Investigation of On-line Monitoring Method on 1500 V Direct Current Cable of Subway

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The traction DC feeder cable is one of the key devices for the safety operation of subway system, but for low voltage DC feeder cable (<3000 V) for subway, little attention has been paid by investigators on its online monitoring technology. With an introduction of cable laying and operation environment for the cable, this paper investigated the on-line monitoring technology of 1500 V DC feeder cable of subway. Firstly, in the text, the fault model of 1500 V DC cable was proposed based on the analysis of the fault type of the DC feeder cable, and then put forward synthetically on-line monitoring discharge signal and DC leakage current signal to assess DC feeder cable insulating state. The results of laboratory experiment prove that the proposed methods are feasible and can be implemented on-line monitor on DC feeder cable of subway.

Keywords : Subway, DC feeder cable, DC leakage current, Discharge, On-line monitor

1. INTRODUCTION

Along the development of subway system, more and more DC feeder cables are being used, According to the statistics the length of subway line in the world has amounted to 5,200 kilometers to 2004[1]. The track transportation security is a huge complex system, there are many factors affecting its security running, and the power supply is one of major factors[2]. The traction DC feeder cable is one of the key devices for the safety operation of subway system; it is used to connect the high speed DC switch with contact net. The insulation status of the DC feeder cable directly affects the security of electricity supply of rail traffic, but because the laying environment is bad, the cable took placed insulation faults sometimes[3]. The power traction system of Shanghai subway had happened power failure accidents for many times just because of the faults of DC feeder cables. Investigators can't pay attention to the on-line monitoring technology of this kind of cable for its operational voltage is lower (1500 V) and the relevant research is scarcely carried out.

Now, the testing method for this kind of cable is mainly measuring the resistance of cable to obtain the insulation state of cable's insulation periodically. The practice effect implies that the current method can't assess the insulation state of cable effectively and timely, which makes the subway can't avoid the fault of breakdown in cable effectively when the insulation status of cable would be bad and affect the normal operation of subway. So, carrying out research on the online monitoring technology to the cable and get the insulation status of the cable timely not also embodies the economic benefit but also adequate social benefit to maintain the operation of subway.

This paper investigated the online monitoring technology to 1500 V DC feeder cable in shanghai subway traction substation on the basis of analyzing the fault type of the subway DC feeder cable and its operation characteristic. The results of lab experiment imply that the proposed on-line monitoring method is feasible to assess the state of cable.

2. ELECTRIC CONNECT OF DC FEEDER CABLE AND ITS FAULT ANALYSIS

2.1 Electric connect of direct current feeder cable

As Fig. 1 showed, it is a classic traction substation in Shanghai subway. The traction substation connects to power system by 110/33 kV transformer, and the transformer connects to the power system by single bus mode on the high voltage end of transformer, which collocate four vacuum circuit breakers, two rectifier groups made up of rectification transformers, rectifier, and 1500 V isolating switch, and adopted unearth operation mode[4].

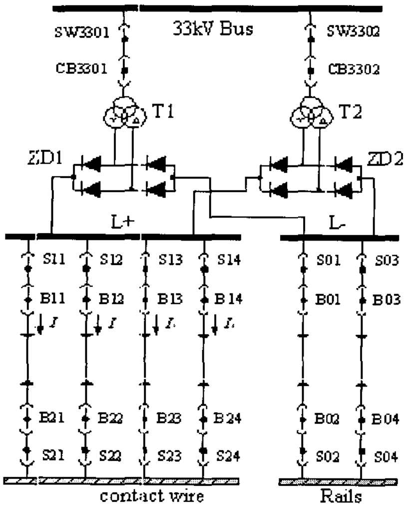


Fig. 1. Sketch map of electric wiring of traction substation.

DC 1500 V feeder cable is used to connect the fast-break switch to the contact wire with more than one cable connects parallel in general. DC feeder cable is the ERP cable without armor or tarp. The cable laying adopted tree types: direct buried in soil, bridge and channel. When the locomotive passing, the load current flowing through the cables. When there is no locomotive passing, or when the subway stops in the night, no load current flowing through the cables. The operational voltage of the cable exits over-voltage phenomenon, which goes far beyond cable operation voltage 1500 V, and the max peak value of over-voltage could reach 3000 V; there are abundant high harmonic in the system too.

2.2 Analysis of cable fault

Until now, there had happened many faults of DC cable in shanghai subway, and the statistic result of the faults of DC feeder cable from 2001 to 2005 year was listed as following Table1. After the analysis on the environment of faulty place and the statistic result, we class the reason caused fault of DC cable as follows:

① *Insulation deterioration caused by moisture*

The latex and PVC electric characteristic including its resistance would drop under the reaction of voltage after it filters water[5,6]. This kind of fault mainly took place on channel-laying cable in the under traction substation and direct burying cable on the ground traction substation. The insulation of cable in channel is easy to injure when it is put into the channel for the limited space of channel and the difficulty of construction. The insulation of cable would age when it filtered water, as time goes by, the insulation deterioration would grow into the ground fault. The faults happened in Jing'an temple and Longyang station were this model.

The cable would take place intermittent short till break after directly burying and operation if the jacket of cable injured in the construction. The fault can maintain a long time and burn many cables at the same time. The faults happened in Lianhua Road, Xin'zhuang and the Vehicle Sect station belonged to this kind.

② *Insulation deterioration caused by the high frequency pulse[7]*

The voltage changes as the load variety and over voltage takes place usually, even can reach to 3000 V, which is far in excess of the rate voltage of cable (1500 V), the rail in subway adopts the PWM to adjust velocity, the rail can result in abundant high order harmonic, the high voltage pulse and harmonic can speed the aging of insulation of cable[8], which caused

Table 1. Fault statistics of dc feeder cable of shanghai subway.

No.	Substation Name	Laying Model	Date	Fault*
1	Shanxi Road	Bridge	2001	Caused power failure
2	Jinanshi	Bridge	2001	Caused power failure for 35 Mins and influence running
3	Lianhua Road	Direct buried	2002	Caused power failure for 50 Mins and influence running
4	Vehicle Sect	Direct buried	2002	Caused power failure
5	Lianhua Road	Direct buried	2003	Caused power failure for 18 Mins and influence running
6	Lianhua Road	Direct buried	2003	Caused power failure for 12 Mins and influence running
7	Xinzhuang	Channel	2004	Caused power failure
8	Xinzhuang	Channel	2005	-
9	Longyang Road Garage	Channel	2005	-
10	Lianhua Road	Channel	2005	Caused power failure

***Note:** The influence movement is refers creates the subway train to suspend shipment above 5 minutes.

the drop of resistance of cable and the fault to the subway operation.

③ *Insulation crack caused by electric strength*

The load of cable is intermittent; the electric strength emerged during operation results in the injury of insulation in cable by swaging cable and striking cable to the bridge, at the end, the cable happened earth fault. The fault of shang'xi road DC cable is this kind fault.

④ *Insulation crack caused by inadequate curvature of layout*

DC cable on the ground station usually is directly buried, on the bottom of tower, for the inadequate curvature layout, the outer layer of insulation in cable cracks and grows into ground fault for the injury of its insulation. This kind fault usually takes place in Lianhua Road station.

3. MONITOR METHOD INVESTIGATED

3.1 Fault model and monitor method proposed

The analytic result to fault implies that the insulation of cable is very important to the operation of subway. The traditional method is not satisfied with the need of safety operation to the subway. Cables laid by using three layout all take place fault, and the fault factor is various, but the phenomenon can be attributed as follows: ①the injury of insulation resulting the ground fault. ② the heat and electric break caused by the insulation deterioration .

Until now, the research of online monitoring method mainly concentrates on the AC cable, and constructs the fault model as well as relevant detecting methods[6]. Although the characteristic of cable is different between AC and DC voltage, it is significant to borrow AC monitoring technology to DC monitoring technology for DC feed cable. The judgment and the analytic model are different between each other.

The field test and lab result indicate that the subway DC cable can still operate when its insulation has some slight crack and low resistance, which is different from high voltage cable. The method adopted by now can't timely evaluate the state of cable and avoid the further development of fault, which might result in breakout of subway. The author thinks if we can get the real state of insulation, it is real sense from point of project to prevent the cable from sick operation even widening the fault. So, this paper pays attention to the research on online monitoring technology to cable in the special state.

A. DC leakage current method

There is a good line relationship between DC leakage current and insulation resistance of insulation material:

$$R = U / I_e \tag{1}$$

So, by detecting the resistance, the DC leakage current can reflect the state of insulation in cable under DC voltage. The DC cable in station can illustrate by the equal model as follows:

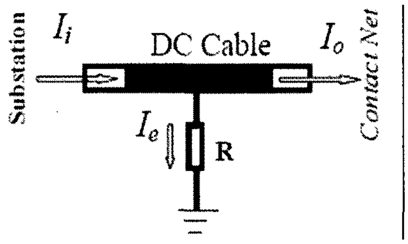


Fig. 2. Equivalent circuit of DC feeder cable.

In the graph, I_i is the input current, I_o is the load current, I_e is the DC leakage current of cable, and R is the equal resistance of the insulation of the cable, that is to say:

$$I_e = I_i - I_o \tag{2}$$

According to aforementioned, the load current in DC feeder cable has such characteristic: when the locomotive passes, then the very big load current, 2000 A, flows through the cables; but when there is no locomotive passing, or when the subway stops in the night, no load current flows through the cables, e.g. Io=0. Then,

$$I_e = I_i \tag{3}$$

So, by monitoring the DC leakage current of cable when the engine stopped, we could get the value of DC leakage current, and get the information of insulation of the cable.

B. Discharge method

In section 2.2, the analysis result of fault in feeder cable implies that the main reason of fault in DC 1500 V cable is that the injury of insulation results in the ground fault and the heat and electric break caused by the insulation deterioration. The investigated results indicated when the insulation layer of the cable cracks (the conductor core of the cable does not bare and connect to ground), it is difficultly found by monitoring DC leakage current because the insulation resistance does not obviously decrease, but the cable would discharge to ground or bridge under the moisture and dirty operation.

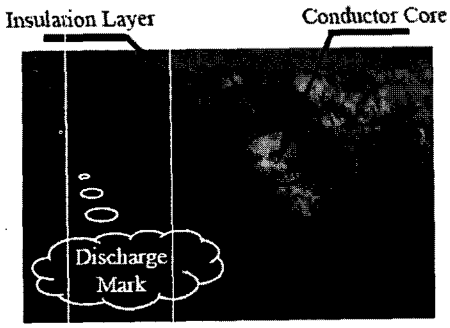


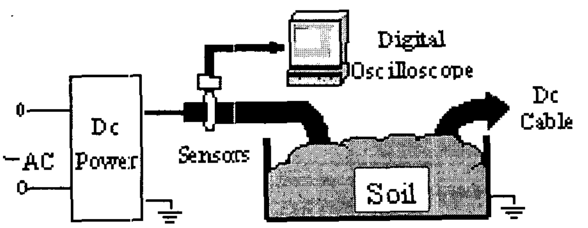
Chart 3. Photograph of faulty cable.

Chart 3 is the photograph of faulty cable coming from the field. The chart shows the severe breakage of insulation clearly. The conductor core of cable is uncovered. There is an obvious mark caused by the discharge. According to the substation worker introduced this discharge continued about three days. So it makes sense to actual project through evaluating the state of insulation by monitoring discharge signal and can find the initial defect of cable.

3.2 Investigating feasibility of the methods

The feasibility of proposed methods was investigated by using the experimental circuit as Fig. 4 showed in laboratory.

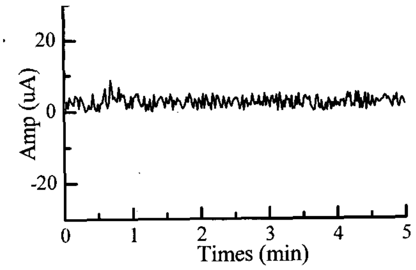
In the experiment, the DC leakage current signal was measured by a DC current sensor working on the principle of magnetic balance; the discharge pulse signal was detected with a HFCT sensor having a frequency bandwidth from 100 kHz to 50 MHz; and the detected signal went to a digital oscilloscope, the features of which were used to observe and record information. The oscilloscope was a Tektronix TDS754A, with a bandwidth of 500 MHz and a sampling rate of 2 GS/s.



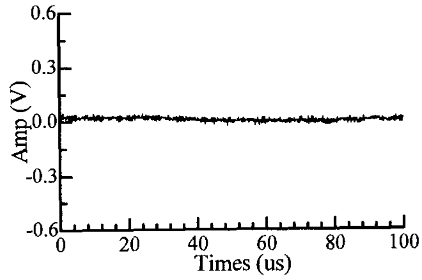
(a) Experimental circuit

(b) Specimen

Fig. 4. Experimental circuits and the specimen.



(a) DC leakage current signal



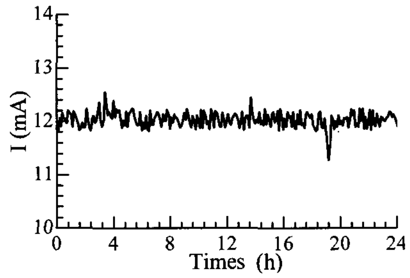
(b) Discharge signal

Fig. 6. Leakage current signal and discharge signal of healthy cable.

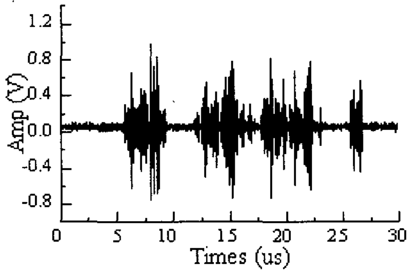
The specimen cable, EPR cable without armor, came from the field. Firstly, the healthy cable was put in moist soil, and the DC leakage current signal and discharge signal were measured under DC 1500 V operation, respectively. The results of experimentation were shown in Fig. 6.

Then, the defect cable was put in the moist soil too, and measured the DC leakage current signal and discharge signal were measured. The defect cable was the aforementioned healthy cable damaged by the trier, and the crack reached to conductor from the outer sheather, as Fig. 4 showed. The results of experimentation are shown in Fig. 7.

Comparing Fig. 6 with Fig. 7, it can concluded that the healthy cable didn't happen discharge, but the cable would take place discharge to the ground when its insulating layer has slightly cracks, the repeat rate of discharge is high; and continues period of time; the leakage current value will be more larger than healthy state when its dielectric resistance drops, and the maxim leakage current value can reach mA level, of course the cable still can operate. For the reason that the cable cannot embody the phenomena mentioned above when it in healthy condition, so the author think if the discharge signal and DC leakage current signal grow up, it can



(a) DC leakage current signal



(b) Discharge signal

Fig. 7. DC leakage current signal and discharge signal of the defect cable.

conclude that the insulation of cable has happened fault. Laboratory test proved that it was feasible to assess the insulating state of the cable by synthetically monitoring the discharge signal and leakage current signal. The methods have actual project significance.

4. CONCLUSION

This paper investigated the on-line monitoring technology of DC feeder EPR cable of subway under special condition. Research results indicated that it was feasible to assess the insulating state of the cable by synthetically monitoring the discharge signal and DC leakage current signal. Proposed monitor methods have actual project significance because it can avoid the accidence caused by the defect cable operating, and provide theory reference for implementing on-line monitor to the DC feeder cable of subway.

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