Influence of Operating Environment on Harmonic Transfer Characteristics of CVT

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Abstract. In order to obtain the influence of operating environment factors on the harmonic transfer characteristics of capacitive voltage transformer (CVT), this paper establishes the high-frequency equivalent model of 35kV capacitive voltage transformer, and uses the equivalent transformation method to transfer function and simplify the solution; under the influence of different environmental factors, theoretically analyze the impact of environmental factors on the internal structure of CVT. Based on the MATLAB simulation platform, the variation law of CVT transmission characteristics under environmental changes is simulated and analyzed. It is found that the temperature mainly affects the inductance value, main capacitance value and stray capacitance value of the CVT compensation reactor; the frequency offset mainly causes the CVT output to shift, which affects the harmonic transfer characteristics of the CVT.

Introduction

Capacitor voltage transformer (CVT) is widely used in power systems of 35kV and above. With the development of power systems, the nonlinear load of power systems is also increasing. Harmonic problems in power systems are receiving more and more attention, and the need to measure harmonic voltages using CVTs is becoming more and more urgent[1].

At present, domestic and foreign scholars have done a lot of research on the factors affecting the harmonic transfer characteristics of CVT. The basic structure and mathematical model of CVT are constructed in [2,3], which proves that CVT will produce large errors in harmonic measurement. Literature [4] analyzed the influence of CVT circuit parameters on its harmonic transfer characteristics by establishing a CVT equivalent model.

Based on the circuit principle to establish the CVT high-frequency equivalent model, this paper fully considers the changes of temperature, environmental electric field, frequency and humidity in the actual operating environment of CVT, theoretically analyzes the influence of environmental factors on the internal structure of CVT, and based on simulation software. Analyze the specific effects of CVT transfer characteristics when the environment changes.

High Frequency Equivalent Model of CVT

The main components of the CVT include a capacitor divider, a compensating reactor, an intermediate transformer, and a secondary loop load. In addition, it is known from the electromagnetic field theory that there is a capacitive effect between the conductors, which affects the high frequency response of the CVT. The stray capacitance factor must be considered when establishing a high-frequency equivalent circuit model for a capacitive voltage transformer. Figure 1 shows a typical equivalent circuit for a CVT structure with stray capacitance.

In Figure 1, C1 and C2 represent high voltage and medium voltage capacitors; ZS represents the impedance model of the compensating reactor; CC represents the equivalent stray capacitance of the compensating reactor; Zm represents the excitation impedance of the medium voltage transformer T; RT1, L1T1,RT2,L2 represent the winding resistance and winding leakage inductance of the primary and secondary sides respectively; Cp1 represents the stray capacitance of the primary side winding to the ground; Cp2 represents the spur of the secondary side winding to the ground.
Capacitor, \( C_{p12} \) represents the coupling capacitance between the primary side and the secondary side winding; \( L_b, R_b \) are the load inductance and resistance converted to the primary side. Since the load is taken to be large enough after the primary side is converted, the damper can be ignored. So the damper is ignored in the above figure.

\[ H(s) = \frac{(Z_i/Z_1)(Z_2/Z_3)(Z_2/Z_4)(Z_4/Z_5)}{(1/sC_c + Z_i + Z_2)(1/sC_c + Z_5)} \]

In formula (1) :
\[
\begin{align*}
Z_1 &= (Z_2/Z_3) + \frac{1}{sC_c} \quad Z_2 = \frac{1}{sC_c} \\
Z_5 &= \frac{1}{sC_{p12}} \quad Z_3 = \frac{1}{sC_{p2}}
\end{align*}
\]

Theoretical Study on the Influence of Environment on the Harmonic Transfer Characteristics of CVT

Influence of Temperature on Harmonic Transmission of CVT

The change of ambient temperature is an important factor affecting the harmonic transfer characteristics of CVT. DL/T 1251-2013 "Technical Specifications for the Use of Capacitor Voltage Transformers for Power" sets the ambient temperature for normal use of CVT to three categories, as shown in Table 1.

<table>
<thead>
<tr>
<th>Type</th>
<th>Minimum temperature(^\circ)C</th>
<th>Maximum temperature(^\circ)C</th>
</tr>
</thead>
<tbody>
<tr>
<td>-5/40</td>
<td>-5</td>
<td>40</td>
</tr>
<tr>
<td>-25/40</td>
<td>-25</td>
<td>40</td>
</tr>
<tr>
<td>-40/40</td>
<td>-40</td>
<td>40</td>
</tr>
</tbody>
</table>

The influence of temperature on capacitive voltage transformers is mainly divided into three aspects. First, the temperature affects the magnetic permeability of the ferromagnetic material in the transformer; second, the effect of temperature on the capacitive element and stray capacitance; and third, the effect of temperature on the copper resistance. Since the internal resistance of the CVT and the impedance of the intermediate transformer have little influence on the harmonic transfer characteristics of the CVT, and the space is limited, this paper will not discuss it.

The Effect of Temperature on the Magnetic Permeability of CVT. At present, the CVT core material used in the power grid is cold-rolled silicon steel sheet, the Curie temperature of the
cold-rolled silicon steel sheet is 1000 °C, and the magnetic permeability changes by about 0.3% every time the temperature changes by 25 °C [5]. It can be known from the internal structure of the CVT that the magnetic permeability affects the inductive component of the compensating reactor.

Reference [6] deduces the formula for calculating the inductance of the inductor:

\[ L = \frac{\mu_0 \mu_r N^2 D}{l} \]  

(2)

In formula (2): \( \mu_0 \) represents the vacuum permeability, \( \mu_r \) represents the core permeability, \( N \) is the number of turns of the coil, and \( l \) is the average length of the turns.

The normal temperature of 20 °C is the reference of the operating temperature of the CVT. When the temperature changes by 20 °C, the magnetic permeability changes by about 0.3%. Since the core magnetic density is generally 0.2 T when designing the CVT compensation reactor, The \( B-H \) and \( \mu-H \) curves in [7,8] show that when the magnetic field strength \( B \) is below 1.0 T and within 125 °C, the magnetic permeability increases with increasing temperature. Let the temperature coefficient of magnetic permeability be \( T_\mu \) and the temperature change \( \Delta T \), so the relationship between the inductance of the compensation reactor and temperature is:

\[ L_T = \frac{\mu_0 \mu_r (1+T_\mu \Delta T) N^2 D}{l} \]  

(3)

**Effect of Temperature on Capacitance.** When the temperature changes, the capacitance value of the capacitor divider is changed. The capacitor divider uses a film paper or a full-film capacitor. The temperature coefficient of the capacitance is about \(-1\sim 2\times 10^{-4}/°C\), and the change is 20 °C. Change the capacitance value by 0.25% to 0.5% [5]. Let the temperature coefficient of the voltage divider capacitor be \( T_c \) and the temperature change \( \Delta T \), so the formula of the voltage divider capacitance with temperature is:

\[ C_T = C_{20°C} (1+T_c \times \Delta T) \]  

(4)

For stray capacitances present inside the CVT, the CVT is not known for its stray capacitance parameters. In [6], from the perspective of electric field energy, the calculation formula of the stray capacitance of the inductor is obtained by theoretical derivation and experimental verification:

\[ C_p = \frac{4(n-1)e_\varepsilon_0 e_r n D N}{3n^2 d} \]  

(5)

where: \( N \) is the number of turns of the coil; \( n \) is the number of coil layers; \( l \) is the average length of the turns and \( d \) is the distance between the winding layers; \( e_\varepsilon_r \) is the relative dielectric constant.

When the temperature changes, the dielectric constant of different materials will change negatively or positively with temperature. According to the stray capacitance formula (4), the size of the stray capacitance is proportional to the relative dielectric constant. It can be known from the internal structure of CVT that the relative dielectric constant is considered to be between insulating oil and insulating varnish when estimating the value of stray capacitance. The literature [9,10] points out that for every 20 °C increase in temperature at 100 °C, dielectric The constant changes by about 1%.

**Influence of Frequency on Harmonic Transmission of CVT**

Since the load in the power system and the output of the generator set are changing at any time, when there is an active power imbalance between the generator and the load, the system frequency will change. Therefore, the frequency of the power system is in the process of supplying electricity. Fluctuating within a certain range. According to the national standard "Power Quality - Power System Frequency Allowance" GB/T 15945-2013: the system normal frequency deviation is allowed to be 0.2 Hz; when the system capacity is small, it can be relaxed to 0.5 Hz.

Obviously, the frequency variation will deviate from the amplitude-frequency characteristics and phase-frequency characteristics of the CVT. When it is necessary to measure the grid harmonics
within a certain accuracy. If the deviation value is greater than the specified requirement, the measurement data is meaningless. Therefore, the influence of frequency on the transmission characteristics is one of the contents of the analysis.

**Study on the Influence of Environmental Factors on the Harmonic Transfer Characteristics of CVT**

**Simulation and Actual Measurement Comparison**

The basic parameters of a 35 kV capacitive voltage transformer at 20 °C are shown in Table 2. The frequency characteristics of the transfer function are calculated and analyzed. The amplitude-frequency characteristic curves given in this paper are all represented by relative values.

Table 2. Basic parameters of CVT at normal temperature.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_1$</td>
<td>0.0404 μF</td>
</tr>
<tr>
<td>$R_{T1}$</td>
<td>511 Ω</td>
</tr>
<tr>
<td>Ratio $n$</td>
<td>173.2</td>
</tr>
<tr>
<td>$C_2$</td>
<td>0.0396 μF</td>
</tr>
<tr>
<td>$L_{T1}$</td>
<td>5.38 H</td>
</tr>
<tr>
<td>$C_c$</td>
<td>517.7 pF</td>
</tr>
<tr>
<td>$R_s$</td>
<td>56 Ω</td>
</tr>
<tr>
<td>$R_{T2}$</td>
<td>0.01513 Ω</td>
</tr>
<tr>
<td>$C_p$</td>
<td>293.4 pF</td>
</tr>
<tr>
<td>$L_s$</td>
<td>126.6 H</td>
</tr>
<tr>
<td>$L_{T2}$</td>
<td>15.8 μH</td>
</tr>
<tr>
<td>$R_b$</td>
<td>80 Ω</td>
</tr>
<tr>
<td>$L_b$</td>
<td>0.191 H</td>
</tr>
</tbody>
</table>

Through the above calculation formula of the stray capacitance, the parameter value of the stray capacitance at normal temperature can be calculated. By comparing the field measured curve and the simulation curve, it is judged whether the model and parameters in this paper can reflect the characteristics of this model CVT more realistically. The relative error curves of the measured pictures and the measured and simulated curves are shown in Figure 2 and Figure 3.

As can be seen from Figure 4, the mathematical model in this paper has a high degree of fit to the actual CVT, the simulation results are more reliable.

**Simulation Verification of the Influence of Environmental Factors on the Harmonic Characteristics of CVT**

**Effect of Temperature on Harmonic Transfer Characteristics of CVT.** In order to analyze the influence of ambient temperature on the harmonic transfer characteristics of CVT, the historical temperature of 2017 in Guangzhou is taken as a case study. The highest temperature in Guangzhou...
in 2017 is 39.8 °C, and the lowest temperature is 5 °C. The temperature changes by 34.8 °C, so due to the temperature difference, it will inevitably lead to a large difference in the harmonic transfer characteristics of CVT in different seasons.

Based on 20 °C, the magnetic permeability changes from -0.025% to 0.3% when the temperature changes from 5 °C to 39.8 °C. It is known from equation (3) that the magnetic permeability of the core is proportional to the inductance. Therefore, the variation range of the compensation reactor inductance value is 126.3289 H~ 126.9936 H; from equation (4), the high voltage capacitance variation range is 0.0405 μF ~ 0.0403 μF, and the medium voltage capacitance variation range is 0.0397 μF ~ 0.0395 μF.

The formula (5) is from 511.929 μF to 522.271 μF; the variation range of C_{pt} is 290.466 μF to 296.334 μF. Therefore, when the ambient temperature changes from 5 °C to 39.8 °C with the season, the effect on the harmonic transfer characteristics of CVT is shown in Figure 4.

It can be seen from Fig. 4 that the influence of temperature on the inductance value and stray capacitance of the CVT compensating reactor causes the CVT ratio and phase shift to change when the harmonics are transmitted at 20 °C relative to the normal temperature. Additional error of harmonic measurement results; it can be seen from the figure that temperature has a great influence on the harmonic ratio of CVT. In this case, the highest relative error is 7% at 600 Hz, and the temperature has the greatest influence on phase shift which up to 4.3°.

**Effect of Frequency on Harmonic Transfer Characteristics of CVT.** In the national standard, the normal frequency deviation of the system is allowed to be 0.2 Hz; when the system capacity is small, it can be relaxed to 0.5 Hz. When the frequency is deviated, its frequency varies from 49.5 Hz to 50.5 Hz. From the CVT transfer function, it can be inferred that the resonant point of the transfer characteristic will inevitably shift, and the ratio and phase shift will also change with frequency. Changes, at the same time, when the power frequency shifts, the harmonics will also change in multiples. Therefore, when the simulation frequency affects the harmonic transfer characteristics of CVT, the simulation must directly adopt the harmonic integral change; the specific influence of the frequency on the transfer characteristics is shown in Figure 5.

It can be seen from Figure 5 that when the fundamental frequency is shifted, the harmonic frequency will also have a corresponding offset, and the harmonic offset has a great influence on the harmonic transfer ratio of the CVT, and the maximum influence of the 12th harmonic reaches 10%. The frequency change also has an effect on the phase shift which up to 5°.
Summary
Based on the establishment of the CVT equivalent circuit model, this paper analyzes the environmental factors that may affect the harmonic transfer characteristics of CVT and verifies it through simulation. The main conclusions are as follows:

1) The temperature mainly affects the compensation reactor inductance value, main capacitance value and stray capacitance value in the internal structure of the CVT, thus affecting the harmonic transfer characteristics of the CVT; the temperature has a large impact on harmonic transfer ratio and phase shift to the CVT.

2) The frequency offset has a great influence on the high frequency band of the CVT harmonic transfer characteristic. In the case, the frequency has a maximum influence on the transmission ratio of up to 10%, and the influence of the frequency on the phase offset is greater than the influence of the temperature on the phase offset, and the deviation is up to 5°. The main reason found in the simulation is that after the frequency shifts, the CVT output shifts, which leads to a large error in the ratio.

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