complexity of its geometry, which requires a 3-D coordinate system, and the complex physical phenomena such as the interactions with the walls (e.g., erosion, ablation).

Some researchers have studied the arc–wall interactions and the influence of the nature of the wall material on the arc behavior in the low-voltage circuit breaker. Rodriguez et al. [11] carried out the experimental investigations of the interaction between an electrical arc and the insulating sidewalls in low-voltage circuit breakers. The influence of this on the breaking capacity, dielectric strength, and device overheating after breaking were studied. In the work of Toumazet et al. [12], an inverse diagnostic method was used to study the behavior of the arc for arc-breaking chambers composed of several materials and for various arc currents. A hydrodynamic model was developed by Doméjean et al. [13] to study the interaction between the electrical arc and the sidewall in a low-voltage circuit breaker. The model was based on an energy balance at the boundary but was 2-D and did not consider the different thermodynamic and transport properties of air and polymer mixture. Swierczynski et al. [7] studied the dynamics of the arc in the chamber of a low-voltage circuit breaker. They investigated the influence of the proportion of PA6 on the arc movement but did not consider the interaction of arc and sidewalls. In particular, in the past simulation works about arc chambers of low-voltage circuit breaker, the distribution of the polymer vapor’s concentration in the chamber is not obtained.

This paper presents a study of arc behavior in a low-voltage circuit breaker, taking into account the effect of wall ablation. A 3-D mathematical model including a mass-fraction equation is developed. The influence of the polymer vapor on the thermodynamic and transport properties of the gas mixture is...
considered. This paper is organized in the following order. First, the arc model consisting of mass, momentum, and energy partial differential equation and the mass-fraction equation of the polymer vapor are described. Second, the thermodynamic and transport properties of the mixture of air and polymer vapor are presented. Third, the computational results including the distribution of arc temperature, arc pressure, and the polymer vapor’s concentration in the chamber are presented. Finally, the influences of the polymer vapor on arc voltage and arc displacement is also investigated in detail.

II. MATHEMATICAL MODEL AND BOUNDARY CONDITIONS

The arc model is based on the finite-volume method and uses the user subroutines of the commercial software Fluent to take the magnetic hydrodynamic (MHD) effects into account. The model is based upon the following assumptions.

1) The electrical potential is calculated by

\[ \nabla \cdot (\sigma \nabla \phi) = 0. \]  

2) The momentum equation

\[ \frac{\partial \rho \vec{v}}{\partial t} + \text{div}(\rho \vec{v} \vec{v}) = -\frac{\partial p}{\partial x_i} + \sum_{k=1}^{3} \frac{\partial}{\partial x_k} \left[ \eta \left( \frac{\partial v_i}{\partial x_k} + \frac{\partial v_k}{\partial x_i} \right) \right] + (\vec{J} \times \vec{B})_i. \]  

3) The energy equation

\[ \frac{\partial (\rho H)}{\partial t} + \text{div}(\rho \vec{v} H) - \text{div}(\lambda \text{grad} T) = \frac{\partial p}{\partial t} + V - S_R + \frac{1}{\sigma} \vec{J}^2. \]  

4) The electromagnetic equation

\[ \frac{\partial \vec{B}}{\partial t} = \nabla \times \vec{A}, \]  

\[ \vec{J} = -\sigma \nabla \phi. \]

In the earlier equations, \( t \) is time; \( x_i \) and \( x_k \) are Cartesian coordinates; \( v_i \) is the velocity in \( i \)-direction \((i = x, y, z)\); \( p \) is the pressure; \( T \) is the temperature; \( H \) is the dynamic enthalpy; \( \vec{B} \) is the magnetic-flux density; \( V \) is the viscous dissipation function; \( S_R \) is the radiative-emission coefficient; \( \rho \) is the mass density; \( \eta \) is the viscosity; \( \lambda \) is the thermal conductivity; \( \sigma \) is the electrical conductivity; and \( \vec{J} \) is the current density. In order to simplify the calculation of the radiation energy from the arc column, we assume the plasma to be optically thin [16]

\[ S_R = 4\pi \varepsilon_n \]

where \( \varepsilon_n \) is the net-emission coefficient.

5) Mass-fraction equation

The mixing of polymer vapor in the mixture is determined by convection and diffusion as described by the mass-fraction equation for the polymer vapor

\[ \frac{\partial (\rho c_m)}{\partial t} + \text{div}(\rho c_m \vec{v}) - \text{div}(\Gamma c_m \nabla c_m) = 0 \]

where \( \rho \) and \( \vec{v} \) are, respectively, the density and the mass-averaged velocity of the mixture, \( c_m \) is the mass fraction of polymer vapor in the mixture defined by

\[ c_m = \frac{m_{\text{poly}}}{m_{\text{poly}} + m_{\text{air}}} = \frac{n_{\text{poly}} M_{\text{poly}}}{n_{\text{poly}} M_{\text{poly}} + n_{\text{air}} M_{\text{air}}} \]

where \( m_{\text{poly}} \) is the mass of polymer vapor, \( m_{\text{air}} \) is the mass of air, \( n_{\text{poly}} \) and \( M_{\text{poly}} \) are, respectively, the molar number and molar mass of polymer vapor, and \( n_{\text{air}} \) and \( M_{\text{air}} \) are, respectively, those of air. \( \Gamma c_m \) is the diffusion coefficient.

B. Geometry and Boundary Conditions

A simplified arc chamber is set up in this paper. The geometry of the arc chamber is shown in Fig. 1. The left-hand wall is cathode, and the right-hand wall is anode; the top wall is air vent. The thickness of the electrode is 1.5 mm. The width of the upper part of the arc chamber is 20 mm, and the width of the lower part of the arc chamber is 4 mm. The opening angle \( \alpha \) is 120°. The front and the back walls are ablated walls. The calculation domain is made of 32,600 computational cells. The detailed sizes of the geometry are labeled as shown in Fig. 1.

An average current density distribution \( j \) at the current inlet is used to define the electrical-potential boundary condition

\[ j = I/S \]

where \( I \) is the total current and \( S \) is the area of current inlet.

Since the anode is a collector, which absorbs electrons emitted by the cathode, a zero potential is applied.
According to the general way to deal with the velocity in hydromechanical computation, no-slip boundary condition is imposed on the wall–arc interfaces. The static pressure of the outlet is set to zero, and all the outside of the sidewalls have a temperature of 300 K. The heat flux from the plasma to the outer atmosphere through the electrodes can be defined by one-dimension equation [17]

$$q_c = -k(T - T_0)/d$$  \hspace{1cm} (12)

where $k$ is the thermal conductivity of the electrode material, $T$ is the temperature of the internal surfaces of electrodes, $T_0 = 300$ K, and $d$ is the thickness of electrodes.

C. Arc–Wall Interaction Modeling

The ablation model is applied at the boundary between the arc and the sidewall. The model takes into account the arc radiation and the energy thermally conducted from the arc. Because of the complex physical phenomena of arc–wall interaction, this paper makes some assumptions as follows.

1) The wall surface is assumed to be fixed during ablation, i.e., the geometrical alteration during ablation is not taken into account.

2) The melted material mass is assumed to be vaporized instantaneously.

At the sidewall surface, the total heat flux $q$ can be expressed as the sum of the radiation heat flux $q_R$ and the heat flux due to conduction from arc $q_{CA}$ minus the heat flux due to conduction from the arc plasma to the outer atmosphere through the sidewalls $q_{CW}$

$$q = q_R + q_{CA} - q_{CW}$$  \hspace{1cm} (13)

The term $q_R$ can be expressed as the difference between the radiation absorbed from the arc $q_{RP}$ and the radiation emitted from the wall surface $q_{RM}$

$$q_R = q_{RP} - q_{RM}.$$  \hspace{1cm} (14)

The radiation contribution to the anode flux can be calculated using the view-factor method as an integral over the entire domain [18], as shown in Fig. 2. The integral is evaluated for each wall surface element, and the integration is over each volume element of the plasma arc. $S_R$ represents the term of radiative losses which is calculated through (8), $r_{i,j}$ is the distance between the wall surface element $(i)$ and the volume element of the arc $(j)$.

$$q_{RP} = \int \frac{S_R}{V_j} \cos(\Psi) dV_j.$$  \hspace{1cm} (15)

The radiation flux emitted from the wall surface refers to the black-body radiation relation

$$q_{RM} = \varepsilon\sigma_{SB}T^4$$  \hspace{1cm} (16)

where $\varepsilon$ is the surface emissivity and $\sigma_{SB}$ is the Stefan–Boltzmann constant ($\sigma_{SB} = 5.67 \times 10^{-8}$ W·m$^{-2}$·K$^{-4}$).

In (13), we assume that the Kirchoff law is valid, i.e., the total emissivity is equal to the absorbability of the material. The emissivity value is strongly dependent on the surface status, and it is an unknown. In all our calculations, we assume the blackbody emissivity ($\varepsilon = 1$) [18].

The heat transferred by conduction from the arc is calculated from

$$q_{CA} = \kappa_A \cdot \frac{\partial T}{\partial y}$$  \hspace{1cm} (17)

where $\kappa_A$ is the thermal conductivity of arc

$$q_{CW} = \kappa_W \cdot \frac{\partial T}{\partial y}$$  \hspace{1cm} (18)

where $\kappa_W$ is the thermal conductivity of sidewalls.

The rate of ablation is determined by (18)

$$q = \dot{m}h_a$$  \hspace{1cm} (19)
where \( \dot{m} \) is the rate of ablation per unit area and \( h_{\alpha} \) is the total energy required to melting, vaporizing, and raising a unit of ablated vapor from room temperature to 3700 K [19].

III. CALCULATION OF COMPOSITION, THERMODYNAMIC PROPERTIES, AND TRANSPORT COEFFICIENTS OF AIR–POLYMER MIXTURE

The composition of the plasma at a given temperature and pressure was calculated by minimizing the Gibbs free energy of the gas mixture, under the constraints of chemical element conservation and zero-net charge. The composition, together with the thermodynamic properties of the individual species, was then used to calculate the thermodynamic properties of the plasma. The methods used have been given elsewhere [20].

The methods used have been given elsewhere [20]. The species considered in the calculation were as follows: \( \text{Ar, Ar}^+, \text{Ar}^{2+}, \text{Ar}^{3+}, \text{C}, \text{C}^-, \text{C}^+, \text{C}_2^+, \text{C}_3^+, \text{C}_2, \text{C}_3, \text{C}_4, \text{C}_5, \text{CH}, \text{CH}^+, \text{CH}_2, \text{CH}_3, \text{C}_2\text{H}, \text{C}_2\text{H}^+, \text{C}_2\text{H}_2, \text{C}_2\text{H}_4, \text{CH}_2\text{O}, \text{CH}_3\text{O}, \text{HCO}, \text{HCO}^+, \text{HCO}_2^-, \text{HCN}, \text{HNO}, \text{HNO}_3, \text{HONO}^\text{cis}, \text{HONO}^\text{trans}, \text{CN}, \text{CO}, \text{CO}_2, \text{CO}_2^-, \text{H}, \text{H}^+, \text{H}_2^+, \text{H}_2, \text{H}_2^-, \text{H}_2\text{O}, \text{N}, \text{N}^+, \text{N}_2^+, \text{N}_2^2, \text{N}_2, \text{N}_2^+, \text{NH}, \text{NH}_3, \text{NO}, \text{NO}^-, \text{NO}_2, \text{NO}_2^-, \text{NO}_3, \text{NO}_3^-, \text{N}_2\text{O}, \text{N}_2\text{O}^+, \text{O}, \text{O}^-, \text{O}_2^+, \text{O}_2^-, \text{O}_2, \text{O}_3, \text{OH}, \text{OH}^+, \text{OH}^+, \text{electrons} \).

Transport properties were calculated using the Chapman–Enskog method [21]–[23]. The approaches used, and the methods used to calculate most of the collision integrals have been given by Murphy et al. [20], [24], [25]. However, some collision integrals have been revised because of the availability of improved data. Furthermore, additional collisional integrals are required for interactions involving molecules that contain hydrogen species, since Murphy [25] only treated interactions involving hydrogen and argon species.

Other collision integrals for neutral species were calculated using the Lennard–Jones potential following the methods of André et al. [27] and Hirschfelder et al. [22]. Where data were not available, collision integrals for interactions between unlike neutral species (\(X–Y\) interactions) were calculated by interpolating between the collision integrals for the \(X–X\) and \(Y–Y\) interactions using the method of Svehla and McBride [28]. For other ion–neutral interactions, the polarization potential was used. For the e–OH, e–HCN, e–CH\_2O, e–CH, e–CN, and e–NH interactions, the relation given by André et al. [27], allowing the momentum-transfer cross section to be calculated in terms of the dipole moment of the molecule and the momentum-transfer cross section for the e–H\_2O interaction, was used. For other electron–neutral interactions, the polarization potential was used to estimate the collision integrals.

Combined ordinary diffusion coefficients were calculated as described by Murphy [29], [30]. The coefficients describe the diffusion of one “gas,” such as nitrogen, with respect to another, for example, the polymer vapor. Each gas may consist of any number of species; for example, at high temperature, the species \(N_2, N_2^+, N, N^+, N^+, N^2+, N^3+, \) and electrons may all be present in the nitrogen gas. The combined diffusion coefficients are defined by the expression for the mass flux of gas A

\[
\dot{J}_A = \frac{n^2}{\rho} \frac{m_A m_B}{\bar{D}_{AB}^T} \nabla T_B - \bar{D}_{AB} \nabla \ln T.
\]

IV. SIMULATION RESULTS OF ARC MOTION

A. Arc Characteristics During Arc Motion

Considering Wall Ablation

During the simulation, the arc starts from the position of 10 mm higher than the bottom of the arc chamber. Its initial
state is a cylinder with a 10 000-K temperature; the radius of the cylinder is 1 mm. When the simulation begins, the arc runs under the magnetic force induced by the rails. The calculation current of 500 A is applied in this paper. The outlet area equals to 80%.

Fig. 6 shows the temperature distribution sequences of arc plasma during arc motion. First, moving along the parallel electrodes, the arc reaches the edge of the V-shaped zone when \( t = 0.20 \) ms. After stagnating for a little time, the arc root shifts to the chute, and the arc expands along the V-runners. From \( t = 0.20 \) ms to \( t = 0.80 \) ms, the arc is elongated between V-runners. In this period, the occurrence probability of back-striking is higher than the other periods. After \( t = 0.80 \) ms, the arc reaches the upper parallel area, and at \( t = 1.10 \) ms, it arrives at the upper barrier, which has 60% area of air vent.

Fig. 7 shows the pressure distribution sequences of arc plasma. At the beginning of the simulation, the region of arc column has a higher pressure because of higher temperature. With the pressure wave propagating to the two ends, the pressure of lower region is higher than that of upper region because of the motion of gas flow; the pressure wave on the top because the bottom of this chamber is close but the upper barrier is open with 60% area of air vent. After \( t = 0.20 \) ms, the arc begins to propagate and reaches the top region at \( t = 0.40 \) ms. After \( 0.40 \) ms, the pressure propagates backward and reaches the bottom end again at \( t = 0.80 \) ms. This propagation and reflection will repeat several times, and finally, the maximal pressure locates in the region close the upper barrier.

The POM mass-fraction distribution on the \( Y-Z \) symmetry plane of arc chamber during arc-motion process is shown in Fig. 8. The initial condition of arc chamber is filled with pure air. When the arc column is moving under the effect of magnetic force induced by the rails, the inside wall of the arc chamber is ablated by the very high temperature arc plasma. The POM vapor from the ablated wall surface mixes with air as a result of convection and diffusion. From Fig. 8, we can note that the POM mass concentration behind the arc column is higher than that in front of the arc column. This can be explained by the gas-flow condition of the arc chamber. From Fig. 9, we can note that there are two vortices near the arc core, and the gases near the lateral walls flow toward the opposite direction of arc movement. Therefore, the ablated vapor forming at the ablated wall surface is blew by the adjacent gas flow, and the mass concentration behind the arc column is much higher.

B. Influence of POM on Arc Characteristics During Arc Motion

In low-voltage circuit breakers, when the arc is created and moves in the arc chamber, organic vapors appear from the plastic walls. The arc behavior will be influenced by the polymer vapors. In this paper, the influences of POM on arc motion and arc voltage in the arc chamber are investigated.

The influence of POM on the arc-root position along \( z \)-axis is shown in Fig. 10. It can be clearly seen that the POM can speed up the arc motion. In the first 0.2 ms, this influence is not obvious because the gassing material on the lateral wall surface is ablated in just a short time, and the polymer vapors have not diffused adequately. As the arc moves in the arc chamber, the acceleration influence is more distinct due to convection and diffusion of polymer vapor. Such effect is mainly caused by pressure difference between the front and the rear of the arc column. When the arc is created and during the displacement phase, the lateral wall with gassing material is ablated and produces a lot of polymer vapors. It is noticeable that, when the POM is not used, the movement of the arc becomes very slow on the chutes, and back-commutation motion occurs. It can be included that using the polymer could accelerate arc movement and reduce the probability of occurrence of back-striking.

Fig. 11 shows the simulation results for chambers with different cross section of the vents. In the first 0.2 ms, it seems that there is no influence of the ventilation on the arc motion. This reason can be deduced from the pressure distribution in the chambers: During this period, the pressure expands from the arc upward toward the upper end of the arc chamber and has not reached the upper barrier and has not been reflected yet. After this period, the pressure wave propagates downward and hampers the movement and elongation of the arc. The influence of different cross section of the upper barrier becomes distinct. The larger the ventilation cross section is, the less influence of the pressure wave has on the arc movement, and the faster the arc moves. From the simulation results, we can conclude that increasing the cross section of the barrier could accelerate the movement.

Arc-root positions for chambers with different current intensities are shown in Fig. 12. The current intensity applied in the simulation is 500, 1000, and 1500 A, respectively. From the figure, we can note that increasing current can accelerate the movement of arc. This can be explained in two aspects. First, magnetic force induced by the rails is increasing with the current intensity. Second, larger current causes higher temperature in the arc chamber and higher mass fraction of polymer. The influence of polymer on the arc motion is more distinct.

The influence of polymers on the arc voltage in the arc chamber during arc motion is shown in Fig. 13. The arc voltage starts with a value of 26 V. From Fig. 13, we can see that the use of polymers can increase arc voltage. This can be explained
Fig. 6. Temperature distribution on the $X$–$Z$ symmetry plane of arc chamber during arc-motion process considering wall ablation.

Fig. 7. Pressure distribution on the $X$–$Z$ symmetry plane of arc chamber during arc-motion process considering wall ablation.

Fig. 8. POM mass-fraction distribution on the $Y$–$Z$ symmetry plane of arc chamber during arc-motion process considering wall ablation.

by the change of electrical conductivity for air–polymer vapor mixtures. The electrical conductivity of air–POM vapor mixtures decreases with the increasing of the mass fraction of POM vapor; this causes the increase of the arc voltage.

Fig. 14 shows the arc-voltage variation with different cross sections of air vents. The arc voltage starts with a value of 26 V and reaches 88 V or so at the end of the simulation when 80% vent. For the first 0.2 ms, the arc voltage almost does not change versus time. Moreover, different cross sections of air vent have little effect on the arc voltage in this period. After this stage, the arc voltage rises faster when the arc position has reached the lower edge of the V-area. The arc is elongated by
Fig. 9. Double vortices on the $Y-Z$ symmetry plane of arc chamber during arc-motion process at $t = 0.40$ ms.

Fig. 10. Arc-root position for chambers with and without POM.

Fig. 11. Arc-root position for chambers with different cross sections of air vents.

Fig. 12. Arc-root position for chambers with different current intensities.

Fig. 13. Arc voltage for chambers with and without POM.

Fig. 14. Arc voltage for chambers with different cross sections of air vents.

The V-runners, and the arc voltage keeps increasing sharply until the arc arrives at the upper edge of the V-area. The simulation shows that, in this stage, the effect of air vent is more evident, and larger air vent can cause the arc voltage to rise faster. When
the arc reaches the upper parallel runners, the arc voltage keeps stable.

The total mass produced by ablated wall during arc motion with different current intensities is shown in Fig. 15. The current applied is 500, 1000, and 1500 A. The ablated mass increases with the current intensity because of arc energy injected into the sidewalls increases with current. It can be noted that, in the first 0.20 ms, the mass produced by the ablated wall increases slowly; after 0.20 ms, the ablated rate increases promptly. This difference can be attributed to the change of arc energy. When arc shifts to the chutes, arc voltage rises sharply because of the elongated arc column between V-runners. The rising of arc voltage causes the increasing of arc energy and the ablated mass rate consequently.

V. CONCLUSION

The numerical investigations of the influence of the polymer of POM on the arc behavior during arc-motion process have been studied in this paper. A 3-D air–arc plasma model considering the ablation of sidewalls is built based on MHD. This model concludes the mass-fraction equation and the traditional mass, momentum, and energy-balance equations. The simulation results reveal the influence of polymers on the arc behavior during arc motion in the following aspects.

1) The vapor concentration behind the arc column is higher than that in front of the arc column because of the existence of “vortex” in the arc chamber.

2) The simulation results show that arc movement in the divergent area is slower than that in the parallel area. The use of polymers benefits the arc motion and reduces the probability of occurrence of back-striking.

3) The variation of the arc voltage corresponds to the variation of arc-root position. The use of polymers increases the arc voltage because of the decrease of the electrical conductivity of air–polymer mixtures.

4) The total mass produced by ablated wall during arc motion increases with the current intensity because of arc energy injected into the sidewalls increases with current.

In the first 0.20 ms, the mass produced by the ablated wall increases slowly. After 0.20 ms, the ablated rate increases promptly, because arc voltage rises sharply when arc runs between V-runners.

REFERENCES


Qiang Ma was born in Shandong Province, China, in 1979. He received the B.S. and M.S. degrees in electrical engineering from Xi’an Jiaotong University, Xi’an, China, in 2002 and 2005, respectively, where he is currently working toward the Ph.D. degree in electrical engineering.

His research interests include the simulation and experimentation of arc plasma in the low-voltage circuit breaker.

Mingzhe Rong (M’98) was born in Shanxi Province, China, on October 8, 1963. He received the B.Sc. and Ph.D. degrees from the Department of Electrical Engineering, Xi’an Jiaotong University, Xi’an, China, in 1984 and 1990, respectively.

He has been involved in arc physics, electrical-contact theory, intelligent electrical apparatus, and condition monitoring technique for switchgear. Since 1984, he has over 130 papers published.

Dr. Rong is member of IEICE and China Electrotechnical Society.

Anthony B. Murphy was born in Sydney, Australia, on January 22, 1960. He received the B.Sc. (with honors) and Ph.D. degrees from the University of Sydney, Sydney, in 1981 and 1987, respectively.

He is currently a Senior Principal Research Scientist with CSIRO Industrial Physics, Sydney, where he has worked on thermal plasmas and solar hydrogen production.

Dr. Murphy is a Fellow of the Institute of Physics (U.K.) and the Australian Institute of Physics.

Yi Wu was born in Jiangsu Province, China, in 1975. He received the B.S. and Ph.D. degrees from Xi’an Jiaotong University, Xi’an, China, in 1998 and 2006, respectively.

He is currently with the State Key Laboratory of Electrical Insulation and Power Equipment, School of Electrical Engineering, Xi’an Jiaotong University. His research fields have been involved in arc simulation and analysis of the low-voltage circuit breaker.

Tiejun Xu was born in Shannxi Province, China, in 1976. He received the B.S. and M.S. degrees from Xi’an Jiaotong University, Xi’an, China, in 1999 and 2004, respectively.

He is currently with the State Key Laboratory of Electrical Insulation and Power Equipment, School of Electrical Engineering, Xi’an Jiaotong University. His research fields have been involved in arc experimental analysis of the low-voltage circuit breaker.