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Cascade Style Composite Insulation Dry Type Current Transformer for EHV Applications

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SUMMARY

A cascade style composite condenser insulation dry type current transformer up to 600 kV has been successfully developed. This type of construction is very suitable for EHV and UHV CTs. Since 2004 forty-eight (48) cascade style CTs rated between 220 and 330 kV have been installed and operating reliably on various power systems. The cascade design utilizes two lower voltage CTs connected in series and offers the following advantages over single unit CTs: a simpler insulation construction that significantly reduces the amount of insulation materials required; better heat dissipation; reduced lead times; increased production pass rates; less complicated shipping requirements and easier installation. And it retains the explosion and maintenance-free properties of the dry type design. This paper briefly introduces composite condenser dry type CTs and gives detailed descriptions about the principles, design and testing of the cascade style version for EHV applications. It also provides solutions for insulation design and error calculation, highlighting the measurement of VI excitation curve data and the attention that needs to be paid in its use. The 600 kV cascade style CT is used as an example in the paper. The paper considers this type of CT as a novel type worth promoting.

KEYWORDS

EHV Cascade style Composite insulation Dry type CT

1 Introduction

Composite insulation dry type CTs are a new type of CT whose inner insulation material is composed of PTFE film with a silicone gel capillary interface (used to fill micro gaps and expel air bubbles) and an outer insulation of HTV silicone rubber sheds. Compared with conventional CTs, they offer several advantages including compactness, lightweight, good anti-flashover capability, non-flammability as well as being explosion-proof and maintenance free.

Based on the composite insulation dry type CT, cascade versions were developed in 2004 with subsequent new models being added. The highest voltage level now has reached 600 kV. Figure 1 (a) shows the first cascade style composite insulation dry type CT developed for 200 kV. Figure 1 (b) shows a 220 kV high current (4000/5A) cascade style composite insulation dry type CT. Figures 1(c) and 1(d) show a 300 kV and a 600 kV cascade style composite insulation dry type CT respectively.


Figure 1(a)


Figure 1(b)


Figure 1(c)

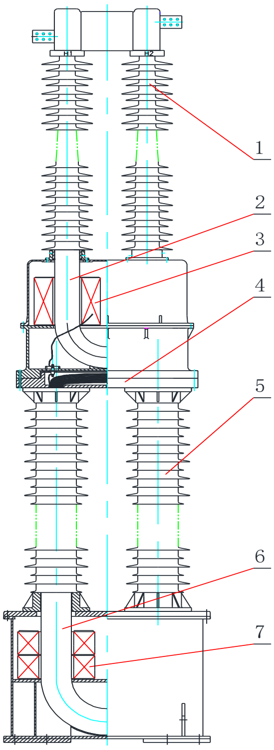

Figure 1(d)

A cascade style CT is composed of not less than 2 CTs with lower voltage levels. When compared to the single-stage versions, it offers the following advantages:

a. The lower-voltage CTs use thinner insulation structures which is easier to manufacture. The simpler manufacturing process allows for larger insulation margins to be achieved thereby increasing insulation reliability.
b. The cascade style CT utilizes less insulation materials, reducing insulation material costs and shortening lead time for core manufacture.
c. Thinner major insulation is good for heat dissipation of primary conductor.
d. These lower-voltage CTs can be packed and shipped separately, which simplifies shipping and installation.

2 Construction

The basic construction of a 2-stage cascade CT is shown in Figure 2 below.



1 —Upper CT;

2—Upper primary winding;

3—Upper secondary winding;

4—Duct board;

5—Lower CT;

6—Lower primary winding;

7—Lower secondary winding;

Figure 2 - Cascade CT construction

As can be seen in Figure 2, the cascade CT is composed of 2 separate CTs whose insulation levels are nearly the same. The primary winding of the upper CT is connected to the grid and is at high potential. The upper CT primary’s last layer, secondary winding, casing and duct board are connected with the primary of the lower CT which are at intermediate potential. The secondary winding and casing of the lower CT are at zero potential, i.e. earth potential. The secondary of the upper CT and the primary of the lower CT are in series connection, the secondary winding of the lower CT is connected to an external burden.

Another example of a cascade design is the high current cascade CT shown in Figure 1(b). This type of construction offers some great advantages. The upper CT is a low- insulation-level CT which is entirely equipotential with the grid voltage.The voltage is entirely withstood by the lower CT which has a short conductor, solving the problems of temperature rise and electro-dynamic forces in high current CTs. Its construction is shown in Figure 3.

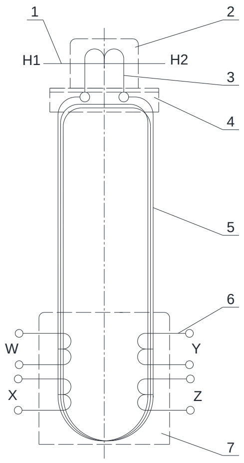


Figure 3 - High current cascade CT construction

Where:

1—the primary winding of upper CT;
2—the casing of upper CT;
3—the secondary winding of upper CT;
4—Duct board;
5—the primary winding of lower CT;
6—the secondary winding of lower CT;
7—the casing of lower CT;

3 Principle of the Cascade CT

For this discussion the double-decker cascade CT (see Figure 1 (a)) is considered.

3.1 Current Ratio

If the current ratio of the upper CT is K_1 ,and the current ratio of the lower CT is K_2 , the current ratio K of the entire cascade CT is: $K = K_1 \times K_2$.

For example, the current ratio of the upper CT is 2000/20A, and the current ratio of the lower CT is 20/5A, then the current ratio of the entire cascade CT is 2000/5A.

If the current error of the upper CT is f_1 , the phase error is δ_1 , the composite error is $\dot{\varepsilon}_1$; and the current error of the lower CT is f_2 , the phase error is δ_2 , the composite error is $\dot{\varepsilon}_2$, then the current error, phase error and composite error for the entire cascade CT will be defined by the following equations:

$$f = f_1 + f_2 \tag{1}$$

$$\delta = \delta_1 + \delta_2 \tag{2}$$

$$\dot{\varepsilon} = \dot{\varepsilon}_1 + \dot{\varepsilon}_2 \tag{3}$$

The equivalent circuit of the cascade CT is shown in Figure 4, with components converted to the lower CT secondary side.

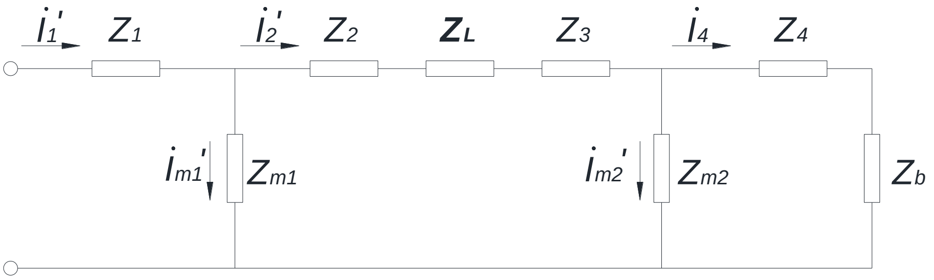


Figure 4 - Cascade CT equivalent circuit

Where:

i'_1 is the primary current of the upper CT,

i'_2 is the secondary current of the upper CT, also primary current of the lower CT,

i_4 is the secondary current of the lower CT,

i_{m1}' is the exciting current of the upper CT iron core,

i_{m2}' is the exciting current of the lower CT iron core,

Z_1 is the primary impedance of the upper CT,

Z_2 is the secondary impedance of the upper CT,

Z_L is the leakage reactance created by lower CT primary,

Z_3 is the primary impedance of the lower CT（This value excludes the winding part outside the iron core. The primary winding of the lower CT also functions as the burden of the secondary winding of the upper CT, so this part should not be ignored in the calculation. ***Note*** [1]）,

Z_4 is the secondary impedance of the lower CT,

Z_b is the burden impedance of the lower CT, i.e. the burden of the entire cascade CT,

Z_{m1} is the excitation impedance of the upper CT,

Z_{m2} is the excitation impedance of the lower CT.

(Note [1]: The primary winding of the lower CT usually uses multi-turn construction, and the wire exposed out of the iron core is long hence higher leakage reactance; therefore this part of leakage reactance Z_L ***and*** Z_3 ***is shown as 2 parts.）***

3.2 Voltage distribution

Both the upper and lower CTs of the cascade CT use capacitance-graded insulation whose equivalent capacitance distribution is shown in Figure 5.

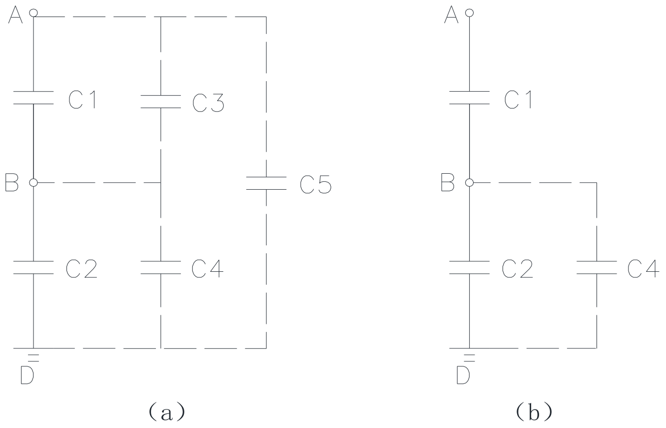


Figure 5 - Cascade CT capacitance distribution

Where:

C1 - Upper capacitance
C2 - Lower capacitance
C3 - Stray capacitance between the upper HV side and the intermediate potential
C4 - Stray capacitance between the intermediate potential and earth
C5 - Stray capacitance between the upper HV side and earth

In Figure 5(a), C5 is unrelated to the voltage distribution of the upper and lower CTs while it is known from actual measurement that C3 is so small that it is negligible. Therefore the capacitance distribution can be simplified as shown in Figure 5(b). The voltage division ratio of the upper and lower CT approximates (C2+C4):C1. In the capacitance-graded insulation designs, we must take C4 into consideration while trying to make C1 equal as close as possible (C2+ C4) so that the insulation levels of the upper and lower CTs are approximately the same.

4. Design

When designing a cascade CT two major areas have to be looked at; the material costs and insulation reliability.

4.1 Insulation Design

With the increase in voltage level the amount of insulation materials consumed is related to the square of the multiple of the voltage increase, i.e. $(U_2/U_1)^2$ and the higher the voltage the larger the insulation consumption. For example, the insulation material for a 220 kV CT is about 5 times that of a 110 kV CT while the insulation material for a 500 kV CT is about 8 times of that of a 220 kV CT.

When a cascade approach is used for composite insulation dry type CTs, the insulation material used is only what is required for the lower voltage design; e.g. a 220kV cascade CT is composed of two 110 kV CTs in series connection. Therefore the cascade design can greatly reduce the insulation material consumption. Since the insulation material used in the composite insulation dry type CT is an expensive PTFE film, the cascade CT design can greatly reduce insulation material costs.

The lower-voltage CTs use thinner insulation structures which are easier to manufacture. The simpler manufacturing process allows for larger insulation margins to be achieved thereby increasing insulation reliability. Each stage of a cascade CT has secondary windings, meaning more cost for the secondary windings and the secondary winding casings. When designing the insulation for cascade CTs, the designer has to take into account both the costs for the insulation materials and the secondary windings, and choose an appropriate number of stages to achieve the best performance at the lowest cost.

4.2 Electromagnetic Design

The electromagnetic design for current transformers is related to the design of the secondary windings whose costs usually depend on the iron core weights.

For example a cascade CT composed of 2 CTs has an equivalent circuit as shown in Figure 4. The upper CT primary current i_1', the lower CT secondary current i_4, and the lower CT burden (the entire cascade CT burden) Z_b are values specified by the user while the other parameters need to be determined by the design.

I_2' is both the upper CT secondary current and the primary current of the lower CT, and this is the parameter that needs to be determined first. On the condition that accuracy is guaranteed, design formulas tell us that the larger the number of ampere turns the smaller the iron core will be while the larger the burden the larger the iron core will be. So how does the designer select the upper and lower CTs? It is known that the higher the ratio of primary ampere turns and rated secondary current, the smaller the secondary iron core. Therefore, for the upper CT, the smaller the i_2' the better and for the lower CT, the larger the i_2' the better. Meanwhile, the more lower CT primary turns, the larger its number of primary ampere turns and the smaller the secondary iron core. However, when the lower CT primary turns increase, its impedance, i.e. Z_L+Z_3 in Figure 4 will increase, and that increases the secondary burden of the upper CT, causing a larger secondary iron core for the upper CT. Of course the larger the user's CT secondary burden Z_b, the larger the secondary iron core will be.

To sum up, the task of the electromagnetic design is to try to reduce the weight of the upper and lower CT iron cores while still meeting the accuracy requirements.

5. Tests

5.1 Insulation tests

The insulation tests for cascade CTs are the same as those for normal dry type CTs, and are conducted in accordance with the user requirements and international standards.

5.2 Cascade CT composite error test

Steady-state errors include the metering error and the protection error at rated current. In general a single-decker CT's composite error can be obtained by the indirect method of looking for corresponding current values on the CT secondary VI excitation curve based on the calculated values of the secondary limiting e.m.f. However for cascade CTs the indirect method of using the lower CT secondary VI excitation curve does not correctly determine the entire CT's composite error due to the higher leakage reactance Z_L produced by the lower primary. Also a direct method is difficult for both manufacturers and users, so the following method was adopted.

It can be seen from Formula (3) that a cascade CT error equals the vector sum of the upper and lower CT errors, $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$, and the maximum value of the cascade CT error can be deduced as:

$$\dot{\varepsilon}_{\max} \le |\dot{\varepsilon}_1| + |\dot{\varepsilon}_2| \qquad (4)$$

Therefore, for the cascade CT error design the accuracy class requirements will be met, as long as we make sure the sum of the absolute values of upper and lower errors is smaller than the error required by corresponding accuracy classes.

During routine testing, the VI excitation curves for the upper and lower CTs are plotted and with the indirect method the composite errors for the upper and lower CTs based on the secondary limiting e.m.f. are obtained. The maximum possible error is then calculated which should meet the accuracy requirements of the user or the standard. It must be noted that when calculating the secondary limiting e.m.f. of the upper CT and using it to get the upper composite error, the leakage reactance Z_L must be accounted for.

To sum up, every stage of a cascade CT is an independent CT and the current ratio and burden for each CT is different, so every CT needs to be measured for its VI excitation curve separately. The composite error for each CT stage must be obtained from the VI excitation curve data and the sum of these composite errors is the composite error for the entire cascade CT (which by formula (4) will be smaller than the sum of the absolute values of the composite errors of each CT stage).

5.3 600kV Cascade CT Tests

Using a 600 kV CT tender from a western Canadian utility as an example, a cascade design was developed based on the following specifications:

- Nominal System Voltage: 500kV;
- Nominal Operation Voltage Range:475 to 550 kV;
- Maximum Continuous Operation Voltage: 600kV;
- Rated Frequency: 60Hz;
- BIL: 600/860/1300/1800kV;
- Short-time Thermal Current: 63kA,1s;
- Dynamic Current:150kA;
- Number of Secondary Windings: 4;
- Ratio: 2000x4000 to 200x400-5-5-5-5A;
- Accuracy Class and Burden: 2.5L800 and 0.3B1.8 at 0.9 P.F.
- Continuous Thermal Current Rating Factor: 1.0.

Figure 1(d) is the 600 kV cascade CT in question（LRGBJ-ZH-600). Figure 7 shows its basic construction.

Table 1 is a comparison of the tendered 600 kV CT insulation level requirements and the insulation requirements specified by IEC 61869 for 220kV CTs. It can be seen from Table 1that a cascade 600 kV CT can be made with two 220 kV CTs. Due to the fact that the 220kV class composite insulation dry type CT is already a technically mature technology the cascade design will come with a very high degree of reliability.

Table 2 shows the turns and current for one of the secondary windings of this cascade CT.

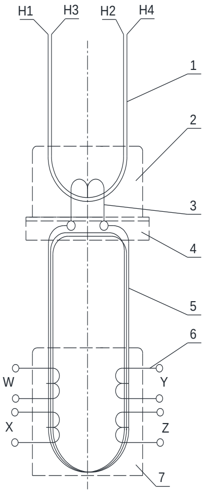


Figure 7 - Construction of LRGBJ-ZH-600

Where:

1 - Upper CT primary winding, 2 sections (H1H4 and H2H3) Turns N1: 2 turns for series connection and 1 turn for parallel connection
2 - Upper CT casing;
3 - Upper CT secondary winding; Quantity: 1 (turns N2: 250)
4 - Duct board;
5 - Lower CT primary winding (turns N3: 75);
6 - Lower CT secondary windings; Quantity: 4. W, X, Y, Z (turns N4: 48-120-144-240 for taps1-2-3-4-5. Using W as an example; W3-W4 is 24, W2-W3 is 72, W4-W5 is 96, W1-W3 is120, W1-W4 is 144, W2-W5 is192, W1-W5 is 240);
7 - Lower CT casing;

Table 1 - Insulation Level Comparison of 600 kV CT and 220 kV CT

Voltage class（kV）	1min, power frequency（kV）	Lightning impulse voltage withstand, full wave（kV）	Switching impulse voltage withstand（kV)
600	860	2070	1300
220	460	1050	750
Ratio	1.87	1.97	1.73

Table 2 - Relationship of upper and lower CT currents and turns (Winding W)

Upper primary current, A	2 x 200	2 x 600	2 x 800	2 x 1000	2 x 1200	2 x 1600	2 x 2000
Upper primary winding turns	2	2	2	2	2	2	2
Upper secondary current, A	1.6	4.8	6.4	8	9.6	12.8	16
Upper secondary winding turns	250	250	250	250	250	250	250
Lower primary current, A	1.6	4.8	6.4	8	9.6	12.8	16
Lower primary winding turns	75	75	75	75	75	75	75
Lower secondary ampere turns	120	360	480	600	720	960	1200
Lower secondary current, A	5	5	5	5	5	5	5
Lower secondary winding turns	24	72	96	120	144	192	240

Lower secondary tap sign	W3-W4	W2-W3	W4-W5	W1-W3	W1-W4	W2-W5	W1-W5
Lower secondary metering	0.6 B 0.1	0.3 B 0.5	0.3 B 0.9	0.3 B 0.9	0.3 B 0.9	0.3 B 1.8	0.3 B 1.8
Lower secondary protection	2.5 L 20	2.5 L 100	2.5 L 200	2.5 L 400	2.5 L 400	2.5 L 400	2.5 L 800

It can be seen from Table 2 that the upper CT is actually a 4000:16A CT and the lower CT has the current ratio of 1200/960/720/600/480/360/120:5 A. This should be kept in mind when designing and testing.

The 600 kV CT passed all insulation tests according to the requirements of the IEEE and CAN/CSA Standards and the specified tender conditions. Metering error tests and protection error tests at rated current (steady state) were conducted using the direct method, and each winding proved to be able to meet its corresponding accuracy error requirements at all ratios.

The composite error test was conducted with the indirect method to measure the upper and lower CTs separately, and the test results for Winding W are shown in Table 3. From Formula（4）it is known that the maximum value of the total error is the sum of the absolute values of the upper and lower errors and since the maximum values at each ratio are lower than 2.5% the technical requirements have been met.

Table 3 - Composite error test result（Indirect method）

The entire ratio	2*200/5	2*600/5	2*800/5	2*1000/5	2*1200/5	2*1600/5	2*2000/5
Secondary terminal	X3-X4	X2-X3	X4-X5	X1-X3	X1-X4	X2-X5	X1-X5
Lower ratio	1.6/5	4.8/5	6.4/5	8/5	9.6/5	12.8/5	16/5
Lower error ε, %	0.30	0.47	0.72	1.13	0.73	0.36	0.58
Upper							
Upper ratio	400/1.6	1200/4.8	2400/6.4	2000/8	2400/9.6	3200/12.8	4000/16
Upper error ε, %	0.014	0.4	0.48	0.55	0.65	0.83	1.13
The sum of the absolute values of upper and lower errors, %	0.314	0.87	1.2	1.68	1.18	1.19	1.71

As a check the X3-X4 tap (200/5) of Winding X was measured with the direct method, and the current was 3760A (18.8 times the rated current; did not reach 20 times the rated current) and the composite error was 0.13%. At the same 18.8 times the rated current the error obtained with the indirect method was 0.185%, so it can be seen that the entire CT error obtained from the direct method was smaller than with the indirect method.

6 Conclusion

This paper provided a detailed introduction of the cascade style composite insulation dry type CT in terms of construction, principle, design and tests, and gave an example of a 600 kV CT. Cascade CTs require significantly less insulation materials, improve the primary conductor heat dissipation and increase insulation reliability. A cascade CT is composed of several lower-voltage CTs in series connection but its testing and operation are the same as a normal single-decker CT. Although the design of a cascade CT is a bit complicated, the less complicated manufacturing process with the inherent cost savings, reduced lead time, higher insulation reliability and easier shipping and installation benefits make the cascade style composite insulation dry type CT worth promoting for EHV applications.

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