Analysis of Action Mechanism of Graphite Bombs and Reaction Method of Power System

Wang Fang, Feng Shunshan, Wu Wenxuan and Liao Fuwang

***Abstract*—The short circuit collapse problem of electric power system attacked by graphite bombs was investigated. The harm of graphite bombs and the vulnerability of electrical network were analyzed. Two kinds of failure modes called direct short circuit failure and indirect short circuit failure were presented accordingly. The arc generation mechanism of conductive filaments dispensed from graphite bombs was analyzed and the concept of compulsively consecutive arc was presented. Then the verifying experiments under the condition of high voltage and small current were done. The short circuit blockade principle of electric power system by graphite bombs was also analyzed. In order to react to the attack of graphite bombs effectively, the clearing methods of conductive filaments such as mechanical removal, combustion and lightning impulse were presented which are helpful to recover the current supply capability of electric power system rapidly.**

***Index Terms*—Blockade, clearing method, compulsively consecutive arc, conductive filaments, graphite bomb, power system, short circuit.**

I. Introduction

BECAUSE of significance of electric power system to the national economy and military affairs, some key electric facilities for example high voltage substations have became the important target of military attack. The graphite bombs technology whose objective was to damage the outdoor high voltage electric facilities was studied firstly by America and used during the first Gulf war in 1991. During the Kosovo war in 1999, the improved graphite bombs were reused by America. Following these attacks lights went out over 70 per cent of Serbia. During the second Chechen war, the air-raid to the electric power system of Chechen anti-government arms was made by Russian air force which caused the large-area long-time power and water failure.

Considering the special function of electric power system for the national economy, the soft-wound ammunitions are generally used during the military attack. The graphite bomb is just the soft-wound ammunition filled with conductive filaments (carbon fiber filaments or glass fiber filaments coated with metal). The scattered conductive filaments from graphite bombs can create the effect of short circuit arc and short circuit blockade on the electric facilities. Thus the electric power system in a certain range loses the capability of transmission, distribution and current supply, which even results in the collapse of all electric power system. The related economic losses and social impact are very severe. Therefore it is necessary to study the problem of protecting the electric power system from the attack of graphite bombs.

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II. Harm Analysis Of Graphite Bombs To Electric Power System

A. Typical Graphite Bombs

Graphite bomb is a popular name. The more scientific name for this kind of bomb is conductive fiber bomb, short circuit bomb or anti-electric facility bomb. The typical graphite bomb is BLU-114/B developed by America and applied in Kosovo wars in 1999. As in Fig. 1, it is carried by such operational aircraft as F-117A, F-16, B-1 or B-2. When approaching the upper air of power plant or electric substation, BLU-114/B bombs are released by SUU-68 ATMD (Advanced Tactical Munitions Dispenser) from the aircraft. Each BLU-114/B falls to a preset altitude and then detonates, filling the air with long, thin, graphite filaments. These filaments are electrically conductive, and when they land on power lines or electrical transformers, they can immediately cause shorts and failures. Power plant or electric substation can thus be disabled.

Bomb

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Filaments
Fig. 1. BLU-114/B Soft Bomb

B. Vulnerability Analysis of High-voltage Electrical Network

In the high-voltage electrical network, the outdoor facilities for example the overhead electric transmission lines, the high-voltage towers and substations are vulnerable to attack from graphite bombs.

1) High Voltage Substation:

High voltage substation, especially extra-high voltage load-center substation is the primary attack target of graphite bombs. It has large area and many high voltage electric equipments. The region vulnerable to attack occupies over 60% of whole substation area. The multiple and complex malfunctions will occur after the short circuit. The system recovery time is long and the influence region is wide. Moreover it can lead to a chain failure of the lower substations and the upstream power plants.

2) High Voltage Tower:

The large high voltage tower has many crisscross electric parts such as wires, lightning conductors and hardware fittings. When the conductive filaments contact the tower, many short circuit modes include two-phase, multiphase or phase to ground occur. Moreover the removal of filaments in the upper air is very difficult.

3) Transmission Lines:

Although the transmission lines are long and thin, they are widespread and cross over various terrains for example mountains, ravines or rivers. When they are attacked by the graphite bombs, the filaments removal and the electricity recovery are very difficult and long.

4) Trans-regional Electric Power System

When a substation or some ones failed due to attack of graphite bombs in a certain large regional system, their load would be transferred to another brother substation which may result in its severe overload. The brother substation received excessive load and may tripped automatically. Then a chain of electricity supply failure like dominos occurred. The spread of dominos effect among the large regional systems would result in paralysis of more and more large regional systems and eventually the national electricity collapse.

Because of large unit capacity, high transmission pressure, wide distribution region, many components and fast response speed of the modern electric power system, its operating characteristic is complex and its control and administration are difficult. A severe disturbance may be spread to many other large regional systems and resulted in severe consequence. This phenomenon happens more easily while the systems operate under the full load and that the larger is the system, the wider is the spread of malfunction and the higher is the probability of system malfunction.

C. Failure Mode of Electrical Network Attacked by Graphite Bombs

From above analysis, it seems that there are mainly two failure modes for electrical network: one is called direct short circuit failure mode and the other indirect failure mode. The direct short circuit failure mode is a period of transmission and distribution failure of a certain electric facility attacked by graphite bombs. The indirect short circuit failure mode is such phenomenon that not only one or several electric facilities lose their own transmission and distribution capabilities under the direct short circuit damage of graphite bombs, but also involves other tightly related electric facilities losing their capacities too. The involved area by the indirect failure, from provincial network to national network, is much larger than the area of direct failure. Therefore it is very important for large regional electric network to improve their capability of self-defense and recovery of power supply under the short circuit damage.

The great power cut accident occurred on Aug. 14th 2003 in North America explained well the characteristic of direct and indirect failure when the electric power system subject to compulsive short circuit action [1]. This calamity makes over 100 power plants trip of America and Canada, including 22 nuclear power plants. The power cut area is over 9300 square kilometers including several states and provinces of North America. The power cut time is about 29 hours and the involved residents are about 5 millions. As shown in Fig. 2, the cause is that the short circuit malfunction occurred when a certain transmission line drooped and contacted a tree, which nature is coincident with the failure under the action of graphite bombs.

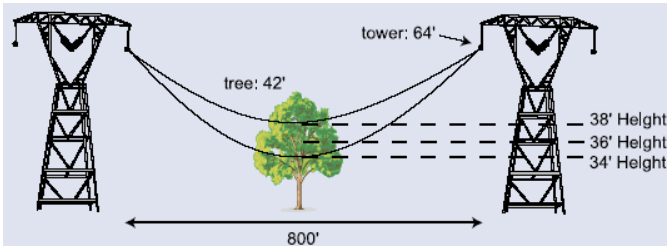


Fig. 2. Cause analysis of great power cut accident happened in North America in Aug. 14th 2003

III. Analysis of Graphite Bombs Action Mechanism to Electric Power System

A. Concept of Compulsively Consecutive Arc

The conductive filament used by graphite bomb is made of

a specially treated carbon graphite fiber or fiber coated with metal, which has the characteristic of creating compulsively consecutive arc [2]. The compulsively consecutive arc is a phase to phase or phase to ground short circuit arc created by conductive filaments or other conductive materials on the high voltage electric facilities, which can be sustained till trip of protecting equipment. Such event can not be eliminated despite of switching on several times. In other words, compulsively consecutive arc, as its names goes, is a phenomenon, that is, a specially designed and manufactured conductive materials (including any conductive fiber or powder) are acted on the electric facilities to destroy the insulation condition and create short circuit arc leading to trip.

To be further, compulsively consecutive arc occurs not briefly but frequently. It makes the protecting equipment lose its reclosing function and forms a "permanent malfunction" (lose power supply for a period of time, need special measures to recover). The harm of compulsively consecutive arc effect differs from other short circuit phenomena caused by nature. Such phenomena are usually transient; sometimes do not trip or just trip once. However, the compulsively consecutive arc effect, especially occurred in the key power facilities, may be extended to the whole electric systems, causing disturbance, malfunction or even collapse of power grid. Therefore it should be paid more attentions to study and analyze.

B. Physical Process of Compulsively Consecutive Arc

As in Fig. 3, when the filament coated with metal falls and lands on the high voltage wires, the inductive effect occurs due to the influence of surrounding electro-magnetic field. Then the coated metal attached to conductive filaments begins to emit electrons, evaporate and then turn to metallic gas. At the same time, the I^2R energy in the filament makes the temperature of filament itself increases rapidly, which leads to free float effect of coated metal and make the metal evaporates rapidly. These effects make the coated metal of filament change into the metallic gas and spread over the high voltage wires. The former inductive effect is the initial source of metallic gas while the latter free float effect is its main source.

The intervention of metallic gas destroys the insulation distance between high voltage wires. Under the action of strong electric field, the order movement of electrons speeds up the destruction of insulation distance. When the air space between phases is filled with metallic gas, the current discharge happens within the air space and the electric arc is created. Thereafter, the base material of conductive filament and surrounding air ionize intensively under the action of such high temperature and strong electrical field. The conductive substance increases and makes the electric arc path and its short circuit capability becomes stronger and stronger [1], [2].

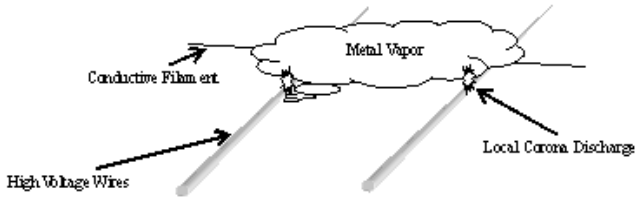


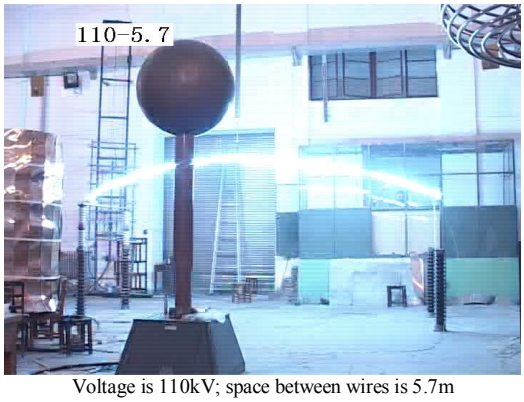
Fig 3. Diagram of short circuit arc generation

C. Experimental Study on Arc Generation of Conductive Filaments under Condition of High Voltage and Small Current

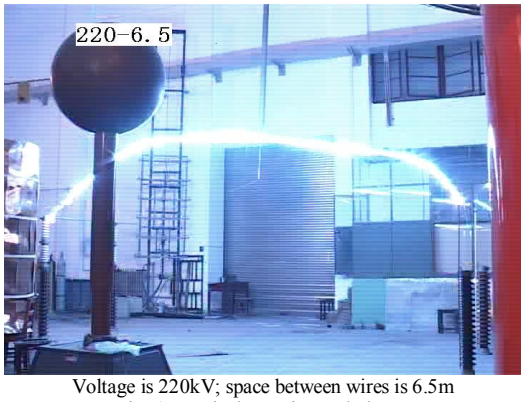
Under the laboratory condition, the experimental study on the phenomenon of arc generation for a certain conductive filaments was carried out [1], [3], [4]. The output voltage changes from 35kV to 220kV, the space between electric lines changes from 1.6m to 7.2m. The standard power of testing transformer is 300 kVA. The standard output current is 1A.

During the experiments, two metal tubes sustained by insulators acted as two wires. The output voltage of testing transformer was adjusted to the preset value, and then a conductive filament was released from the upper air, falling down to the wires. The bright electric arc was created at once.

Fig. 4 was the typical experimental results. These results indicate that only one conductive filament can generate the electric arc between high voltage wires. The duration of arc is long enough to trip.



Voltage is 110kV; space between wires is 5.7m



Voltage is 220kV; space between wires is 6.5m

Fig. 4. Typical experimental photos

D. Analysis of Short Circuit Blockade Mechanism

According to above experimental results, it can be seen that, for one enough long conductive filament acting on the electric facilities, the short circuit can be generated doubtless and the short circuit mode happens randomly. Thus when several conductive filaments act on the electric facilities, all kinds of short circuit modes will be generated and the "permanent malfunction" will occur.

Therefore the short circuit blockade mechanism of graphite bombs to electric power system is that, when a number of conductive filaments act on the high voltage electric facilities, their potential short circuit capabilities make the protecting equipment can not reclose within a period of time, the transmission and distribution capabilities of high voltage electric facilities are blockaded.

When graphite bombs attack the electric power system, there will be hundreds or thousands of conductive filaments acting on the electric network and cause short circuit blockade for a period of time. The filaments clearing is effective only when all filaments within the substation including ones on the electric facilities and other adjacent locations. Otherwise the remnant filaments still have the potential generation capability of compulsively conductive arc and continue to threaten the normal operation of electric power system. If several important electric power systems were blockaded by graphite bombs at the same time, then the large regional, even the national electric network would be blockaded too due to the influence of indirect short circuit failure. The harm is huge.

Suppose the blockade time for a certain high voltage electric facility attacked by graphite bombs is t_{Di}, then this time can be expressed as

$$t_{Di} = t_{D0} + t_{D1} + t_{D2} + t_{D3} + t_{D4} + t_{D5} + t_{D6} + t_{D7} \quad (1)$$

Where

t_{D0} is the acting time of short circuit arc generated by conductive filaments;

t_{D1} is the time of distinguishing position of malfunction;

t_{D2} is the time of dispatching clearing workers and equipments;

t_{D3} is the time of arrival of clearing workers and equipments;

t_{D4} is the clearing time of conductive filaments;

t_{D5} is the detection and first reclosing time, if the reclosing successes, the blockade time ends;

t_{D6} is the time of clearing and reclosing again, if the first reclosing fails, clear and reclose again until reclose successfully;

t_{D7} is the time of recovering power supply and executing other programs.

If the blockade time for a certain region of electric network attacked by graphite bombs is defined as T_{DN}, then T_{DN} is not only dependent on the number, location and failure time of high voltage facilities direct acted by graphite bombs, but also the capability of malfunction administration and the measures of filaments clearing, detection and recovering power supply. T_{DN} can be expressed as

$$T_{DN} = \sum_{i=1}^{N} t_{Di} + T_{\tau} \quad (2)$$

Where,

N is the number of high voltage facilities direct acted by graphite bombs;

t_{Di} is the blockade time of a certain high voltage facilities by graphite bombs;

T_{τ} is the time of recovering power connections among high voltage facilities.

IV. Analysis of Answer Method of Electric Power System

A. Analysis of Answer Method

From above action mechanism of graphite bombs to electric power system, it can be seen that the common scheduling, administration, control and recovery measures of electric power system are not suitable while responding to the attack of graphite bombs. In order to reduce loss from attack, the corresponding defense technology and secure administration measures should be provided. Moreover the necessary secure system recovering power supply rapidly should be established.

Firstly, a set of emergent repair scheme should be prepared in advance, by which the malfunctions can be found and located in time. Secondly, enough trained well personnel, equipments and clearing tools should be prepared, which can answer shortly after the attack of graphite bombs, arrive at the field and clear the conductive filaments as soon as possible. Finally, the clearing effect check-up technology of filaments and safety evaluation method should be done before recovering the power supply.

In addition, exploration of active and passive defense methods are also necessary, which can reduce the attack capability of graphite bombs. In this aspect, some methods for example wind screen defense method, electromagnetic warning system, or shield method have been presented [5]-[6]. However these methods are still in research. Their feasibility and defense effect should be further examined and verified.

B. Discussion of Filaments Removal Method

The clearing method of filaments proved effective by practice is mainly mechanical method with some simple clearing tools and upper air operating trucks. Fig 5 shows a filaments clearing test in a substation by using a rod-type tools designed especially for filaments removal. The test

results indicate that although mechanical method can clear the filaments, the clearing efficiency is not great. Because of small stretching resistance, the conductive filaments are liable to tension fracture. The number of fibers in a strand of filaments are much more than thirties. There are often many short broken filaments hidden in the gaps of electric equipments or on the surface of insulators. As to these situations the common rod-type tools are helpless [7].

Fig. 5. Conductive filaments clearing test results in a substation

According to the performance and clearing difficulties of conductive filaments, the study on four clearing methods were carried out through test, which were mechanical clearing method, combustion, lightning impulse and chemical failure method respectively.

Mechanical clearing method is that using some mechanical tools to wind, pull off, scratch or blow filaments, which is also a common method.

Combustion method is that using high temperature flame to burn the conductive filaments to ashes. According the test results, the oxyacetylene flame with temperature of over 1500℃ is more effective. Because of short combustion time, it is not harmful to the facilities. This method is suitable for clearing the short twisted or hidden filaments among the insulators.

Lightning impulse method is that the impulse voltage is applied to the hidden short conductive filaments and makes them vaporize. This method is mainly used in the insulators of transmission lines, the dielectric strength recovery between lines, or the dielectric strength examination of electric power system after filaments clearing.

Chemical failure method is that using the acid or alkali solutions to react with the conductive filaments and damage their conductivity. The experimental results indicate that although the acid or alkali solutions can damage the form and conductivity of conductive filaments, they are also corrosive to the electric facilities. Therefore the feasibility of this method needs further research.

Considering the situation of modern high voltage substations, through the integrated application of three main filaments clearing methods, which are mechanical clearing, combustion and lightning impulse, a scheme about fast clearing of filaments is presented as follows.

1) Clearing of Filaments on the Lines and Equipments within the Substation

Use winding or pulling methods to remove a majority of filaments on the lines, push the remaining filaments to the ends of lines by scratching method. Then use high temperature flame to burn the short filaments twisted severely on the insulators or the ends of lines. Finally, the residual filaments ashes are removed by blowing method.

2) Clearing of Filaments on the Ground of Substation or the adjacent Buildings

Generally many conductive filaments will fall down on the ground and walls in the substation, the adjacent buildings or trees. All of these filaments need clearing too. Otherwise when the wind comes, these filaments are possibly blown up and fall down on the lines and create the electric arc.

3) Clearing of Filaments on Transmission Lines

High voltage substation is connected tightly with the inlet and outlet lines. Sometimes there are many filaments hanging on the transmission lines. Because of high location and wide span, the clearing of filaments on the transmission lines, especially the field lines, is very difficult only with manual work. At this time, a remote-control filaments clearing equipment is applied. The personnel can operate the remote controller and control the equipment moving on the electric lines and clearing the filaments at the same time.

4) Clearing of Remaining Short Filaments

As to a few of remaining short filaments left on the insulators and lines, the lightning impulse method is used. The filaments can be removed gradually with several strikes and the dielectric strength can recover to the normal level.

V. Conclusion

The harmfulness of graphite bombs to the electric power system and the vulnerability of high voltage electrical network were analyzed in detail. Two kinds of failure modes each called direct short circuit failure and indirect short circuit failure were presented accordingly.

The concept of compulsively consecutive arc was presented. The physical procedure of the compulsively consecutive arc was described. The experimental study under the condition of high voltage and small current were carried out, whose results indicate the rationality of theory. Then the short circuit blockade principle of electric power system by the graphite bombs was also analyzed.

According to the characteristics of conductive filaments, the effective clearing methods such as mechanical removal, combustion and lightning impulse were studied and analyzed. At last, a set of scheme about fast clearing of filaments was presented, which are helpful to recover the current supply capability of electric power system rapidly.

VI. Acknowledgment

The authors gratefully acknowledge the contributions of Wang Chao, Ji Liuqi of Beijing Institute of Technology, Li Qiang and Ii Di of Fujian Electric Power Test and Research Institute for their work on the experiments of this paper.

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VIII. Biographies

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