Method for Detecting DC High-resistance Ground Faults with High Current Arcs in DC Traction Systems

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The detection of high-resistance ground faults in DC 1.5 kV traction power supply systems has remained an unresolved problem for years. There are several methods to detect such faults using additional devices and/or wires installed along tracks. However, due to cost and maintenance problems, there has been a demand for a fault detection method which uses only electrical measurements inside traction substations. To this end, we analyzed a recorded current waveform of an actual fault to find out its characteristics. Based on the results obtained, we proposed a novel method for detecting high-resistance ground faults with a discharging arc of more than a thousand amperes DC current.

Keywords: high-resistance ground fault, protection relay, atmospheric arc discharge, random fluctuation

1. Introduction

Detection of high-resistance ground faults has remained one of the most difficult problems to solve in DC traction power supply systems for years, especially for systems using running rails as a return conductor. Once a ground fault occurs on DC traction system, it may continue to operate without automatic detection due to the small current involved, and fixed installations may be damaged due to arcs and/or electric fires, which often lead to significant disruptions to train operations. DC 1.5 kilovolts system is, in Japan, mainstream for heavy traffic commuter lines, subways and intercity main lines; therefore, reliable fault detection is an important subject to avoid such disruptions.

There are several known remedies against ground faults: the most common method today is to install some kind of switching device which turns on in case of a fault and creates a current return path from the masts of contact line system, roofs of platform, steel bridges, etc., to the running rails. Such devices are often called “voltage-limiting devices” (VLDs) and have recently been standardized in IEC 62848-2. In Japan, the Great Seto Bridge (Seto Ohashi) and the Sky Gate Bridge R (Kansai International Airport Access Bridge) use similar switching devices [1] partially equivalent to VLD-F. VLD-F and its equivalents are very reliable solutions; however, they need to be installed on every mast along tracks on non-conductive structures (embankments, viaducts, tunnels). This incurs not only initial costs but also future inspection and maintenance costs due to the large numbers of VLDs, and poses a labor problem for railway operators. Interconnecting wires between masts can be used to reduce the number of VLD-Fs but this might raise concerns about electrolytic corrosion from stray current in moist circumstances. Therefore, VLD-F or its equivalents are still considered only as special measures in Japan and are not yet widely used.

Other methods using additional wire and varistor/diode to conduct voltage rise of masts to protection relays in substations have also been studied but have not been put into practical use because of the increments of maintenance newly required for the additional wire [2]. Meanwhile other research and development has been underway to find methods for determining faults using only information about voltage and current, etc., collected from substations without the need for additional equipment to be added to the overhead wire system [3][4]. However, most of these methods have not been put into practical use due to their insufficient performance. For example, the method using a statistical approach to monitor trends in DC feeder line current values over time, still has the problem of delayed detection, up to several minutes or more, and the possibility of false detections due to a special train. Another method superimposes an AC current on a DC feeder and measures impedance, similar to a distance relay in an AC feeder. However, in this method it is difficult to determine the appropriate threshold value, because the parameters unobservable by a protection relay itself, such as the number of trains on the line or the inductance of DC input filter reactors for onboard traction systems, may likely affect proper detection.

As such, the authors planned to reconsider how to detect DC high-resistance ground faults using only substation measurements. A detailed, high-sampling rate waveform data under a DC high-resistance ground fault was recorded by accident, which yielded valuable knowledge to the authors. Consequently, we proposed a novel detection method, drawing on a method using electric arc vibration, once studied in Japan in the 1950s. We managed to confirm that when a ground fault current is about 1000 amperes or more, the ground fault can be detected in about 5 seconds if it generates an arc. The proposed method makes it possible to detect some DC high-resistance ground faults that have not been detected by conventional DC feeder protection relays up until now [5].

2. Basic investigation on electrical phenomena with test rigs

The authors performed a basic test with two test rigs to examine electrical phenomena on high-resistance DC ground fault [5]. One consisted of a flat steel bar and a steel
plate in an air gap of about 40 millimeters with a strip of lathe waste as an arcing lead wire attached every time; the other involved a piece of concrete pole with partially exposed reinforcement bars and a pole band. DC power was fed from a DC 1.5 kilovolts 6-pulse rectifier via a 16-ohm resistor.

In the case of the air gap discharge, as shown in Fig. 1(a), the arc voltage randomly fluctuated and thus a random current fluctuation up to 10 amperes was seen. Since the arc voltage variation from 40 up to 200 volts was reflected as if it were a voltage variation in a resistor, the amplitude of current fluctuation on this examination is a quotient of fluctuation amplitude of voltage divided by the resistance. In the case of the concrete pole, as shown in Fig. 1(b), however, since the arc voltage fluctuation was much smaller, it was difficult to see the small random fluctuations in the current as a waveform, due to the large amplitude of the rectified ripple of the 6-pulse rectifier.

The reason for the small fluctuation in the latter case is explained as follows:

(a) In the case of concrete poles, the arc discharge was initially enclosed in a very small space between the pole band and the reinforcing bars in the concrete pole. The space was semi-enclosed due to the surrounding concrete, so that the length of arc did not fluctuate so much during arc discharge unless the pole band melted off the pole.

(b) In this test, the lead wires were tightly connected to the reinforcing bars of the concrete pole and the pole band with wire clips and bolts, so that no arc was generated at those tightened points.

These results showed that, in the case of a DC high-resistance ground fault in which a relatively large current flows and a free space atmospheric arc discharge occurs, the current fluctuates randomly. The random fluctuation of the current made us that there is a possibility of fault detection only by measurement at the substation by some means of extracting the randomness. On the other hand, a high-resistance ground fault without atmospheric arc or with small current seems to be hard to be detected because of the small randomness of the current.

In an actual ground fault caused by a conductive flying object or the fall of an electric wire due to a deterioration in an insulator, the surface of the electric wire and the structures of an overhead contact line only come into contact with each other and are not tightened. Therefore, it is estimated that the phenomenon is a little closer to the situation of atmospheric arc discharge.

3. Analysis using a real high-resistance ground fault current waveform

An accidental DC high-resistance ground fault was successfully recorded, with its corresponding fault current waveform, using a data acquisition device installed in a nearby substation. The sampling rate was 1000 hertz, with a resolution of 10 amperes, for a duration of 30 seconds [5][6]. This was the first time such a waveform had been acquired over such a duration, with such a high-sampling rate, in Japan. Based on the data provided from the railway operator, the authors analyzed the ground fault phenomenon.

Figure 2 gives a schematic overview of the ground fault. The ground fault occurred on an overhead contact line connected to a feeder line named ‘12’. It has been confirmed that a tremendous arc was generated from various facilities in the same vicinity at the time of the ground fault. After that, self-release of the DC high-speed circuit breaker at the substation occurred due to the transformation of the ground fault to a metallic short-circuit.

The recorded current waveform is shown in Fig. 3, and the frequency analysis of this recorded waveform are shown in Fig. 4 and Fig. 5. The current of feeder line ‘12’ contains not only usual rectified ripple components derived from the utility frequency but also many spectra with recognizable intensities especially in the relatively low frequency bands, of approximately 200 hertz or less. This means the current in feeder ‘12’ contained large random fluctuation components like 1/f, which are unusual in
feeder line current. It is considered that this phenomenon on feeder ‘12’ was caused by the momentary deformations of the atmospheric arc, changing the arc length randomly, and the arc voltage accordingly. On the other hand, the intensity of random components on the feeder lines ‘11’, ‘13’, and ‘14’ were smaller than for ‘12’, despite all feeder lines being fed from the same DC bus.

This fault was categorized as a case with a relatively large current of about 1000 to 2000 amperes despite the DC high-resistance ground fault. However, in the case of faults with smaller currents, for example about several tens of amperes, since the intensity of the random component is estimated to be smaller, it is difficult to detect these ground faults using the random component.

4. Novel fault detection algorithm

4.1 Basic policy

Through the investigations described in Sections 2 and 3, the possibility of detection by observing only the current at the substation could be discovered if the DC high-resistance ground fault both had relatively large current and atmospheric arcs. Therefore, we decided to study and propose a method that can detect high-resistance ground faults with severe arcing of about 1000 amperes or more. The method aims mainly to avoid a faulty status continuing for long periods, and to reduce the risk of severe fire damage to trackside equipment, such as contact line masts, signalling and telecommunication system equipment.

Other influencing factors for this method, were that it had to be quick to implement, low cost and require little construction work. As such the following approach was adopted:

(a) Detection shall be possible only by observing current at the substation, i.e. without any additional trackside equipment.

(b) Detection shall only require common arithmetic elements with as little computational load as possible; it shall be implementable into protection relay hardware with limited processing performance and memory capacity.

(c) If possible, the existing current sensors for protection relays (Hall CTs, shunt resistors, etc.) will be used for additional cost reduction.

(d) The detection algorithm should be explicitly defined without any ‘black-box’ elements and fully explainable. This is because a rational explanation of the reason for non-detection and proof of fact are essential if the fault cannot be detected or the power supply cannot be stopped when the proposed method is used. For example, if fire were to begin due to a ground fault causing injury to passengers and the public, it may be subject to investigation by the Japan Transport Safety Board (under the Ministry of Land, Infrastructure, Transport and Tourism).

The ‘arc vibration type’ approach which focuses on the random component of a current caused by an arc, was already the subject of studies conducted in Japan between 1950 and 1959. The principle of the method was based on determining whether the content of kilohertz AC components in a feeding current exceeded a threshold value. Several tests at that time showed the possibility of detecting arcing faults to some extent. However, the method often caused false results due to the kilohertz band noise originally present in the feeder line current which is caused by commutator sparks of DC traction motors and rotary converters, noise from mercury rectifiers, contact loss with the pantograph, etc. Additionally, short-circuit faults due to commutator flashovers in DC traction motors were often undetected. Hence, the research on ‘arc vibration type’ was discontinued in 1959.

The authors aimed to solve the problems encountered in the ‘arc vibration type’ through a complete reconstruction using modern common signal processing techniques. The target was to supplement ground fault detection in the cur-
rent range of about 1000 amperes to 2000 amperes, which cannot be detected by the conventional DC feeder fault selective relay (ΔI type 50F relay) currently used in Japan.

### 4.2 Detail of detection algorithm and its verification using actual fault data

Figure 6 shows the devised ground fault detection method [5].

First, the feeder current signal is applied to a band-pass filter to extract the traction DC component, extremely low frequency components due to current fluctuations caused by the anti-slip control in traction systems, and high frequency noise components. Next, a comb filter with a signal delay time of utility frequency, i.e., either (1/50) seconds or (1/60) seconds, was applied to attenuate the rectifying ripple component selectively. This process extracted a filtered current waveform mainly composed of random components in a relatively low frequency band shown in Fig. 4 and Fig. 5.

In the method, a counter increases each time the obtained random component waveform crosses predetermined current threshold values (positive and negative respectively) alternately, in other words, at each change in output state of a hysteresis comparator.

The ‘evaluation value’ (tentatively named in this paper) is defined as the current value of the counter, minus the value at a predetermined previous ‘determination time width’. This value means the number of times the random component waveform crosses the positive and negative thresholds alternately during the determination time width. When this ‘evaluation value’ exceeds the predetermined criteria, it is judged as a ground fault. The final output of this algorithm, judgement as a ground fault, is activated when this ‘evaluation value’ exceeds the predetermined criteria. Hence this algorithm has four adjustable parameters: the characteristics of the band-pass filter (may include characteristic of current sensors), the predetermined current threshold, the determination time width, and the predetermined criteria.

Unlike the former ‘arc vibration type’, average rectified value and rms value are not used for evaluation. There are two reasons for this:

(a) To be able to detect the arc discharge based on the existence of a continuous fluctuation in random current, regardless of the amplitude of the fluctuation.

(b) To be able to suppress the effects of large-amplitude transient current changes seen ordinarily, such as when starting up of substation rectifiers, passage of pantographs through an insulated overlap in the catenary, changing of current due to train traction control, etc.

The authors calculated the ‘evaluation value’ to confirm this detection algorithm, using the fault recording current waveform shown in Fig. 3. Figure 7 shows the calculation results with following conditions: a pair of second order Butterworth filters, 15 hertz HPF and 100 hertz LPF, as the bandpass filter, the current threshold 25 amperes positive and negative respectively (i.e. hysteresis band width 50 amperes), and the determination time width 4 seconds. From Fig. 7, it is seen that the ‘evaluation value’ of the feeder line ‘12’ during the fault remained in range of about 130 to 150 continuously from 4 seconds until the interruption of circuit breaker. On the other hand, in each of the feeder lines that displayed a normal status ‘11’, ‘13’, and ‘14’, the ‘evaluation value’ was zero or sufficiently small with respect to the criteria, except for the value immediately before the accompanying interruption of feeder ‘14’. The ‘evaluation value’ of the faulty feeder ‘12’ was sufficiently larger than the other normal-state feeders. Therefore, it is obvious that the proposed detection algorithm should be able to detect DC high-resistance ground faults accompanied by large-current arcs using only feeder current measurement at substations. Note, the criteria are set to 138 as twice the maximum evaluation value in the long-term measurement described later in Section 4.3, but the criteria need to be changed according to the conditions of individual lines and characteristics of trains in operation.

It should be noted that to detect a ground fault with a smaller current (for example 100 amperes) using the proposed method, the current threshold value must be lowered as described later in Section 4.4. However, there is a risk in this case that the background noise of measurement system and the minimum resolution of the A/D converter make it too sensitive as a fault detection relay for daily stable train operation. As described later in section 4.3, unwanted operations are likely to occur due to fluctuation components contained in the current of trains. In addition, if too much focus is attached to fast detection, it increases the likelihood of a false detection of an arc ground fault, from in normal transient events, such as a train passing through a pantograph section. Therefore, there is a trade-off between pursuing fault detection with a small current, quickly, and avoiding false detections. In order to ensure stable and timely train operations on a daily basis, it is necessary to prioritize the prevention of unwanted false detections in normal circumstances, and set a detection limit. This approach is similar to the conventional settling value determination process for DC feeder fault selective relays.

### 4.3 Evaluation of possibility of false detections in normal state

To investigate the possibility of false detection by the proposed detection algorithm, the authors measured the
feeder line current at multiple traction substations during normal operation and calculated the ‘evaluation value’. The measurements were taken at substations A and B on line Y (utility frequency: 60 hertz) and substations C and D on line Z (utility frequency: 50 hertz). Feeder line current waveforms taken from existing Hall CTs were recorded over approximately 10 days at a sampling frequency 256 times the utility frequency (15360 hertz for 60 hertz, 12800 hertz for 50 hertz). Then, the evaluation values were calculated according to the method described in the previous section. Most of trains on line Y had rheostat-controlled or chopper-controlled DC motors, while all trains on line Z had VVVF inverter-controlled induction motors.

Figure 8 shows the calculation results of the evaluation value when the same detection parameter settings as in Section 4.2 were applied. The maximum evaluation value was 69, which occurred on feeder line ‘14’ of substation C. This value had a sufficient margin with respect to the minimum value 130 shown in Fig. 7. Therefore, the possibility of unwanted operations was sufficiently low. In other words, a margin of about twice the maximum of the evaluation value during normal operation could be considered as a criterion for setting the value.

Figure 9 give a detailed overview of the situation when the maximum evaluation value 69 occurred during normal operation. An oscillatory current fluctuation was seen in the feeder line current while a train was presumed to be coasting near the substation, and the amplitude of the comb filter output (= current fluctuation component) increased, exceeding the current threshold value (± 25 amperes). It is presumed that there was another train at that time. This phenomenon was not seen on line Y. Therefore, it is considered that the cause was due to the particular characteristics of the type of train in operation on line Z, or some unknown mutual interference between trains. This indicates that there is a trade-off between sensitivity of the fault detection algorithm and noise current level of trains in operation on a line. It is therefore important to confirm that the noise current of the trains in various states will be enough low to ensure the proposed detection algorithm can be used in practice.

4.4 Evaluation with artificial fault test

The authors conducted a small current artificial fault test about 100 amperes on the feeder circuit between substation A and substation B on line Y [7].

The test rig for the artificial fault was composed of an atmospheric discharge gap between a flat steel bar and steel plate about 40 mm apart (Fig. 10). An arcing lead wire was attached to the gap to start the arc discharge. The flat steel bar as positive electrode was connected to the output terminal of the feeder line ‘14’ switchgear in substation A via a contactor and a 16-ohm resistor, in series. The steel plate as negative electrode was connected to the substation return wire. The reason why the artificial fault circuit was configured as a metallic circuit instead of a ground fault circuit was to ensure safety in test implementation such as avoiding an unexpected fire due to a stray current during a ground fault.

With the same detection parameter settings as in section 4.2, the maximum evaluation value during the test was 3, and no faults were detected. Next, Fig. 11 shows the result with the current threshold changed to ±2.5 amperes, i.e., 1/10 of the original value: this is an equivalent obtained by multiplying the input current signal by 10 while keeping the previous current threshold value. The evaluation value reached around 100 within a few seconds to a dozen seconds after the energization of the substation A feeder line ‘14’. Although it should be noted that the arc discharge phenomenon was not proportional to its current,
it is estimated that the proposed detection algorithm could detect ground faults with atmospheric arc discharge of about 1000 amperes.

5. Conclusions

On the basis of the knowledge obtained from the actual fault current recording waveform, the authors proposed a novel method for detecting DC high-resistance ground faults using only measurements in substations. It was confirmed that the proposed method can detect a high-resistance ground fault with a discharge arc of more than a thousand amperes DC current within about 5 seconds, and that the possibility of unwanted operation is low.

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Fig. 10 Artificial fault test in Substation A

Fig. 11 Test result of artificial fault (after changing current threshold to ±2.5 amperes)

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