Directional control of arcs in liquid nitrogen using externally biased magnetic fields

Muhammad Junaid, Lei Gao, Hongxu Li, Zhiyuan Liu, Yingsan Geng, Jianhua Wang

State Key Laboratory of Electrical Insulation and Power Equipment, School of Electrical Engineering, Xi’an Jiaotong University, Xi’an, P.R China

Email of the corresponding author: junaid@126.com

Abstract. Arc quenching process inside the liquid nitrogen (LN$_2$) can be accelerated by controlling the shape, size and direction of arc plasma through the controlled magnetic fields. This paper demonstrates the experimental investigations of controlling the arcs in specific directions through NdFeB based permanent magnets. The electrodes were shorted by fuse wires to initiate arc plasmas in LN$_2$. The effects of magnetic fields on the arcs inside LN$_2$ were observed for the very first time. The results show that arc plasma can be stretched, lengthened and thinned in the upward and downward directions through the North-South and South-North magnetic fields approach. These findings are good news that arcs can be controlled inside the LN$_2$ environment and several important achievements such as increasing the life time of electrodes, reduction in LN$_2$ consumption, reduction in bubbles formation, reduction in arcing times and getting a regular cylindrical shape, can be obtained through magnetic fields.

1. Introduction

Electrical Power system is subjected to severe environmental conditions. It often experiences short-circuit fault situations due to different climate and weather changes [1]. Power switchgears are designed to clear such kind of faults in the minimal possible time. Circuit breakers are used to operate automatically in such conditions and has to de-energize very heavy currents. Due to the high energy in the system, there is an arc plasma occurrence during the opening operation of the circuit breakers [2]. Many methods have so far been developed to control and minimize the time of such arcs in gases and vacuum [3-7]. For example; In vacuum interrupters, two types of electrodes are now commercially used to rotate or diffuse the arcs, depending on the applications and voltage and current ratings of the breakers [8, 9]. This paper deals with the study of a special case of arc occurrence in a superconducting fault current limiting switchgear. This is a totally R&D based preliminary study on the arc controlling inside LN$_2$ environment. No IEEE and IEC standards for LN$_2$ arc has so far been documented [10]. We have had the privilege of being pioneers of this research study [11-13]. Previously our investigations were based on uncontrolled or stray arcs in LN$_2$ [13-15]. So the arc shape and size were irregular and it was hard to assume a specific shape of arc in LN$_2$ for certain values of voltages and currents. Recently we were successful enough to develop methods to control the arcs in LN$_2$. Until now, no one has ever investigated LN$_2$ arcs under the influence of externally biased magnetic fields. The objective of this work was to control the arc in a specific direction so that its shape and size can be determined.
2. Experimental setup and Apparatus
Experiments were performed on different DC voltage levels such as 200 v, 300 v, 400 v, and 500 v. Figure 1 shows the experimental setup for the tests. K1, K2, K3 and K4 are vacuum contactors used for switching purposes. C1 and C2 are the two high voltage high power capacitors having a combined capacitance of 100mF whereas; L1 and L2 are the high voltage high power inductors having coreless geometry and a combined inductance of 0.101mH. R is the high voltage high power damping resistor; its value is 1 ohm. In addition, K5 is a fast acting 3-phase vacuum circuit breaker used as making switch for the entire circuitry. The overall circuit behaves as LC discharging circuit with damping nature.

2.1. The test object
The test object was designed such that it meets all the safety requirements of the experiments i-e, it shouldn’t explode and the repetitive tests are possible. Figure 2 shows a labeled 3D model of the test object. The whole test object is placed in a 362 x 260 x 155 mm Styrofoam box. Plane-Plane type symmetrical electrodes are used to create arcs and NdFeB, N35 type permanent magnets are put across the electrodes to control the arcs in Air and LN2 environment conditions.
2.2. Permanent Magnets Comparison and Selection

Selection of Magnets is an important part of this experiment. Table 1 shows a comparison table of the different types of permanent magnets. As can be seen here, the most suitable choice for the tests were Neo magnets.

Table 1.

| Type                                | Pros                                                                                     | Cons                                                                                     |
|-------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------|
| Hard Ferrite (aka Ceramic)          | • Cheaper than SmCo<br>• Very corrosion resistant<br>• Good heat resistance (max. 250-300°C/482-572°F)                                 | • Weakest Power<br>• Not good at low temp. (min. -60°C/-76°F)<br>• Low mechanical strength. Ferrite powder can rub off       |
| SrO.6Fe2O3 - BaO.6Fe2O3             |                                                                                                                                 |                                                                                                                                 |
| Alnico (Fe-Al-Ni-Co-Cu)             | • Very heat resistant (max. 450-550°C/842-1022°F)<br>• Cast-able, so complex shapes possible<br>• Mechanical strong and very corrosion resistant<br>• Low change in power with temperature | • Very easily demagnetized<br>• Not very powerful<br>• More expensive than ferrite magnets                                                                         |
| Samarium-Cobalt (Sm2Co17 or SmCo5) | • Powerful and very hard to demagnetize<br>• Very corrosion resistant<br>• Very wide temp. range from Cryogenic max. -271°C/-456°F up to max. 550°C/1022°F | • Most expensive<br>• Very low mechanical strength<br>• Difficult to make large (3")                                                                                                                |
| Neodymium (Nd2Fe14B)                | • World’s strongest permanent magnets<br>• Very hard to demagnetize<br>• Good at low temperature though slightly decrease in strength under -138°C/-216°F | • Most prone to corrode so coating is necessary<br>• Lowest heat resistance (max. 80-230°C/176-446°F)<br>• Slightly expensive<br>• Low mechanical strength |

Neo magnets has a wide range of grading available in the market. N35 types were selected to be used for the experiments. Table 2 shows the detailed specifications of the N35 type magnets;
### Table 2.

| Type                  | Neodymium Iron Boron (NdFeB) |
|-----------------------|-----------------------------|
| Grade                 | N35                         |
| Capacity              | ≈380mT (3800GS)             |
| Exertion Force        | ≈55KG                      |
| External Coating      | Nickel (Ni)                |
| Dimensions            | 100 x 50 x 20 mm            |
| Quantity              | 2                           |

### 3. Methodology

Two symmetrically identical plane to plane types of electrodes were short-circuited through a 5 amps fuse wire to intentionally create arc plasma situation. This free burning arc is then controlled through directionally controlled magnetic fields by employing two powerful N35 permanent magnets. These Neo magnets can operate at LN$_2$ temperatures without losing its efficiency. Tests were executed on two cases of directional magnetic fields, i.e. North-South and South-North magnetic fields arrangements were practiced. In addition, arcing times were measured and compared in four different scenarios, i.e. Arcing time in; Air, LN$_2$, LN$_2$ with magnets placed at 6.15 cm and LN$_2$ with magnets placed at 8.15 cm. High voltage probes and hall effect sensors were used to measure the arc voltages and arc currents. Digital oscilloscopes were used to record the waveforms of the measurements. High speed camera was used for optical observation of the arcs. The arcing times were obtained from the footages of high speed camera and the arc voltage/arc current waveforms. Since LN$_2$ is diamagnetic and is also lighter than water so the GN$_2$ created due to arc plasma, is not affected by the magnetic field. Thus the controlled magnetic fields only pushes the arc plasma in a specific direction.

Figure 3.1 shows the strategy to control the arc in a specific direction. As can be seen here, the current placement of the two magnets will force the arc downwards due to the Fleming’s left hand rule.

![Figure 3.1 Directional Control of arcs (Case 1)](image)

Figure 3.2 shows a different placement of the neo magnets, i.e. from South to North. Therefore, In accordance with the Fleming’s left hand rule, The Arc is forcedly stretched upwards.

![Figure 3.2](image)
4. Results and Discussion

The results are mainly divided into three different sub-sections. Each section is explained and concluded separately.

4.1. Arc stretching in downward and upward direction

Figure 4.1 shows the experimental demonstration of Case 1 in air insulation, i.e. the North-South magnetic field configuration. The photographs show the arc being stretched downwards.

Figure 4.2 shows the actual photographs of Case 2, i.e., South-North magnetic field arrangement. The arc can be seen stretched upwards in air insulation.
Figure 5.1 shows the experimental demonstration of Case 1, i.e., the North-South magnetic field configuration. The photographs show the arc being stretched downwards in LN$_2$ insulation.

![Figure 5.1 Arc stretched downwards in LN$_2$ insulation (Case 1: North-South configuration)](image)

Figure 5.2 shows the actual photographs of Case 2 in LN$_2$ insulation. The magnets were placed in South-North arrangement and the arc can be seen stretched in upwards direction.

![Figure 5.2 Arc stretched upwards in LN$_2$ insulation (Case 2: South-North configuration)](image)

All the footages in figures 4.1, 4.2, 5.1 and 5.2 were taken from the high speed camera. The electrodes used were made of Aluminium alloy (Al6061). The applied voltage was 500 VDC, the magnetic field was 650 mT and the magnets were placed in the front and back manner of the test object at 8.15 cm distance from the centre of the electrodes.

4.2. Arc currents and arc voltages with and without magnetic fields

Figure 6.1 shows Arc Current / Arc Voltage vs Time graph. The Applied Voltage was 500 VDC and the prospective current was 464 Amps. Arc plasmas were created in LN$_2$ environment using Plane-Plane electrodes geometry. The total arcing time was about 185 ms.
Figure 6.1 Arc Current/Arc Voltage vs Time (Without magnetic field applied)

Figure 6.2 shows Arc Current / Arc Voltage vs Time graph. The Applied Voltage was 500 VDC and the prospective current was 464 Amps. Arc plasmas were created in LN$_2$ environment using Plane-Plane electrodes geometry. 2 Neo magnets of 650 mT were placed in South-North arrangement on both sides of the electrodes with a distance of 6.15cm each from the centre of electrodes. The total arcing time was about 40 ms.

Figure 6.2 Arc Current/Arc Voltage vs Time (With magnetic field applied)
When arcs were directed upwards, the GN\(_2\) generated as a result were also moved in upwards direction and it disappeared by itself afterwards. So it can be concluded from the figures 6.1 and 6.2 that the arcing time reduces significantly by using magnetic fields approach.

4.3. Statistics of arcing times in four different scenarios

Figure 7 shows a detailed graph between Mean arcing times and arc currents. Plane-Plane type and Al6061 made, electrodes were used for the experiments. It can be seen that Air insulation has the longest arcing times in all the arc current conditions, while it gets lower in LN\(_2\) insulation and with the introduction of magnetic fields the arcing times can further be reduced. The shortest arcing times were recorded for the LN\(_2\) insulation with magnetic fields closer to the electrodes by the distances of 6.15 cm each. Thus, the stronger the magnetic field is, the shorter the arcing time will be.

![Graph showing arcing times for different scenarios](image)

Figure 7. Arc Currents vs. Arcing time

5. Conclusions and Future work

The arcing times were further shortened by controlling the arc using magnetic fields. Arc lengthening approach was adopted to make it less dense and thus reduce its time duration. This experimental demonstration also proved that arcs can be diffused, constricted, rotated and pushed in a specified direction in LN\(_2\) environment. If the arcs are pushed upwards the bubbles will generate upwards and would disappear by itself due to less density. This experimental study will be helpful in determining the size and shape of the arc. And the overall protrusions and deterioration of electrodes can further be
minimized. It will improve the shelf life of the electrodes. Future research will investigate the optical observation of stray and controlled arcs by image and video processing techniques to evaluate the arc area, shape and possibly volume.

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