Research on the Design of ECT for VFTC Measure with UHV Level

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***Abstract*—For research of VFTC measurement with UHV level, this paper studies the design of electronic current transformer for UHV VFTC measurement. The transient characteristics (amplitude, frequency band and response speed) of VFTC are analyzed. Based on the work mechanism of Rogowski coil, an electronic current transformer for UHV VFTC measurement is designed. On the basis of comparing various kinds of, Rogowski coil with PCB form using external-integral circuit is adopted. Structural designing and electrical parameters calculation are the most important procedure to design the electron current transformer based on Rogowski coil with PCB form. The structural parameters is determined by the manufacturing process of PCB board. According to the manufacture requirements, the inner and outer radius of the coil, the number of turns, the thickness of PCB board and the size of copper foil are calculated. Among them, the size of copper foil is the key design parameter. The electrical calculation include self-inductance, internal resistance, distributed capacitance and sampling resistance. while, sampling resistance is the key electrical parameter, which is mainly determined by the measurement frequency and the coil resistance. In the end, the author summarizes the design procedure of ECT based on PCB Rogowski coil in details. A simulation is carried out to check the correctness of the design, and the result shows that The ECT designed can absolutely be used to measure VFTC with UHV level. In order to verify the correctness of the design, the PCB Rogowski coil is designed and verified. The results show that the PCB Rogowski coil with external integration meets the measurement requirements of UHV VFTC.**

***Index Terms*—VFTC, PCB rogowski coil, integral modes, integrator, design parameters**

I. Introduction

VFTO and VFTC are the most important sources of transient EMI in GIS substations. At present, scholars at home and abroad have concentrated on the research of VFTO, and have made many achievements in the generation mechanism, theoretical calculation method and field test of VFTO. However, there is a relative lack of research on VFTC generated by switchgear operation in GIS. Previous studies have shown that VFTC has the characteristics of short rise time (about 4-10 ns), so when it propagates in GIS, it will produce high frequency (0-MHz) radiated electromagnetic fields [1], [2]. It will leak into the external environment through the structure of inflatable sleeve and insulating flange in GIS, and produce coupling interference in external equipment, which may cause failure of secondary equipment [3]. The higher the voltage level, the more serious the coupling disturbance caused by VFTC. Therefore, it is very necessary to study the characteristics of VFTC.

But up to now, few studies have involved the measurement of VFTC. There are two reasons for the lack of research on VFTC measurement.

1) The requirements for measuring instruments are high. The transient characteristics of VFTC determine its requirements for measuring instruments as follows:① wide range of amplitude measurement (0-tens of kA);② fast dynamic response (ns level); ③ wide range of frequency variation (0-tens of MHz). It is very difficult for existing current measuring equipment to meet the above requirements.

2) Installation requirements are high. The installation of the instrument should have the following installation properties: ① good insulation performance. The measuring instrument should be able to withstand the corresponding power frequency voltage for a long time. When measuring, the switch should be able to withstand VFTO shock under operating conditions. ② Good heat resistance. Under the enclosed environment of GIS, the flow capacity of long term busbar can be prolonged. ③ Good EMC performance. VFTO and VFTC are electromagnetic waves themselves, which will produce electromagnetic interference in the normal measurement of equipment in the process of propagation.

According to the research status of VFTC measurement, the paper carries out the design research of VFTC measuring instrument. And focuses on solving the measuring requirements of instruments.

II. Transient Characteristics of Vftc

Our research group has studied the transient characteristics of VFTC [4]. And acquire some result as shown in Fig. 1 and Table I, respectively.

Fig. 1 (a) shows that the VFTC's amplitude can rise from 0 kA to 7 kA in a few nanosecond, which show fast rising speed and high rise range. Fig. 1 (c) indicate that main frequency of VFTC change at the range of 5MHz to 10MHz.

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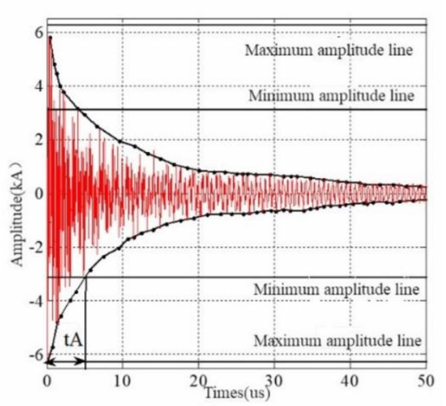
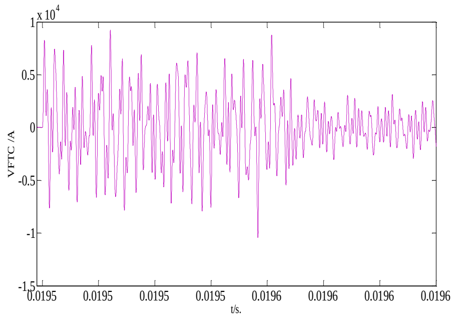
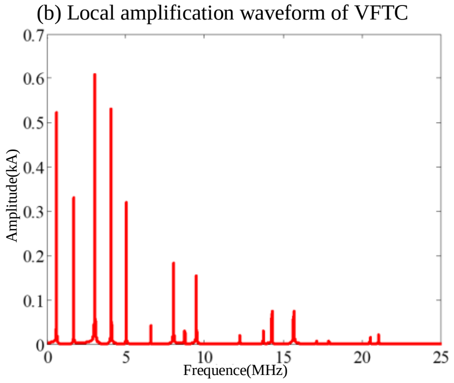


(a) waveform of VFTC



(b) Local amplification waveform of VFTC



(c) Frequency distribution of VFTC

Figure 1. Transient characteristics of VFTC.

According to the transient characteristics of VFTC, the design parameters of ECT to measure UHV VFTC can be easily found, which is shown in Table I.

TABLE I. VFTC MEASUREMENT PARAMETERS

Bandwidth (MHz)	Amplitude (Ka)	Decay time (μs)
0-10	7	3.1

III. DETERMINATION OF ROGOWSKI COIL TYPE

At present,Rogowski coils are available in three types: flexible, rigid and printed circuit board type (ie PCB type) [5]-[7]. Because the PCB type Rogowski coil has small volume, constant coil width and density, and small non-magnetic skeleton temperature expansion coefficient, the measurement stability is high; it is mostly used for measurement of high frequency and large current. It is closest to the measurement requirements of VFTC, therefore this paper intends to design PCB type Rogowski coil to complete the measurement of VFTC.

To measure VFTC, PCB Rogowski coil works in very bad electromagnetic interference environment. In order to improve the anti-interference ability of PCB Rogowski coil, symmetrical wiring for VFTC measurement is designed. As shown in Fig. 2.

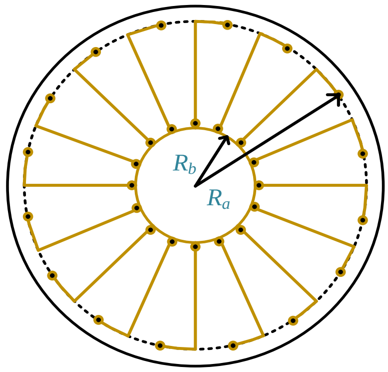


Figure 2. Symmetrically routed PCB Rogowiski coil.

The PCB board is equipped with N uniformly distributed guide holes with equal spacing (angle 2 π/N), and the inner and outer guide holes are dislocated symmetrically. On the front side of PCB board, the outer guide holes are arranged as the starting end in turn, and the small arcs with radius R_a and radian of 2π/2N are set counterclockwise. On the back side of PCB board, the outer guide holes are arranged in turn. At the beginning of the hole, a small arc with radius R_a and radii of 2π/2N is set clockwise. The ends of the arc ends coincide, and all arcs form the circle with a radius of R_a. PCB Rogowski coil with symmetrical wiring. The plane of single-turn coil with symmetrical wiring uniformly and tightly passes through the axis of the coil and is completely perpendicular to the plane of PCB. Therefore, the flux produced by the current-carrying conductor under test can pass through the coil completely, and the accurate mutual inductance coefficient can be obtained [8]-[11].

IV. DESIGN OF PCB TYPE ROGOWSKI COIL

Since the induced voltage generated by the Rogowski coil is small, the input voltage of the commonly connected signal detecting circuit is generally 0.1V~0.2V, so this paper set the induced voltage is $e(t) = 0.1V$. Its upper cutoff frequency is 10MHz.

The design of the PCB type Rogowski coil is to determine the structural geometry and electrical parameters. Due to the plate making requirements of the PCB type Rogowski coil, the thickness of the entire coil and the width of the wire are required. Therefore, the design of the PCB type Rogowski coil should first determine the structural parameters, then determine the electrical parameters according to the structural parameters, and adjust the structural parameters according to the electrical parameters. The specific design steps are shown in Fig. 3.

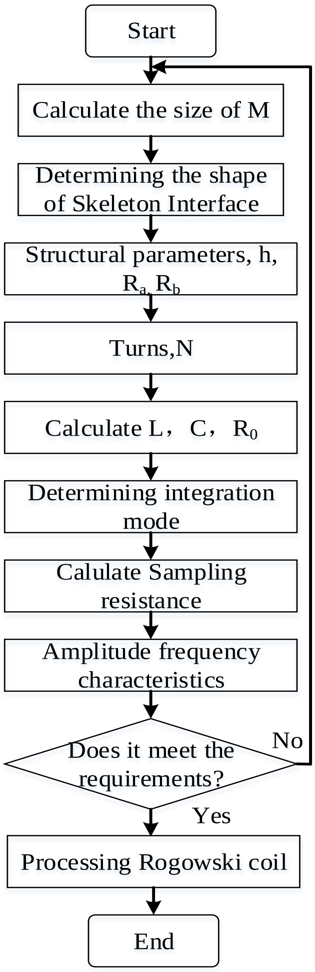


Figure 3. Basic design flow of PCB Rogowski coil.

Among them, the mutual inductance coefficient M can be obtained from the lower form.

$$e=M\frac{dI}{dt} \tag{1}$$

where, Mutual inductance $M=\frac{h\mu_0 N}{2\pi}\ln\frac{R_a}{R_b}$, R_a is the outer radius of the coil, R_b is the internal radius of the coil, h is skeleton height, N is coil winding, μ_0 is permeability of vacuum.

According to the technological requirement and mutual inductance coefficient, the structure parameters such as outer radius Ra, inner radius R_b, skeleton height h, width W_0 of copper foil and thickness h_0 of copper foil are determined. After determining the structure parameters and turns, the inductance L, distributed capacitance C_0 and internal resistance R_0 of the coil are estimated, and the sampling resistance is determined by integrating mode and the size of distributed capacitance. Finally, the frequency characteristics are checked, and the parameters mentioned above are revised until they meet the requirements if the measurement characteristics are not satisfied.

A. Design Structural Parameter

According to formula (1), the mutual inductance coefficient $M=\frac{e(t)}{dI/dt}=\frac{0.1}{7/0.31\times10^{-6}}=0.0455\mu H$.

According to the plate-making process requirements, the rectangular cross-section skeleton is selected. Its inner radius $R_a=126mm$, outer radius $R_b=100mm$, skeleton height $h=2mm$, copper foil width $W_0=127um$, thickness $H_0=1oz=35um$, and copper foil length of single-turn coil is $L_0=R_a-R_b+h=28mm$.

In PCB circuit, distributed capacitance is formed between lines, which will affect the accuracy of measurement when working at high frequencies. Therefore, in order to reduce the distributed capacitance, the distance between turns is increased, making $2\pi R_b>>NW_0$. W_0 is the width of copper foil. At $R_b=100mm$, the width of copper foil is *127um*, and the turns of the coil $N=500$ meet the above requirements. Its structural parameters are shown in Table II.

TABLE II. THE GEOMETRIC PARAMETERS OF THE COIL

Parameter	Specification
Turns, N	500
Inside radius, R_a/mm	100
Outside radius, R_b/mm	126
Thickness of PCB, h/mm	2
Length of copper foil, L_0/mm	28
width of copper foil, $W_0/\mu m$	127
Thickness of copper foil, $h_0/\mu m$	35

B. Electrical Parameter Design

Usually, the expression $\omega L>>R_0+R$ [12] is used to judge whether the integral mode is adopted or not. If $\omega L>>R_0+R$, self-integral mode is adopted; if not, external integral mode is adopted. Moreover, for electrical design, the value of he inductance, capacitance and internal resistance of the coil should be determined first. The inductance, internal resistance and distributed capacitance can be calculated by the following formula.

$$L=\frac{\mu_0 hN^2}{2\pi}\ln\frac{Ra}{Rb} \tag{2}$$

$$R_0=\rho\frac{2NL_0}{W_0h_0} \tag{3}$$

$$C_0=\frac{8\pi^2 L_0}{\ln(R/r)}\varepsilon_0\bullet\varepsilon_r \tag{4}$$

where, μ_0 is permeability of vacuum, $\mu_0=4\pi\times10^{-7}$ (H/m); ρ is brass resistance, $\rho=1.72\times10^{-8}\Omega\cdot m$; ε_0 is Vacuum dielectric constant, $\varepsilon_0=8.86\times10^{-12}$; ε_r is dielectric constant of PCB, $\varepsilon_r=4.5$。

From the calculation, it can be seen that the internal resistance of PCB board is large, reaching 110.24Ω, which is difficult to meet $\omega L>>R_0+R$, so the external integral formula is adopted. In order to prevent serious attenuation of integrators and improve sensitivity, inertial active integrators are usually used. The equivalent circuit is shown in Fig. 4.

Upper cut-off frequency:

$$f_h = \frac{1}{2\pi\sqrt{LC_0}}\sqrt{\frac{R+R_0}{R}} \tag{5}$$

Lower cut-off frequency:

$$f_l = \frac{1}{2\pi R_2 C} \tag{6}$$

L is inductance of coil, C_0 is distributed capacitance, C is filter capacitor, R_0 is self- resistance, R is sampling resistance.

From the above analysis, it can be seen that the sampling resistance R has a direct impact on the measurement accuracy, the transient characteristics of the system and the amplitude-frequency characteristics [13]. The selection of resistance should generally satisfy the following two conditions:

1) $R_0+R>>\omega L$, $R>>R_0$, the larger sampling resistance makes the coil have a higher cut-off frequency.

2) R is much smaller than the input impedance (hundreds $k\Omega$) of distributed reactance between turns and subsequent integration circuits, so that the current mainly flows through the sampling resistance circuit, which can further eliminate the influence of inter-turn capacitance, and the integration circuit can work in an ideal state. Therefore, the sampling resistance is minimized on the premise of satisfying the frequency response.

In summary, the value of sampling resistance R is $2k\Omega$.

In order to ensure that the current in the measuring circuit mainly flows through the sampling resistance, the value of the integral resistance is $100k\Omega$. In practical applications, operational amplifiers and capacitors are not ideal devices. When the input signal is zero, the output voltage of the integrator is not equal to zero, which is the phenomenon of "integral drift". Therefore, in order to reduce the "integral drift", a feedback resistor is connected in parallel at both ends of the integral capacitor, which is called the inertial link. In order to limit the magnification of the integral circuit, the design of the feedback resistance R_2 has a value of $1\,M\Omega$ and a filter capacitor of 1μF.

Self-inductance, equivalent internal resistance and distributed capacitance can be obtained from formulas (2), (3), (4), and their electrical parameters are shown in Table III.

TABLE III. THE ELECTRICAL OF THE COIL

Parameter	Specification
Inductance, L/uh	22.75
Self- resistance R_0 / Ω	110.24
Distributed capacitance, C_0/nF	0.3814
Sampling resistance, R/ Ω	2000
Integral resistance R_1/ $k\Omega$	100
Feedback resistance, R_2/ $M\Omega$	1
Filter capacitor, C/uF	1

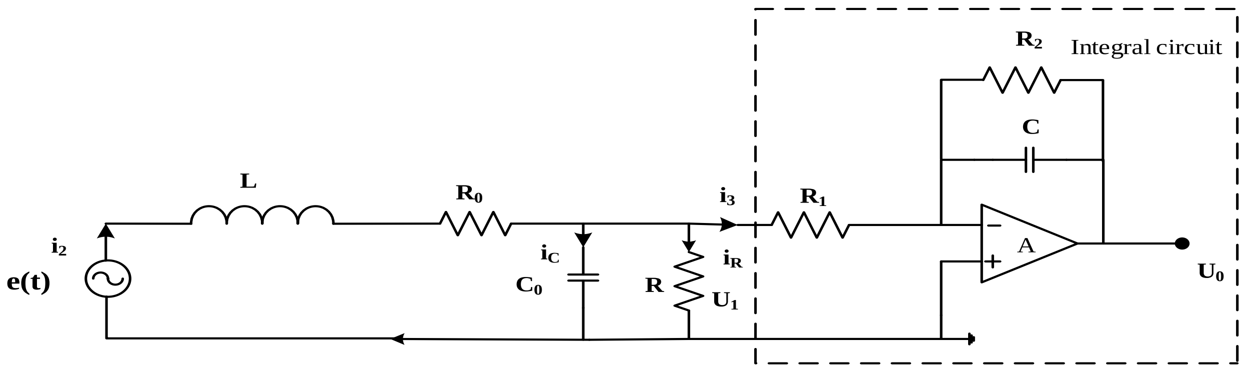


Figure 4. Circuit diagram of Rogowski coil using outer integrator.

V. DESIGN VERIFICATION

In order to verify the accuracy of Rogowski coil design, the frequency characteristics are checked. The equivalent circuit of Fig. 4 is as follows:

$$\begin{cases} e = M\dfrac{di_1}{dt} = L\dfrac{di_2}{dt} + i_2 R_0 + U_1 \\ i_2 = i_c \dfrac{dU_1}{dt} + \dfrac{U_1}{R} \end{cases} \tag{7}$$

Laplace transformation of the upper formula.

$$\begin{aligned} G_1(s) &= \frac{U_1(s)}{I_1(s)} \\ &= \frac{Ms}{LC_0 s^2 + (\frac{L}{R} + R_0 C_0)s + \frac{R_0}{R} + 1} \end{aligned} \tag{8}$$

For the integral circuit, the Laplace transform is obtained:

$$G_2(s) = \frac{U_0(s)}{U_1(s)} = -\frac{R_2}{R_1} \bullet \frac{1}{1+R_2 Cs} \tag{9}$$

We divide the measuring circuit of Fig. 4 into measuring circuit and integral circuit, and its corresponding transfer function is as follows.

$$
\begin{aligned}
G(s) &= G_1(s)\cdot G_2(s) \\
&= -\frac{MR_2}{R_1}\cdot\frac{s}{(R_2Cs+1)[LC_0s^2+(\frac{L}{R}+R_0C_0)\ s+\frac{R_0}{R}+1} \\
&= \frac{4.55\times10^{-7}s}{2.946\times10^{-16}s^3+1.5414\times10^{-8}s^2+1.0378s+1.0378}
\end{aligned}
\tag{10}
$$

It can be seen from the Fig. 5 that the angle limit frequency is as high as (solid line in the figure), and its corresponding frequency f_h*=16MHz*. The VFTC frequency in UHV GIS is 10MHz. The PCB type Rogowski coil of this design can theoretically meet the measurement band requirements for VFTC in GIS.

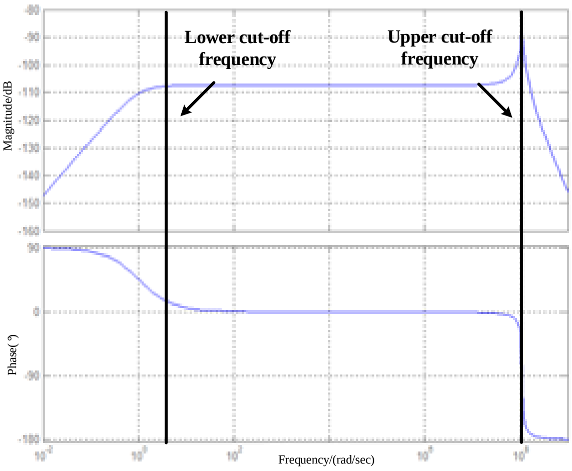


Figure 5. Spectrum characteristics of Rogowski coil.

VI. Conclusion

The transient characteristics of VFTC are analyzed, and the frequency band of the coil is determined. According to the working principle of Rogowski coil and the transient characteristics of VFTC, the symmetrical PCB Rogowski coil is adopted, and the structural and electrical parameters of PCB Rogowski coil are designed. Among them, the size of PCB plate and copper foil is the key structural design parameters, and the sampling resistance is the key electrical design parameters.

Designed and verified for the PCB type Rogowski coil for VFTC measurement, the upper limit cutoff frequency is 16MHz, which meets the measurement requirements. For 10kV power distribution line without mounting grounding line, the LTFR caused by induced stroke lightning is higher than that of direct stroke lightning.

Through detailed theoretical analysis, this paper demonstrates that the PCB Rogowski coil meets the measurement requirements of VFTC, and gives the values of the design parameters. The next step is to further study how to meet the installation requirements of the PCB Rogowski coil.

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