INRUSH CURRENTS OF THREE-WINDING TRANSFORMERS

Minna Laasonen, Ritva Hirvonen

IVO Transmission Services Ltd

P.O. Box 629, 00101 Helsinki
Finland

1. Introduction

Most of the 400/120/21 kV power transformers of IVO Transmission Services Ltd (abbreviation IVS) are three winding full transformers. Aim of this work is to find the way how transformers of IVS should be modelled in transient studies. Three different transformer models (BCTRAN, TRELEG, Saturable Transformer Model) of the Electromagnetic Transients Program EMTP are used to compare the simulations with the measurements and in that way to evaluate the transformer models.

Inrush current measurements for two transformers are used to validate simulations. In the first case 400/120/21 kV Koria transformer is energised from the 400 kV side. In the second case Huutokoski transformer 2 is energised from the 400 kV side while Huutokoski transformer 1, which is connected in parallel with transformer 2, is feeding 150 MW load.

The simulations have been done mainly with the EPRI EMTP version 2.1.

2. Finnish three winding transformers

The main transformers of 400 kV Finnish grid supplying either the 110 kV or 220 kV network are three winding transformers. In the 400 kV station there operates usually two three winding transformers in parallel to maintain the power supply also during maintenance work. Oldest of these transformers are built from three one phase units and all the new ones built after 1960 - 1970's are mainly three phase units.

The wide use of three winding transformers in the Finnish grid originates from the idea of using the tertiary winding of the transformer to connect the reactors consuming the capacitive power produced by lightly loaded 400 kV network. This principle is beneficial for planning and operation of the system if certain aspects are taken into account during transformer construction work.

The nominal voltages of the transformers are 400 ± 6 x 1.33 % / 120 / 21 kV. The phasor group is YNyn0d11. The rating of primary winding (400 kV) and secondary winding (120 kV) is 400 MVA. The rating of tertiary winding is 125 MVA. The short circuit reactances of the transformer are presented in Figure 1 a. The core of the transformer is shell type and the order of the windings is as follows: the 120 kV winding is closest to the core, the 400 kV winding is in the middle and the 21 kV winding is outermost. This arrangement gives some advantages compared to the alternative solutions:

- The three winding transformer operates as two two-winding transformers connected to the 400 kV network as seen in Figure 1 b

-No voltage drop in secondary winding (120 kV) when reactors are switched on and off, the unnecessary tap changer (OLTC) operations are thus avoided

-The regulation range of OLTC can be smaller implying decreased nominal current of 400 kV winding

-Losses in 400 kV winding are smaller because of shorter length of conductors

-Tertiary winding of 125 MVA can better sustain stresses caused by short circuits due to increased leakage reactance

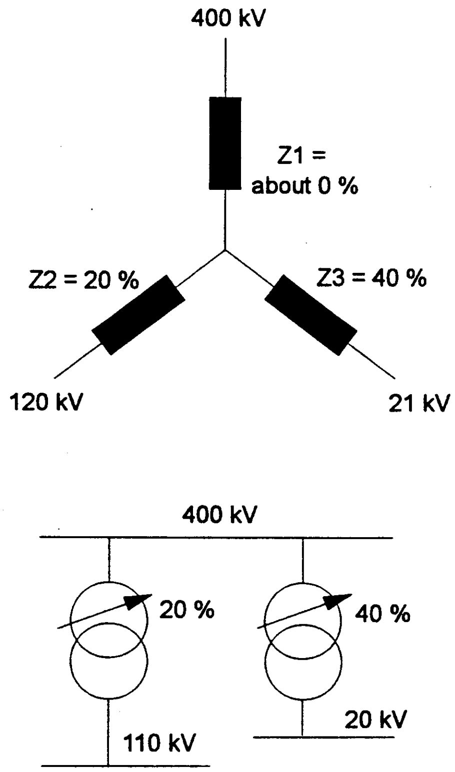


Figure 1. a) The equivalent schema and the reactances of three winding transformers of IVS where Z13 = 40 %, Z12 = 20 % and Z23 = 60 %, b) Operation principle of three winding transformer when 400 kV winding is in the middle.

3. Modelling of transformers in the simulations

Three different transformer models called BCTRAN, TRELEG, Saturable Transformer Model (STM) are tested in the simulations. To build these models information from the standard no-load and short circuit tests of the transformer is needed [1].

The non-linear behaviour of the transformer is modelled with either of the two pseudo-non-linear inductive elements (type 96 or type 98). The saturation curve is calculated from the voltage and current measurements of the no-load test with the auxiliary program CONVERT [1]. The saturation curves for different phases are approximated to be same for each phase although the no-load tests for each phase are available.

The modelling of the saturation determines how close the simulations are to the measurements. The no-load test has usually been performed up to 1.15 per unit voltage. This value is far too small for modelling a complete saturation curve of a transformer. Thus the inrush currents simulated with the saturation curve obtained from the no-load test are too small.

To find the inrush currents close to the measured ones a simple method is attempted to complete the saturation curve. The inductance of the fully saturated transformer iron core is approximated with equation [2]

$$L_{air} = \mu_0 \cdot N^2 \cdot \frac{A_W}{l_W}$$

where μ_0 is the permeability of air

N is the number of the winding turns

A_W is the cross-sectional area of the winding

l_W is the length of the winding

The hysteresis curve for non-linear element of type 96 is calculated with the auxiliary program HYSDAT of EMTP [1]. The current flux pair needed to form the hysteresis curve is taken from the saturation curve built by auxiliary program CONVERT.

The residual flux is modelled inside the 96-type elements. If the 98-type elements are used to describe the saturation the residual flux is represented with dc current sources in parallel with the non-linear elements. These current sources are disconnected at the same instant when the transformer is energised.

The eddy current and hysteresis losses are represented with resistances that are situated in parallel with the non-linear elements. These resistances are calculated from the no-load test losses [3].

The non-linear elements together with the resistances representing eddy current and hysteresis losses are connected to the secondary side of the transformer. The reason for this is that the secondary winding is closest to the iron core and the leakage flux is there smallest [3].

The 400 kV transmission lines from the transformer substation to the neighbouring substations are modelled as distributed lines. The rest of the network is modelled with equivalents consisting of positive and zero sequence impedances and equivalent voltage sources. These network equivalents are placed to the neighbouring substations. The calculation of the equivalents is done with a Power System Simulator / Engineering program (PSS/E) using the complete network model of the Finnish grid.

4. Energisations

Two typical 400/120/21 kV transformers were used in simulations. They were located in Koria and Huutokoski 400 kV stations.

4.1 Koria case

In the first case Koria transformer 2 is energised from the 400 kV busbar as seen in Figure 2.

The energisations of Koria transformer 2 are performed in two situations: 400 kV neutral point is either grounded solidly or through 120 Ω reactor. The 120 kV neutral point is isolated from the earth. The 400 kV lines from the Koria substation to the Loviisa and Yllikkälä substations are modelled as distributed lines. The rest of the network is modelled with equivalents in Loviisa and Yllikkälä substations.

The measurements of the Koria transformer 2 energisations contained peak values of primary currents, sum current value of the phase currents and neutral point current value. The angles of the primary voltage at the instants of energisations are also given but the residual fluxes of the iron core are not known.

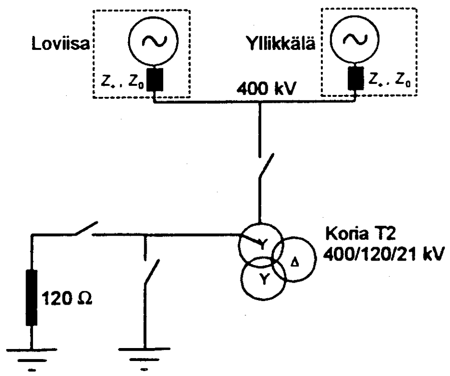


Figure 2. Modelling of energisations of Koria transformer 2 in the simulations

The simulations made with the three transformer models showed that the transformer model has very small influence on the results. The magnitude and curve shape simulated with BCTRAN and TRELEG models are almost the same. The magnitude of inrush currents simulated with STM are little smaller than with BCTRAN and TRELEG because the non-linear elements are connected to the star point inside the model while in the BCTRAN and TRELEG the non-linear elements are connected to a terminal. The 120 kV winding resistance causes voltage drop so the voltage in the star point is smaller than in terminal and this decreases inrush current. The inrush currents simulated with BCTRAN and TRELEG contain more harmonics than the inrush currents simulated with STM. The Figure 3 shows inrush currents simulated with these three transformer models.

In the BCTRAN model there exists no neutral point current in transformer if the non-linear elements are not connected to the side where the transformer is energised. TRELEG and STM models produce always neutral point current.

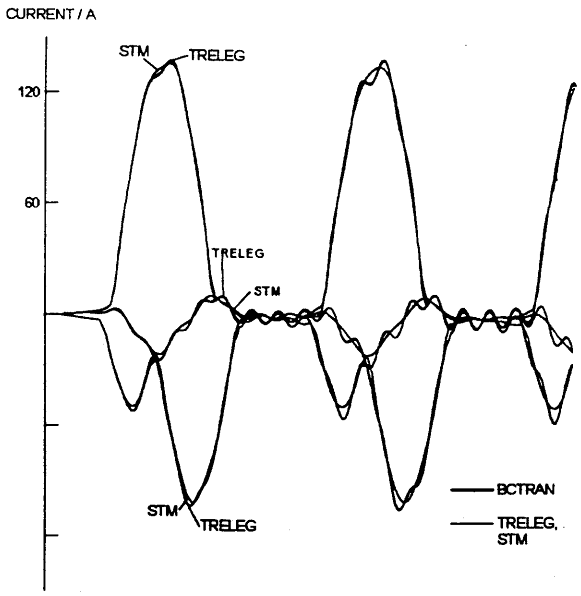


Figure 3. Inrush currents simulated with different transformer models

The inductance L_{air} for Koria transformer 2 is 25 mH. When the saturation curve is completed with this inductance value in the simulations the highest possible inrush currents can be obtained. Most of the simulated inrush currents are near the measured if a multiplied value of the calculated inductance is used. If the calculated value of L_{air} is multiplied with 3.33 the inrush currents where there probably exists no residual flux in the iron core can be simulated. On the other hand, the multiplication $1.2*L_{air}$ is used to simulate the highest measured inrush currents. In 20 different cases of Koria transformer 2 energisation simulations the average multiplied inductance value is $2.3*L_{air}$.

If the no-load current is included to the transformer model it should be excluded from the current values of the non-linear elements [3]. However, in the inrush current simulations this extraction is not necessary because the effect of the no-load current is very small compared to the inrush currents. The differences between the inrush currents simulated with and without the no-load current are below 6 % in the test cases.

4.2 Huutokoski case

The network connection during the Huutokoski transformer 2 energisations can be seen in Figure 4. Huutokoski transformer 1 is connected parallel with the Huutokoski transformer 2 and it is feeding 150 MW load. 400 kV neutral points of Huutokoski transformers are grounded through a joint 120 Ω reactor (commonly used method to ground parallel 400 kV transformers in the Finnish network). 400 kV lines from Huutokoski to Alajärvi, Alapitkä and Yllikkälä substations are modelled as distributed lines. The equivalents that represent the rest of the network are connected to these substations.

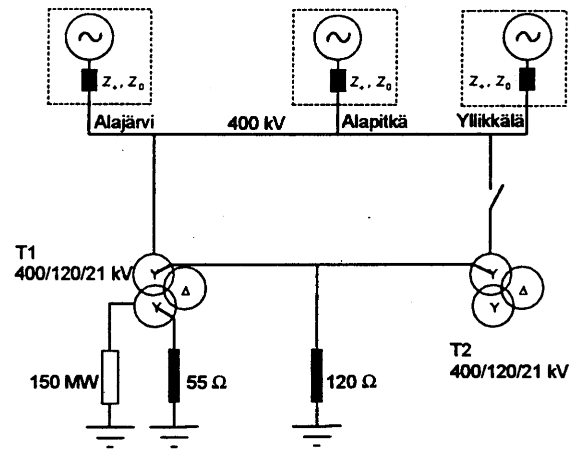


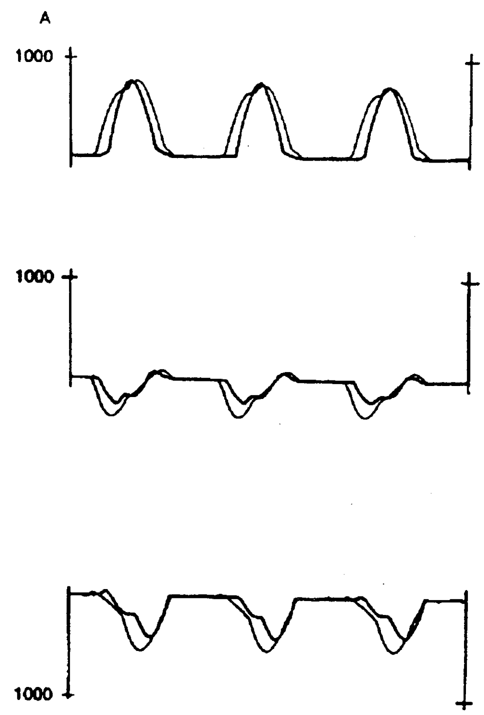
Figure 4. Energisation of the Huutokoski transformer 2

The measurements consist of phase currents, sum current and neutral point current curves. The instants of the energisations are unknown. For the simulations the switching times are estimated from the 20 energisation simulations where the circuit breakers in all three phases close at same time. These simulations are performed for one period (20 ms) of feeding voltage.

The magnitudes of the inrush currents are matched in the same way as in the case of Koria transformer energisation in section 4.1.

Curves of the measured phase currents are also available and they can be compared to simulated phase current curves. The simulated and measured currents seem to have similar curve shapes, although the simulated current curves are wider than the measured ones. Figure 5 shows two energisation cases, test A and B.

TEST A



TEST B

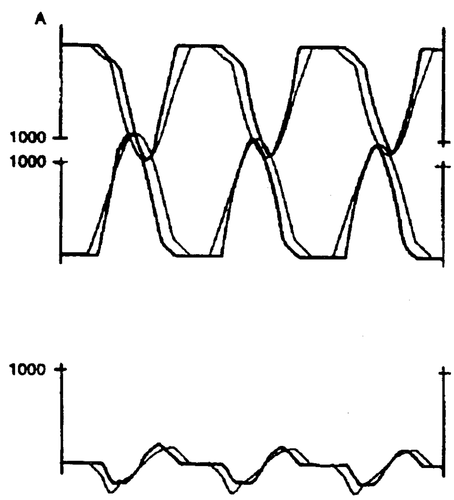


Figure 5. Huutokoski transformer inrush currents in tests A and B. The measured phase currents are drawn with thick lines and simulated phase currents with thin lines.

The damping of inrush currents depends on the resistive power losses of the network. One test case is simulated to compare the damping of the phase currents to the measurement. The network is modelled as in Figure 4. Figure 6 shows that the simulated phase currents decrease to the half values in the same time as in the measurement.

Figure 6. Damping of the measured (curves in the left) and simulated (curves in the right) inrush currents of phases A, B and C in six seconds.

5. Conclusions

The simulations with different transformer models of EMTP show that the transformer model used in the inrush current simulations have very small influence to the results.

The simulated inrush currents are too small compared to the measured ones if the saturation curve is taken from the no-load test. This is because the transformer is not fully saturated at the highest voltage of the no-load test, which is usually a voltage value of 1.15 per unit. If this last measured value is used as a positive saturation point to model the hysteresis curve, the inrush currents simulated are near the measured values. The more reliable way to model the saturation of a transformer is to use the approximated value of the inductance of fully saturated iron core. The simulated peak inrush currents are always higher than the measured values if a saturation curve complemented with this inductance is used in the simulations. This implies conservative results for network planning studies.

The modelling of the residual flux has very important role in inrush current simulations. In the simulations the residual flux is modelled either within the hysteretic non-linear element or with the current source, which is disconnected at the instant of transformer energisation, situated in parallel with the non-linear element. The residual flux could not be inferred from the measurements so it is approximated so that the inrush currents near the measured values are found. Because the transformers in the simulations are five legged and the tertiary winding is delta-connected it is difficult to define the residual fluxes accurately. When the maximum peak inrush currents are needed the maximum residual flux can be used.

The existing transformer models in EMTP can be used in the simulations when the frequency dependence of the transformer is not so important. In the inrush current simulations it is important to know the inductance of the saturated transformer core and model the non-linear behaviour of the transformer and residual flux correctly.

References

[1] Electromagnetic Transients Program Revised Rule Book Version 2.0, Volume 2: Auxiliary Routines, EPRI Report EL-6421-L, Palo Alto, California, 1989

[2] Alternative Transient Program Rule Book, K.U Leuven EMTP Center, July 1987

[3] Electromagnetic Transients Program Reference Manual, Bonneville Power Administration, Vancouver B. C. Canada, 1986