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Compensation method for improving capabilities of AC current test equipment

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ABSTRACT

Testing of electrical equipment with AC currents is a common test in both high power and high voltage laboratories. It implies driving currents, sometimes several tens of kilo-amperes high, through a test object loop conductor. Test transformers are normally used as current sources, but the limiting factor is usually their relatively low rated voltage. Voltage on the test transformer is determined by product of loop impedance and test current. Proposed compensation method deals with reduction of loop impedance which consequently reduces voltage on test transformer and improves test capabilities.

Experimental verification of the method was successfully carried out on two test objects: 110 kV cable and 600 kV transformer bushing.

1. Introduction

Power system equipment is exposed in service to various mechanical, electrical and thermal stresses. Testing of equipment is performed prior to commissioning according to requirements of relevant standards and technical specifications in order to ensure that the equipment will operate as designed and perform as an integral part of the system.

Certain tests, such as temperature rise test [1–3] or heating cycle test [4–6], imply driving current through loop conductor until thermal equilibrium is reached [7–9].

Nowadays test facilities use test transformers (TTs) to generate AC currents up to several tens of kilo-amperes. Fig. 1 shows typical equivalent test circuit for AC current testing which consists of test object loop, TT and power supply, usually a regulation transformer. N_1 and N_2 represent the number of turns of TT's low and high current windings while I_2 represents loop test current.

Loop conductor can be several tens of meters long and may have significant impedance. Voltage at low current side of the TT is equal to the product of loop impedance and test current referred to low current side. In practice rated voltage of TT is relatively low and usually is a limiting factor.

One way to reduce voltage on TT and consequently to improve test capabilities is to use more than one TT. If required voltage on a single TT is still higher than rated, then loop impedance must be reduced. Since loop impedance is an inductive load, adding capacitance in series would reduce impedance.

The principle of series compensation is commonly used to reduce the effective reactance of transmission lines and increase transmission capability [10–12]. Adding capacitor in series with the loop will reduce voltage on the TTs for a given test current I_2. However, the direct connection of capacitor in series with the loop is often not possible or not practical.

This paper gives an overall compensation approach and proposes a new method for series compensation on the high current side using compensating transformer (CT) with capacitor connected to its low current winding. Test loop itself forms the high current winding of CT. The main objective of proposed compensation is to reduce the total loop impedance and consequently reduce the voltage on TT. As a result, capabilities of the test equipment are enhanced.

2. Compensation of the test circuit

2.1. Compensation at low current side

Compensation at low current side of TT affects only the loading of the power supply. Fig. 2 shows the equivalent circuit of a

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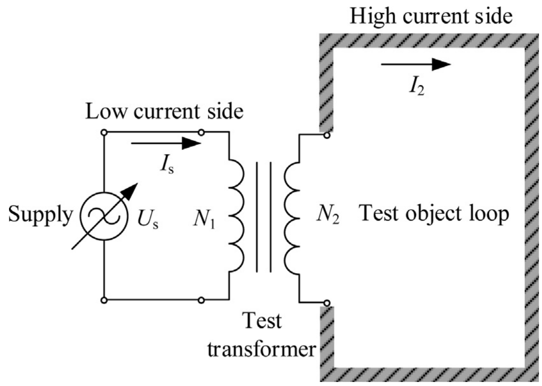

Fig. 1. Test circuit for AC current testing.

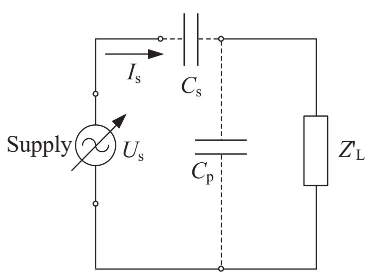

Fig. 2. Equivalent circuit of series and/or parallel compensation at the low current side.

series and/or parallel compensation at low current side. Z'_L represents the loop impedance referred to the low current side. If test conditions require voltages and currents higher than supply ratings then adding appropriate capacitor C_s in series with supply will reduce the supply voltage U_s, while connection of appropriate capacitor C_p in parallel with Z'_L will reduce I_s.

2.2. Application of multiple test transformers

In case when voltage higher than rated voltage of TT is required, multiple TTs can be used in order to reduce the voltage on a single unit. In this case high current windings are connected in series while low current windings can be connected in parallel or series. Fig. 3 shows the test setup for multiple TTs with low current windings connected in parallel, where N_T represents the number of TTs.

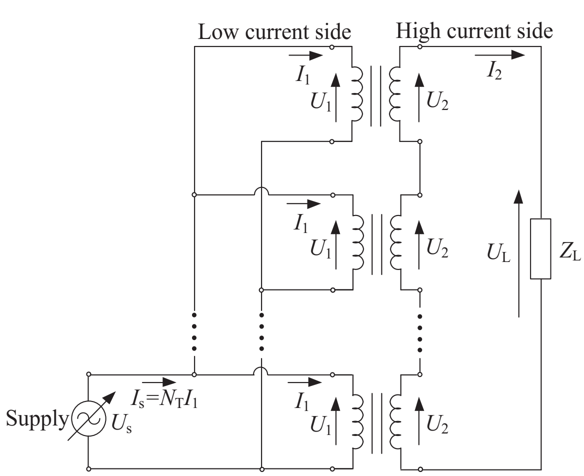

Fig. 3. Test setup – multiple TTs with low current windings connected in parallel.

The loop voltage U_L is equally distributed across the series connected high current windings. Therefore, voltage on low current winding U_1 is given by Eq. (1).

$$U_1 = \frac{U_L}{N_T} \cdot \frac{N_1}{N_2} \quad (1)$$

Test current I_2 flows through series connected high current windings and consequently currents I_1 are equal for all units. Connection of low current windings has no influence on voltage and current of a single TT, but it can affect the loading of supply. If low current windings of N_T transformers are connected in series, the supply voltage and current are determined from Eqs. (2) and (3).

$$U_s = U_L \cdot \frac{N_1}{N_2} \quad (2)$$

$$I_s = I_2 \cdot \frac{N_2}{N_1} \quad (3)$$

It can be seen that in this case N_T does not influence supply voltage and current. However, if the low current windings are connected in parallel, the supply voltage and current are determined from Eqs. (4) and (5).

$$U_s = \frac{U_L}{N_T} \cdot \frac{N_1}{N_2} \quad (4)$$

$$I_s = N_T \cdot I_2 \cdot \frac{N_2}{N_1} \quad (5)$$

In this case, N_T affects significantly both supply current and voltage.

To summarize, the series connection of low current windings is of interest when supply rated voltage U_{sr} is higher or equal to $N_T U_1$ and supply rated current I_{sr} is higher or equal to I_1. The parallel connection of low current windings can be applied when $U_{sr} \geq U_1$ and $I_{sr} \geq I_1 N_T$.

2.3. Compensation at high current side

As described in the previous section, when N_T TTs are used the voltage on a single unit is N_T times lower. But sometimes this is not enough and the voltage on the TT can still be limiting factor. Normally, the high current winding of TT is composed of test loop conductor (usually $N_2 = 1$) so it is sometimes possible to increase N_2 by pooling the loop several times through the TTs which results in decrease of U_1 and increase of I_1. This is often not feasible in practice, since it requires longer loop conductors which results in higher Z_L. Also, conductors are usually not flexible enough to be easily pulled more than once through the TTs.

Another possibility is to reduce the total loop impedance and consequently reduce voltage on the TTs for a given test current I_2. Test loop represents an inductive load which can be compensated by adding capacitor in series. However, the direct connection of capacitor in series with the loop is often not possible or not practical.

In general, loop impedance is unknown, but it can be estimated from voltage and current measurements (known as *U–I* measurement method) at low current side assuming that TTs are ideal transformers. Absolute value of loop impedance $|Z_L|$ can be expressed as:

$$|Z_L| = \frac{U_{s,rms}}{I_{s,rms}} \cdot \left(\frac{N_2}{N_1} \cdot N_T\right)^2. \quad (6)$$

In this paper, a new way of series compensation is proposed in which a loop inductance is compensated with window-type CT and capacitor C_c connected to its low current winding (Fig. 4). The test loop is pulled usually once ($N_{c1} = 1$) through the ferromagnetic core of CT and forms its high current winding. Low current winding of

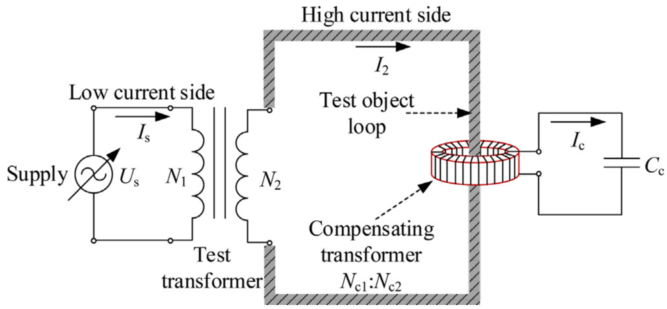

Fig. 4. Test setup with CT connected to high current side ($N_{c1} = 1$).

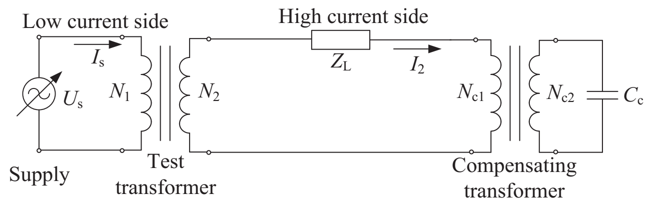

Fig. 5. Equivalent circuit of test setup with CT at high current side.

CT consists of a certain number of turns N_{c2} of insulated conductor with an appropriate cross section.

Equivalent circuit of test setup from Fig. 4 is shown in Fig. 5, assuming that TTs and CTs are ideal.

C_c is referred to the high current side with expression (7) and the equivalent circuit in Fig. 6 is obtained.

$$C'_c = C_c \cdot \left(\frac{N_{c2}}{N_{c1}}\right)^2 \tag{7}$$

Compensated loop impedance equals:

$$Z_{LC} = R_L + j\omega L_L - j\frac{N_{c1}^2}{\omega C_c N_{c2}^2}, \tag{8}$$

where R_L is resistance and L_L is inductance of the loop. The voltage at low current side of TT equals:

$$U_{1,\mathrm{rms}} = I_{2,\mathrm{rms}} \cdot |Z_{LC}| \cdot \frac{N_1}{N_2 N_T}. \tag{9}$$

Voltage U_1 should not exceed the rated voltage of TT's low current winding. Since the I_2 is a given value, from Eqs. (8) and (9) follows that the appropriate C_c can reduce U_1. Furthermore, U_1 depends on N_{c2} so it is preferred that CT is designed as regulation transformer, with the variable N_{c2}. N_{c1} is usually 1, although, if possible, the loop can be pulled several times and thus increase the N_{c1}. It is also possible to use multiple CTs. Their high current windings are connected in series since they are made from the loop itself. Depending on the CT ratings, low current windings can be connected in series or parallel, or multiple CTs can be used as separate units.

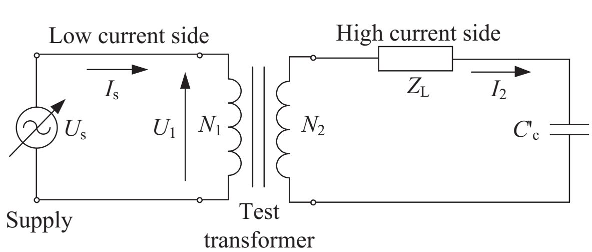

Fig. 6. Equivalent circuit of test setup with C_c referred to high current side.

3. Experimental verification

The experimental verification of the proposed compensation method was carried out on two test objects:

3.1 110 kV AC power cable.
3.2 600 kV HVDC transformer bushing.

Regulation transformer with rated voltage $U_{sr} = 500$ V and rated current $I_{sr} = 100$ A was used as a power supply. Four test transformers ($N_T = 4$) with rated currents $I_{1r}/I_{2r} = 100$ A/20 kA and rated voltage $U_{1r} = 1100$ V were available in laboratory. Test loop forms high current windings of TTs ($N_2 = 1$). Test current I_2 was measured with current transformer and ammeter.

3.1. 110 kV power cable

Developmental testing required AC test current $I_2 = 3$ kA in the loop of 25 m long 110 kV power cable. The cable ends were connected together, forming the closed loop. Fig. 7 shows the test setup for performing AC current test on 110 kV power cable.

At first, current lower than full test current was driven through the loop to determine its impedance Z_L with U–I method. Equivalent circuit of this initial test is shown in Fig. 8.

Digital wattmeter is connected to the low current side to measure supply voltage, current and power factor. From the results of initial test: $U_s = 286.8$ V, $I_s = 13.7$ A, $\cos\varphi = 0.155$, loop impedance $|Z_L| = 8.37$ mΩ is determined. From Eq. (9) with $I_2 = 3$ kA the required voltage at low current side of TT $U_1 = 1256.1$ V is calculated. U_1 is higher than U_{1r}, which implies that more than four TTs should be used. Minimum number of TTs is calculated from the expression (10).

$$N_{T\min} = \left\lceil \frac{U_1 \cdot N_T}{U_{1r}} \right\rceil \tag{10}$$

In this case $N_{T\min} = 5$ which is larger than number of available TTs, so the only way to further reduce the voltage on TT is by reducing the loop impedance. Let Z_{Lr} be the impedance for which voltage on the TT is equal to U_{1r}:

$$|Z_{Lr}| = \frac{U_{1r,\mathrm{rms}} N_T}{I_{2,\mathrm{rms}} N_1}. \tag{11}$$

In this case $|Z_{Lr}| = 7.3$ mΩ, therefore the capacitance C'_c should be added in series with Z_L.

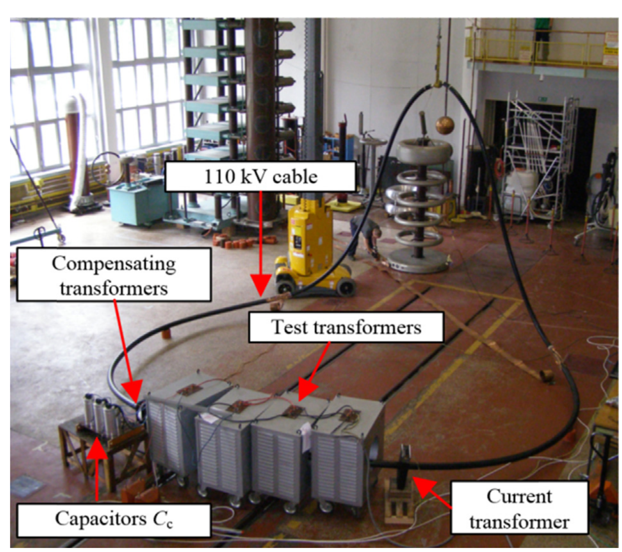

Fig. 7. Test setup for performing AC current test on 110 kV power cable.

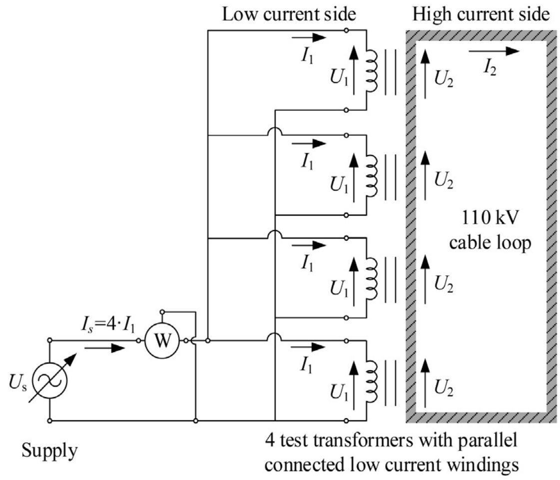

Fig. 8. Equivalent circuit of initial test to determine Z_L.

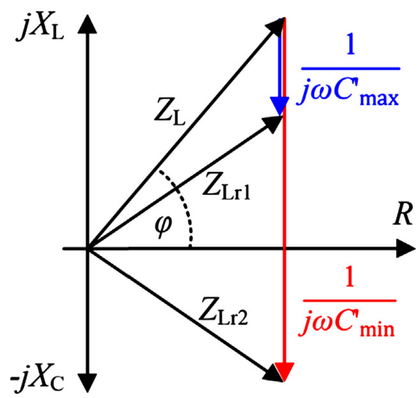

Fig. 9. Impedance diagram; Z_{Lr_1} corresponds to $C'_c = C'_{cmax}$ and Z_{Lr_2} corresponds to $C'_c = C'_{cmin}$; $|Z_{Lr_1}| = |Z_{Lr_2}|$.

Maximum and minimum capacitances for which $|Z_{LC}| = |Z_{Lr}|$ are determined by Eqs. (12) and (13).

$$C'_{cmax} = \frac{1}{\omega \cdot (|Z_L| \cdot \sin\varphi - \sqrt{|Z_{Lr}|^2 - (|Z_L| \cdot \cos\varphi)^2})} \tag{12}$$

$$C'_{cmin} = \frac{1}{\omega \cdot (|Z_L| \cdot \sin\varphi - \sqrt{|Z_{Lr}|^2 - (|Z_L| \cdot \cos\varphi)^2})} \tag{13}$$

Any capacitance C'_c higher than $C'_{cmin} = 205.5$ mF and lower than $C'_{cmax} = 3.02$ F is acceptable for compensation and will result with voltage on the TT lower than U_{1r}. This is shown in impedance diagram (Fig. 9).

Compensating loop impedance by connecting any of these quite large capacitances directly into a cable loop would be technically complicated and expensive solution. Application of CT with capacitor connected to its low current winding is a far more acceptable solution. Loop itself forms the high current winding of CT and capacitance C_c, given by expression (14), is connected to low current winding.

$$C_c = C'_c \left(\frac{N_{c1}}{N_{c2}}\right)^2 \tag{14}$$

C_c must be selected to ensure that CT and capacitor are not overloaded. Voltage on low current winding of CT U_{c2} is given with Eq. (15).

$$U_{c2} = \frac{I_2 N_{c1}}{\omega C_c N_{c2}} \tag{15}$$

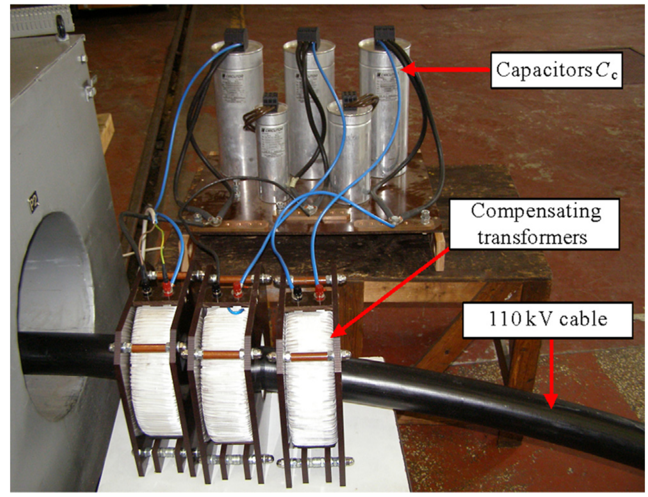

Fig. 10. CTs and capacitors C_c connected to low current windings.

Condition $U_{c2} \leq U_{c2r}$ must be fulfilled, where U_{c2r} is rated voltage of CT's low current winding. Sometimes more than one CT has to be used and then also the following condition has to be fulfilled in order to compensate voltage on TT:

$$C'_{cmin} \leq \frac{C_c}{N_{ct}} \left(\frac{N_{c2}}{N_{c1}}\right)^2 \leq C'_{cmin}, \tag{16}$$

where N_{ct} is the number of CTs. Three machine-wounded toroidal CTs ($N_{ct} = 3$) with $U_{c2r} = 200$ V, $N_{c2} = 127$, $N_{c1} = 1$, $I_{cr} = 45$ A and three capacitors $C_c = 386$ μF, 500 V were available in the laboratory. From Eq. (15) follows $U_{c2} = 195$ V so condition $U_{c2} \leq U_{c2r}$ is fulfilled. Since the condition (16) is also fulfilled, this arrangement was used to compensate loop impedance (Fig. 10).

From Eq. (8) the loop impedance after compensation is calculated and equals $|Z_{LC}| = 6.86$ mΩ. In order to check calculation result, measurement was made and the actual loop impedance was 7.15 mΩ which is 14.6% less compared to case without compensation at high current side.

At test current I_2, calculated voltage at low current side of TT is $U_1 = 1029$ V while measured voltage was $U_1 = 1080$ V, which is lower than U_{1r}. Since $U_1 > U_{sr}$ a series compensation $C_s = 173$ μF is applied to reduce supply voltage. Fig. 11 shows final test setup and measured power factor was $\cos\varphi = 0.917$.

The flow chart of the presented compensation method is shown in Fig. 12.

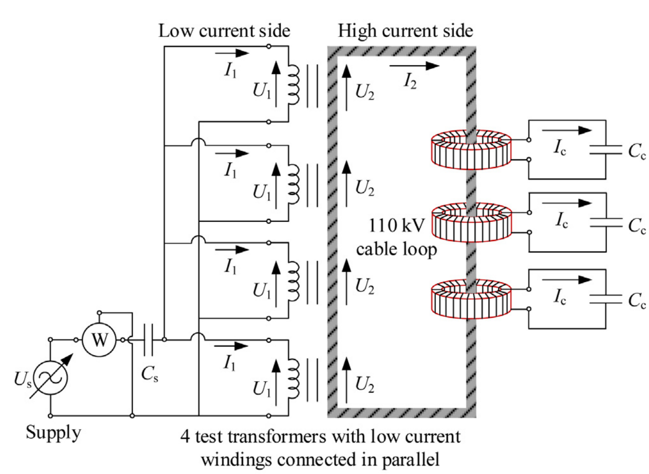

Fig. 11. Test circuit with compensation at the high current side and low current side.

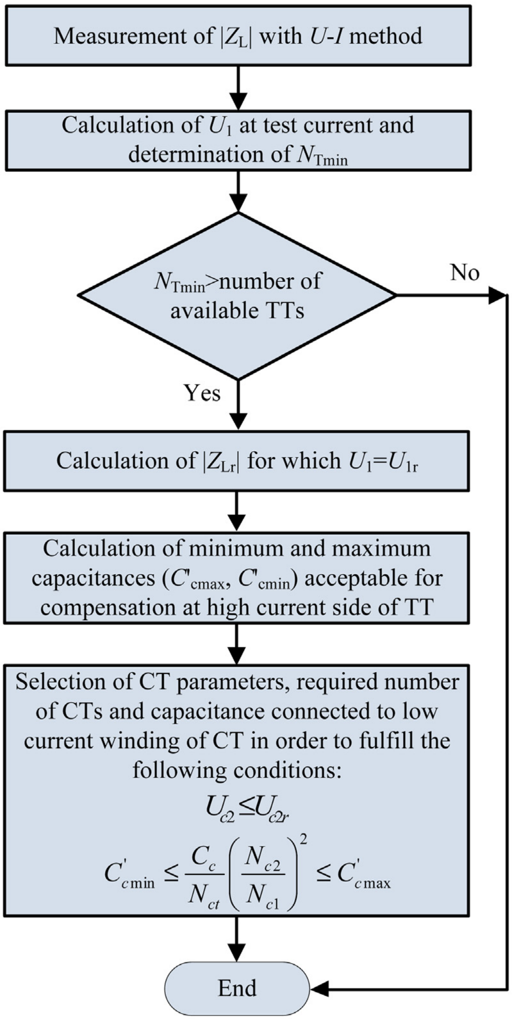

Fig. 12. Flow chart of the proposed compensation method.

3.2. 600 kV HVDC transformer bushing

Temperature rise test was carried out on 600 kV HVDC transformer bushing. The test requires current I_2 = 4 kA in the loop of transformer bushing. The test setup is shown in Fig. 13. During the

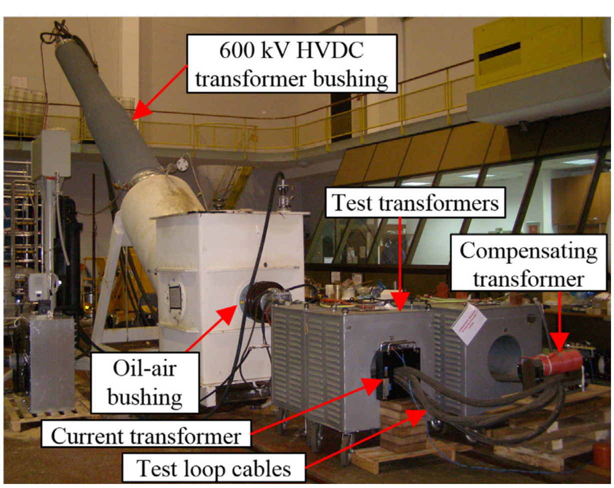

Fig. 13. Test setup for performing AC current test on 600 kV HVDC transformer bushing.

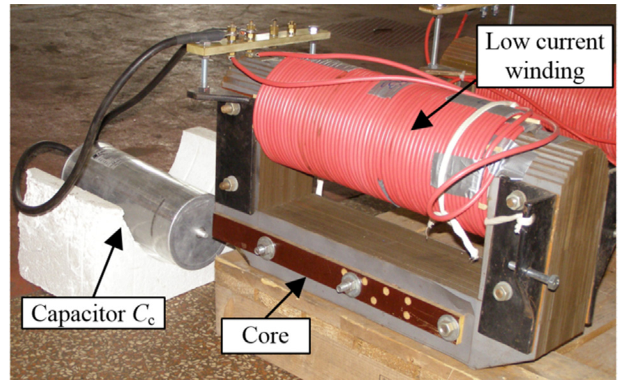

Fig. 14. CT and capacitor C_c connected to its low current winding.

test the bushing was mounted on an oil filled tank. The current loop was 31 m long and consisted of the test object conductor, water-cooled cables on air-side, tank between test object and additional oil-air bushing to provide passage of the loop through the test tank.

The same procedure is applied as in Section 3.1. The loop is pulled through the four TTs and forms their high current windings. Loop impedance $|Z_L|$ = 5.88 mΩ is determined from the results of the initial test: U_s = 201 V, I_s = 16.67 A, cos φ = 0.166.

From Eq. (9) with I_2 = 4 kA the voltage at low current side of TT U_1 = 1176 V is calculated. U_1 is higher than U_{1r}, which implies N_{Tmin} = 5 according to Eq. (10), but only four TTs are available. Therefore loop impedance has to be reduced. From Eqs. (11)–(13) follows that any capacitance C'_c higher than $C'_{cmin} = 283.9$ mF and lower than $C'_{cmax} = 8.2$ F is acceptable for compensation.

Since the windows of previously used CTs were too narrow for this test loop, hand-wound CT with construction that allows the loop to be pulled through it was manufactured with the following parameters: N_{c2} = 117, U_{c2r} = 400 V, N_{c1} = 1, I_{cr} = 45 A. Capacitor C_c = 294 μF, 500 V was available in the laboratory. From Eq. (15) follows U_{c2} = 370 V so condition $U_{c2} \leq U_{c2r}$ is fulfilled. Since the condition (16) is also fulfilled, this arrangement was used to compensate loop impedance (Fig. 14).

After compensation, loop impedance calculated according to Eq. (8) equals $|Z_{LC}|$ = 5.10 mΩ. In order to check calculation result, measurement was made and the actual loop impedance was 5.10 mΩ which is 13.3% less compared to case without compensation at high current side.

At test current I_2, calculated voltage at low current side of TT is U_1 = 1021 V while measured voltage was U_1 = 1068 V, which is lower than U_{1r}. Since $U_1 > U_{sr}$ a series compensation C_s = 252 μF is applied after which measured power factor was cos φ = 0.999.

4. Discussion

In both experiments, measured loop impedance after compensation slightly differs from the calculated one because it is assumed in the calculations that TTs and CTs are ideal. However, leakage inductance, nonlinearity and magnetization inductance of CT influence compensation effectiveness. If the equivalent circuit of a real transformer is considered, leakage inductance is connected in series with capacitor C_c. This increases the total loop impedance and thus reduces the effect of compensation. Magnetizing inductance, connected in parallel with capacitor, reduces the total loop impedance and thereby enhances the effect of compensation. Table 1 shows data on CTs used in the examples 3.1 and 3.2.

In the example shown in Section 3.1, measured loop impedance after compensation is 4% higher than the calculated one. This is caused by leakage inductances of three machine-wounded CTs

Table 1
CTs data.

CT type Core type	Hand-wounded Window-type	Machine-wounded Toroidal
Mean magnetic path length	1440 mm	688 mm
Core cross-section	66.5 cm^2	125 cm^2
Number of turns	117	127
Wire cross-section	10 mm^2	10 mm^2

which have greater impact on compensation than the magnetizing inductances.

In the example shown in Section 3.2, measured loop impedance after compensation is equal to the calculated one. Hand-wounded CT used in this example has larger leakage inductance compared to machine-wounded toroidal transformer and lower magnetizing inductance due to the longer magnetic path of the core with weaker magnetic properties. Since the calculation and measurement show excellent agreement one can conclude that CT is almost ideal which is not true since the effects of leakage and magnetizing inductance on compensation cancel out.

Finally, from the conducted analysis it is obvious that effects of both leakage and magnetizing inductances of TTs and CTs can be neglected in the calculations since very good matching between measurements and calculations was demonstrated. This simplifies and speeds up the compensation method since no additional measurements are needed. However, if a more detailed analysis is required, these effects can be included in the calculation provided that both leakage and magnetizing inductances of TTs and CTs are known.

If the test requirements overcome the capabilities of TTs there are several possibilities listed below:

- Application of additional TTs which are often custom made and fairly expensive, with long delivery period.
- Adding capacitor directly in series with the loop, which is technically complicated and expensive solution because the minimum required capacitance in the analyzed cases was 205.5 mF while commercially available AC capacitors have capacitances less than 2 mF. This means that hundreds of these units connected in parallel should be used for direct compensation.
- Pooling the loop several times through the TTs which results in decrease of U_1 and increase of I_1. This is often not feasible in practice, since it requires longer loop conductors which results in higher Z_L. The major disadvantage is that conductors are usually not flexible enough to be easily pulled more than once through the TTs and a size of TT window is a limiting factor.
- Application of CT with capacitor connected to its low current winding, which is a simple and very acceptable solution, less expensive than additional TT or direct loop compensation. The compensation set can be assembled in total or partially with items that are usually on disposal of test facilities.

5. Conclusion

A new compensation method for improving capabilities of AC current testing equipment has been presented. The method is based on the application of series compensation at high current side using compensating transformer with capacitor connected to its low current winding. The main objective is to reduce the total test loop impedance and consequently reduce the voltage on test transformer.

The advantage of the presented compensation method is its easy and fast implementation in practice during different AC current tests such as temperature rise test or heating cycle test. Direct series compensation by connecting the capacitor in series with the test loop is often not possible or not practical. Also, the number of test transformers is often limited in laboratory. By using the compensating transformer which can be easily manufactured if not available, with capacitor connected on its low current winding, very good compensation results are obtained. This reduces both the total loop impedance and the voltage on test transformer, which consequently enables to achieve high test currents while keeping the voltage on test transformer under its rated value.

Experimental verification of the proposed method was successfully carried out on two test objects: 110 kV AC cable and 600 kV HVDC transformer bushing. Proposed compensation reduces loop impedance (14.6% in case of cable and 13.3% in case of bushing) and consequently reduces the voltage on test transformer. The comparison between the measured and calculated loop impedance after application of compensation show good agreement.

The presented calculation and measurement results confirm validity and effectiveness of the proposed compensation method and its simple applicability during AC current tests.

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