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Optimization of stray capacitance based on CVT har-monic voltage measurement

RAN ZHUO[1], WANWEI WANG[2], YAN LUO[1], RONGFU ZHONG[2] , ZHIMING HUANG[1], AND YQIYE DU[2].

[1]The State Key Laboratory for Management and Control of Complex Systems, Institute of Automation, Chinese Academy of Sciences, Beijing 100190, China
[2]The Macao Institute of Systems Engineering, Macau University of Science and Technology, Macao 999078, China
[1]Honors School, Monmouth University, W. Long Branch, New Jersey, USA
[2]Department of Computer Science and Software Engineering, Monmouth University, W. Long Branch, New Jersey, USA.
[1]Dongguan bureau of power supply, Guangdong power grid CO.LTD, Dongguan, China
[2]High Voltage Research Department, CSG Electric Power Research Institute CO.,LTD, Guangzhou, China
[1]High Voltage Research Department CSG Electric Power Research Institute CO., LTD Guangzhou, China
[2]Dongguan bureau of power supply Guangdong power grid CO.LTD Dongguan, China

Corresponding author: Yan Luo (e-mail: luoyan1009@yeah.net).

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ABSTRACT With the wide application of nonlinear power electronic devices in power systems, the problem of harmonic pollution is becoming more and more serious, which significantly affects the measurement accuracy of voltage transformers (especially capacitive voltage transformers, CVT). The existing research focuses on the performance optimization of CVT under power frequency conditions, and the research on measure-ment error under harmonic conditions is insufficient. In particular, the influence of stray capacitance on harmonic transmission characteristics has not been fully paid attention to. Therefore, this paper aims to solve the problem of CVT measurement error in harmonic environment. By proposing an optimization method based on equivalent circuit model, the key stray capacitance parameters are accurately identified and corrected, to improve its measurement accuracy. Firstly, the equivalent circuit model of CVT is estab-lished, and the resonance phenomenon data is captured by Simulink simulation technology. The objective function based on the relative error of voltage transfer coefficient is defined, and the Pareto solution set is calculated by optimization algorithm to identify the optimal stray capacitance parameters. After applying this parameter to the circuit model, the voltage transfer coefficient of CVT is corrected, which significantly reduces the measurement error in harmonic environment. This study not only provides a theoretical basis for the high-precision measurement of CVT in power system, but also provides a reference for practical technical application.

INDEX TERMS CVT, Stray capacitance, Simulink, MOGWO, Pareto.

I. INTRODUCTION

WITH the continuous improvement of UHV AC and DC transmission levels in China, nonlinear power electronic equipment has been widely used, and the prob-lem of harmonic pollution in power systems has become increasingly serious. Based on the voltage transformer de-signed under the condition of power frequency, the internal inductance, capacitance and stray capacitance will have a significant impact on the measurement accuracy under the action of harmonics [1-3]. Therefore, it is necessary to carry out research on harmonic characteristics to provide a basis for optimizing the design of voltage transformer, to improve its detection accuracy of power system voltage in harmonic environment. Capacitor Voltage Transformer (CVT) has the advantages of small size, high measurement accuracy, easy maintenance and low cost compared with traditional voltage transformers under power frequency voltage. However, in the harmonic environment, the existence of harmonic compo-nents will amplify the influence of stray capacitance, which will adversely affect the measurement accuracy and operation reliability of CVT [4-6]. Therefore, to ensure that CVT can accurately measure voltage parameters, it is very important to study and control the influence of stray capacitance on its measurement accuracy. In recent years, scholars at home and abroad have done a lot of research on the influence of capacitive voltage transformer on harmonic and stray capacitance, mainly focusing on the simulation model in harmonic environment, the establishment of electromagnetic transient model, and the influence of these factors on measurement accuracy through simulation and experiment. Reference [7] analyzed various resonance modes caused by stray capacitance under the condition. Reference [8] proposed a method to obtain the harmonic transfer function of CVT by measuring the parameters of each component of CVT, but this method failed to fully consider the influence of stray capacitance. Reference [9] proposed a CVT stray capacitance parameter estimation method based on improved particle swarm optimization algorithm. Reference [10] studied the influence of stray capacitance on CVT harmonic measurement error, and proposed an error correction method based on BP neural network. Reference [11] studied the harmonic transfer characteristics of CVT, and found that the stray capacitance significantly affected the harmonic transfer characteristics of CVT, resulting in measurement errors. Reference [12] studied the transient characteristics of 500kV capacitor voltage transformer by MATLAB / Simulink simulation, analyzed the stray capacitance parameters between the two conductors in CVT and the influence of ferromagnetic resonance circuit on it, but did not provide a specific solution to eliminate the fluctuation of stray capacitance parameters. In reference [13], the harmonic equivalent circuit of CVT is studied and established, and the measurement error source of CVT under harmonic condition is analyzed, but the influence on stray capacitance is not considered comprehensively. Reference [14] studied the key influence parameters of CVT harmonic transmission characteristics, and pointed out that stray capacitance has a significant effect on harmonic transmission. Therefore, it is very important to solve the problem of harmonic measurement in the power grid. It is necessary to propose a more accurate measurement method to effectively correct the harmonic measurement results of CVT to improve the measurement accuracy. This study employs an equivalent circuit model to analyze the impact of stray capacitance on CVT accuracy under harmonic conditions. Simulink simulation is used to validate the model and quantify the influence of stray capacitance on CVT output characteristics. Furthermore, a Multi-Objective Grey Wolf Optimizer (MOGWO) is applied to identify the optimal stray capacitance parameters. This integrated approach ensures improved voltage measurement accuracy of CVT in harmonic environments.

II. CVT EQUIVALENT CIRCUIT MODEL

CVT mainly includes two parts: capacitive voltage divider and electromagnetic unit. Among them, the capacitor voltage divider is composed of high voltage capacitor (C_1) and medium voltage capacitor (C_2), the electromagnetic unit is composed of compensation reactor (L), intermediate transformer (T) and damper (C_X, L_X, R_Z). F is the arrester, its function is to prevent the secondary side short circuit caused by the voltage rise and breakdown compensation reactor, as shown in Fig. 1.

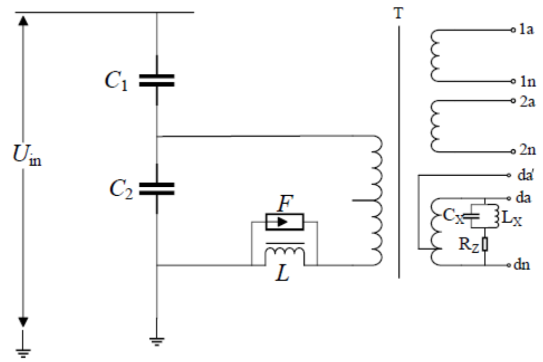


FIGURE 1. Electrical schematic diagram of CVT.

In the case of harmonic interference, the components inside the CVT are in a high-frequency environment, which will increase the stray capacitance in the circuit and the coupling capacitance between the components. To study the influence of stray capacitance, it is necessary to establish the equivalent circuit model of CVT. In this model, the stray capacitance that has the most significant impact on CVT mainly includes the stray capacitance (C_s) of the compensation reactor and the ground-to-ground stray capacitance (C_{p1}) of the primary winding of the intermediate transformer. Therefore, this study only considers these two types of stray capacitances, while ignoring the effects of other stray capacitances[15], as shown in Fig. 2.

U_{in} represents the input voltage of the primary side; U_{out} represents the converted secondary side output voltage; C_1 and C_2 represent high-voltage capacitance and medium-voltage capacitance, respectively. R_1 and R_2 represent the equivalent loss resistance of the high-voltage capacitor and medium-voltage capacitor, respectively. R_S and L_S are the resistance and inductance of the compensation reactor; C_S is the equivalent stray capacitance of the compensation reactor; C_{p1} is the equivalent stray capacitance of the primary winding of the intermediate transformer to the ground. R_{T1}, L_{T1}, R_{T2}, L_{T2}, R_{T3} and L_{T3} are the resistance and leakage inductance of the primary winding, the secondary measuring winding, and the residual winding of the intermediate transformer, respectively. R_m and L_m are the excitation resistance and inductance of the intermediate transformer, respectively. R_d, C_d, L_d and r_d are the resistance, capacitance, inductance, and small resistance of the resonant damper. R_z and L_z are load resistors.

To facilitate the calculation of the transfer function of the CVT equivalent circuit, let: $Z_1 = R_1 + \frac{1}{sC_1}$, $Z_2 = R_2 + \frac{1}{sC_2}$, $Z_s = (R_s + sL_s)//\frac{1}{sC_S}$, $Z_{p1} = \frac{1}{sC_{p1}}$, $Z_{T1} = R_{T1} + sL_{T1}$, $Z_{T2} = R_{T2} + sL_{T2}$, $Z_{T3} = R_{T3} + sL_{T3}$, $Z_m = R_m//sL_m$, $Z_d = (r_d + sL_d)//\frac{1}{sC_d} + R_d$, $Z_z = R_z + sL_z$, the equivalent circuit of CVT after conversion is shown in Fig.3.

After conversion, the transfer function H is

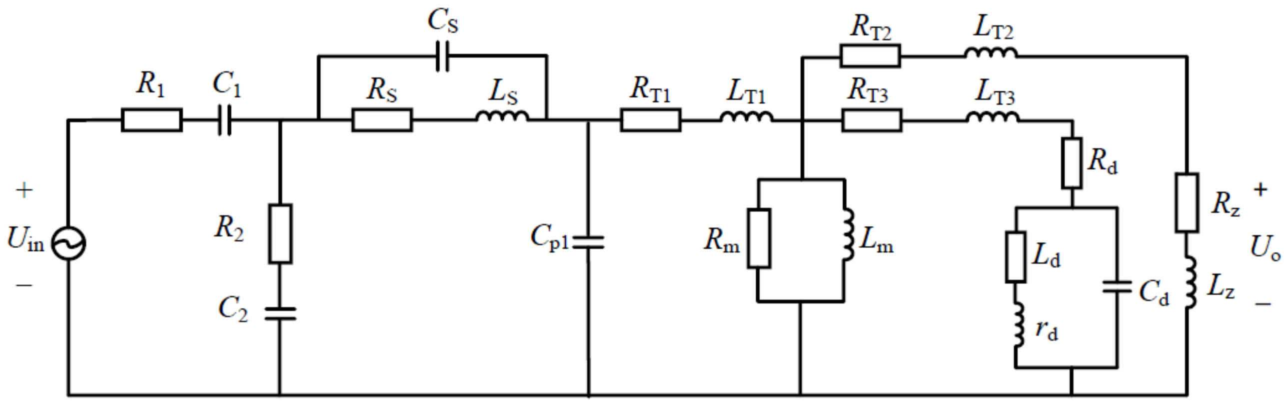


FIGURE 2. Broadband equivalent circuit model of CVT.

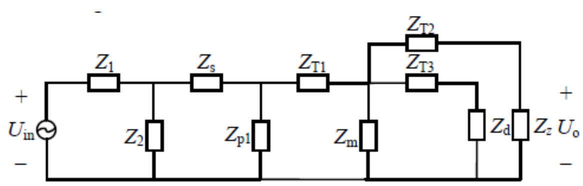


FIGURE 3. The converted CVT broadband equivalent circuit.

$$H = \frac{Z_2}{Z_1+Z_2}\cdot\frac{Z_{p1}}{Z_s+Z_{p1}}\cdot\frac{Z_m//(Z_{T3}+Z_d)//(Z_{T2}+Z_z)}{Z_{T1}+Z_m//(Z_{T3}+Z_d)//(Z_{T2}+Z_z)}\cdot\frac{Z_z}{Z_{T2}+Z_z} \tag{1}$$

In this paper, TYD35/$\sqrt{3}$-0.02HF CVT is taken as an example to illustrate the principle and method. The basic parameters are shown in Table 1.

TABLE 1. Basic parameters of TYD35/$\sqrt{3}$-0.02HF CVT

Parameter	Parameter Value	Parameter	Parameter Value
C_1 / pF	40400	R_z / Ω	533300
C_2 / pF	39600	L_z / H	1273
R_1 / Ω	100	R_d / Ω	364520
R_2 / Ω	140	L_d / H	1766
L_S / H	126.6514	r_d / Ω	16470
R_S / Ω	56	C_d / pF	5736
R_{T1} / Ω	511	L_{T1} / H	5.38
R_{T2} / Ω	453.8734	L_{T2} / H	0.474
R_{T3} / Ω	359.9789	L_{T3} / H	0.654
R_m / Ω	7141800	L_m / H	40045

In CVT, the value of stray capacitance is usually affected by many factors, including physical design parameters, environmental conditions and manufacturing tolerances. Usually, the stray capacitance value of each winding of the intermediate transformer is about several hundred picofarads (pF). Due to its large inductance value and more coil turns, the stray capacitance value of the compensation reactor may reach the nanofarad (nF) level. Therefore, in this study, the value range of stray capacitance is set as follows: 100pF $\leq$ CS $\leq$ 10nF, 100pF $\leq$ Cp1 $\leq$ 1nF, to cover the possible range of stray capacitance in practical applications.

The accurate modeling of Capacitive Voltage Transformers (CVTs) under harmonic conditions has been the focus of extensive research. Numerous studies have proposed equivalent circuit models and optimization techniques to analyze and improve CVT performance. For example, prior works have investigated resonance modes caused by stray capacitance and its impact on measurement accuracy. Optimization methods such as particle swarm optimization (PSO) and neural networks have been applied for parameter calibration. However, these studies often lack a comprehensive approach to accurately quantify the influence of stray capacitance and effectively optimize parameters under multi-objective conditions.

On the basis of these studies, this paper introduces a CVT equivalent circuit model for optimizing stray capacitance, and carries out simulation modeling analysis. And the model considers the harmonic interference, which provides a theoretical basis for the subsequent use of multi-objective grey wolf optimization algorithm (MOGWO) to optimize the key parameters.

III. SIMULATION MODELING AND ALGORITHM INTRODUCTION

A. SIMULINK EMULATION MODELING

Based on the Simulink simulation environment, this study takes the 35kV voltage level CVT with the model of TYD35/$\sqrt{3}$-0.02HF as the object, and constructs its equivalent model for simulation analysis. Since the value range of stray capacitance has been clarified in the previous section, any stray capacitance value in this range is selected as the model parameter in the simulation process. The simulation model is shown in the figure.

In the simulation process, each harmonic signal with a harmonic content of 10% is applied to the primary side of CVT. By measuring the harmonic content ratio diagram and the ratio diagram of CVT with or without stray capacitance, the influence of stray capacitance on CVT performance can be further verified. This method is helpful to quantify the influence of stray capacitance on CVT output characteristics under different harmonic conditions.

It can be observed from Fig. 5 that when there is stray capacitance, the harmonic voltage fluctuation of CVT increases

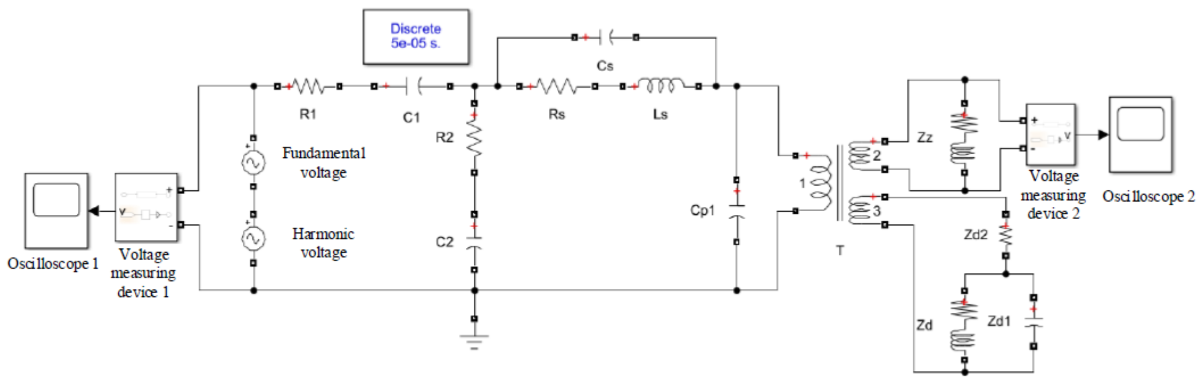


FIGURE 4. CVT simulation model circuit diagram.

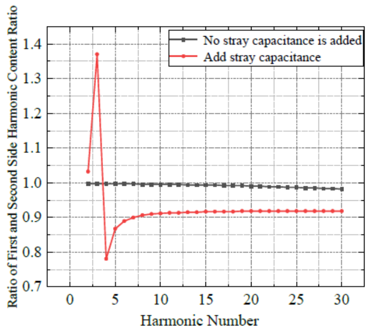


FIGURE 5. CVT harmonic content ratio.

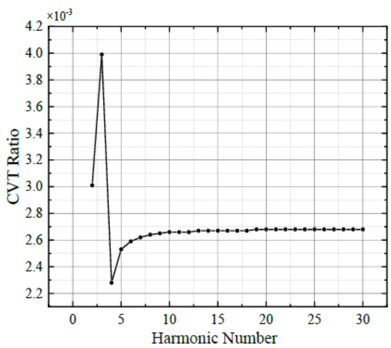


FIGURE 6. CVT voltage ratio.

significantly, especially under low-order harmonics. Fig. 6 further shows the voltage ratio characteristics of CVT, where the first resonance peak and valley appear at frequencies $f_1 = 150\,\text{Hz}$ and $f_2 = 200\,\text{Hz}$, respectively. This indicates that the stray capacitance has a significant effect on the transmission characteristics of CVT in these frequency ranges. Therefore, it can be inferred that the stray capacitance is closely related to the resonance point of CVT 15, which directly affects the measurement accuracy of CVT under harmonic conditions.

Therefore, in this study, the frequency range of stray capacitance parameter optimization is set between 150 Hz and 200 Hz to simulate and correct the voltage transfer characteristics of CVT more accurately.

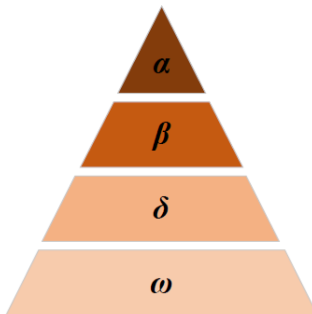


FIGURE 7. Hierarchical stratification of grey wolf optimization algorithm.

B. MULTI-OBJECTIVE GREY WOLF OPTIMIZATION ALGORITHM

Based on the equivalent circuit model and simulation modeling results proposed in the previous section, it is further necessary to optimize the key parameters to improve the measurement accuracy and stability of CVT in harmonic environment. Therefore, this paper introduces the multi-objective grey wolf optimization algorithm (MOGWO) to optimize the stray capacitance parameters.

The GWO algorithm 16 was proposed by Mirjalili et al. in 2014. Grey wolves' social leadership and hunting techniques are the main sources of inspiration for the algorithm. To mathematically model the social hierarchy of wolves when designing GWO, the most suitable solution is alpha (α) wolves, the second and third best solutions are named beta (β) and delta (δ) wolves, respectively, and the remaining candidate solutions are omega (ω) wolves. In the GWO algorithm, hunting (optimization) is guided by α, β and δ. The ω wolf follows these three wolves to find the global optimum. Its social hierarchy is shown in Fig. 7.

In addition to social leadership, in order to simulate the siege behavior of gray wolves in the hunting process, the following formulas are also proposed:

$$\vec{D} = \left|\vec{C} \cdot \vec{X}_p(t) - \vec{X}(t)\right| \tag{2}$$

$$\vec{X}(t+1) = \vec{X}_p(t) - \vec{A} \times \vec{D} \tag{3}$$

t is the current iteration number, $\vec{A}$ and $\vec{C}$ are the coefficient vectors, $\vec{X}_p$ is the position vector of the prey, and $\vec{X}$ is the position vector of the gray wolf. Eq. (2) is the distance between the gray wolf and the prey, and Eq. (3) is the position update formula of the gray wolf.

The calculation methods of vectors $\vec{A}$ and $\vec{C}$ are as follows:

$$\vec{A} = 2\vec{a} \cdot \vec{r}_1 - \vec{a} \tag{4}$$

$$\vec{C} = 2 \cdot \vec{r}_2 \tag{5}$$

Among them, $\vec{r}_1$ and $\vec{r}_2$ are two random number vectors with one-dimensional components in [0,1]. Their role is to increase randomness and avoid the algorithm falling into local optimum. $\vec{A}$ is used to simulate the attack behavior of gray wolves on prey, and its value is affected by the convergence factor $\vec{a}$. The convergence factor $\vec{a}$ is a key parameter to balance the exploration and exploitation capabilities of GWO. The value of $\vec{a}$ decreases linearly from 2 to 0 as the number of iterations increases. Through this linear attenuation, the balance between exploration and exploitation is realized. In the early stage, a wider range of possible solutions is found, and in the later stage, the details are optimized to improve the convergence efficiency of the algorithm.

Because GWO is prone to falling into local optima and cannot fully solve multi-objective optimization problems, in 2016, Seyedali Mirjalili's team extended GWO by adding multi-objective capabilities. The MOGWO algorithm [17] added two components to the basic grey wolf optimization algorithm. The first part is the Archive, which is used to store and retrieve the most suitable non-dominated solutions (Pareto optimal solutions) obtained during the optimization process. The second part is the leader selection mechanism, which helps select α, β, and δ from the solutions saved in the archive to overcome the defect that the head wolf cannot accurately guide the pack hunting in multi-objective GWO problems.

IV. CALCULATION OF STRAY CAPACITANCE

Based on the introduction of the basic principle of the grey wolf optimization algorithm (GWO) in the previous section, it is known that the algorithm is suitable for calculating the optimal values of multiple stray capacitances. Therefore, the next steps include setting the objective function, defining the relevant parameters, and using the previously determined range of stray capacitance values. Then, the data results obtained by simulation are substituted into the optimization algorithm code for calculation, to obtain the optimal solution of stray capacitance.

A. ESTABLISHMENT OF OBJECTIVE FUNCTION

To determine the optimal stray capacitance values, they can be substituted into the equivalent circuit model to minimize the relative error between the calculated voltage ratio and the actual voltage ratio of CVT. Therefore, the objective function can be set to minimize the relative error between the calculated ratio and the actual ratio. Hence, the objective function can be expressed as:

$$k_{cn} = |H_n| \tag{6}$$

$$O_n = \min\left(\left|\frac{k_{cn} - k_{an}}{k_{an}}\right| \times 100\right) \tag{7}$$

Where O_n is the nth objective function, $n = 1, 2, 3, \ldots$; H_n is the CVT transfer coefficient calculated by the basic parameters of CVT under frequency f_n; k_{cn} is the calculated ratio of CVT under f_n; k_{an} is the actual ratio of CVT under f_n.

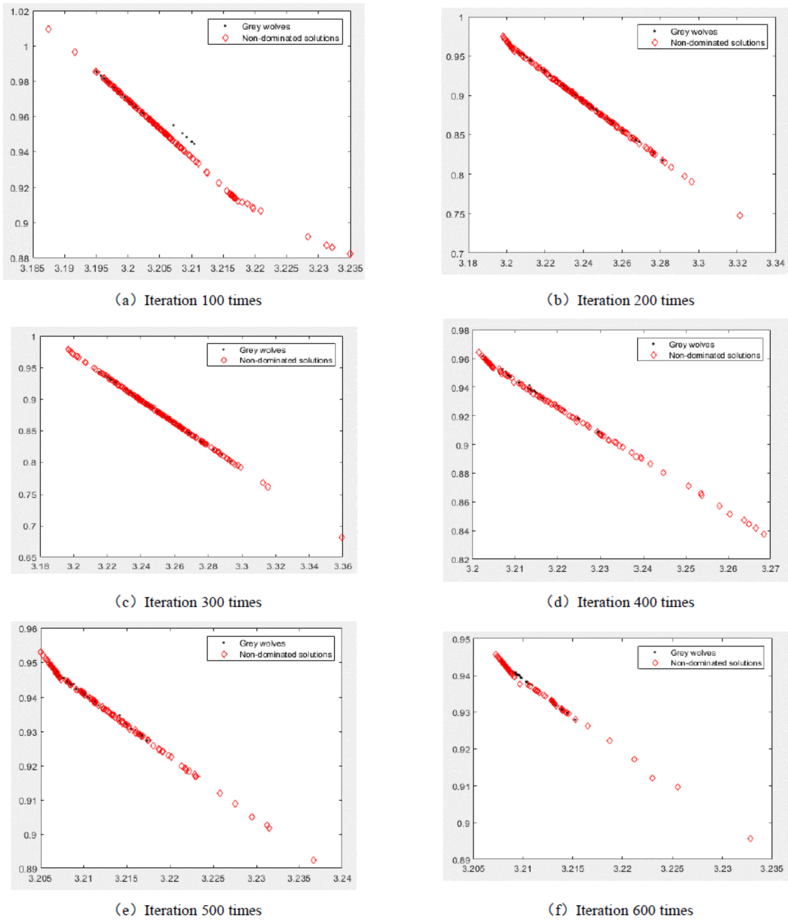
B. CALCULATION OF THE STRAY CAPACITANCES C_S AND C_{P1}

When using the multi-objective grey wolf optimization algorithm to calculate the stray capacitance, the frequency range is first determined at the resonance point, and then the parameters in Table 1 and the objective function in Equation (7) are input into the algorithm code for calculation. In order to ensure that the algorithm can fully explore the solution space and find the optimal solution, this study sets the iteration range to 100 to 600 times, the number of gray wolves to 100, and obtains the Pareto frontier graph, as shown in Figure 8.

It can be observed from the figure that as the number of iterations increases, the distribution of solutions gradually becomes denser and more uniform, tending to stabilize in certain regions. This indicates that the algorithm may be close to or has reached a convergence state. The red marks represent the non-dominated solutions. It can be clearly seen that with the increase in the number of iterations, these non-dominated solutions become more closely distributed along the boundary region. This shows that the algorithm can effectively find better solutions and improve the quality of solutions during continuous optimization.

From these Pareto frontier diagrams, it can be preliminarily judged that the quality of the solution increases with the number of iterations. Especially at 300 iterations, the distribution of solutions is more uniform, and the number and compactness of non-dominated solutions reach a high level, indicating that the algorithm may be close to the optimal solution at this iteration count. When the number of iterations reaches 400 or more, although the solution distribution remains compact, it does not seem to improve significantly. On the contrary, at 600 iterations, the distribution of non-dominated solutions becomes somewhat sparse, suggesting that the algorithm's convergence state may have been reached. Continuing to increase the number of iterations will not bring significant optimization results. Therefore, it is preliminarily judged from the graph that 300 iterations may be the better choice to obtain the optimal solution.

The values of all solution sets are taken and compared, as shown in Fig. 9.



(a) Iteration 100 times
(b) Iteration 200 times
(c) Iteration 300 times
(d) Iteration 400 times
(e) Iteration 500 times
(f) Iteration 600 times

FIGURE 8. Pareto front graphs with different number of iterations.

It can be seen from the diagram that the solution set of the stray capacitance C_{p1} is mostly concentrated in the low-end value range, while the solution set of the stray capacitance C_S is mainly concentrated in the lower value area. Moreover, many solutions are located at the boundary of the stray capacitance interval, indicating the presence of some outliers, which may adversely affect data analysis.

Because there is a large amount of data generated in each iteration, the average value of the solutions obtained in each iteration is selected, as shown in Table 2.

TABLE 2. Stray capacitance values under different iterations

Iteration Times	C_S (pF)	C_{p1} (pF)
100	457.562	111.788
200	271.128	110.058
300	257.236	111.506
400	333.528	109.222
500	297.748	110.926
600	312.166	109.942

To improve the robustness and accuracy of the analysis results, these outliers need to be removed. After removing outliers, the remaining solution set is further analyzed to obtain more accurate and reliable results. Fig. 10 shows the distribution of the solution set after removing the outliers.

It can be seen from the figure that the solution set is mostly distributed in a small value interval, which indicates that the distribution of the solution set tends to be concentrated after the outliers are removed. Since all the solutions in the Pareto solution set are optimal solutions, and there is no clear condition to limit the exact value, the solution set after removing outliers can be averaged as a set of representative optimal solutions. These mean values represent the optimal solutions of stray capacitances C_S and C_{p1} under different iterations, as shown in Table 3.

Although the representative optimal solution can be obtained by averaging the results of the above iteration times, there will still be multiple solutions. To more accurately determine the optimal stray capacitance value without specific requirements, the variation of the optimal objective function value with the number of iterations can be evaluated by calculating the fitness, as shown in Fig. 11.

It can be seen from the figure that the error value of the algorithm is at a low level, indicating that the selection of the optimal stray capacitance is reasonable. Moreover, when the number of iterations is 300, compared with other iterations studied in this paper, the objective function value of the

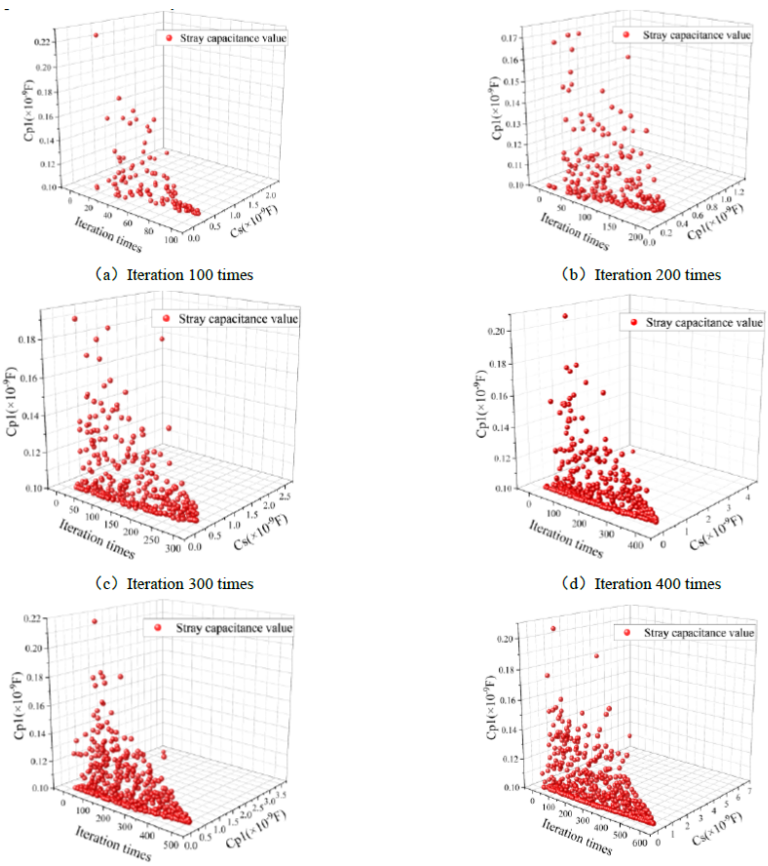


FIGURE 9. The distribution of solution set under different iterations.

TABLE 3. Stray capacitance values under different iterations (Remove outliers)

Iteration Times	C_S (pF)	C_{p1} (pF)
100	470.238	118.822
200	300.843	115.598
300	287.598	116.672
400	366.530	116.076
500	319.372	116.595
600	343.852	116.137

current solution is the closest to the known optimal solution. Therefore, in the research of this paper, when the number of iterations is 300 times, the stray capacitance value is optimal. The error comparison between the opti-mal stray capacitance and the conventional stray capaci-tance at different frequencies is shown in the figure.

The figure shows the error reduction achieved by optimizing the stray capacitance parameters relative to the default stray capacitance parameters over the 0 2500 Hz frequency range. The optimized parameters consistently show lower errors, especially at higher frequencies, indicating the effectiveness of the optimization process in minimizing harmonic errors.

When the frequency is 150 Hz and 200 Hz, the transmission coefficients of CVT are 0.00301 and 0.00286 respectively. By introducing the optimal stray capacitance value, the voltage ratio is calculated and analyzed, and the transfer coefficient is 0.0030. Substituting the transfer coefficient into the objective function calculation formula, the relative error is 0.33%. Using the obtained transfer coefficient, it can be applied to the input voltage of CVT to obtain a more accurate output voltage.

C. ABLATION STUDY

To evaluate the contribution of key components in the proposed method, ablation studies were conducted on the MOGWO algorithm and the CVT optimization model.

1) Algorithm Parameter Analysis
The key parameters of MOGWO are tested under different settings, including the number of iterations, population size and convergence factor. Among them, the number of iterations increased from 100 to 300, the optimization accuracy increased by 12%, and the effect of further increase to 600 times was negligible. Similarly, compared with the fixed value, the use of linear attenuation convergence factor α can speed up the convergence rate.
2) Stray Capacitance Model Analysis
By removing C_S or C_{p1} from the model, the voltage transfer error increased significantly, highlighting the importance of optimizing both stray capacitances. Using un-optimized default values (100 pF for C_S

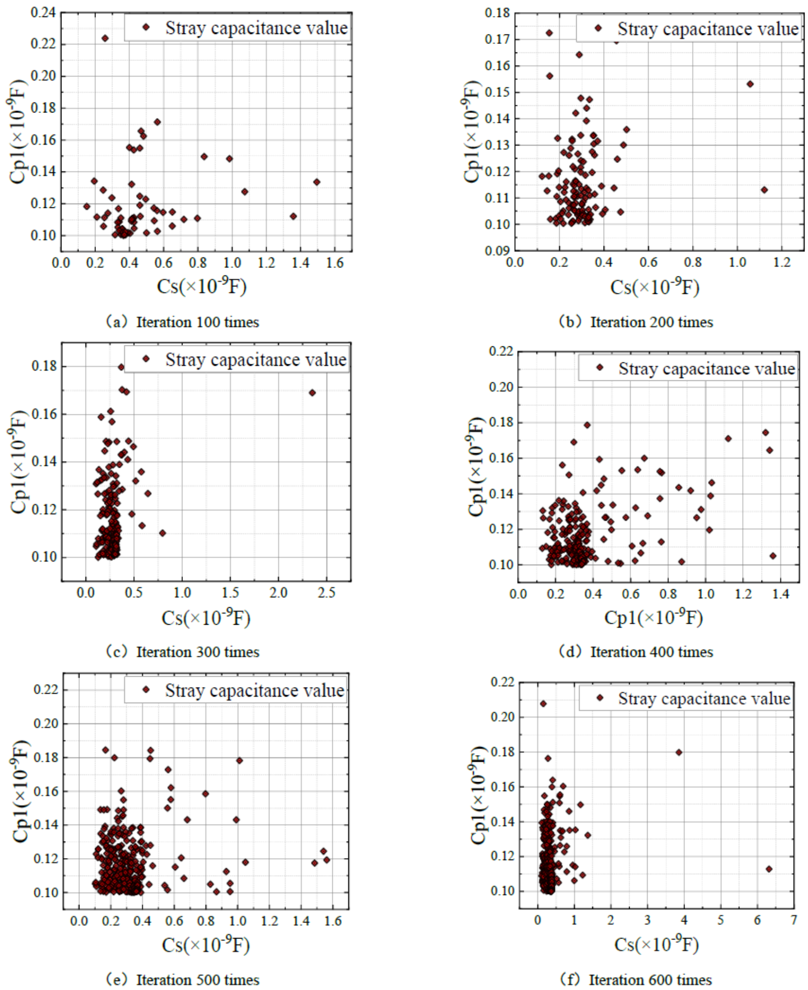


FIGURE 10. The distribution of solution set under different iteration times after deleting abnormal values.

and C_{p1}) resulted in a 56% higher error compared to optimized values.

3) Multi-Objective Optimization Analysis
Replacing the Multi-objective optimization with a single-objective approach led to imbalanced error reduction across frequencies. While the error at 150Hz was reduced, the error at 200Hz increased by 38%, demonstrating the necessity of multi-objective optimization.

These results validate the effectiveness of the proposed parameters, model components, and optimization strategy in achieving accurate CVT measurements under harmonic conditions.

V. CONCLUSION

Aiming at the significant influence of stray capacitance on CVT in harmonic circuits and the difficulty in obtaining accurate values, this paper studies a method to calculate stray capacitance and correct the CVT harmonic voltage transfer coefficient. The following conclusions are drawn:

1) By establishing the equivalent circuit model of CVT and using Simulink to build and simulate the circuit model, resonance is determined to occur at frequencies $f_1 = 150$ Hz and $f_2 = 200$ Hz, thus defining the key frequency range.
2) The multi-objective grey wolf optimization algorithm (MOGWO) is employed to obtain the corresponding Pareto solution set under different iterations by combining circuit parameters with the preset objective function. Analysis of the solution set and fitness calculation indicates that at 300 iterations, the optimal stray capacitance values are obtained: compensation reactor stray capacitance $C_s = 287.598$ pF, and primary side stray capacitance of the intermediate transformer $C_{p1} = 116.672$ pF.
3) Although the proposed method for calculating stray capacitance is effective, the actual value should be determined based on specific application requirements. Different scenarios may have varying harmonic characteristics and frequency distributions, necessitating targeted optimization. By adjusting stray capacitance,

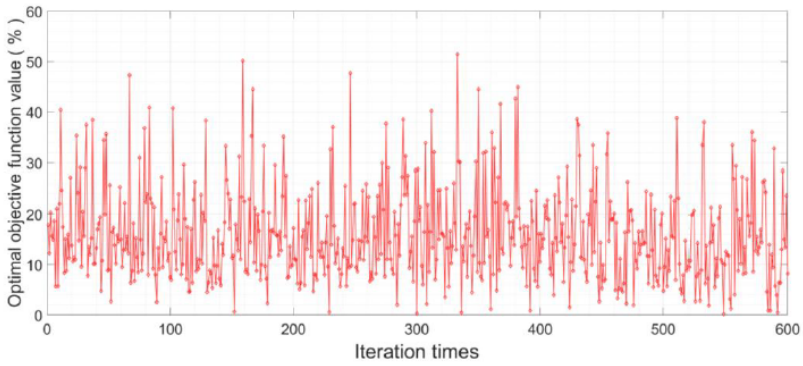


FIGURE 11. Change of optimal objective function value with the number of iterations.

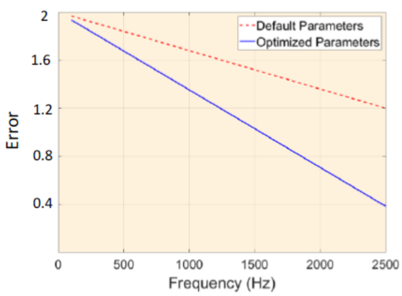


FIGURE 12. Hierarchical stratification of grey wolf optimization algorithm.

the voltage transfer coefficient can be effectively corrected, reducing the CVT voltage transfer error under harmonic conditions to 0.33%.

The proposed method holds significant practical value. Optimizing stray capacitance parameters can substantially improve the measurement accuracy and stability of CVTs in complex harmonic environments, especially in ultra-high voltage transmission systems and high harmonic content scenarios. Moreover, this approach can be extended to optimize other power equipment like capacitors, reactors, and transformers, supporting accurate monitoring and mitigation of harmonic interference.

Future research should focus on enhancing the computational efficiency of the MOGWO algorithm for real-time optimization in dynamic power systems. Additionally, the adaptability and stability of the method need verification under complex nonlinear load and high-order harmonic interference conditions, complemented by experimental validation in practical engineering environments. Integration of this optimization strategy with smart grid systems could further advance harmonic monitoring and optimization in modern power systems.

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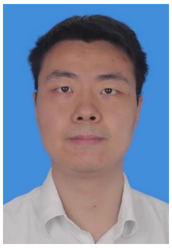
RAN ZHUO was born in 1986. He is currently a Professor-level Senior Engineer at Electric Power Research Institute of China Southern Power Grid. His research interests include transformer equipment insulation state detection and diagnosis technology, environmental protection insulation gas application technology, and new power equipment application and detection technology.

WANWEI WANG was born in 1982 in Hubei Province, China. He is currently a Senior Engineer at Dongguan Power Supply Bureau of Guangdong Power Grid Co., Ltd. His research interests include power grid stability analysis, reactive power compensation, and new energy access to the grid.



YAN LUO was born in 1991. He is currently a Senior Engineer at Electric Power Research Institute of China Southern Power Grid. His research interests include research and development of new technologies for substation equipment and safe operation of equipment.

RONGFU ZHONG was born in 1988. He is currently a Senior Engineer at Dongguan Power Supply Bureau of Guangdong Power Grid Co., Ltd. His research direction includes high voltage power equipment.

ZHIMING HUANG was born in 1985. He is currently a Senior Engineer at Electric Power Research Institute of China Southern Power Grid. His research interests include numerical modeling and simulation, transformer oil-paper bushings, and gas discharge mechanisms.

QIYE DU was born in 1988. He is currently a Senior Engineer at Dongguan Power Supply Bureau of Guangdong Power Grid Co., Ltd. His research direction includes high voltage power equipment.