The combined transformer - an optimal solution for HV substations

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The basic characteristics of a new concept of combined transformers consisting of an inverse current transformer and a voltage transformer with open core are described. Thanks to its technological design and simplicity, the new concept allows the commercial manufacture of combined transformers for the highest equipment voltages up to 420 kV inclusive. The main advantages of combined transformer installation in power-system are described and explained.

The combined transformer is defined as a transformer consisting of a current transformer and a voltage transformer in the same enclosure. Because of many advantages, this technical solution is very popular in many countries. Reports say that in the most developed industrial countries, the population share of combined transformers in the total number of instrument transformers at the voltage levels 123 kV and 245 kV amounts to approximately 50%. According to these reports, no combined transformers with oil-paper insulation are installed at voltages higher than 300 kV.

There are in principle two main combined transformer designs, which have been used in service up to now. The first one, oil-paper insulated, consists of an inverse current transformer placed in the head of the combined transformer, and an inductive voltage transformer with a closed core, placed at the bottom of the transformer in a separate metal enclosure. The main insulation of these transformers forms two separate capacitive bushings which are placed in the same insulator. This is considered to be a fundamental drawback of the solution, because the voltage is distributed along the height of the individual bushings is of opposite polarity, and points of equal potential are distributed in space.

The second design of combined transformer has SF6 gas as its main insulation. The most frequent solution using this technology is with the current transformer and the voltage transformer installed in the combined transformer head, where the voltage transformer with closed core can be above or below the inverse current transformer. At lower voltages this solution maintains the advantages and drawbacks of separate designs of SF6-gas insulated current and voltage transformers. At higher rated voltages the solution become voluminous because of the increase of the transformer head dimensions. For this reason, the ability of the transformer to resistance mechanical forces in operation is reduced, and its stability is reduced because of its high centre of gravity.

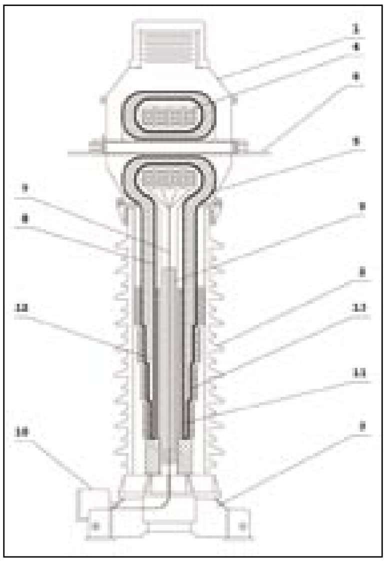

Fig. 1: Longitudinal cross-section of combined transformer.

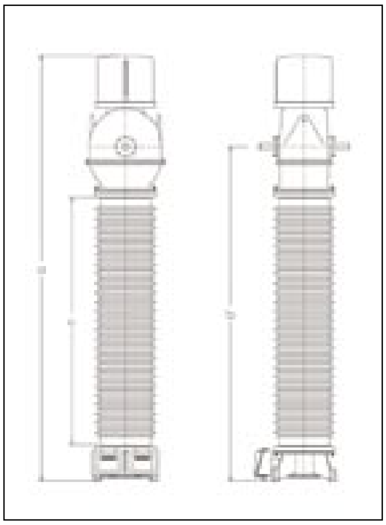

Fig. 2: Sketch drawing of combined transformer VAU type.

Description of the new solution

A few years ago a new type of combined transformers was developed bt the Konca Group. The concept of the new solution is based primarily on the many years of positive experience in the production and operation of voltage transformers with open magnetic core and inverse current transformers. The combined transformer according to the new solution is shown in Fig. 1 and consists of the head (1), a pin-type insulator (2), and casing (3).

As for the inverse current transformer, the cores and the secondary windings (4) of the current transformers are placed in the head, and insulated from the head potential by means of paper-oil insulation (5). Joined to this insulation, as an inseparable whole, there is the insulation (12) of a supporting mechanical tube (8) through which the secondary terminals of the current transformer (7) pass. The primary winding (6) of the current transformer is shown in this design as a bar-type winding. In practice there are other versions with a more turns and multiple reconnection on the primary side. Basically, the usual concept of inverse current transformer has been used for the combined transformer in such a way that the open magnetic core (9) and the voltage transformer secondary winding (11) are placed inside a hollow tube (8). The voltage transformer primary winding (13) is distributed on the main insulation (12) periphery in the transformer vertical axis. Depending on the rated voltage, it can be divided into several and up to several dozens of sections.

The new concept, in relation to other known solutions, is characterised by a number of advantages as follows:

- Combined transformers of this design, take relatively small space. This is

Fig. 3: Combined instrument transformer VAU-420 undergoing lighting impulse test of 1300 kV.

achieved by placing the voltage transformer with open magnetic core and secondary windings inside the supporting tube, which carries the active part of the current transformer.

- The voltage transformer primary winding which is distributed along the pin-type insulator height, optimises the potential distribution along the transformer height and also contributes to space saving.
- By placing the voltage transformer core and windings inside the pin-type insulator, a uniform distribution of weight inside the transformer is obtained which contributes to the improvement of its mechanical stability.
- The technology of manufacture and assembly of combined transformer of this concept is similar to the manufacture and assembly of inverse type current transformers which allows relatively simple production for higher voltages, e.g. for U_m = 420 kV.
- Due to open core of the voltage transformer, this design is ferro-resonance free.
- Inductive voltage transformers as a part of a combined transformer have relatively large primary winding cross sections, so the transformer is very capable in discharging of transmission lines.

Main characteristics of the new combined transformers

The new design combined transformer has been produced up to the highest voltages from 72,5 kV to 420 kV. They are manufactured in many variants depending on number of current transformer cores,

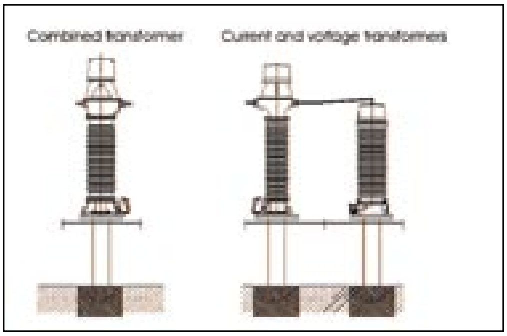

Fig. 4: Advantages of combined transformers.

rated primary and secondary currents, number of secondary windings of voltage transformers, rated primary and secondary voltage, rated voltage factor and its duration, rated burdens and accuracy class requirements. The main dimensions and a drawing are given in Table 1 and Fig. 2.

Generally, it can be said that current part of combined transformers can have up to six cores. The maximum value of the rated primary current relatively is high. For current transformers with where the primaries ane nor re-connectable, the maximum rated primary current is 6000 A. For current transformers with re-connectable primaries, the maximum values of the rated transformer primary currents are 2 x 2000 A, or 4 x 1000 A. The voltage part of combined transformer can have up to four secondary windings.

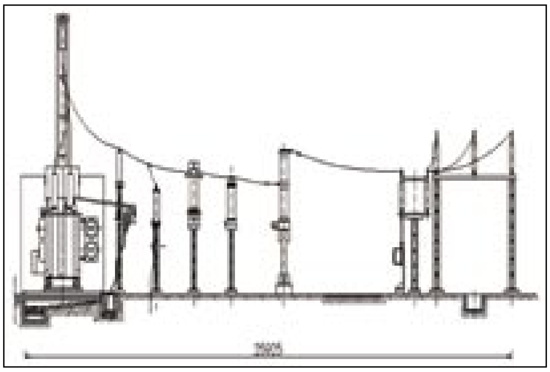

Fig. 5: Cross-section of 123 kV switchyard with seperate current and voltage transformers.

Combined transformers in substations

The main advantages of the installation of combined instead of seperate current and voltage transformers in substations can be described and derived from Fig. 4.

From Fig. 4, it is quite clear that organisations that use combined transformers in service instead of separate current and voltage transformer units, derive the following benefits:

- in principle pay lower prices for transformer(s)
- have less transportation costs
- need less clamping materials
- have less components in a substation (less service and mechanical defects)
- require less space for installation
- need fewer pylons
- need less foundations

Fig. 5 and Fig. 6 gives cross sections of typical 123 kV switchyards, and show that the total required space for the complete switchyard is significantly reduced by about about 7,7 %, when combined transformer type VAU-123 is used instead of separate current and voltage transformers.

Ferro-resonance phenomena

The ferro-resonance phenomena can occurr through switching operations in a network, where the non-linear reactance of inductive voltage transformers and the capacitance of the network form a resonant circuit. The result of a ferro-resonance is stable oscillation, which may damage transformers by over-heating and/or over-voltage stresses. Typical network configurations, which may lead to ferro-resonance, are as follows:

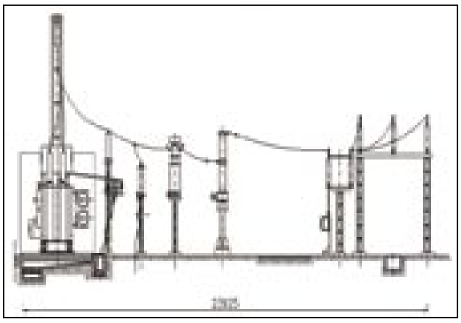

Fig. 6: Cross section of 123 kV switchyard with combined transformers.

- Single-phase ferro-resonance in a configuration where an inductive voltage transformer is connected to a high voltage line, which is de-energised but running alongside another, energised line.
- Single phase ferro-resonance between a inductive voltage transformer and HV/MV capacitance of a supply transformer.
- Single phase ferro-resonance between

Type: VAU-	a [mm]	b [mm]	c [mm]
72,5	2415 ± 20	1630 ± 20	1000
123	2615 ± 20	1830 ± 20	1200
170	3045 ± 20	2265 ± 20	1640
245	3750 ± 20	2950 ± 20	2160
362	4580 ± 20	3750 ± 20	2960
420	5680 ± 20	4630 ± 20	3540

Table 1: Main dimensions of combined transformer VAU type.

a inductive voltage transformer and the grading capacitance of an open circuit breaker

- Three phase ferro-resonance with an inductive voltage transformer connected to a system with isolated neutral and very low zero sequence capacitance.

In practice it is not always possible to avoid the configurations sensitive to the ferro-resonance. Since ferro-resonance occurs only in unfavourable combinations of capacitance and the non-linear reactance of inductive voltage transformers, it is however important to recognise these configurations.

For a better understudying of the ferro-resonance phenomena, Fig. 7 provides a graphical solution for the serial connection of a capacitor and non-linear inductor. In Fig. 7, voltages across the non-linear inductor (U_L) and capacitor (U_C) are given versus their currents. Theoretically, the supply voltage of the serial combination for a stable condition is given by curve (U_L - U_C). U_1 is the voltage under normal service conditions accross the non-linear resistor, and I_1 is the current flowing through the capacitor flows current. If we assume that the supply voltage suddenly reaches a value of U_2 and exceeds it a little, then the supply current moves from a value of I_2 to a much higher value I_3. If we then reduce the supply voltage to the normal value U_1, a current I_4 much higher then I_1 will now flow in the circuit. At the same time, the voltages across the inductor and capacitor are much higher then in normal conditions. This condition can last for a long time, and may cause voltage stressing(over-voltages) and overheating(over-currents) of the non-linear inductor and capacitor.

Why is the new combined transformer design free of ferro-resonance?

The voltage part of the new combined transformer consists of an inductive voltage transformer with an open core, and the magnetic flux path is closed through neighbouring air. Due to this fact, the magnetising current is relatively high, and the magnetising characteristics of such a transformer (U - I diagram) more defined in respect of the current axis then in the case of transformers with closed core (Fig. 8). For the most unfavourable values of capacitance which in practice can result in ferro-resonance (capacitance of substation busbars, capacitance of current and power transformers, capacitance of circuit breaker grading capacitors, etc.), the intersection between magnetising characteristics of combined transformer type VAU and the capacitor line is

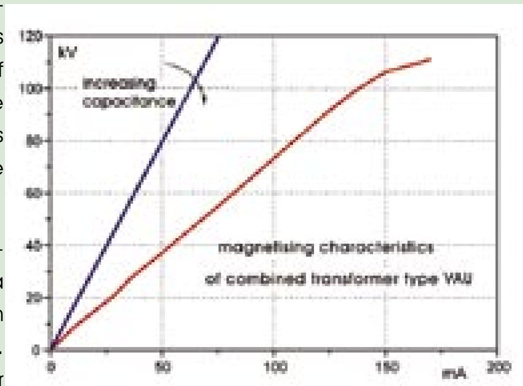

Fig. 8: Magnetising characteristics of combined transformer VAU-123 and typical capacitance U-I diagram.

impossible (see Fig. 8). Even if intersection becomes possible for particular network combinations, the above-mentioned low value of rated induction ensures that the exciting voltage for ferro-resonance is very low, and the possibility of ferro-resonance is therefore very remote. In addition, a special compensating winding built into the transformer provides a very effective damping burden to suppress transient phenomena.

As a manufacturer of inductive voltage transformer with open core for more of 40 years, we have never encountered a problem of ferro-resonance with this type of transformer.

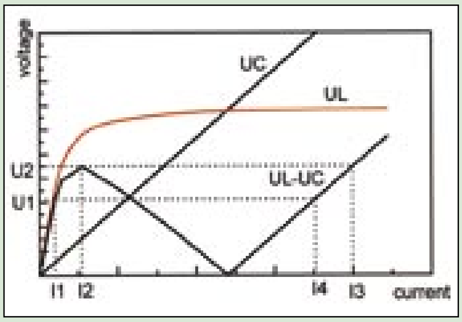

Fig. 7: Graphical solution of ferro-resonance phenomena.

Conclusion

Generally, combined transformers are popular electrical devices in many developed countries. The main advantages are described in above. If combined transformers are used instead of seperate current and voltage transformers, it can be shown that savings in substations amounting to about 7,7 % for 123 kV and about 4% for 420 kV can be achieved.

Compared to other designs of combined transformers, the new combined transformer type VAU described has several additional advantages. The most important of these are: optimal potential distribution and voltage stresses along insulator height; very good mechanical stability; ability to be manufactured very simply, even for very high voltages e.g. 420 kV; excellent ferro-resonance characteristics; and the ability to discharge transmission lines.

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