

The Influence of Stray Capacitor on the Harmonic Transmission Characteristics of CVT

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Abstract—In view of the fact that the harmonic transmission characteristics of capacitive voltage transformers (CVT) are unclear and not suitable for harmonic voltage measurement, considering the influence of the internal stray capacitance factors, an equivalent circuit model is established and analyzed by transfer function. Stray capacitance has a significant effect on the harmonic transmission characteristics of CVTs. The reference of the distributed capacitance in the CVT is calculated based on the structure of the CVT circuit element in combination with the distributed capacitance derivation. Based on the MATLAB/Simulink simulation tool, the influence of each stray capacitance on the transmission characteristics of various harmonics of CVT was studied, and the relative error caused by stray capacitance change was quantified. Studies have shown that the stray capacitance of the compensation affects the frequency range after the extremum point of the CVT amplitude transfer characteristic, the stray capacitance of the primary side of the intermediate transformer and the coupling capacitance between the primary side and the secondary side affect the entire frequency of the CVT amplitude transfer characteristic. In the segment, the stray capacitance to the ground on the secondary side of the intermediate transformer has no effect on the harmonic transmission characteristics of the CVT.

Keywords—capacitor voltage transformer; harmonic; transfer function; frequency characteristics; stray capacitance

I. INTRODUCTION

When the CVT is operating at harmonic frequencies, its internal stray capacitance interacts with capacitance and inductance in the main circuit parameters, and unexpected changes to the original model structure of the CVT occur. This will cause the secondary signal of the measurement to have greater error, cannot reflect the actual harmonic level in the electrical network correctly. At present, the research on stray capacitance in CVT focuses on qualitative analysis^[1]. Reference[2] pointed out that stray capacitance is an indispensable factor in the study of the frequency characteristics of CVT. Reference [3] analyzed the influence of stray capacitance on the CVT amplitude-frequency curve, but it did not deeply analyze the stray capacitance and the error caused by it.

This article analyzes the internal stray capacitance of the CVT and compares the effects of stray capacitance on the harmonic transmission characteristics of the CVT using the transfer function. The reference of the distributed capacitance in the CVT is calculated based on the structure of the CVT circuit element in combination with the distributed capacitance

derivation. Based on the MATLAB/Simulink simulation tool, the influence of each stray capacitance on the transmission characteristics of various harmonics of CVT was studied, and the relative error caused by stray capacitance change was quantified.

II. EQUIVALENT CIRCUIT MODEL OF CVT

According to the actual structure of the CVT can be set up its equivalent circuit model shown in Figure 1 in the solid line, Correspondingly, C_1 and C_2 are the capacitive voltage dividers; L_S and R_S are the reactance and resistance of the compensation reactor respectively; L_{t1} and R_{t1} are the equivalent leakage impedance of the intermediate transformer primary side; L_{t2} and R_{t2} are the equivalent leakage impedance of the intermediate transformer secondary winding for protection use; R_m and L_m are the intermediate transformer excitation impedance; R_b and L_b are the load impedance. When considering the influence of stray capacitance at high frequencies, the equivalent circuit model is shown by the solid line plus dashed line in Figure 1. Correspondingly, C_s is the stray capacitance of compensation reactor; C_{p1} is the primary side stray capacitance of the intermediate transformer; C_{p2} is the stray capacitance to the ground on the secondary side of the intermediate transformer; C_{p12} is the coupling capacitance between the primary side and the secondary side. CVT is equipped with a damping device, and most of them use a fast saturation damper. When the system is subjected to an over-voltage generated by impulse voltage, a large amount of resonance energy can be consumed in a short time (such as 0.5s) to suppress its own ferromagnetic resonance. Avoid causing the CVT to malfunction or affect the secondary device. The fast saturated damper does not participate in the normal operation of the CVT, so the equivalent impedance of the damper is neglected in the high-frequency equivalent circuit model.

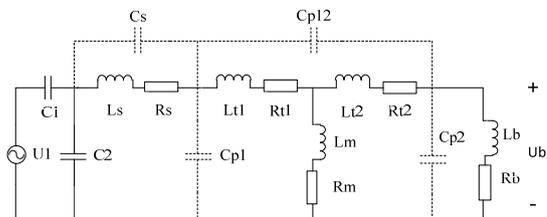


FIGURE I. EQUIVALENT CIRCUIT MODEL OF CVT

In order to further study the effect of stray capacitance on the CVT model, this section will derive the relationship

between the output voltage of the stray capacitance CVT and the input voltage from the perspective of the transfer function, and plot the transfer function curve of the circuit. CVT intermediate transformer core can be regarded as working in the linear section of the magnetization curve, ignoring the core of the magnetic induction. In the simulation study process, a CVT with a model of TYD110/ $\sqrt{3}$ -0.01H was selected as the study object. The main parameters are shown in table 1.

TABLE I. PARAMETERS OF CVT

Parameter	Value	Parameter	Value
C ₁	0.01257 μ H	U ₂	100/ $\sqrt{3}$ V
C ₂	0.04885 μ H	L _s	164.96H
U ₁	110/ $\sqrt{3}$ kV	Load capacity (100%)	100VA/0.8

The transfer function of the CVT equivalent circuit model without considering the stray capacitance can be derived from Figure 1, as shown in formula (1).

$$H_1(s) = \frac{Z_1}{Z_1 + Z_2 + Z_3 + Z_4 + Z_5} \quad (1)$$

The transfer function of the CVT equivalent circuit model considering the stray capacitance is derived, as shown in formula (2).

$$H_2(s) = \frac{[Z_1 // Z_9 + (Z_2 + Z_3) // Z_8] // Z_7 + Z_4 // Z_6}{[Z_1 // Z_9 + (Z_2 + Z_3) // Z_8] // Z_7 + Z_4 // Z_6 + Z_5} \quad (2)$$

Where:

$$\begin{aligned} Z_1 &= s * L_b + R_b, & Z_2 &= s * L_{t2} + R_{t2}, & Z_3 &= s * L_{t1} + R_{t1}, \\ Z_4 &= s * L_s + R_s, & Z_5 &= \frac{1}{s(C_1 + C_2)}, & Z_6 &= \frac{1}{s * C_s}, \\ Z_7 &= \frac{1}{s * C_{p1}}, & Z_8 &= \frac{1}{s * C_{p12}}, & Z_9 &= \frac{1}{s * C_{p2}} \end{aligned}$$

Equations (1) and (2) can be obtained through the computer programming transfer function H₁(s) and H₂(s) amplitude-frequency characteristics, as shown in Figure 2. It can be seen from the Figure that the CVT amplitude-frequency characteristic curve is monotonically decreasing and the degree of distortion is small when the circuit does not consider the stray capacitance; when considering the stray capacitance, the CVT harmonic measurement curve has severe distortion at the 16th harmonic position. Extremum points appear, that is, CVTs have the effect of amplifying or reducing harmonics of different orders. It can be seen that the stray capacitance has a great influence on the measurement characteristics of the harmonics of the CVT, and the influence of the stray capacitance should be fully taken into account in the measurement and correction of the CVT harmonics.

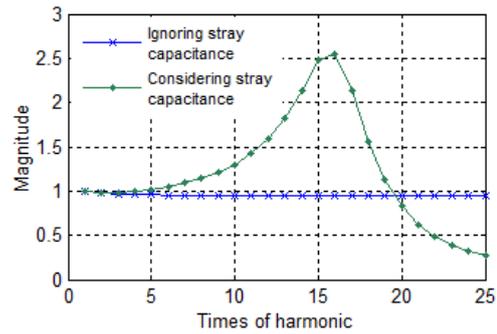


FIGURE II. CVT AMPLITUDE-FREQUENCY CHARACTERISTIC CURVE

III. ANALYSIS OF STRAY CAPACITANCE

According to the capacitance formula of two parallel plates $C = \epsilon S / d$, after the CVT leaves the factory, the shape and size of the internal components and the relative position between the conductors have been determined, and the ambient temperature and humidity have little influence on them and can be basically ignored. Therefore, it is important to consider that the medium between conductors is affected by environmental factors and affects the stray capacitance. The main dielectric material of the capacitor is insulating oil, which can ignore the influence of humidity, but the influence of temperature on the dielectric constant cannot be ignored. The capacitance temperature coefficient is generally less than or equal to $-4 \times 10^{-4}/K$. When the ambient temperature changes $\pm 40^\circ C$, it may bring about a change of 3.2% in dielectric constant, which will directly affect the accuracy of harmonic transmission of CVT. At the same time, for different types of CVTs, stray capacitance values are different and are not stable values, but stray capacitances can be estimated through known structural parameters. This will make sense for follow-up studies of CVTs.

A. Compensation Reactor Stray Capacitance

From the previous analysis, it can be seen that the change in the dielectric constant causes about 3% error. The compensating reactor has an adjustable air gap, and each tap has an adjustable amount of $\pm 2\%$, causing the variation of the equivalent stray capacitance C_S of the compensating reactor to be about $\pm 2\%$. Consider the change in C_S overall within $\pm 5\%$.

In [4], the electromagnetic field theory is used to analyze the distributed capacitance of the U-shaped row winding induction coil. The results show that for the reactor of the n-layer winding, the equivalent distributed capacitance is shown in Equation (3):

$$C_x = \frac{4(n-1)\epsilon_r\epsilon_0 lDN}{3n^2 d} \quad (3)$$

Where: l is the average length, D is the diameter of the conductor cross-section, d is the distance between layers, and N is the number of turns in each layer. The stray capacitance of

the compensating reactor is calculated as 80.3 pF, as shown by the commonly used compensation reactor parameters provided by a factory (n=10 layers, N=300, l=82.4mm, D=0.25mm, d=0.18mm, $\epsilon_r = 2.2$) and in combination with formula (3).

B. Distributed Capacitance Parameters of Intermediate Transformer Windings

The middle transformer of CVT will change the intermediate voltage of 13~20kV into the secondary voltage. The core uses high quality cold-rolled silicon steel sheet to improve the antiferromagnetic resonance characteristics. For C_{p1} , C_{p2} , and C_{p12} , $\pm 5\%$ of the regulation winding is designed for the primary winding of the intermediate transformer. Consider C_{p1} , C_{p2} , and C_{p12} variations over a wide range. Take $\pm 10\%$ of the study here.

According to the capacitance divider composed of C_1 and C_2 , the primary winding voltage of the intermediate transformer can be calculated as $U_p = U_1 C_1 / (C_1 + C_2) = 12997.4V$, and the rated secondary voltage of the CVT is $100/\sqrt{3} V$. At present, the potential of number of turns(T) of the intermediate transformer is generally taken $e_1 = 1.3V/T$. From this, it can be seen that the primary winding of intermediate transformer $N_1 \approx 10000T$, the secondary winding of intermediate transformer $N_2 \approx 45T$.

The intermediate transformer winding and the compensation have a similar structure, so the distributed capacitance parameters of the intermediate transformer winding can also be calculated with reference to formula (3), including the primary side-to-ground stray capacitance of the intermediate transformer and the secondary side-to-ground stray capacitance. The primary winding parameters are: n=16 layers, N=650, l=58.6mm, D=0.25mm, d=0.18mm, $\epsilon_r = 2.2$; the primary winding parameters are: n=2 layers, N=25, l=49.4mm, D=0.25 mm, d=0.18 mm, $\epsilon_r = 2.2$. It can be seen that $C_{p1} = 80.5pF$, $C_{p2} = 11.1pF$; C_{p12} is assumed to be 80pF.

IV. CAPACITANCE EFFECTS ON CVT

This section builds a MATLAB/Simulink simulation model based on the CVT equivalent circuit model, as shown in Figure 3. The stray capacitance calculated above is taken as a reference value into the model, and its internal stray capacitance parameters are simulated and analyzed.

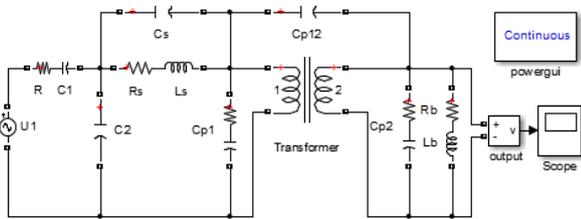


FIGURE III. SIMULINK MODEL OF CVT

A. Effect of Compensating Reactor Equivalent Stray Capacitance

Figure 4 shows the CVT ratio transfer characteristic curve and error curve when C_s changes by $\pm 5\%$. From an intuitive point of view, changes in C_s can affect the amplitude transfer characteristics of CVT, and have little effect on the harmonic transformation ratio before the extreme point, resulting in a maximum variation error of only 1%. The harmonic transformation ratio after the extreme point has a great influence, and can reach 8% at the 23rd harmonic.

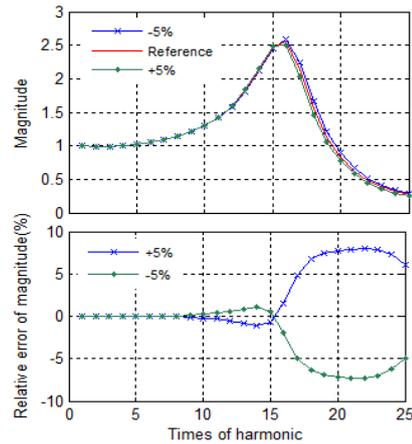


FIGURE IV. CVT AMPLITUDE-FREQUENCY CHARACTERISTIC AND ERROR WHEN C_s CHANGES WITHIN $\pm 5\%$

B. Distributed Capacitance Parameters of Intermediate Transformer Windings

When C_{p1} changes by $\pm 10\%$, the CVT transfer curve is plotted, as shown in Figure 5. Intuitively, changes in C_s affect the amplitude transfer characteristics of CVTs, affecting the harmonic transformation ratio prior to the extreme point of around 5%. The harmonic transformation ratio after the extremum point has a great influence, reaching 7.8% at the 19th harmonic.

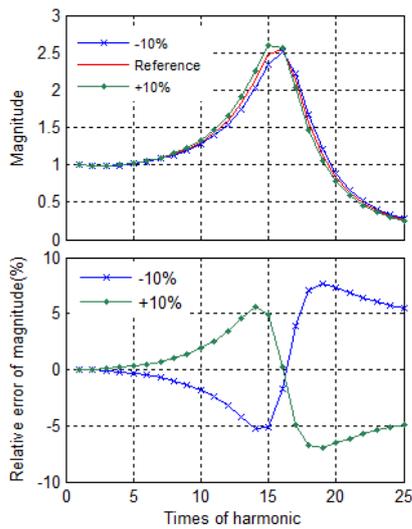


FIGURE V. CVT AMPLITUDE-FREQUENCY CHARACTERISTIC AND ERROR WHEN C_{p1} CHANGES WITHIN $\pm 10\%$

When C_{p12} changes at $\pm 10\%$, the CVT transmission curve is plotted, as shown in Figure 6. It can be seen that the change of C_{p12} will affect the amplitude transfer characteristics of CVT, and the influence of C_{p1} on the amplitude transfer characteristics is similar, and the harmonic transformation ratio before the extreme point affects about 5%. The harmonic transformation ratio after the extremum point has a great influence, reaching 7.8% at the 19th harmonic.

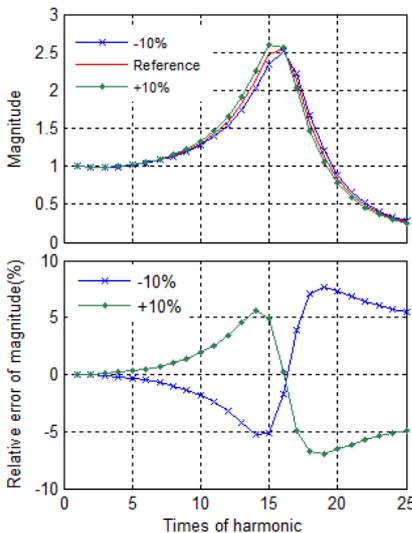


FIGURE VI. CVT AMPLITUDE-FREQUENCY CHARACTERISTIC AND ERROR WHEN C_{p12} CHANGES WITHIN $\pm 10\%$

When C_{p2} is changed by $\pm 10\%$, the CVT transfer characteristic curve when C_{p1} changes is plotted, as shown in Figure 7. It can be seen that the C_{p2} change has no effect on the amplitude transfer characteristics of the CVT.

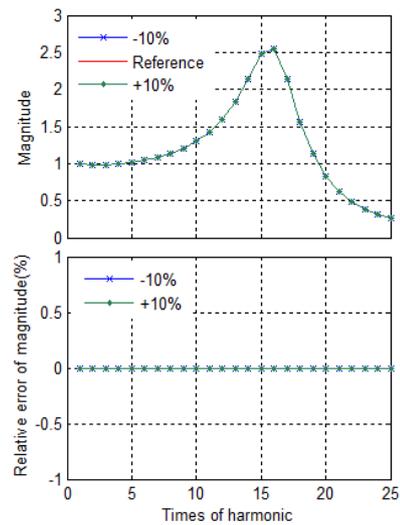


FIGURE VII. CVT AMPLITUDE-FREQUENCY CHARACTERISTIC AND ERROR WHEN C_{p2} CHANGES WITHIN $\pm 10\%$

V. CONCLUSION

This article deeply analyzes the stray capacitance characteristics and deduces its reference value theoretically. It calculates the harmonic transmission characteristics of CVT and completes the simulation verification work. The main conclusions are as follows:

Considering the influence of stray capacitance, the extreme value point of the amplitude and frequency characteristic curve of CVT will appear, leading to a larger measurement error;

C_S affects the frequency range after the extreme value point of the CVT amplitude transfer characteristic. C_{p1} and C_{p12} affect the entire frequency range of the CVT amplitude transfer characteristics, while C_{p2} does not have any effect on the harmonic transmission characteristics of the CVT.

The maximum influence error of C_S at $\pm 5\%$ is 8%, and the maximum influence error of C_{p1} and C_{p12} within $\pm 10\%$ is 7.8%, which shows that C_S has more significant influence on the harmonic transmission characteristics of CVT.

Therefore, when studying the harmonic transmission characteristics of CVT, the effects of stray capacitance, primary stray capacitance, and secondary-side coupling capacitance of the compensation reactor should be fully considered.

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