INFLUENCE OF NSDD PHENOMENON ON POWER QUALITY AFTER BREAKING OF VACUUM CIRCUIT-BREAKER

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ABSTRACT

Vacuum circuit-breaker is an important electrical equipment for power system, and the switching capacitive current is its important performance test. In the switching capacitive current test, the vacuum circuit-breaker is easy to produce the situation of NSDD (non-sustained disruptive discharge). NSDD is a voltage breakdown after the vacuum circuit-breaker breaking the capacitive current which will not cause the recovery of power frequency or capacitive current in main circuit. Although the impact of NSDD on the vacuum circuit-breaker itself is not very serious, the voltage change will have some influence on the insulation of the nearby electrical equipment. At the same time, there are six kinds of power quality disturbance signals in power system, including voltage sag, voltage swell, voltage interruption, transient pulse, transient oscillation and harmonics. When NSDD occurs, transient pulse will occur in the supply voltage, while the load voltage will not occur charging and discharging process. The transient pulse phenomenon will cause a certain degree of influence on the power quality of the power system. Therefore, this paper presents the analysis of the effect of NSDD phenomenon on the power quality after breaking of the vacuum circuit-breaker.

2 ANALYSIS OF BASIC PRINCIPLES

2.1 Transient power quality

Power quality problems in power systems are mainly classified into two categories: steady-state and transient. Among them, transient voltage disturbance refers to various problems of power quality pollution caused by the distortion of sinusoidal waveform of power supply voltage when it receives transient voltage disturbance. Transient power quality problems are characterized by frequency spectrum and transient duration, which are generally divided into two types: transient pulse and transient oscillation. It mainly includes transient resonance, transient pulse and transient voltage swell and voltage sag[1][2]. Figure 1 shows several power quality disturbance signals.

1 INTRODUCTION

In recent years, with the pervasion of power electronics apparatus and non-linear loads, the power quality problems have been more and more deteriorated by the distorted waveform of voltage and current in power system. These include voltage sag, voltage swell, transient oscillation, transient pulse and other transient power quality effects. However, many sensitive users such as computers, microelectronics and communications have put forward high requirements for power quality. Therefore, in order to ensure the safe, reliable and economic operation of power grid and electrical equipment, certain control and compensation technology must be adopted to improve the power quality of power system. Correct judgment of different transient power quality problems in power system is also an important part of power quality research[1][2].

Vacuum circuit-breaker is an important electrical equipment for power system, and the switching capacitive current is its important performance test. In the switching capacitive current test, the vacuum circuit-breaker is easy to produce the situation of NSDD (non-sustained disruptive discharge). When NSDD occurs, transient pulse will occur in the voltage of supply side, while the voltage of load side will not occur charging and discharging process. The transient pulse phenomenon will cause a certain degree of influence on the power quality of the power system. Therefore, this paper presents the analysis of the effect of NSDD phenomenon on the power quality after breaking of the vacuum circuit-breaker.

a) transient oscillation

b) transient pulse

c) voltage swell

d) voltage sag
Transient pulse represent a phenomenon or quantity change that occurs in a very short-time between two continuous steady states. Transient pulse can be either unidirectional pulse of any polarity or the first peak of a footprint oscillation wave occurring at any polarity. Typical transient pulse characteristics are shown in table 1.

<table>
<thead>
<tr>
<th>Level</th>
<th>Typical frequency spectrum</th>
<th>Typical duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>ns</td>
<td>Rising edge of 5ns</td>
<td>&lt;50 ns</td>
</tr>
<tr>
<td>µs</td>
<td>Rising edge of 1µs</td>
<td>50 ns~1ms</td>
</tr>
<tr>
<td>ms</td>
<td>Rising edge of 0.1ms</td>
<td>&gt;1ms</td>
</tr>
</tbody>
</table>

The mathematical model of transient pulse is generally shown in equation (1).

\[ u(t) = \sin(2\pi f_d t) + \sum \delta(t_i) \]  

(1)

Where, \( t_i \) is the time when the pulse occurs, \( t=0\sim0.5s \).

Generally, it is believed that the cause of transient pulse is caused by lightning strike or inductive circuit breaking and closing. However, in this paper, the NSDD phenomenon occurring during the cable-charging current switching test of the vacuum circuit-breaker is also a kind of transient pulse.

### 2.2 Analysis of NSDD phenomenon

Oscillations following NSDD are associated with the parasitic capacitance and inductance local to or of the circuit-breaker itself. NSDD also involve the stray capacitance to earth of nearby equipment. An NSDD exhibits itself as a partial voltage change. This is particularly true in three-phase tests when the same polarity and magnitude of voltage change is observed in all three phases as the result of a shift in the voltage of the parasitic neutral capacitance to earth of a non-effective earthed load produced by an NSDD\(^3\).

The neutral point non-effective grounding system is used in the distribution system of 40.5kV and below voltage level in China. In IEC 62271-100, the three-phase switching cable-charging current test is used for the circuit-breaker in the neutral point non-effective grounding system, and the neutral point of the power supply side should be insulated. But at the same time, for the convenience of the test, the equivalent replacement circuit is put forward, that is, the neutral point of the power side is connected to the earth star connection, the replacement circuit of the load side is neutral point ungrounded star connection, because the triangle connection can be equivalent to the star connection method\(^4\).

Due to the existence of a line impedance \( L_{01} \) and \( L_{02} \) connected to the power and capacitor, the vacuum circuit-breaker itself has parasitic capacitance and parasitic inductance, and the other electrical equipment around it has certain parasitic capacitance and inductance, so the actual equivalent three-phase circuit diagram is shown in Figure 2\(^5\)[6].

![Figure 2: Three-phase equivalent circuit diagram](image)

Where, \( U \)=Supply voltage  
\( L_{01} \)=Equivalent impedance of supply  
\( \text{CB} \)=Vacuum circuit-breaker  
\( L_{01}, L_{02} \)=Equivalent impedance of line  
\( C_{\text{st}}, C_{\text{sp}} \)=Parasitic capacitance of supply side  
\( C_{\text{ld}}, C_{\text{lp}} \)=Parasitic capacitance of load side  
\( C \)=Capacitor

For the single phase, three-phase circuit diagram can be simplified to the equivalent single-phase circuit diagram, as shown in Figure 3.

![Figure 3: Single-phase equivalent circuit](image)

Where, \( C_1=C_{\text{st}}+2C_{\text{sp}} \)  
\( C_1=C_{\text{ld}}+2C_{\text{lp}} \)

After the vacuum circuit-breaker breaking capacitive current, the frequency of the supply side is shown as equation (2). The bus usually connected with many cables,overhead lines and various kinds of electrical equipment, although \( L_0 \) is smaller, but the frequency is low, its value is generally 1~20kHz. The voltage of \( U_{CS} \) can be represented by the equation (3).

\[ f_i = \frac{1}{2\pi \sqrt{L_0 C_i}} \]  
\[
U_{CS} = U + IX_i = \sqrt{2} U \cos \omega t
\]  

(2)  

(3)
After the vacuum circuit-breaker breaking capacitive current, the oscillation frequency of load side is mainly determined by the load side inductance and capacitance. The high frequency oscillation will be produced by the C-L2-C1 circuit for load side (ignore \( L_0 \)), eventually making voltage balance between \( U_{CL} \) with \( U_C \), the oscillation frequency is shown as a equation (4).

\[
f_L = \frac{1}{2\pi \sqrt{L_2 C_L}}
\]

(4)

Due to the capacitor value of the parasitic capacitance relative to the value of the capacitor \( C \) for load side is smaller, to have to equation (5).

\[
f_L = \frac{1}{2\pi \sqrt{L C_L}}
\]

(5)

In general, the value of \( C_L \) is very small, it will make the value of \( f_L \) may be very high, the fracture of the vacuum circuit-breaker will produce high frequency oscillation. If the fracture of the vacuum circuit-breaker can't bear the high frequency recovery voltage, it will inevitably produce restrike or NSDD, resulting in different overvoltage. High frequency transient process can also cause a greater impact on the adjacent phase by capacitive coupling.

Loop current method are used after the vacuum circuit-breaker breaking capacitive current and load side circuit lag range's equation is shown as a equation (6).

\[
LP(\omega) + \left( \frac{1}{P L} + \frac{1}{P C_L} \right) IP(\omega) = \frac{U_C}{P} - \frac{U_{CL}}{P}
\]

(6)

\[
I(\omega) = \frac{U_C - U_{CL}}{\omega L} \cdot \frac{\omega L}{\omega^2 L^2 + \omega^2 L^2}
\]

(7)

Where, \( \omega_L \) = Angular frequency of load side.

According to the equation (7), the load current original function after breaking is shown as a equation (8).

\[
i_L = \frac{U_C - U_{CL}}{\omega_L} \sin \omega_L t
\]

(8)

The \( U_{CL} \) is shown as a equation (9).

\[
U_{CL} = \frac{1}{C_L} \int i_L dt = \frac{U_C - U_{CL}}{\omega_L^2 L C_L} \cos \omega_L t + K
\]

(9)

If \( t=0 \), \( U_{CL} = U_{CL0} \), the integral constant is shown as a equation (10).

\[
K = U_{CL0} + \frac{U_C - U_{CL}}{\omega_L^2 L C_L}
\]

(10)

Thus, the voltage of \( U_{CL} \) is shown as an equation (11).

\[
U_{CL} = \frac{U_C - U_{CL}}{\omega_L^2 L C_L} \cos \omega_L t + U_{CL0} + \frac{U_C - U_{CL}}{\omega_L^2 L C_L}
\]

(11)

The maximum recovery voltage of \( U_{CL} \) may be shown as an equation (12).

\[
U_{CL,max} = \frac{2U_C}{\omega_L^2 L C_L} + U_{CL0}
\]

(12)

If the dielectric strength of the vacuum circuit-breaker is not fully restored after breaking, the voltage will cause a high frequency discharge of the vacuum circuit-breaker fracture. That is to say, high frequency discharge may produce NSDD phenomenon.

3 TEST RESULTS AND ANALYSIS

3.1 Test circuit

In this paper, cable-charging current switching test (test current of 18A) of a 40.5kV vacuum circuit-breaker is studied. NSDD phenomenon occurred in the vacuum circuit-breaker during the test and the results of NSDD are analyzed.

According to IEC 62271-100, the schematic diagram of the test circuit is shown in Figure 4.

![Figure 4: Test schematic diagram](image)

Where, \( G = \) Short-circuit generator
\( GB = \) Protective circuit-breaker
\( MS = \) Making switch
\( MB = \) Master breaker
\( L = \) Adjustable reactor
\( T = \) Short-circuit transformer
\( C_5, R_7 = \) TRV device
\( TO = \) Test object
\( R = \) Resistance
\( C = \) Capacitor
\( U = \) Voltage measurement
\( I = \) Current measurement

3.2 Analysis of test results

The oscillogram of the occurrence of NSDD is shown in Figure 5.
The voltage of the load side capacitor when NSDD occurs is shown in Figure 6. From the voltage waveform $U_{La}$, $U_{Lb}$, $U_{Lc}$ of the load capacitor, the voltage on the load capacitor has no obvious change. From the oscillogram amplification can be seen, the voltage of $U_{La}$ and $U_{Lb}$ are very slight changes when NSDD occurs, no change of voltage polarity. The voltage on the capacitor after the breaking is stable, indicating that there is no charge and discharge of the capacitor, which means that the charging current of the capacitor will not be generated only after restrike. That is to say, the occurrence of NSDD has no effect on the voltage of load side.

The fracture voltage of vacuum circuit-breaker is shown in Figure 7. Vacuum circuit-breaker appear fracture voltage pulse for the first time, B phase voltage to converge to zero, A, C phase voltage in the same direction of change, and the amplitude are basically the same. It conforms to the typical NSDD phenomenon, namely B phase NSDD, B phase fracture voltage in a very short period of time tend to be zero. At the same time, because of the three-phase non-effective grounding system, A and C phase voltage change in the same direction.

Vacuum circuit-breaker fracture voltage appeared the second pulse, A phase voltage to tend to be zero, B, C phase voltage in the same direction of change, and the amplitude are basically the same. It also conforms to the typical NSDD phenomenon, namely A phase NSDD. A phase of voltage in a very short period of time tend to be zero. At the same time, because of the three-phase non-effective grounding system, B, C phase voltage change in the same direction.

Table 2 shows the transient pulse data generated by the NSDD phenomena after the vacuum circuit-breaker breaking capacitive current.

<table>
<thead>
<tr>
<th>NSDD occurrence</th>
<th>Phase</th>
<th>Maximum voltage value (kV)</th>
<th>Rising/ trailing edge, (kV/μs)</th>
<th>Pulse duration (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>A</td>
<td>133</td>
<td>0.76</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>133</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Second</td>
<td>A</td>
<td>16</td>
<td>1.18</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>76</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>23.9</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As can be seen from Table 2, the transient pulse duration caused by NSDD phenomenon is 1.4 ms in the capacitive current switching test of vacuum circuit-breaker. When the first NSDD occurs, the rising edge of the transient pulse is 0.76 kV/μs. When the second NSDD occurs, the trailing edge of the transient pulse is 1.18 kV/μs. Moreover, for each phase of the pulse signal, the polarity is unidirectional. These characteristics indicate that the pulse generated after NSDD is the transient pulse in the power quality.

Transient pulse generated by NSDD phenomenon is mainly reflected in the supply voltage of vacuum circuit-
breaker. In the power system, the transient pulse will directly react on the bus in the substation, which will seriously affect other sensitive electrical equipment connected on the bus.

4 CONCLUSION

In this paper, the main transient power quality is briefly introduced, and the mechanism of NSDD phenomenon is analyzed. Cable-charging current switching test of a 40.5kV vacuum circuit-breaker is studied. NSDD phenomenon occurred in the vacuum circuit-breaker during the test and the results of NSDD are analyzed. The test data of transient pulse generated by NSDD are given. These data characteristics indicate that the pulse generated after NSDD is the transient pulse in the power quality. Transient pulse generated by NSDD phenomenon is mainly reflected in the supply voltage of vacuum circuit breaker. In the power system, the transient pulse will directly react on the bus in the substation, which will seriously affect other sensitive electrical equipment connected on the bus.

In summary, although the impact of NSDD on the vacuum circuit-breaker itself is not very serious. However, the transient pulse generated by NSDD phenomenon is a new type of transient power quality problem, which should be paid attention to.

REFERENCES