Numerical simulation for arc-plasma dynamics during contact opening process in electrical circuit-breakers

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Abstract. The high-energy, high-current thermal plasma that develops between electric contacts in a gas circuit-breaker during circuit interruption is an important phenomenon in the power transmission industry. The high temperature and pressure arc dissipates the tremendous amount of energy generated by the fault current. Simultaneously, this energy has to be transferred away from the contacts to build the dielectric strength level of the circuit-breaker. In order to interrupt the current, the arc must be weakened and finally extinguished. We model these phenomena by using a computer software code based on the solution of the unsteady Euler equations of gas dynamics. We consider the equations of fluid flows. These equations are solved numerically in complex circuit breaker geometries using a finite-volume method. The domain is initially filled with SF₆ gas. We begin our simulations from cold mode, where the fault current is not present (hence no arc). An axis-symmetric geometry of a 145 kV gas circuit-breaker is considered to study the pressure, density, and temperature profile during contact opening process.

1. Introduction

Plasma is an attractive state of matter that finds potential uses ranging from everyday applications to industrial applications [1]. Gas discharging is a common phenomenon, where a plasma can be observed in the form of electric arc. Electric arc is a high temperature plasma occupying a region, which is an electrically conducting band between the electrodes and through which an electric current can flow. The core area of an electric arc is formed by a thermal plasma. This is an important process in electrical devices like circuit breakers, where it is necessary to understand the arc plasma behaviour to optimize the performance and design of the circuit-breaker [2].

Electrical circuit-breaker is a mechanical device capable of making, carrying and breaking currents under normal circuit conditions and also making, carrying for a specified abnormal circuit conditions such
that as those of short circuit, where an electric arc is formed between the contacts. In other words, electrical circuit breaker is a switching device, which main task is to protect the network in fault conditions. This device has a set of mechanically separated electrodes. When the contacts circuit breakers separate, a plasma arc is developed. The arc voltage causes temperature in this arc to approach 25,000 K. To extinguish the arc, it must be cooled to such a level that the space between the contacts can act as an insulator. It is important to know the properties of this arc to design electrical switchgears. In vacuum circuit breakers, it is a vacuum arc burning in electrode vapour. In other types of circuit-breakers, the high-pressure arc burns in the corresponding mediums such as air, oil and SF₆.

On high-voltage network, a circuit breaker uses a gaseous jet of compressed sulphur-hexafluoride (SF₆) to confine, cool, and extinguish the electric arc during short-circuit operations. In SF₆ circuit-breaker, the current continues to flow after contact separation through the arc whose plasma consists of ionized SF₆ gas. For, as long as it is burning, the arc is subjected to a constant flow of gas, which extracts heat from it. The arc is extinguished at a current zero, when the heat is extracted by the falling current. The continuing flow of gas finally de-ionizes the contact gap and establishes the dielectric strength required to prevent a re-strike. The direction of the gas flows, i.e., whether it is parallel to or across the axis of the arc, has a decisive influence on the efficiency of the arc interruption process. Research has shown that an axial flow of gas creates a turbulence, which causes an intensive and continuous interaction between the gas and the plasma as the current approaches zero. Hence, the fluid flow phenomena is very important during the opening of the circuit-breakers that can be governed by the equations of compressible flows coupled to radiation transport and electromagnetic interactions. During the switching process, there are lot of physical mechanisms such as gas convection, conduction, radiation and magnetic forces acting on the arc motion together. Also, the Lorentz force plays a fundamental role in these types of arcs at high currents. Particularly, in the electrode regions, where the current density is higher. This arc plays a crucial role in current interruption. When two current-carrying contacts open, an arc forms between the contact gaps that prevent an abrupt interruption of the current. Proper design of a circuit-breaker with the required interruption performance necessitates an understanding of the physical behaviour of the arcing process and the complex interactions between the plasma field and the electromagnetic field. The inclusion of electromagnetic forces is essential to investigate the plasma arc behaviour that has great relevance to the development of the switching devices, better understanding of the opening mechanisms of contacts, and the switching reliability of the circuit breakers. Hence, high-energy thermal plasma arcs in the switchgear industry are very important for development and validation of the model. Numerical approaches to complex problems of this nature have become feasible due to the rapid improvement in computer performance in recent times. A software has been developed for the simulation of SF₆ gas flow and electric arc in circuit-breakers. This can simulate plasma arc on the basis of the Euler’s model of equations whereby source terms related to Ohmic heating, radiation magnetic forces, and material ablation have been included.

In this paper, we model these phenomena by using a compute code based on the solution of the unsteady Euler equations of gas dynamics. We consider the equations of fluid flows; these describe the flow of plasma in the presence highly insulating gas. These equations are solved numerically in complex circuit-breaker geometries using a finite-volume method. The domain is initially filled with SF₆ gas. We begin our simulations from cold mode, where the fault current is not present (hence no arc). Following the given input current, the simulation enters in the arc mode, where contacts are fully separated and a core of ionized gas (plasma) exists between the contacts. The strong electric field between the contacts drives the high arc current, which dissipates large amount of energy further ionizing the gas and raising the pressure in the heating volume. When the current decays during the AC (alternating current) cycle, the high pressure in the heating volume drives the plasma flow which extinguishes the arc. The geometry of 145 kV gas circuit breaker is considered to study the pressure, density, and temperature profile during contact
opening process. The material ablation due to plasma radiations is also considered for simulation. The basic mathematical formulation of the problem for the given geometry is underlined in section 2 of the paper. The process of numerical simulation along with numerical explanation is also discussed in the same section. The results are presented in section 3. A short conclusion is mentioned in the last section of the paper.

2. Mathematical formulation and simulations

The axis-symmetry geometry of a 145 kV gas circuit-breaker (GCB) for closed position is depicted in figure 1(a). The model dynamics is divided in two categories: cold gas flow and plasma arc dynamics. The dynamics of unsteady compressible fluid flow within geometries with moving boundaries (related to grid motion) can be understood by Euler’s equation. The Euler’s equation in cylindrical co-ordinate system can be written as below [7].

\[
\frac{\partial \vec{U}}{\partial t} + \frac{1}{r} \frac{\partial (r \vec{F})}{\partial r} + \frac{\partial \vec{F}}{\partial t} = \vec{S},
\]

where \(\vec{U}, \vec{F}, \vec{F}, \vec{S}\) are fluid velocity vector, radial and axial forces (including pressure and radiation forces), and source energy vector (including Ohmic and radiation energy terms), respectively, \(r\) and \(z\) are the radial and axial co-ordinates, respectively. Equation (1) is valid for plasma as well as cold gas. In case of cold gas, the plasma force and radiation energy terms will be zero. We limit our study to a fully ionized plasma without taking into account the ionization process which may not be complete at the relatively cold wall region. The following equations governing the main features of the plasma dynamics will be solved in cylindrical coordinates. These equations express the evolution of the plasma density \(n\), the evolution of the plasma velocity \(\vec{u}\), the evolution of magnetic field \(\vec{B}\), and the evolution of the thermal pressure \(p\) as follow [8]:

\[
\frac{\partial n}{\partial t} + \nabla \cdot (n \vec{u}) = 0, \tag{2}
\]

\[
n \frac{\partial \vec{u}}{\partial t} = -n \vec{u} \nabla n - \nabla p - \vec{J} \times \vec{B}, \tag{3}
\]

\[
\frac{\partial p}{\partial t} = -\vec{u} \nabla p - \eta \nabla \cdot \vec{u} + (\gamma - 1)[\eta \vec{J}^2 + \nabla \cdot (\kappa \nabla T)], \tag{4}
\]

\[
\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{u} \times \vec{B}) - \nabla \times (\eta \vec{J}), \tag{5}
\]

\[
\nabla \cdot \vec{B} = 0, \tag{6}
\]

where \(\vec{J} = \mu_0^{-1}(\nabla \times \vec{B})\) is the current density, \(T = R^{-1}(p / n)\) is the temperature, \(\gamma\) is the ratio of specific heats, \(\mu_0\) is the permeability of vacuum, \(R\) is the gas constant, \(\eta = \eta T^{-\alpha}\) is the resistivity tensor, \(\kappa = \kappa T^{\beta}\) is the thermal conductivity tensor, \(\vec{u}\) is the plasma particle velocity, \(\vec{E}\) and \(\vec{B}\) are the electric and magnetic field vectors, respectively.
The equations mentioned above are solved numerically by a computer simulation code [6]. This is LINUX operating system based computer code written in FORTRAN language. The source code of this software is based on the solution of the unsteady Euler equations of gas dynamics. The solver computes the solution by integration of the Euler equations on a moving and deforming unstructured triangular grid using a finite-volume method. This software is having the capabilities of solving problems of gas flow dynamics with high temperature arc as well without arc including the material ablations, plasma radiations, and MHD. This software run in two operating modes: COLD (Computation and Optimization of Local Dielectric strength) mode and ARC (Analysis with Real Current) mode. In COLD mode, a simulation of the operation of the circuit-breaker without an electric arc is done. The solutions of electric field (as well as dielectric strength) can be obtained inside the chamber. In ARC mode, a simulation of the operation of the circuit-breaker with an electric arc can be done. The computation of the Ohmic heating, the Lorentz force, and the radiation transfer can be included in ARC mode. Following working steps were taken to run the desired simulation: (a) geometry formation, (b) zoning and meshing, (c) boundary conditions and initial simulation parameter imposition, and (d) results visualization. The physical quantities such as pressure, temperature, density, electric field, electric potential, and Mach number can be appeared from the output of this simulation.

The simplified axis-symmetry geometry of a circuit-breaker chamber of 145 kV GCB is shown in figure 1(b). The dimensions of the geometry are $1500 \times 160 \ mm$ in the $x, y$ direction and point O is the origin of the co-ordinate. The circuit-breaker chamber contains the copper electrodes (electrical contacts), Teflon nozzle, and side walls. Single motion system is considered, where the right-hand side contacts is moving and left-hand side contact is stationary. The chamber is completely occupied by SF6 gas. This gas is purposeful due to its high dielectric-strength and stable thermal-stability. The used initial simulation parameters are shown in table.1.
Table 1. The input numerical parameter used for simulation operation.

| Physical Quantities       | Values                        |
|---------------------------|-------------------------------|
| Circuit-breaker rating    | 145 kV, 40 kA, T60            |
| Reference temperature     | 300 K                         |
| Reference pressure        | 6 bar                         |
| Ignition current          | 200 A                         |
| Ignition voltage          | 1000 V                        |
| Arc radius                | 3 mm                          |
| Peak TRV                  | $2.8 \times 10^{'$ V         |
| TRV frequency             | 50 Hz                         |
| Arc duration              | 12.5 ms                       |
| Contact breaking time     | 18.25 msec.                   |
| Total simulation time     | 50 msec.                      |
| Gas composition           | SF₆ (100%)                    |

Following the simulation code, we create an unstructured mesh of the given geometry (as shown in figure 2) that is having 11000 triangles. We define the boundary conditions such as Neumaan and Dirichlet boundary conditions. In fluid boundary conditions, we define the internal fictitious boundaries, solid wall, outlet boundary, axis symmetry, clapet (valve), and ablated wall (lower part of the main Teflon nozzle and auxiliary nozzle). We define the boundary conditions for incident radiations corresponding to the fluid boundary conditions. The Marshak boundary condition is used to the electrodes (arcing contacts). Two nodes are pointed out on the arcing contact to define the opening time of the contacts. As these two nodes coincide, the arc is generated and hence, circuit-breaker opens. Apart from this, we also define four positions in the geometry (piston, poireau, auture, and tulip, cf. figure 1b), where the all given physical quantities will be calculated. The time step is chosen 0.5 msec. for output collection data corresponding to the number of iterations (25) [6].

![Figure 2. Axis-symmetry unstructured mesh of the geometry of 145 kV gas circuit breaker chamber.](image)

3. Simulation results
We run the simulation for a 145 kV GCB (T60 current duty, 12.5 msec. arcing time). Total given time for simulation is 50 msec. including 12.5 msec. arcing time (18.25-30.75 msec.). Quadratic motion of the moving parts of the circuit-breaker is used for simulation. It is noted that the used units of length, time, pressure, density, current, and time are millimetre, millisecond, bar, $kgm^{-1}$, Ampere, Volt, respectively. To run this software, we need to give input arc current profile (shown in figure 3). The peak input current is 33450 A. The simulation runs following the given arc current profile. First, it runs without arc as circuit-
breaker is in closed position. Due to the mechanical relay system, the contacts move from their position. Due to the movement of the piston, the gas pressure increases in the thermal chamber. The gas density is also varied corresponding to the gas pressure in the chamber. In this position, the gas temperature does not change much as there is no arc. The small temperature variation is due to the mechanical energy generation.

At time 18.25 ms (at 18,000 A peak current), the contact separates, and hence, an arc is formed between the contacts. After the separation of the contact, simulation runs in arc mode. Before to explain the arc mode results, let us discuss the basic mechanism of arc quenching in GCB as follows: when the contacts of a circuit-breaker separate, an arc-plasma is developed. The arc voltage causes temperature in this arc to approach 25,000 K. To extinguish the arc, it must be cooled to such a level that the space between the contacts can act as an insulator. In an SF₆ circuit breaker, the current continues to flow after contact separation through the arc whose plasma consists of ionized SF₆ gas. For, as long as it is burning, the arc is subjected to a constant flow of gas, which extracts heat from it. The arc is extinguished at a current zero, when the heat is extracted by the falling current. The continuing flow of gas finally de-ionizes the contact gap and establishes the dielectric strength required to prevent a re-strike. The direction of the gas flows, i.e., whether it is parallel to or across the axis of the arc, has a decisive influence on the efficiency of the arc interruption process.

Research has shown that an axial flow of gas creates a turbulence, which causes an intensive and continuous interaction between the gas and the plasma as the current approaches zero. These phenomena can be observed from figure 4, where the plasma arc temperature contours at different times are shown. The initial arc radius is 3 mm (considered as input data in simulation). Due to the input energy from the large fault current, the gas ionizes and a plasma is formed between the contacts. The gas ionization process is extremely rapid; hence, we consider it a fully ionized plasma. As we know that plasma is a collection of charged and neutral particles. The strongly electronegative SF₆ gas catches the hot plasma electrons from the core of the arc that try to cool the arc. However, SF₆ gas decomposes in its sub-components but no further reaction are observed among them because of its chemical stability of SF₆. The arc radius increase with arc current due the Ohmic heating enhancement, \( S_{\text{elec}} = \sigma |\vec{E}|^2 \), where \( \sigma \) is the electrical conductivity depends on the local temperature and pressure. The high temperature region is initially located midway between the contacts. The arc body then bends increasingly in the \( x \) direction under the influence of the cold gas pressure.
Figure 4 (colour online). Plasma arc dynamics (arc temperature contour) at times (a) 18.50 msec., (b) 20 msec., (c) 25 msec., and (d) 30.5 msec.. The contacts are separated at 18.25 msec. following the 12.5 msec. input arcing current. The temperatures are shown on the right-hand side of the contour in the unit of degree Kelvin.
The increase in heat transfer from the arc as the relatively colder gas starts to flow into the chamber causes the diameter of the arc to decrease and its length to increase [9]. In a result, the electrical resistance increase, hence, the arc voltage and these is a possibility at current zero to quench the arc for a successful operation of a circuit breaker.

We have defined the four points to collect the pressure, density, and temperature data. These are as following: (a) Piston-Top right corner of puffer chamber, (b) Poireau- Top right corner of thermal chamber, (c) Autre : Bottom right corner of Main nozzle, and (d) Tulip : Bottom right corner of Aux nozzle. The pressure plots in the cold as well in arc mode are presented in figure 5.

![Gas Pressure Plot](image)

**Figure 5 (colour online).** Variation of gas pressure (absolute, in bar) with time (in msec.) at different given points for the full operation of a circuit breaker. The dark red line shows the arc current in Ampere.

This figure shows the variations of gas pressure ($p$) with time ($t$) during circuit-breaker operation. The input current profile is also shown in the same curve. From this curve, the pressure variations at different position mentioned above in the arc mode can be observed. It is observed that the gas pressure increase gradually in cold mode (where no arc). The gas pressure in the thermal chamber increases roughly just after arc ignition due to piston force. The large temperature difference between the arc and the surrounding clod gas supports to increase the gas pressure in the middle of the channel. The plasma arc generates several types of forces such as Lorentz force (electromagnetic force), electrostatic force, space charge force, and radiation force. In the influence of these forces, the plasma particles accelerate and radiate energy in the form of electromagnetic radiations (ultraviolet and infrared radiations). These energetic radiations may be ablated due to their absorption by the Teflon material [10]. In this simulation, we have considered the ablation factor value, 0.8. Following this ablation factor, the nozzle ablation can be observed. This material ablation should be in control, the access material ablation may be the reason for circuit breaker failure.
4. Conclusion
In conclusion, from a computer simulation code, we have study the arc-plasma dynamics including the gas dynamics in the chamber of a gas-circuit-breaker. Axis-symmetry geometry of a circuit-breaker is considered for simulation to predict the arc-plasma flow inside the chamber. A compressible flow solver using a finite-volume method in moving triangular grid has been used, where the Ohmic heating and metal ablation effects are included. Based on fluid-flow equations, the plasma dynamics was simulated during contact opening process in cold mode as well as in arc mode. Before contact opening, the gas flows due to piston motion. The sudden rise in the fault current ionizes the gas and a plasma (having the core temperature about 25,000 K) performs between the contacts. The gas pressure varies due to arc heating and other inherited forces that suppress the hot region. The zero value of an AC current cycle provides a chance to quench this high temperature arc without burning the system. Therefore, the hot plasma region becomes cool and moves towards the exhaust side. The knowledge of the physical behaviour of this plasma arc can be used in future development of the gas circuit-breaker chamber to enhance the efficiency of the system.

References
[1] Chen F F 1974 Introduction to Plasma Physics and Controlled Fusion (New York: Plenum)
[2] Boulos M I, Fauchais P and Pfender E 1994 Thermal plasmas: Fundamental and applications (New York: Plenum)
[3] Nakanishi K 1991 Switching Phenomena in High-Voltage Circuit Breakers (New York: Marcel Dekker, Inc.)
[4] Dufournet D 1995 IEE Digest 3 1995
[5] Zhang X D, Trepanier J Y and Camarero R 1994 Comp. Fluid Dyn. 2 41
[6] http://www.cerca.umontreal.ca/
[7] Thompson Philip A 1972 Compressible Fluid Flow (New York: McGraw-Hill)
[8] Griffiths David J 1999 Introduction to electrodynamics (Singapore: Prentice Hall).
[9] Aubrecht V and Bartlova 1997 IEEE Trans. Plasma Sci. 25 815-23
[10] Ruchti C B and Niemeyer L 1986 IEEE Trans. Plasma Sci 14 423-34