Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 3, No. 3, 2022

Rapid and Safe Arc Quench by Using External Magnetic Coil in Power Interruption

Qian Wang[1, *], Fangwei Liang[1], Xinmiao Zhou[2]

[1]Department of Electrical Engineering, Tsinghua University, Beijing 100084, China

[2]State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University, 710049, Xi'an, China

[*]Corresponding author: Qian Wang, hjd_2009@126.com

Abstract: Low-voltage arc quench is one of the most processes for a successful power interruption in circuit breakers. Typical circuit breakers are designed to switch off the fault current within half a cycle, less than 10 milliseconds, which requires an efficient arc quench and thus poses great challenges in power interruption. Apart from using power electronics, which is very expensive and of low capacity, the classical circuit breakers that uses a stack of steel plates to split the fault-current arc into many sub-arcs are still dominant for both industry and residential installations. Due to the high current, the self-induced magnetic field will drive the arc towards to the steel plates and force the arc being spitted into many sub-arcs, from which the arc-steel plate interfaces generates multiple voltage drops. Once the sum of all voltage drops increases and exceeds the source voltage, the arc will extinguish and quench. Due to the ferromagnetic effect, the magnetic field increases dramatically during arc splitting by steel plates. However, the self-induced magnetic field have reversed direction on both sides of the steel plates which pushes the sub-arcs to opposite directions and prevents concurrent and even arc splitting. In this report, we report a new technique to compensate the self-induced the magnetic field by using a background magnetic coil, thus, to give an even and simultaneous arc splitting and guarantee the power interruption.

Keywords: Circuit breaker, Ferromagnetic effect, Voltage drop, Power interruption, Concurrent splitting.

1. Introduction

Electric arc quench plays an very important role in many applications, such as plasma torches[1], circuit breakers[2-8], arc welding[9], surface flashover[10-12] and charge generation[11, 13, 14]. In a low voltage circuit breaker, when fault current happens, the opening of contacts will generate an electric arc. The arc quench is accomplished by a stack of steel plates which cut the arc into many sub-arcs and thus increase the total arc voltage. Once the arc voltage increases and exceeds the power source voltage, the electric arc will not be sustained and thus quench. This technique is regarded as a very reliable method to instantly switch off the power supply at the extreme conditions like fault current occurring in the power system.

Lots of research work have been performed to study the behaviors of electric arc [15-18], arc-electrode interactions[19, 20] and electrode erosion[21, 22]. The energy from an electric arc can be huge as the electric arc happens under a fault-current condition. Most of low-voltage circuit breaker uses a stack of steel plates to split the arc, due to the ferromagnetic effect which will strength the magnetic field and accelerate the arc interruption. Some study [4, 23] investigated the arc splitting in a circuit breaker with considering the ferromagnetic effect and concluded that steel plates have a big influence on arc's motion. Because of the fault current is very high, like over thousands ampere, the magnetics field is very strong, and the saturation properties of ferromagnetic materials, like steel, also has a remarkable influence on the arc splitting which still needs more investigations.

Generally, the self-induced Lorentz force and the arcing induced uneven pressure together dominate the arc dynamics. Meanwhile, some heuristic techniques have been raised for accelerating the arc interruption, like external magnetic field and wall ablation. For example, high-current vacuum arc has been simulated under the transverse magnetic field which strengthens the magnetic force[24, 25] and thus can accelerate the process of power interruption. If the low voltage circuit breaker is placed within a magneto coil that can generated the magnetic field in the same phase and thus helps to push the arc towards the steel plates which, consequently, accelerate the arc splitting and arc extinction [26]. This technique is also expected to ensure the arc splitting successfully and shorten the duration of arcing. All of these necessitate the implementation of accurate magnetic field modeling in arc simulation. Placing the circuit breakers, relying on the arc splitting technique for power interruption, inside a background magnetic field will improve the design of practically oriented low-voltage circuit breakers. Therefore, this report will firstly introduce the power interruption technique of low-voltage circuit breaker, and then explain the underlying challenges in the arc splitting and propose a solution to this challenge. The concluding remarks are drawn in Section 3.

2. Results

2.1. Arc Splitting Phenomenon

Low low-voltage circuit breaker (LVCB) in a power system is to protect the electrical components and to isolate the abnormal energy supply in the power grid. Generally, the circuit breakers typically have to interrupt the power supply within half a cycle once fault current occurs. Under the situation of fault current, the opening of circuit breaker contacts will generate an arc plasma due to the gas medium breakdown. The initialized arc plasma inside the circuit breaker will continue the fault current which poses a big threat to the power system and installations.

For a typical circuit breaker as illustrated in **Figure 1**, the main parts are copper contacts (one is fixed contact and another one is mobile contact), a stack of steel plates and some insulating materials like (nano-coated) dielectric polymer which can absorb substantial heat and generate great amount of polymer vapor. If the housing of the LVCB is made up of polymers[27-29] that are easily gasified in high temperature environment, large volume of polymer vapor generation will tremendously increase the local pressure and alter the flow field which, consequently, accelerates the arc motion and expedite arc extinction. As a supplementary to this technique, we will introduce using external magnetic coil to ensure a rapid and safe arc quench.

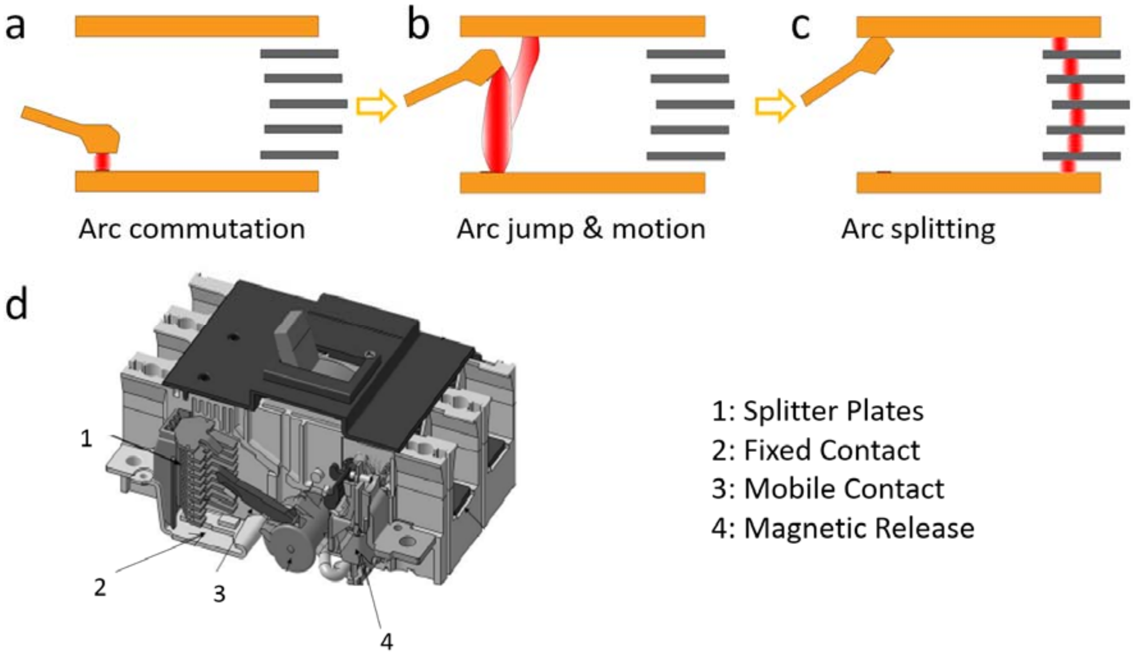

Figure 1. Arc splitting and power interruption under a fault current situation. (a, b, c) The typical three stages of arc interruption: arc commutation, arc motion towards the steel plates and arc splitting and quench. (d) A typical design of circuit breaker.

The illustration of three stages of arc interruption is shown in **Figure 1**. When the fault current occurs, the release mechanism of the contact is triggered. The opening contact will give rise to an arc initialization, which is the arc commutation. Along with the contact opening, the arc will then jump to the top contacts. Then the self-induced magnetic field will push the arc towards the steel plates. The whole arc is expected to be cut into many sub-arcs that will multiply the number of potentials drop. The potential drop across the arc-electrode interface can be as high as tens or hundreds of volts. The exact value of the potential drop across the sheath is inconclusive, for example, 10-30 volts[30], 300 volts [31], and current density dependent values [30, 32] are reported.

Accelerating the arc towards to the steel plates and forcing the arc evenly being cut and split can help to fulfill the efficient power interruption. Some techniques like imposing a gas flow [33] from the polymer dielectric polymer to interact with the thermal arc are proposed to expedite the power interruption.

2.2. Challenges

The even and concurrent arc splitting is preferred to introduce more voltage drop and thus to increase the arc voltage to exceed the source voltage. However, the experimental observation shows that some sub-arcs may stay at the end of the steel plates as shown in **Figure 2**, which actually prevents further arc splitting. The thermal arc moves under the combined effect of Lorentz force and thermal buoyance. Huo et al.[5, 6] has explained the uneven arc splitting induced by the reversed magnetic field by the steel plates for the first time, and proposed a solution of imposing an pressure or external magnetic force onto the thermal arc.

For high-current discharge, the Lorentz force is the major driving force for the arc movement. The fast motion of the arc can be easily cut into many sub-arcs if there is no reversed magnetic field. The reversed magnetic field will not be obvious at first but become remarkable once the sub-arc motion at quite different locations, because the current going through the steel plate in vertical direction in **Figure 2**b will generate very strong magnetic field due to the ferromagnetism effect, with opposite directions on both sides. Such magnetic field is strengthened if the vertical distance between these two sub-arcs is increasing, which will force the left sub-arc remain at the bottom. As a result, the high-current arc normally has a very irregular shape, and the arc will not be spitted sufficiently.

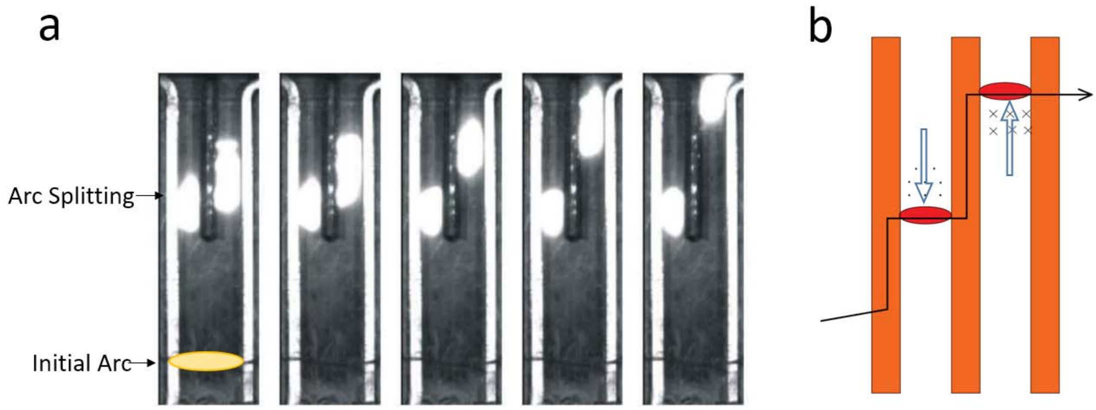

Figure 2. (a) Uneven arc splitting and stagnation. (b). The illustration of the reversed magnetic field that causes the sub-arcs stagnation at the bottom.

From the Figure 3, we can find the magnetic force increases dramatically after the arc reaches the steel splitters. Unexpectedly, some sub-arcs in the middle area move ahead of their neighbors, and some remain at the bottom. Since the frontier of the pressure wave is generally aligned, the failure of arc-splitting outside (both left and right) results from the reversed magnetic force given by the adjacent steel plates. The sub-arc in the center moves faster than its neighbors, which causes the current to go through the steel splitter. The self-induced magnetic field by the current carrying steel splitter is very strong but in the opposite direction on two sides of the steel splitter. This magnetic field will accelerate the upper sub-arcs in the center moving faster, but it will push the lower sub-arcs downwards and prevent the additional splitting as illustrated by **Figure 3**a. In other words, the self-induced magnetic field may have a negative influence on the sub-arc splitting. The corresponding technique identified is the externally applied transversal magnetic field [34], which is expected to compensate the self-induced magnetic field with reversed direction on two sides of the steel plates. Such external magnetic field can be applied by the coils connected to the concerned circuit with the circuit breaker installed as shown in **Figure 3**b. The magnetic coil can be installed away from the circuit breaker and will not impacted by the thermal arc and be free from thermal or mechanical damage, like erosion or fatigue[35].

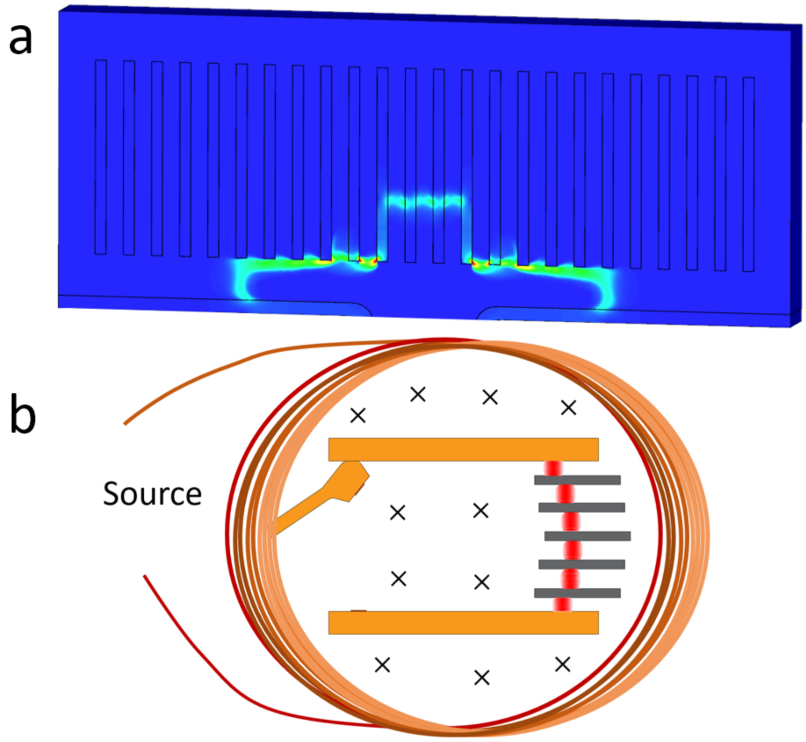

Figure 3. Uneven arc splitting and background magnetic field. (a) the uneven arc splitting within a stack of steel plates. (b) The installation of background magnetic field by a coil connected in the circuit system.

So, one important issue is that the imposed magnetic field should be aligned with arc-induced magnetic field such that the external magnetic will help to push the arc towards the steel plates. In this way, the external magnetic field will accelerate the arc motion towards the steel plates and also prevent the uneven arc splitting in the steel plates. The self-induced magnetic field intensity should be high enough to offset the reversed magnetic field by the steel plates. Besides, the internal pressure field also plays an important role in forcing the arc being spitted. In other words, if the pressure is high enough, the reversed magnetics filed that causes the sub-arc stagnation will not occur.

Some dielectric ablative materials are urgently needed for arc extinction cases. Optical radiation is one of the major ways to dissipate the energy of the arc. It has been found that extremely small or nanoparticles could shift the absorption spectrum of the substrate material and provides a potential way to manufacture highly ablative materials. For example, PMMA has excellent transmissivity and PMMA film can be made by solution casting and doped with nanocomposites to form an ablation resistance coating layer[36].

3. Conclusion

In this report, we present the arc splitting technique in accomplishing the power interruption in a typical low-voltage circuit breaker. From the experimental observation, after the steel plates cut the arc into many sub-arcs, the current through the steel plate will generate a strong magnetic field that will cause the reversed magnetic field and prevents an even and concurrent arc splitting. In order to solve this problem, we discussed the solution of using a background magnetic coil which is able to compensate the reserved magnetic field and thus prevent the sub-arc stagnation at the end the steel plates. Another effect of background magnetic field is that it can accelerate the arc travelling towards the steel plates. In short, both effects of external magnetic field will contribute to an efficient arc splitting and safe power interruption. Apart from using the external magnetic field, another technique is using highly ablative insulating polymer insider the circuit breaker, which can be gasified in contact with the thermal arc, and thus generate great amount polymer vapor which will increase the local pressure and thus push the arc towards the steel plates and prevent the sub-arc stagnation. Both techniques are expected to improve the design of practically oriented low-voltage circuit breakers.

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