FREQUENCY RESPONSE TEST AND KEY PARAMETER ESTIMATION OF OIL-IMMERSED CAPACITIVE VOLTAGE TRANSFORMER

Mingxing ZHU Yadong JIAO
Anhui University – China
xysah@163.com jiao12345ya@163.com

Wei HUANG
Asian Power Quality Initiative – China
alex.huang@copperalliance.asia

Qing ZHONG
South China University of Technology – China
epqzhong@scut.edu.cn

Jan MEYER
Technische Universität Dresden – Germany
jan.meyer@tu-dresden.de

ABSTRACT

The increasing applications of CVTs can cause significant error in the harmonic voltage measurement. The correct measurement of the frequency response and the accurate parameter estimation are two main components for the calibration of CVTs. This paper establishes an experimental platform for the measurement of the frequency response of high voltage and medium voltage oil-immersed CVTs. Because the parameters of the oil-immersed CVTs are consistent, a key parameter optimal estimation model is developed based on the comparison of the measurement and simulation. A simplified equivalent circuit model is taken as the simulation model. The estimation results show that the optimal model brings more accurate parameters and reduces the experimental workload.

INTRODUCTION

During these decades, the harmonic sources in transmission system increase rapidly, such as wind and solar power plants, HVDC stations, SVCs and so on. Therefore, TSOs interest about the power quality issues in the transmission system is increasing, especially in harmonics [1]. At the same time, capacitive voltage transformers (CVTs) are applied in the transmission system above 35kV widely. Oil-immerse CVTs are very reliable with high insulation ability and are highly accurate at rated frequency [2]. But because of the frequency response, CVTs will introduce significant errors during harmonic voltage monitoring. In some situation, difference up to 200% and more can be observed [3]. To use the measurement data for further processing is impossible because of its accuracy. Therefore, it is very important to understand the frequency response of CVTs, including the parameters which will affect the response.

There are several papers concerned about the harmonic voltage measurement of CVT. CVTs were designed and can only ensure the precision at fundamental frequency, but this ratio is not constant with the frequency. So CVTs were advised not to be used for harmonic voltage measurement [4]. While the CVTs are installed widely because of its low cost, many approaches had been researched for the regular calibration of the harmonic voltage measurement. Using the transfer function to compensate the CVT response at harmonic frequencies was a good way [5]. But it required offline tests to determine the transfer function. Ghassemi sensors technique was applied to harmonic voltage measurement with CVTs by adding some current sensors [6]. This technique needed to know the parameters accurately and didn't consider the stray parameters. The stray parameters of the CVT can affect the frequency response significantly [6][7], especially the stray capacitors in the transformer windings. Therefore, the theoretical analysis and simulation are not enough to correct the harmonic voltage measurement of the CVTs. Experimental measurement of frequency response is very important way to calibrate CVTs, especially for wide range of frequency extended beyond the 50th harmonic. For MV voltage transformer, a setup for the measurement had been established. It allowed calibrations using distorted waveforms, with a fundamental tone at medium voltage level and superimposed harmonics up to 20% and 15 kHz [8]. As we know, the frequency responses of CVTs are scattered because of different designers and manufactures. Moreover, the environmental conditions like burden and temperature can have a significant impact on the frequency response [9]. The measurement needs very extensive laboratory facilities. Parameter estimation is also an effective way to correct the errors of CVTs.

In this paper, an experimental test platform of the frequency response of CVTs is developed. A set of oil-immersed CVTs for four voltage levels has been tested with the platform. The experimental results showed that the frequency characteristics of the same type CVTs from the same manufacturer were very close. Because the parameters of the oil-immersed CVTs is more consistent, an optimal key parameter estimation model was developed based on the comparison of the simulation and measurement results. A simplified equivalent circuit model was used as the simulation model. The equivalent resistance and the stray capacitor of the compensated inductor and the stray capacitor of the transformer windings were the key estimated parameters. With the optimization, the equivalent resistance can be achieved and other two parameters are more accurate than the parameters calculated from the measured resonance frequency. The estimated parameters can serve as base for a future calibration of the CVTs and to determine their application bandwidth.

EXPERIMENTAL TEST OF FREQUENCY RESPONSE OF CVT

Experimental test platform

The layout of the experimental test platform to measure the frequency response of CVTs is shown in Figure 1.

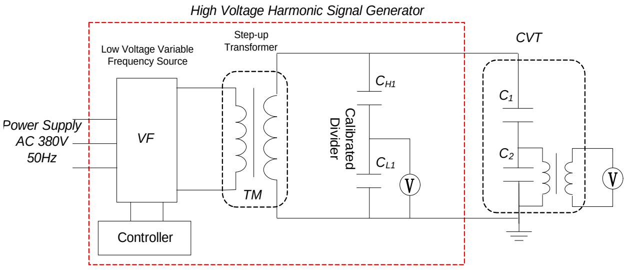


Figure 1 Layout of the experimental test platform

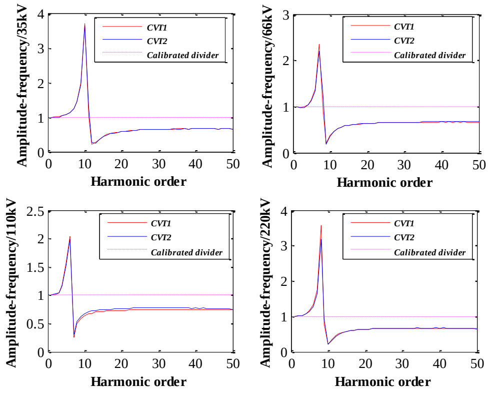
The platform is composed of the high voltage harmonic signal generator (HVHSG) and the equipment under test (EUT). HVHSG is composed of the low voltage variable frequency source, step-up transformer and calibrated divider, as shown in the red box in Figure 1. The low voltage variable frequency source can generate the sinusoidal voltages with different frequencies and is controlled by the computer as the controller. Step-up transformer is used to increase the output voltage as the source of the CVT. Capacitive voltage divider was used as the calibrated divider for the CVT. A field picture of the platform was given in Figure 2.

Figure 2 field picture of the platform

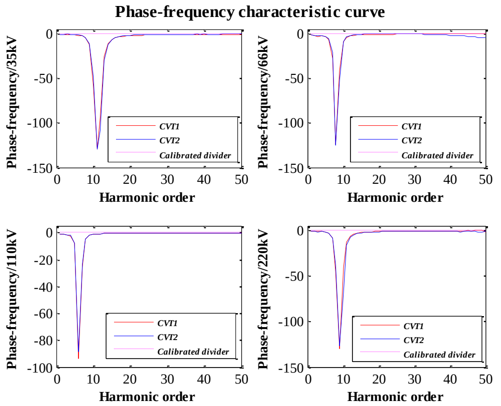
Experimental test results

The HVHSG generates the fundamental voltage added with 2nd -50th order harmonic voltage in sequence. The output of the CVT and calibrated divider are measured at the same time. Compare the measurement results, the frequency response of the CVT and the errors are identified.

A set of oil-immersed CVTs for four voltage levels including 35kV, 66kV, 110kV and 220kV was tested. Some of the test results are given in Figure 3. The measured amplitudes and phases on the resonance frequency are given in Table 1. The frequency response of CVTs for different voltage level are also different. Among all the samples, the largest error of the measured amplitude-frequency characteristics is 0.13p.u., while the largest error of the measured phase-frequency characteristics is 5.16 degrees.


Amplitude-frequency characteristic curve

(a) amplitude-frequency characteristics


Phase-frequency characteristic curve

(b) phase-frequency characteristics
Figure 3 Frequency response of the EUTs

Table 1 The measured amplitude and phase

Voltage level	CVT type	Frequency(Hz)	Amplitude (p.u)	Frequency(Hz)	Amplitude (p.u)	Frequency(Hz)	Phase(°)
35kV	CVT1	500	3.71	600	0.22	550	-129.49
	CVT2		3.63		0.23		-129.85
66kV	CVT1	350	2.34	450	0.2	400	-123.48
	CVT2		2.21		0.18		-124.6
110kV	CVT1	250	2.03	350	0.26	300	-93.52
	CVT2		1.98		0.31		-88.36
220kV	CVT1	400	3.56	500	0.2	450	-130.3
	CVT2		3.47		0.21		-126.99

According to the test results, the frequency response of the same type CVT from the same manufacturer are very close, if tested under similar conditions. Therefore, the key parameters of the same batch of CVTs can be estimated by several test results, which can reduce the burden of the experimental test.

KEY PARAMETER ESTIMATION

Impedance model of CVT

A simplified impedance model of CVTs had been developed for estimation of key parameters and simulation of the frequency characteristics. A common impedance model of CVT is shown in Figure 4. In the figure, R_1, C_1, R_2 and C_2 are the serial capacitors and equivalent resistances on the high and medium voltage respectively. L_s, R_s and C_c are the inductance, equivalent resistance and capacitance of the compensated inductor respectively. T is an ideal transformer with the ratio n:1. R_m and L_m are the equivalent resistance and inductance of the excitation circuit. $R_{T,1}$, $L_{T,1}$, $R_{T,2}$ and $L_{T,2}$ are the winding resistance and leakage inductance of primary and secondary side of the transformer. $C_{p,1}$ and $C_{p,2}$ are the stray capacitances of primary and secondary side to ground. $C_{p,12}$ is the stray capacitance between primary and secondary side. R_D and L_D are the equivalent resistance and inductance of the load. The impedance $Z_{p,2}=(1/j\omega C_{p,2})$is much larger than $Z_D=R_D+j\omega L_D$, therefore $C_{p,2}$ can be ignored. To eliminate the ideal transformer T in the circuit, all the impedances on the secondary side can be translate to the primary side.

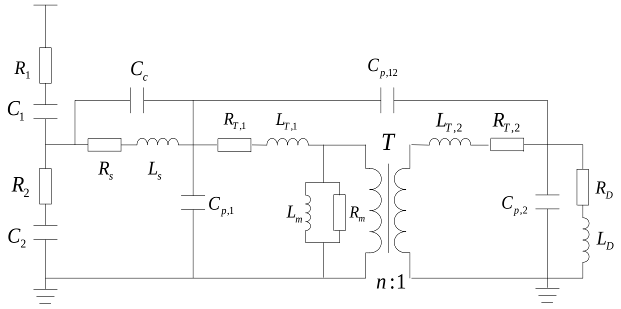


Figure 4 Impedance model of CVT

The current through $C_{p,12}$ is:

$$i_1 = C_{P,12}\frac{d(u_1-u_2)}{dt} = C_{P,12}(1-\alpha)\frac{du_1}{dt} \tag{1}$$

where $\alpha = u_2/u_1$, u_1 , u_2 are the voltage on the primary and secondary side, respectively. According to the circuit shown in Figure 4, α is:

$$\alpha = \frac{u_2}{u_1} = \frac{1}{n}\cdot\frac{Z_m}{Z_m+Z_{T,1}}\cdot\frac{Z_D}{Z_D+Z_{T,2}} \tag{2}$$

where $Z_{T,1}=R_{T,1}+j\omega L_{T,1}$, $Z_m=R_m+j\omega L_m$ and $Z_{T,2}=R_{T,2}+j\omega L_{T,2}$. Because $Z_m \gg Z_{T,1}$, then $Z_m/(Z_m+Z_{T,1}) \approx 1$. According to equation (2), it follows that $0<\alpha\le\frac{1}{n}$. The transformer ratio n in China is always in the range of $(100\sim 200)/\sqrt{3}$. Therefore, α is very close to 0. $C_{p,12}(1\text{-}\alpha)$ is consequently very close to $C_{p,12}$. Then the impedance model can be simplified as Figure 5, where $C_p=C_{p,12}+C_{p,1}$. The simplified impedance model was taken as the simulation model of CVT.

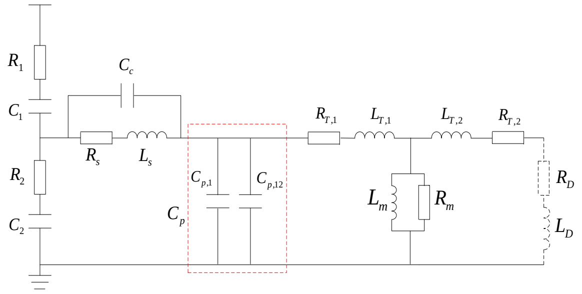


Figure 5 Simplified impedance model of CVT

Key parameter optimal estimation

The parameters of CVT include the manufacturing parameters and stray parameters. Manufacturing parameters can be calculated from name plate values or measured by experiments. But the stray parameters are very difficult to calculate or measure. Based on the circuit shown in Figure 5, the serial resonance frequency h_s and parallel resonance frequency h_p are given as equation (3) and (4).

$$h_s = \frac{1}{2\pi f_1\sqrt{L_s(C_c+C_p)}} \tag{3}$$

$$h_p = \frac{1}{2\pi f_1\sqrt{L_sC_c}} \tag{4}$$

Therefore, among the stray parameters, C_c, R_s and C_p are the key parameters which will affect the frequency response.

If the resonance frequency could be measured precisely, the key parameters can be calculated. Because the measurement of the frequency response is not continuous, there must be errors between the calculated values and measured values.

Comparison of the simulation and measurement results is a good way to reduce the estimation error. Consequently, an optimization model was applied to estimate the key parameters of CVT. Least square method was used to establish the objective function given as equation (5).

$$\begin{aligned}\min f(C_c,C_p,R_s) &= \sum_{h=1}^{n}([H_m(h)-H_s(h)]^2 \\ &+[A_m(h)-A_s(h)]^2)\end{aligned} \tag{5}$$

where $H_m(h)$ and $A_m(h)$ are the measured amplitude-frequency response and phase-frequency response under different frequency, $H_s(h)$ and $A_s(h)$ are the simulated amplitude-frequency response and phase-frequency response under different frequency. We can achieve an optimal set of key parameters to achieve the minimal errors by solving this optimizing model. Particle Swarm Optimization (PSO) is applied to solve the model.

PARAMETER ESTIMATION RESULTS

Four CVTs for different voltage level were investigated here. The parameters provided by manufacturer are given in Table 1. Three key parameters have to be estimated for every CVT.

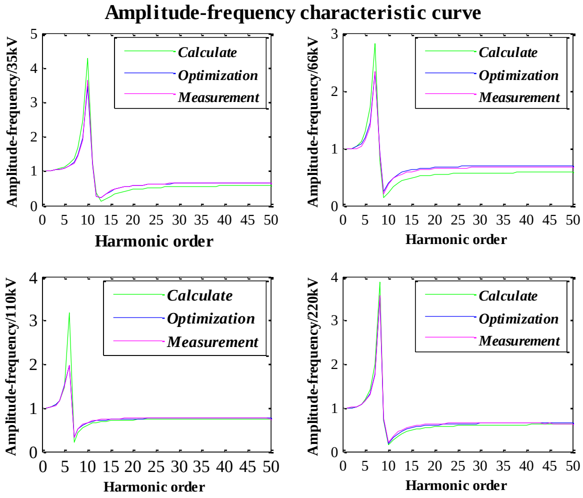
Table 1 Parameters of CVTs provided by manufacturer

Types	TYD35-134037	TYD66-121703	TYD110-134606	TYD220-134570
C_1(μF)	0.04028	0.01352	0.01473	0.01193
R_1(Ω)	41.10	119.40	123.20	152.30
C_2(μF)	0.04035	0.03879	0.0319	0.0646
R_2 R_2(Ω)	39.40	42.20	51.90	27.60
L_s(H)	94.48	162.00	202.20	97.30
$R_{T,1}$(Ω)	1408.00	1427.00	1612.00	1135.00
$L_{T,1}$(H)	28.55	26.33	28.37	22.16
$R_{T,2}$(Ω)	0.05	0.05	0.03	0.02
$L_{T,2}$(μH)	383.90	389.20	100.00	176.00
R_m(MΩ)	6.50	6.50	3.94	2.38
L_m(kH)	22.60	22.60	24.60	18.60
n	$10/(0.1/\sqrt{3})$	$10/(0.1/\sqrt{3})$	$20/(0.1/\sqrt{3})$	$20/(0.1/\sqrt{3})$

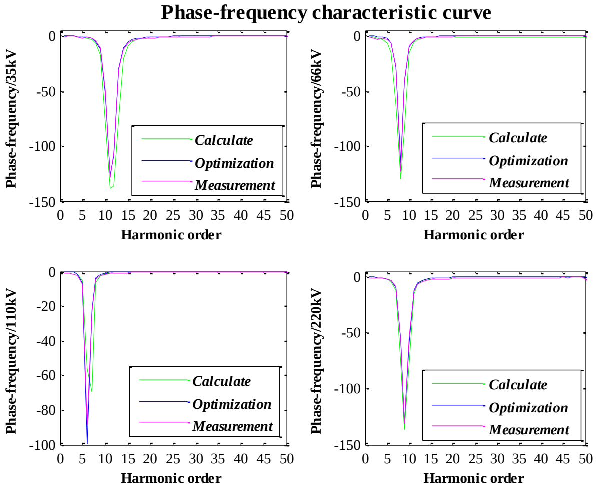
With the measured resonance frequency, the key parameters can be calculated. The key parameters can also be estimated by solving the optimization model as (5). The comparison of the parameter estimation results is shown in Table 2. The comparison of the frequency response among the measured, the calculated parameters and the optimal parameters is shown in Figure 6. The biggest deviations between frequency response of two type estimated parameters and the measured result are given in Table 3. The optimization approach can reduce the deviations significantly. The deviations of amplitude can be reduced up to 93.77%. The deviations of phase can be reduced up to 89.35%.

Table 2 Comparison of the key parameter estimation results

Types		CVT-TYD35	CVT-TYD66	CVT-TYD110	CVT-TYD220
Calculated parameters	C_c(pF)	637	773	1027	1042
	C_p(pF)	436	506	366	587
Optimal parameters	C_c(pF)	699.11	819.11	1139.44	1070.46
	C_p(pF)	329.63	316.77	333.36	504.84
	R_s(Ω)	9006.27	14513.54	12528.05	7963.41



(a) amplitude-frequency characteristics



(b) phase-frequency characteristics

Figure 6 Comparison of frequency reponse

Table 3 Biggest deviations of different estimation approach

Voltage level	Approach	Biggest deviation of amplitude (p.u.)	Biggest deviation of phase (°)
35kV	Calculated parameters	1.13	63.57
	Optimal parameters	0.21	6.77
66kV	Calculated parameters	0.88	58.49
	Optimal parameters	0.23	9.23
110kV	Calculated parameters	1.21	56.54
	Optimal parameters	0.08	11.91
220kV	Calculated parameters	0.57	31.94
	Optimal parameters	0.16	8.56

According to the comparison, it can be found that there are two advantages for the proposed method. One is that the equivalent resistance of the compensated inductor R_s can be calculated. The other is that the estimated key parameters are more accurate than ones obtained from the measured resonance frequency.

The conclusion drawn from the experiment test results is that there is high similarity between the frequency responses of CVTs of the same type. Using the key parameter estimation can reduce the workload for the experimental test significantly. The estimated parameters could be a base for a future method to calibrate the CVTs.

CONCLUSION

Comprehensive experimental results show that the parameters of the same type of oil-immersed CVTs from the same manufacturer are consistent under similar environmental conditions. By comparison of the measurement and simulation, an optimal model for the key parameter estimation was establish by the least square method. The optimal estimation results are more accurate than the parameters just calculated from the measured resonance frequency. The proposed method can also reduce the experimental workload for the same batch of the CVTs.

Further research is needed to verify the stability of the parameters under the influence of environmental parameters, like temperature and burden. If the stability of the frequency response and the estimated parameters respectively can be proven for typical variations of the environmental parameters, a calibration of harmonic measurements based on curves provided by manufacturers will be possible in future.

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