A Dynamic Model of Transformer with Tap Changer Using BCTRAN-Routine and 94-Type

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Abstract – *This paper presents a dynamic time-domain model of transformer with tap changer. The model is based on the mutually coupled [RL] matrix. The elements of the matrix are calculated from the rated data of the transformer by rated position of the tap changer using BCTRAN-Routine. Later on the elements can be modified corresponding to the switching sequence of the tap changer according to adequate mathematical equations. The Norton type-94 is used to enable a dynamic change of the matrix elements during the Program execution.*

The model is suitable for low-frequency transient studies.

Keywords: *BCTRAN-Routine, Norton Type-94, Phase-shifting transformer, Regulating transformer, Tap Changer.*

1 Introduction

1.1 Important and classification of regulating transformers

In the era of privatization and deregulation of the power supply industry the need for dynamic controlling the voltage and the power flow in the system is growing rapidly. The regulating transformers (RT) are suitable instruments for this purpose, hence they have been increasingly applied. This means that a dynamic precise model is necessary to perform the simulation of Power system containing regulating transformers. Such a model enables both simulation of the system under influence of position change of the tap changer (TC) and the testing of protection and regulating concepts for the transformer himself.
The regulating transformers are divided in two groups: I- Transformers, which provide means for increasing or decreasing the circuit voltage at its location under load, called by “in-phase RT”, II- Transformers, which change the phase-angle under load as well, called by “phase-shifting RT”.
By means of design a distinction is drawn between: stand alone RT and RT in connection with “ exciting transformer “.
The principle of regulating transformers is simple: With an on-load tap-changer the transformer voltage ratio can be varied in steps by adding or subtracting turns. The transfer of the load current from the connected to the pre-selected tap is either achieved by means of resistor transition or reactor transition.

1.2 Modeling of regulating transformers

The is a deference between models used for power system analysis [1] [2], and models used for system simulation.

For power system simulation there exist following tow possibilities:

I- Models, whose elements are derived from the transformer's geometrical arrangement, the calculation principle is presented in [3] and [4], an application is given in [5].

Such models are detailed and allow to carry out simulations of the transformer.

Disadvantages: The dimensions of the transformer are needed, but they are often unavailable, moreover a connection with a power system is pretty difficult.

II- Models suggested in the users newsgroup of EMTP-ATP: to build a phase-shifting transformer using conventional transformers and thyristors. Such model is dynamic but not accurate, it doesn't reproduce the physical change in the equivalent network elements of the transformer.

Other suggested possibility is to calculate the elements R and L by "TRANSFORMER"-special request card based on the turn number by a desired tap changer position. It is a static model, and its accuracy is questionable.

In this contribution it is tried to develop a model that on the one hand fulfills the need of a dynamic accurate model and on the other hand is easy to use, and to connect with a power system.

2 Mathematical derivation of the model

The theoretical idea is presented in [6], it is based on the physical concept of representing windings as coupled coils, so a system can be described with two matrices [R] and [L], in the case of a three-phase transformer with two windings, these matrices are of order 6:

$$[\boldsymbol{R}] = \begin{pmatrix} \boldsymbol{R}_{1(i)} & 0 & 0 & 0 & 0 & 0 \\ 0 & \boldsymbol{R}_2 & 0 & 0 & 0 & 0 \\ 0 & 0 & \boldsymbol{R}_{3(i)} & 0 & 0 & 0 \\ 0 & 0 & 0 & \boldsymbol{R}_4 & 0 & 0 \\ 0 & 0 & 0 & 0 & \boldsymbol{R}_{5(i)} & 0 \\ 0 & 0 & 0 & 0 & 0 & \boldsymbol{R}_6 \end{pmatrix} \qquad [\boldsymbol{L}] = \begin{pmatrix} \boldsymbol{L}_{1(i)} & \boldsymbol{L}_{12(i)} & \boldsymbol{L}_{13(i)} & \boldsymbol{L}_{14(i)} & \boldsymbol{L}_{15(i)} & \boldsymbol{L}_{16(i)} \\ . & \boldsymbol{L}_2 & \boldsymbol{L}_{23(i)} & \boldsymbol{L}_{24} & \boldsymbol{L}_{25(i)} & \boldsymbol{L}_{26} \\ . & . & \boldsymbol{L}_{3(i)} & \boldsymbol{L}_{34(i)} & \boldsymbol{L}_{35(i)} & \boldsymbol{L}_{36(i)} \\ . & . & . & \boldsymbol{L}_4 & \boldsymbol{L}_{45(i)} & \boldsymbol{L}_{24} \\ . & . & . & . & \boldsymbol{L}_{5(i)} & \boldsymbol{L}_{56(i)} \\ . & . & . & . & . & \boldsymbol{L}_6 \end{pmatrix}$$

The model is created in two steps:

I- using BCTRAN-routine of ATP the matrices [R] and [L] modelling a regulating transformer with nominal position of the tap changer (0 position) are calculated [7].

II- In this step the ratios between the elements of two successive positions *i* and $i \pm 1$ of the tap changer are derived.

The inductance of the primary coil, where the tap changer is located, is considered as main inductance L_m and leakage inductance L_σ:

$$L_p = L_m + L_\sigma \qquad (1)$$

The main inductance is given by the following equation:

$$L_m = \frac{N^2}{R_m} \tag{2}$$

where N is the number of turns and R_m is the magnetic resistance. Thus the subsequently given relation can be derived:

$$L_{m(i\pm1)} = L_{m(i)} \cdot \left(\frac{N_{i\pm1}}{N_i}\right)^2 \tag{3}$$

The leakage inductance between two coils can be calculated from the electromagnetic energy stored in the coil. The Calculation method of the leakage inductance is in presented and carried out for a real transformer. the results shows, that the change of this inductance is small.

From these relations we can calculate a "new" self inductance for another tap changer position:

$$L_{1,3,5(i\pm1)} = L_{p(i\pm1)} = L_{m(i\pm1)} + L_{\sigma(i\pm1)} \tag{7}$$

In order to describe the mutual inductance by the new position *i±1* of the tap changer, we have to define the factor ε as the ratio of the leakage factor σ_{ps} of tap changer position *i±1*, and the leakage factor of the tap changer position *i*,

$$\varepsilon = \frac{\sigma_{ps(i\pm1)}}{\sigma_{ps(i)}} = \frac{L_{p(i)}L_s - M^2_{ps(i)}}{L_{p(i\pm1)}L_s - M^2_{ps(i\pm1)}} \cdot \frac{L_1}{L_{p(i\pm1)}} \tag{8}$$

Thus the following relations for the calculation of the mutual inductances result:

$$M_{ps(i\pm1)} = M_{ps(i)}\sqrt{\varepsilon}\sqrt{\frac{L_{p(i\pm1)}}{L_{p(i)}}}\sqrt{1+\frac{1-\varepsilon}{\varepsilon}\cdot\frac{L_{p(i)}L_s}{M^2_{ps(i)}}} \tag{9}$$

$$M_{ps(i\pm1)} = \frac{N_{i\pm1}}{N_i} \cdot M_{ps(i)} \tag{10}$$

$$M_{pp(i\pm1)} = \left(\frac{N_{i\pm1}}{N_i}\right)^2 \cdot M_{pp(i)} \tag{11}$$

Equation (9) represents the mutual inductance for the case when the windings are on the same leg, for the case when the windings are situated on different legs the mutual inductance is calculated by (10). Equation (11) delivers the set of mutual inductance's for the primary windings.

The resistance will be determined as follows:

$$R_{i\pm1} = \frac{N_{i\pm1}}{N_i} \cdot R_i \tag{12}$$

The change period between two position can be modeled by means of the switching sequence of the tap changer, the switching process is described in detail in [8].

We consider a resistor type OLTC. The switching operation sequence and a common timetable are demonstrated in Fig. 1.

The matrices [R] and [L] calculated in step I reproduce the state a) and the matrices modified in step II the state e) .

For other states the matrices have to be modified in the following way:

Taking the voltage increasing direction:

State b): $R(1,1) = R(3,3) = R(5,5) = R_i + R_A$ (13)

State c): $R(1,1) = R(3,3) = R(5,5) = \text{real part } [(R_i + j.L_i) + [((\Delta R + R_B) + j.\Delta L)//R_A]]$ (14)

$L(1,1) = L(3,3) = L(5,5) = \text{imaginary part } [(R_i + j.L_i) + [((\Delta R + R_B) + j.\Delta L)//R_A]]$ (15)

Were: $\Delta L = R_{i+1} - R_i$, $\Delta L = L_{i+1} - L_i$

State d): $R(1,1) = R(3,3) = R(5,5) = R_{i+1} + R_B$ (16)

The same equations in the voltage decreasing direction with replacing L_{i+1} and R_{i+1} by L_i and R_i, L_i and R_i by L_{i-1} and R_{i-1} respectively.

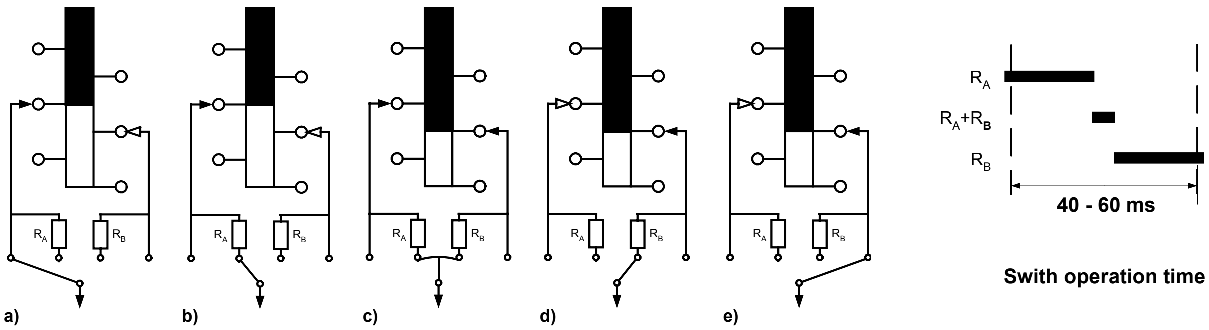


Fig. 1. Diverter switch operation sequence

3 Implementation with Norton Type-94

The type-94 (Thevenin, iterated, or Norton) is a nonlinear single- or multi-phase circuit component [9], it allows to simulate arbitrary nonlinear circuit.

For the modeling the NORTON type was chosen.

In the NORTON type, the circuit sees the component as a Norton equivalent an admittance to ground in parallel with a current source. For a multiphase component, the admittance to ground is a matrix, and there is a current source at each node. The component receives node voltage values, and calculates the admittance and current source to be used in the circuit solution at the next time step. No iteration is performed by ATP.

The Norton type-94 is faster than the Thevenin or iterated, because ATP is not required to calculate a Thevenin equivalent at each time step (like Thevenin and iterated), and because no iteration is taking place (like iterated).

Disadvantages are: that the changes in values take effect with a delay of one time step. But a single time step delay is not a problem in means of TC- position change in a power system. Numerical instability can be expected when the represented element is not a passive circuit element.

In the EXEC procedure the calculation equations for series Connection of [R] and [L] are used [7]:

The branch current:

$$\left[i_{km}(t)\right] = \left[G_{series}\right]\left\{\left[v_k(t)\right] - \left[v_m(t)\right]\right\} + \left[hist_{series}(t-\Delta t)\right] \tag{17}$$

and the history term:

$$\left[hist_{series}(t-\Delta t)\right] = \left[G_{series}\right]\left\{\left[v_k(t-\Delta t)\right] - \left[v_m(t-\Delta t)\right]\right\} + \left[Z\right]\left[i_{km}(t-\Delta t)\right] \tag{18}$$

with:

$$\left[R_{series}\right] = \left[R\right] + \frac{2}{\Delta t}\left[L\right],\ \left[G_{series}\right] = \left[R_{series}\right]^{-1} \text{ and } \left[Z\right] = \frac{2}{\Delta t}\left[L\right] - \left[R\right] \tag{19}$$

4 Example

A regulating transformer (in-phase RT) with following rated data:

<table>
<tr><td colspan="2">Power rating S</td><td colspan="10">ONAF 250 MVA</td></tr>
<tr><td colspan="2">Voltage rating</td><td colspan="10">230 kV ± 15% with 9 taps / 63 kV</td></tr>
<tr><td colspan="12">Windings number</td></tr>
<tr><td colspan="3">Low voltage winding</td><td colspan="3">high voltage winding</td><td colspan="3">coarse winding</td><td colspan="3">tap winding</td></tr>
<tr><td colspan="3">256</td><td colspan="3">450</td><td colspan="3">90</td><td colspan="3">(9 × 9) × 2</td></tr>
<tr><td colspan="12">Direct measurements</td></tr>
<tr><td colspan="6">Excitation test</td><td colspan="6">Short-circuit test</td></tr>
<tr><td colspan="2">voltage</td><td colspan="2">current</td><td colspan="2">losses</td><td colspan="2">current</td><td colspan="2">voltage</td><td colspan="2">Losses</td></tr>
<tr><td colspan="2">100 %</td><td colspan="2">0.049 %</td><td colspan="2">93.9 kW</td><td colspan="2">100 %</td><td colspan="2">17.7 %</td><td colspan="2">536 kW</td></tr>
</table>

4.1 Calculation of the leakage inductance

Fig. 2. shows a front view of a core of the transformer with real representation of the horizontal dimensions proportions of the high, coarse and fine winding. The fine winding consists of two parts of turns, the upper is coiled in the direction of the other tow windings, and the lower part in the opposite direction.

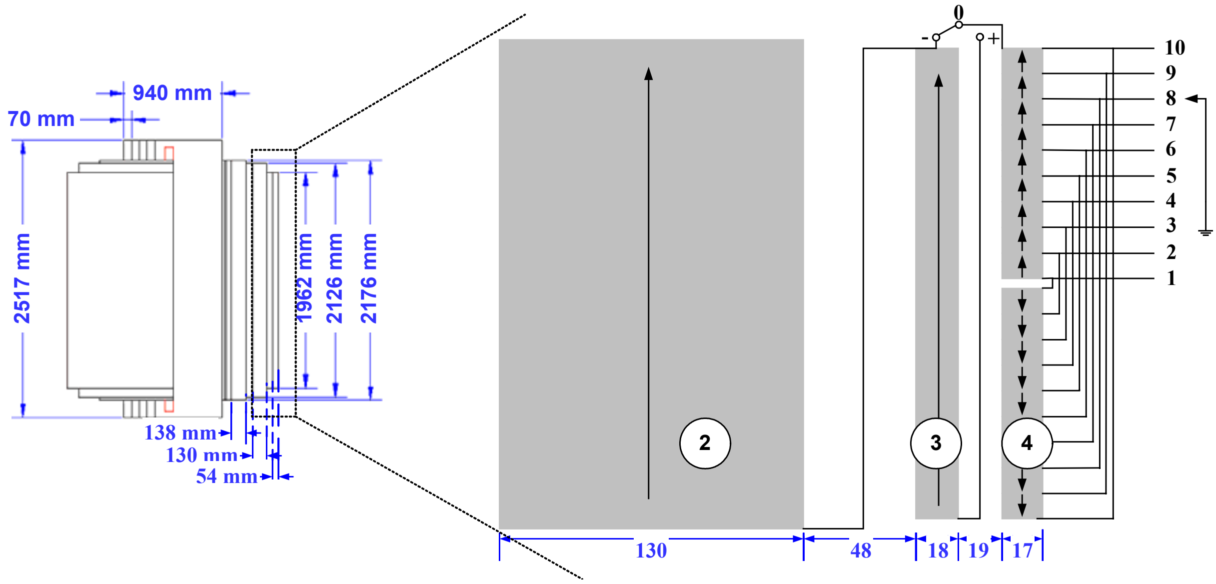


Fig. 2. Dimensions of the windings

The leakage inductance can be calculated from the electromagnetic energy stored in the coils:

$$W = \frac{\mu_0}{2} \iiint_V H^2 dV \tag{20}$$

at the same time the total leakage inductance of the winding can be calculated using the equation:

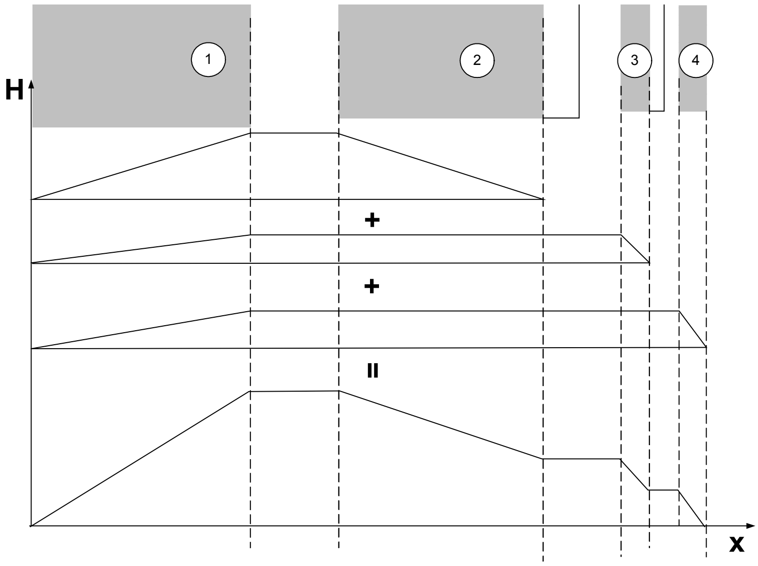
$$W = \frac{1}{2} L_\sigma i^2 \tag{21}$$

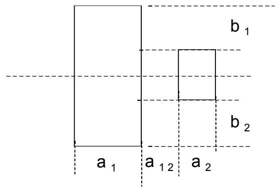
by comparing the equations (20) and (21) the leakage inductance can be determined
The three dimensional integral can be reduced to a one dimensional integral namely over x, as long the windings are about the same height, because of the two following hypotheses:

- magnetic-field is parallel to the axis of the core.

- magnetic-field is symmetric in the relation to the core axis.

Furthermore, a hypothetical short circuit analysis can be used for easy calculation of the H field [4], in Fig. 3. the use of the hypothetical short circuit analysis is demonstrated, the field is the sum of the fields between the under voltage winding and other windings one after the other, whenever the concerned winding is short-circuited.





$$k_h = \frac{b_1 k_1 + b_2 k_2}{b_1 + b_2}$$

$$k_i = 1 + 0.1 \left[\frac{b_i}{f} \right]^{1.6}$$

$$f = a_{12} + \frac{a_1 + a_2}{3}$$

Fig. 3. Distribution of magnetic-leakage field intensity in the windings and the using corrector factor

By the calculation of the stored energy between the lower voltage winding and the tap winding (fine), the hypotheses are not always sustained, however the field H alternatively the energy can be calculated with the one dimensional integral, but in this case a corrector factor should be included. As proposed in [10] and presented in Fig. 3. a correction factor was used. The leakage inductance by tap changer positions { [0-10] (+) } is presented in Fig. 4.

By tap changer position 1 (nominal tap changer) the ratio L_σ/L_m amounts about 0.0055 %, it's to mention that the value calculated from rated data is around this value, that shows the validity of the calculation method. By Tap Changer Position 10 (L_σ/L_m) amounts about 0.0077 % .

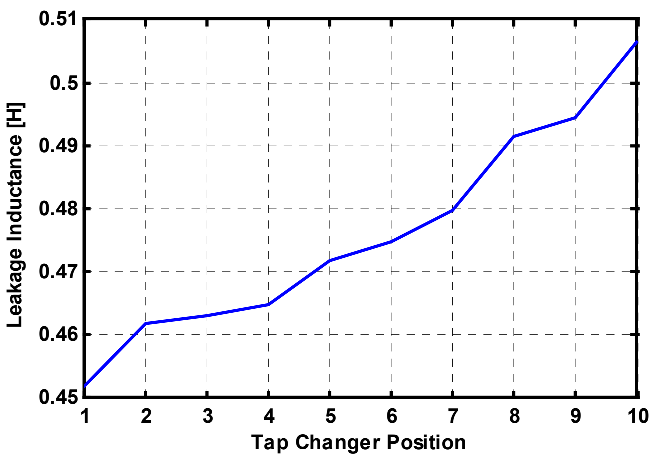


Fig. 4. Leakage Inductance at the different TC Positions

The example shows that the change of leakage inductance is small in comparison to the change of mean inductance, that means neglect of leakage inductance change is tolerable, if the geometry data of the transformer are not available.

4.2 Implementation and Simulation results

The implementation process is shown in Fig. 5. Simulated is the transformer by TC-Position change from -10 to –9, transition resistor $R_A = R_B$ =2.8 Ω and time step Δt = 1.E-5 s

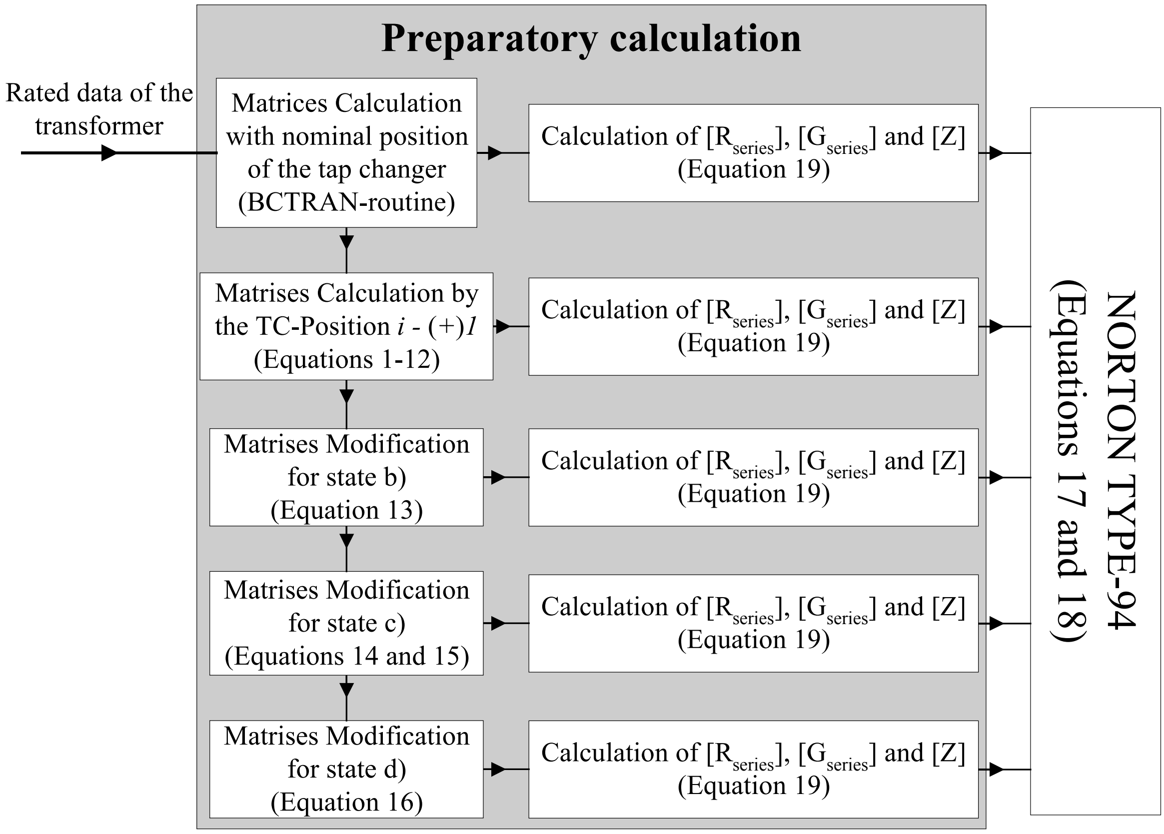


Fig. 5. Process progression

The change time is chosen as following:

t1 {dflt: 0.040}
t2 {dflt: t1+0.02}
t3 {dflt: t2+0.01}
t4 {dflt: t3+0.01}

The Norton component is specified in the ATP-file as follows:

94X0011A REGELT NORT 1
94X0012A
94X0011B
94X0012B
94X0011C
94X0012C
>SSV X0001A
>SSV X0002A
>SSV X0001B

```
>SSV   X0002B
>SSV   X0001C
>SSV   X0002C
>SSI   X0001A
>SSI   X0002A
>SSI   X0001B
>SSI   X0002B
>SSI   X0001C
>SSI   X0002C
>END
```

In Fig. 6. and Fig. 7. simulation results of the secondary voltage winding and of both winding currents are demonstrated.

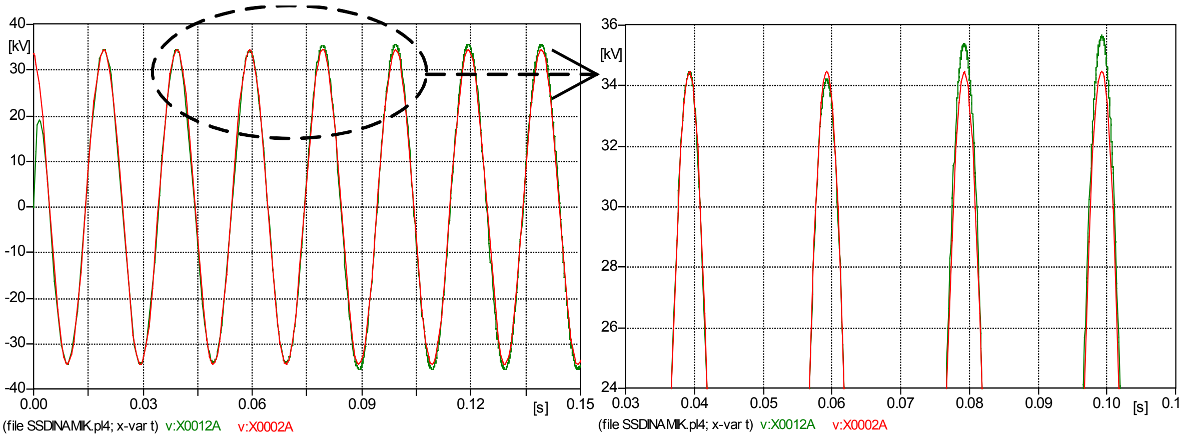


Fig. 6. Secondary Voltage change by TC switch operation at 0.04 ms (Position -10 to -9)

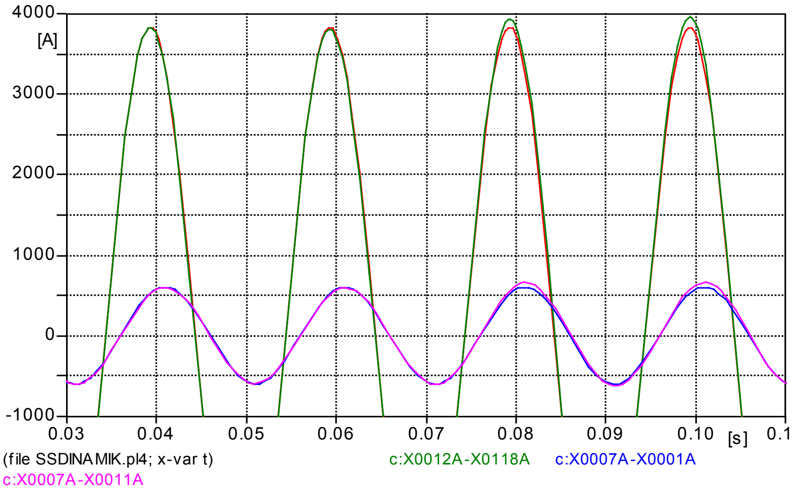


Fig. 7. Primary and Secondary currents (TC switch operation at 0.04 ms), Position -10 to -9.

5 Conclusion

In this contribution a dynamic model of transformer with tap changer was presented, both the mathematical derivation and the implementation with subroutine of ATP-EMTP simulation program were shown. Simulation results for a real transformer were presented as well. The model can be extended to three-phase transformer with three windings.

6 References

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