Optimal Design of a Follow Current Disconnector for DC Arresters in Traction Vehicles

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Received July 04, 2016; Revised July 16, 2016; Accepted July 18, 2016

This paper dealt with the optimal design of a follow current disconnector for DC arresters used in electric traction vehicles. The disconnector separates the ground lead from an arrester to prevent a line-to-ground fault of an aged arrester and should not affect the operation and function such as the reference and the clamping voltage of the connected arrester. The designed disconnector is composed of a resistor, a spark gap, and a cartridge. The results showed that the sparkover voltage increased with the gap distance whereas the reference voltage was almost the same as that without the disconnector. The sparkover voltage was 3.95 kV when the gap distance was 0.5 mm. Regardless of the gap distance, the reference and the clamping voltage of the assembled disconnector with an arrester were measured to be the same as those of the arrester alone.

Keywords: Arrester, Disconnector, Sparkover voltage, Clamping voltage, Voltage-current characteristic

1. INTRODUCTION

The safety and reliability of electric traction vehicles are seriously endangered by external lightning strokes and internal switching surges which result from the operation of circuit breakers or the moving contact between the pantograph and the overhead catenary wire. Overvoltages in electric traction vehicles are much higher than the rated voltages of railway system, causing server damage to the insulation of electrical equipment and resulting in personal injury. A metal-oxide surge arrester, which has the advantages of non-linear voltage-current (V-I) characteristic, fast response, and large energy absorption capability, is usually connected in parallel with the equipment or the overhead line to protect them from overvoltages [1,2]. However, the arrester ages gradually when subject to defects during manufacture, moisture ingress, and excessive surge current. If the deteriorated arrester is not removed, thermal runaway may occur owing to the increase in leakage current, even at rated stress, leading to a line-to-ground fault and consequent electrical hazards [3-6]. Figure 1 shows a photograph of an arrester failure, leading to

Fig. 1. Photograph of an arrester failure.
the breakdown of the traction vehicle. An arrester disconnector, also known as a ground lead disconnector or isolator, is mounted in series with the arrester to disconnect the ground lead in the case of a failure of the arrester [7,8].

Until now, metal-oxide surge arresters and arrester disconnectors used in AC systems have been well specified [9,10]. However, relevant works for DC network such as the railway system have not been discussed in detail. This paper dealt with the optimal design of a follow current disconnector for DC arresters in traction vehicles.

2. SURGE PROTECTION FOR DC TRACTION VEHICLES

2.1 Characteristics of arrester

The supply voltages of DC traction systems are given in Table 1, where \( U_n \) is the nominal voltage of a system, \( U_{\text{max}1} \) and \( U_{\text{max}2} \) are the highest permanent and non-permanent voltage, respectively, and \( U_{\text{max}3} \) is the highest long term overvoltage [11,12]. The values in Table 1 are used for the dimensioning of a proper arrester for a specific system. Taking the recommendations for an AC system into consideration, the continuous operating voltage of an arrester for a DC electric traction vehicle should be equal to or higher than \( U_{\text{max}2} \). In addition, the rated voltage should be selected with respect to the temporary overvoltages. The magnitude and probability of the surge current determine the nominal discharge current of the arrester [13-15].

Arresters for DC railway system are classified as A1 and A2 type. The A1-arresters are installed at each distribution point, at end of supply sections, at coupling points, and at power demand points to reduce the overvoltage to a harmless value. Additional arresters should also be considered at the sections where lightning strikes frequently occur. The A2-arresters are installed between the return line and the equipotential bonding bar to limit the potential rise of the rail [15,16]. Arresters for traction vehicles are the A1 type and are usually installed on the roof of the traction vehicle and at the base of the pantograph.

Figure 2 shows the equivalent circuit of a metal-oxide surge arrester. \( L \) is the inductance of the conducting leads. \( C \) and \( R_{\text{in}} \) are the capacitance and the resistance of the intergranular material, respectively. \( R_{\text{bulk}} \) is the bulk resistance, which is due to the intrinsic resistivity of the zinc oxide grains [17,18]. At normal stage, the leakage current flowing through the arrester is tens of microamperes. During overvoltage, the resistance of the arrester is reduced in order to limit the voltage across the equipment. Although the arrester has high reliability with a failure rate of less than 1%, it deteriorates gradually, resulting in an increase in leakage current and a decrease in reference voltage \( (V_{\text{ref}}) \).

Figure 3 compares the V-I characteristics between a new arrester and a deteriorated arrester for a 1.5 kV traction vehicle. The deteriorated arrester was applied by a standard impulse current of 8/20 µs and 5 kA for 1,000 times. Its leakage current at nominal voltage did not significantly change, whereas the \( V_{\text{ref}} \) at 1 mA decreased from 4.07 kV to 3.01 kV. If such an arrester is not removed from the system, the deterioration will be accelerated and finally thermal runaway occurs. In contrast to the silicon carbide surge arrester that consists of valve element and series gap, the metal-oxide arrester is a gapless device; its failure will therefore lead to a line-to-ground fault. Therefore, it is necessary to disconnect the failed arrester from the system.

2.2 Arrester disconnector

The function of the disconnector is to separate the ground lead from the button of the arrester in case of (1) an excessive surge current higher than the withstanding current of the arrester; (2) a fault current caused by the deterioration or thermal runaway of the arrester, so that the arrester can be removed from operation, preventing its explosive failure [7,19].

Figure 4 shows a schematic of the proposed arrester disconnector. The arrester disconnector is mounted on the ground lead of an arrester and consists of a resistor, a spark gap, and a cartridge. The arrester with a rated voltage of 2.6 kV and continuous operating voltage of 2.0 kV is used for the traction vehicle in a 1.5 kV system.

The resistor, used as a grading component, provides a path for the leakage current to flow from the base of the arrester to the ground. It is a cement resistor of 10 kΩ, which is resistant to heat generated by high current density. During steady operation, the leakage current of the arrester is 88 µA and the voltage drop across the resistor is therefore 0.88 V. The spark gap is connected in parallel with the resistor. When the arrester is subject to excessive surge current or increase in the leakage current, the voltage drop across the resistor rises high enough to cause the gap to spark over, generating heat which ignites the cartridge.

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**Table 1. Supply voltages of DC traction systems.**

<table>
<thead>
<tr>
<th>( U_n ) (V)</th>
<th>( U_{\text{max}1} ) (V)</th>
<th>( U_{\text{max}2} ) (V)</th>
<th>( U_{\text{max}3} ) (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>720</td>
<td>770</td>
<td>1,015</td>
</tr>
<tr>
<td>750</td>
<td>900</td>
<td>1,000</td>
<td>1,270</td>
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<tr>
<td>1,500</td>
<td>1,800</td>
<td>1,950</td>
<td>2,540</td>
</tr>
<tr>
<td>3,000</td>
<td>3,600</td>
<td>3,900</td>
<td>5,075</td>
</tr>
</tbody>
</table>

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3. EXPERIMENT AND ANALYSIS

3.1 Experimental setup

An impulse current generator was used to investigate the variation of the sparkover voltage with the gap distance, as well as the variations of $V_{ref}$ and clamping voltage of the arrester after fitting the disconnector.

As shown in Fig. 5, the impulse current generator was composed of an HVDC module (40 kV, 5 mA), a charging resistor $R_c$ and capacitor $C_c$, a spark gap, an inductor ($L$), equipment under test (EUT), and a discharging resistor $R_d$. In addition, a charging switch $S_c$ and a grounding switch $S_g$ were used, which were controlled by a programmable logic controller. The virtual front time and time to half value of the current impulse can be modified by adjusting $C_c$ and $L$. The impulse current was measured using a current transformer (Stangenes, 3-0.01) with an output sensitivity of 0.01V/A, and the voltage was measured using a high voltage probe (Tektronix, P6015) with a ratio of 1,000:1.

3.2 Results and analysis

The sparkover voltage was measured at different gap distances when 5 kΩ, 10 kΩ, and 20 kΩ resistors were connected. The results are shown in Fig. 6. The sparkover voltage increased with the gap distance and was not affected by the value of the resistance. It increased from 2.88 kV at a gap distance of 0.2 mm to 6.36 kV at 1 mm.

Table 2 shows the reference voltage at 1 mA when DC voltage was increased gradually. The reference voltage did not change after fitting the disconnector. In addition, it was verified that the same V-I characteristic was acquired.

Figure 7 shows the reference and clamping voltage of the arrester alone, the arrester fitted with a disconnector with gap distances of 0.2 mm and 0.5 mm at surge impulse currents of 5 kA, 8 kA, and 10 kA. It can be seen that the reference voltages were almost the same and the same clamping voltages were measured regardless of the connection of the disconnector, which meant that installation of the disconnector did not affect the response of the arrester, but can remove an aged or a failed arrester. The 10 kΩ resistor was used and the gap distance was selected as 0.5 mm to ensure that the voltage drop across the resistor can cause sparkover of the gap, so that the disconnector can operate to separate the ground lead from the base of the arrester, and avoid the unpredictable ignition of the cartridge.

![Fig. 4. Schematic of an arrester disconnector.](image)

![Fig. 5. Impulse current generator. (a) Circuit diagram and (b) photograph.](image)

![Fig. 6. Variation of sparkover voltage with the gap distance.](image)

![Table 2. Reference voltage at 1 mA.](image)

<table>
<thead>
<tr>
<th>Arrester</th>
<th>Arrester fitted with disconnector</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2 mm</td>
<td>4.07</td>
</tr>
<tr>
<td>0.5 mm</td>
<td>4.07</td>
</tr>
</tbody>
</table>

![Fig. 7. Variation of reference and clamping voltage with impulse current.](image)
Figure 8 shows the typical waveforms of applied impulse current, clamping voltage, and sparkover voltage when the assembly of the arrester and disconnector with a gap distance of 0.5 mm was applied by a standard lightning impulse current of 8/20 µs and 10 kA. The reference and clamping voltage were 5.80 kV and 8.54 kV, respectively. The voltage drop across the resistor was 6.04 kV, which can trigger the sparkover of the gap.

4. CONCLUSIONS

Although the metal-oxide surge arrester provides outstanding protection for traction vehicles against overvoltages, it can deteriorate and finally fail owing to various types of stresses. It is then necessary to remove the failed arrester using the disconnector to avoid a line-to-ground fault and the consequent electrical hazards and personal injuries. The arrester disconnector for DC traction vehicles was proposed in this paper. It was verified that the sparkover voltage increased with the gap distance and was not affected by the value of the resistance. The sparkover voltage at a gap distance of 0.5 mm was 3.95 kV. The reference and clamping voltage of arrester did not change after fitting the disconnector. The proposed disconnector can separate the ground lead from the failed arrester without affecting the operation and function of the normal arrester.

ACKNOWLEDGMENT

This research was financially supported by the Ministry of Science, ICT and Future Planning (MSIP) and INNOPOLIS Foundation (2015BSI1051).

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