4. Transformer

Three kinds of menus are applicable in ATP-EMTP to represent transformers.
- Saturable transformer component (TRANSFORMER)
- XFORMER
- BCTRAN

From the author's experience, the first one is most convenient to represent power transformers due to well representing physical image of the hard wear and electrical phenomena. Also many data are common to general power system analyses. So in the chapter, mostly the first one is explained.

Note:
The features of the latter two (XFORMER, BCTRAN) are,
- From general test data of transformers, data to be applied to transient calculations are directly calculated.
- The data are in the form of "mutually coupled inductors" (actually in "PI-EQUIVALENTS" form, the function of which perfectly covers "Mutually-coupled R-L Elements", see Rule Book)
  For example, three-phase two winding and one core transformer is represented by six mutually coupled inductors.
- Saturation characteristics are not covered within the scope. So, another saturable non-linear element(s) is to be introduced out side. The influence by the saturation on the self/mutual inductance(s) can never be considered.
- Magnetising inductance corresponds to self-inductance of the relevant winding, but leakage inductance cannot directly represented.
- Total procedure is "BLACK BOX" like one.

Single-phase two winding transformer

In Fig. 4.1, physical image of single-phase two winding transformer is shown.

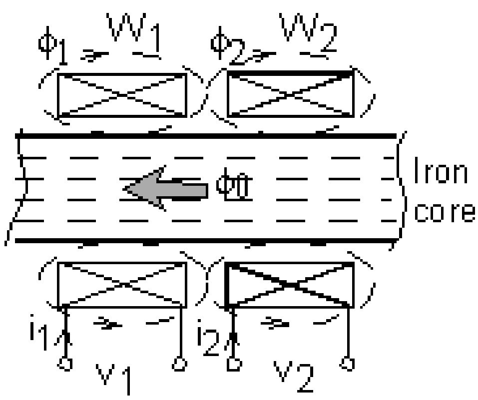

Fig. 4.1 Physical image of 2-winding transformer

Fig. 4.1 shows typical physical image of single-phase two winding transformer,
Where,

W_1, W_2: windings

ϕ_1,ϕ_2: fluxes linked with only W_1 or W_2

ϕ_0: commonly linked flux

v_1, v_2, i_1, i_2 respective winding voltages and currents

The following equations are easily written.

$$v_1 = i_1 r_1 + n_1 \frac{d\phi_1}{dt} + n_1 \frac{d\phi_0}{dt}$$

$$v_2 = i_2 r_2 + n_2 \frac{d\phi_2}{dt} + n_2 \frac{d\phi_0}{dt}$$

Replacing

$$n_1\phi_1 = l_1 i_1, \quad n_1\phi_0 = L_0 i_0 \quad n_2\phi_2 = l_2 i_2$$

it is understood that Fig. 4.2 represent the same contents, so Fig. 4.2 can be a perfect equivalent circuit of a two windings transformer. The "Saturable transformer component" menu in ATP is base on the principle of this circuit.

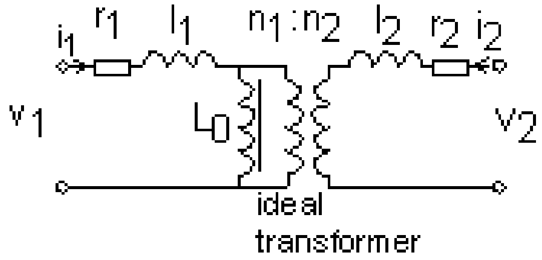

Fig. 4.2 Equivalent circuit

The features of the circuit are:

- Using the menu, parameters are to be obtained beforehand. Generally they are used in power system analysis etc.
- l_1 / l_2 is named as leakage inductance which is not much influenced by saturation. The main part of the flux pass is not in the iron core. So linear inductor is applicable with enough accuracy.
- L_0 can be saturable, so non-linear inductor such as type 98 (default) or type 93 (optional, initial residual flux is applicable) is applicable.
- L_0 can, in principle, be connected any side of the ideal transformer. As the default, it is connected to the primary side.

Small note:

- In Fig. 4.1, it is apparent that, if W_1 and W_2 are divided into plural parts and located every other, ϕ_1 and ϕ_2, consequently l_1 and l_2 can be very low. The method is occasionally applied for power transformers, and typically for ones for audio, where quasi-ideal (no leakage inductance) transformers are required.

Single-phase three winding transformer

Likewise three winding transformer can be modelled by one magnetising inductance and three leakage inductances. In principle, three coupled inductors are represented by three self-inductances and three mutual inductances, total six inductances. Therefore by four inductances in the above, two are shortage. Nevertheless, experience shows actual three winding transformers can be represented by the model with enough accuracy. Leakage inductance values of respective windings are generally obtained from the manufacturer, so these are directly applicable.

Care should be taken that in the menu minus value, for inductance/resistance, is not favourable. Occasionally manufacture supplied equivalent leakage inductance is minus, though very low value. In such case, the value is to be change to be very low plus value.

Three-phase one core (three legs or five legs) transformer

For three-phase transformer composed of three single-phase ones, three of single-phase ones are applicable without any difficulty. Care should be taken that delta-connected tertiary windings are not to be excluded, which may strongly dominate the zero sequence short-circuit impedance.

For three-phase five-leg-core transformer, as zero sequence flux pass exists in the iron core, conditions are the same as three of single-phase ones. So, of cause, three of single-phase transformer is applicable.

For three-leg core type and without delta-connected winding one, which is most popular for medium and low capacity of three-phase transformer, as the zero-sequence flux pass mostly exists outside of the core, special care is to be taken regarding zero-sequence parameters. Also in this case three of single-phase ones are applied. For representing very low zero-sequence magnetising inductance, another dummy windings for three-phase are introduced, which are connected in delta. The leakage inductances of which are to be adjusted, i.e. zero-sequence magnetising inductance from the primary side is equal to the sum of the primary side and the relevant winding leakage ones. Actually, while zero-sequence magnetising, some portion of the flux exists in the iron core part, so the magnetising inductance is higher than the short-circuit one. Therefore positive value of leakage inductance in the dummy winding is possible.

More details are shown in Role Book – IV, E, 4, though in somewhat different way.

Notes:
- In any of transformer menu, each winding is considered as one lump element, i.e. the current in one winding is uniform. This seems to be correct up to the fundamental inherent frequency of the winding. The value is in the order of a few --- several kHz for most power transformers.
- In calculating TRV, for example, the prospective frequency of the TRV is dominated by both the transformer elements and system ones such as lines, cables, etc. So, the frequency is never higher than the transformer's inherent one. Therefore, transformer menu in this chapter is applicable.
- For much higher frequency of phenomena such as by lightning surges or VFT switching surges, another models are required. Depending on the frequency concerned, respective models are to be considered. In most cases, considering the physical constructions, parameters are to be calculated. "Mutually coupled R-L elements" and additional capacitors are mostly applied.

A few examples

i) 537kV/287.5kV Auto-transformer, inrush magnetising current

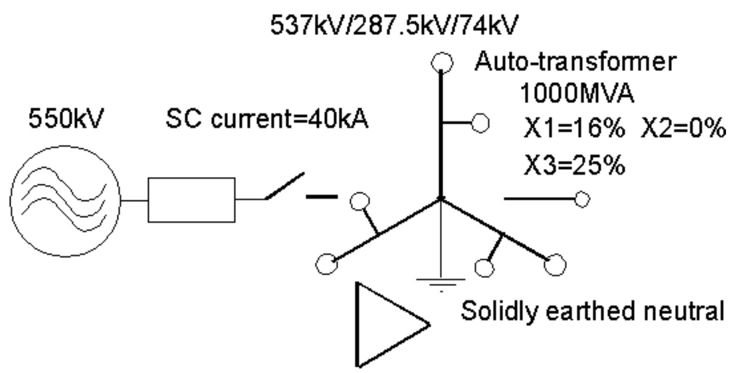

Fig. 4.3 537kV Auto-transformer

The first example is as for inrush magnetising current in an auto-transformer. (The maximum tap voltages of the transformer are shown in the figure. The maximum system voltages are 550kV and 300kV.) As shown in Fig. 4.3, each phase has a common winding (287.5kV) and a branch winding (537kV – 287.5kV). Also delta-connected tertiary winding (74kV) exists. For details of the data description, see the attached data file.

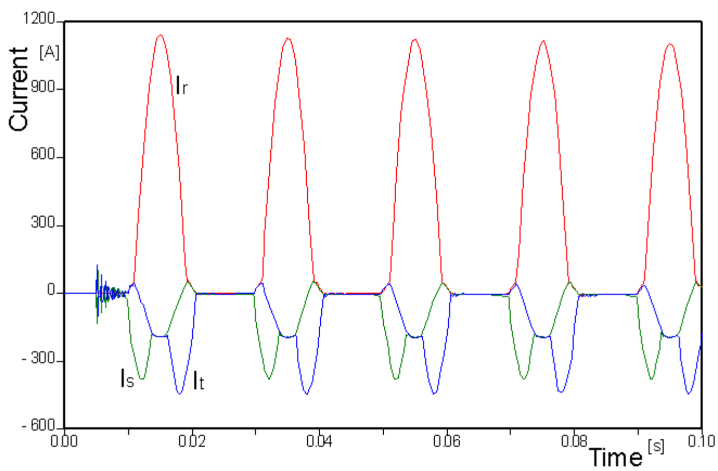

Fig. 4.4 Inrush magnetising current in 550kV

Calculated inrush magnetising current from 550kV system side is shown in Fig. 4.4. The inrush current lasts several tens seconds. For the calculation of the time, correct resistance values both for the system and transformer are required. Also, correct Φ-I characteristics in the relevant current range is important.

ii) Transformer limited short circuit current breaking

In Fig. 4.3, 550kV side circuit-breaker is permanently closed, and the 300kV side terminals are short-circuited (three phase). The short circuit is cleared at the location. Such is called as transformer limited fault clearing (breaking). Three phase breaking currents and TRVs are shown in Fig. 4.5.

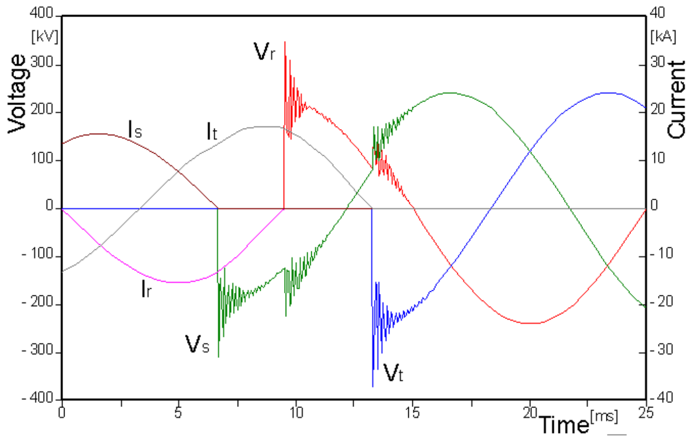

Fig. 4.5 Transformer limited SC current breaking

It should be noted that as for TRVs, of the first-pole-to-clear is lowest and the third one is highest. In Fig. 4.3, as for short-circuit reactance looked into from 300kV side, positive and negative sequence ones the sum of the transformer's and the system's. But as for zero sequence, tertiary winding's one is connected in parallel. So, if the transformer reactance is predominant, i.e. in very high short-circuit capacity of system, zero sequence short-circuit reactance is lower than positive/negative one. "First-pole-to-clear factor", i.e. the ratio of the first pole TRV to the phase voltage based one, is given as:

$$\frac{3X_0}{X_1 + 2X_0}$$

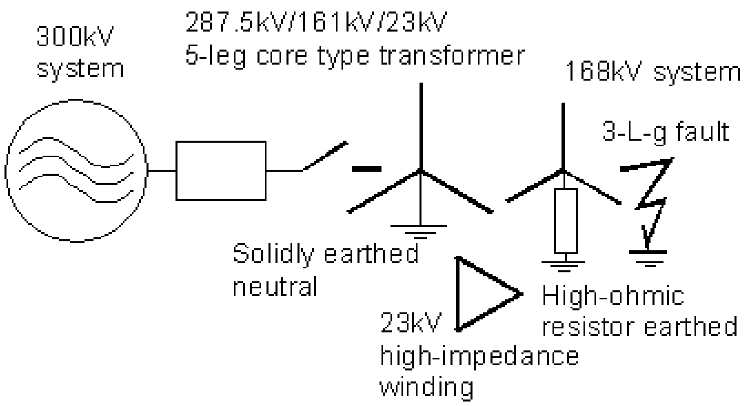

Fig. 4.6 Transformer limited fault clearing
Grounding fault in non-solidly earthed side

where, X_1 and X_0 are positive and zero sequence short-circuit reactances respectively.

If $X_0 < X_1$, then the first pole's TRV is lower than last pole one, which may be general in a very high capacity of system.

Note:

- In IEC standard, considering also the case shown in the following, the first-pole-to-clear factor in transformer limited fault breaking is specified as 1.5, also for systems of solidly earthed neutral.

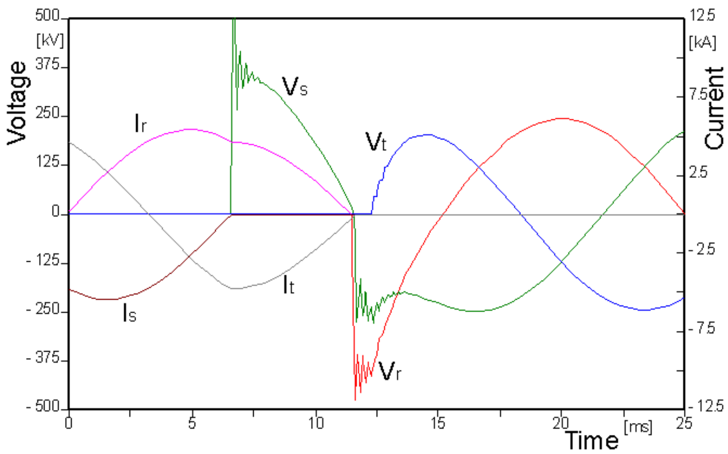

Fig. 4.7 Transformer limited fault clearing,5-leg core with high-impedance delta connected winding

iii) Transformer limited fault, but which is non-solidly earthed system side

As shown in Fig. 4.6, in the next example, three-phase grounding fault locates in the non-solidly earthed system side. The short-circuit is cleared by the solidly earthed side circuit-breaker.

The transformer is assumed to be:

- The iron core is 5-leg type, i.e.

zero sequence magnetic flux passes in the core.

- Delta-connected tertiary winding (generally exists for station-internal power source or eliminating third harmonic component) is of high impedance type.

The breaking currents and TRVs are shown in Fig. 4.7. Both the currents and TRVs show as phenomena in non-solidly earthed system, though the circuit-breaker is located in the solidly earthed side. The first-pole-to-clear TRV (V_s) is based on 1.5 times phase voltage. Considering such case, in IEC standard, TRVs for transformer limited cases are specified to be based on non-solidly earthed condition.

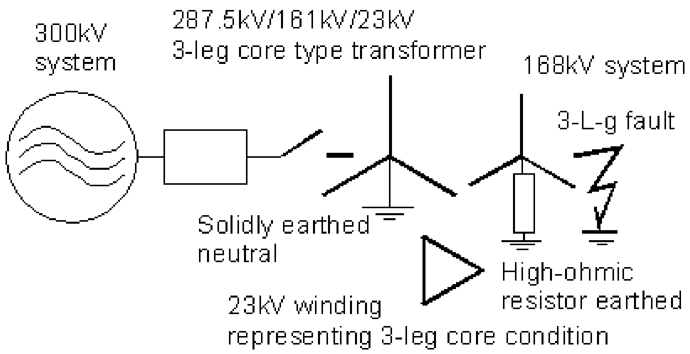

Fig. 4.8 Same as Fig. 4.6, but in 3-leg core or lower impedance of delta connected winding condition

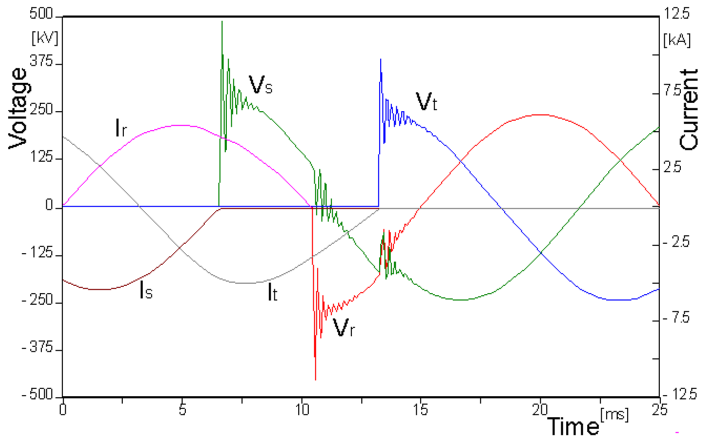

Fig. 4.9 Transformer limited fault clearing, under solidly earthed system condition

Care should be taken, in Fig. 4.7, 2nd pole TRV (T_r) is not equal (in magnitude) to 3rd one, due to non-perfectly floating neutral condition.

For the case power source exists in 161kV side and fault at the left side of the circuit-breaker, breaking current and TRV situation are the same as in this case.

ⅳ) Ditto, but transformer with 3-leg iron core or lower impedance of delta-connected winding condition.

In 3-leg iron core type transformer, as shown before, due to the high reluctance as for zero sequence flux, the zero sequence short-circuit impedance is lower, e.g. 2 --- 3 times of positive/negative one. Even for 5-leg type, if the capacity of the delta-connected winding is relatively higher such as for application of compensation circuit, the zero sequence impedance is also lower. For both cases, applying lower impedance of delta-connected winding as shown in Fig. 4.8 can represent the circuit condition.

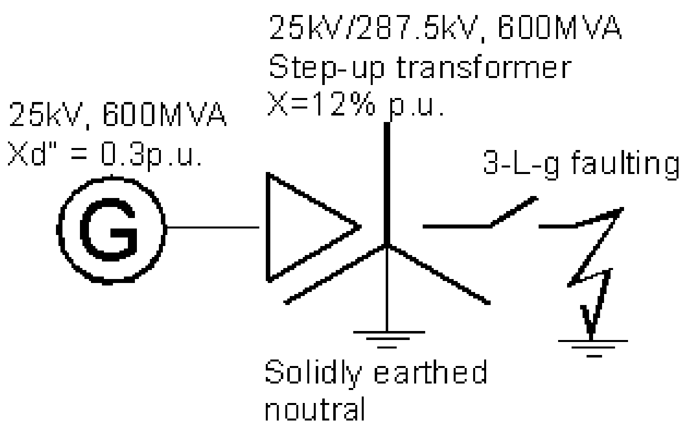

Fig. 4.10 Generator step-up transformer circuit

In Fig. 4.9, calculated breaking currents and TRVs are shown, where three-phase TRVs appear in similar magnitude, i.e. solidly earthed condition.

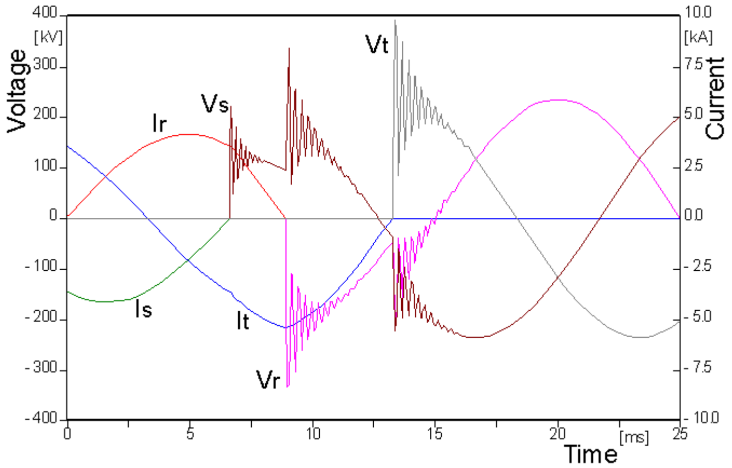

Fig. 4.11 Three-phase grounding fault clearing in generator step-up transformer circuit

v) Generator step-up transformer circuit

In power stations located in HV/EHV solidly earthed systems, the generators are connected to the systems via step-up transformers, the primary (generator) side of which are delta connected, as shown in Fig. 4.10.

For the case, three-phase breaking currents and TRVs are shown in Fig. 4.11.

As for short-circuit impedance seen from the system side, zero sequence one is only of the transformer though the neutral of the generator is high-Ohmic resistor earthed in the case, while to positive/negative one the generator's one is included. So the zero sequence one is lower. As the result, the breaking current enhances at the final stage (1LG condition) and the TRV is lowest in the first-pole-to-clear. Such are the typical in generator step-up transformer circuit.

For details of modelling generators, see the following chapter(s).

Attached data files for this chapter

- Data4-01.dat 537kV/287.5kV/74kV auto-transformer, inrush magnetising current calculation.
- Data4-02.dat Ditto transformer, transformer limited fault current clearing at 287.5kV side
- Data4-03.dat 287.5kV/161kV 5-leg core type transformer limited fault clearing at solidly earthed side
- Data4-04.dat Ditto, but 3-leg core type or with lower impedance of delta-connected winding
- Data4-05.dat Generator step-up transformer circuit, fault clearing in the solidly earthed system side.

Followings are for Appendix

- Data4-06.dat 50-turn, air-core reactor, VHF response calculation by ramp-and-DC voltage
- Data4-07.dat Ditto reactor, impedance vs. frequency characteristic calculation

Appendix 4.1 Response to fast/very fast transient voltage (VFT)

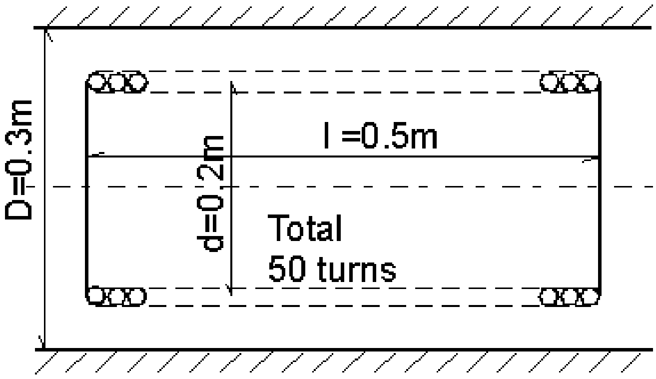

Fig. 4A.1 Air-core reactor in a metal cylinder

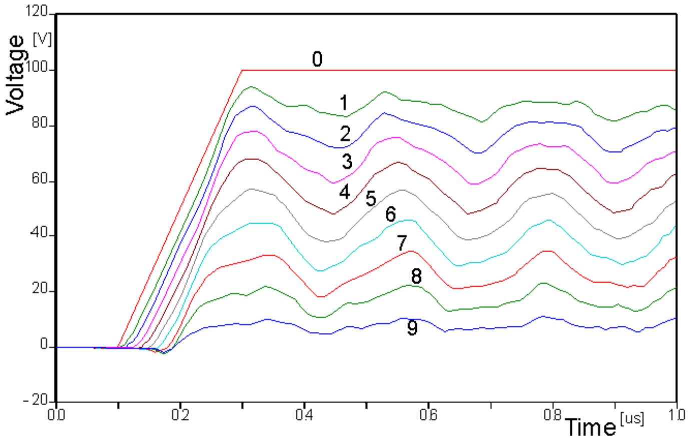

Fig. 4A.2 Ramp & step voltage application

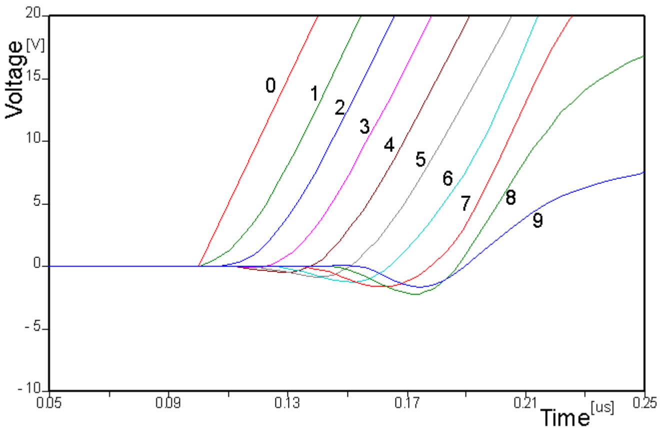

Fig. 4A.3 Initial part zooming of the above

In the transformer model i.e. "TRANSFORMER", "XFORMER" or "BCTRAN" in ATP-EMTP, each winding is modelled as one inductance, where current value and voltage distribution rate are uniform along the turns. By higher frequency of voltage application than the fundamental inherent frequency, these relationship can never been held. It is known by steep front of over-voltage application, the voltage stress around the entrance terminal winding is severe.

Here, an air-core reactor located in a metal cylinder (earthed), detailed dimensions of which are shown in Fig. 4A.1, is taken up. The reactor is divided to ten sections, each consists of five turns, having self and each other mutual inductances. Also capacitances within turns and to cylinder exist. All values are shown in the attached data file.

Note:

- For stable transient calculation, these inductances (both self and mutual) are to be calculated as best appropriate as possible. Inserting resistors of appropriate values in series to the self inductances, which are easily introduced in "Mutually-coupled R-L elements", may bring better result.

When steep ramp and step voltage being applied from one terminal while the other side is earthed, voltages in every 5 turns are shown in Fig. 4A.2, the enlargement of the very initial part of which is in Fig. 4A.3. From these, voltage stresses at inside part are apparently delayed, i.e. by very steep voltage stress, only the entrance part is stressed.

In Fig. 4A.4 and 4A.5, voltages at every 5 turns are shown while 1A (crest value) of AC current in wide range of frequency is applied. Fig. 4A.4 shows voltage magnitude that corresponds to impedance in ohm.

Fig. 4A.5 shows phase angle, corresponding to impedance phase angle. Positive one corresponds to inductive one. From these two figures, up to the fundamental inherent frequency, i.e. ca. 2 MHz, voltages are in linear relation along the turns. Also the phase angles are uniform. This

means up to the frequency the reactor can be as one inductance.
For higher frequencies, such relations can never been kept, therefore, multi-inductance modelling is inevitable.

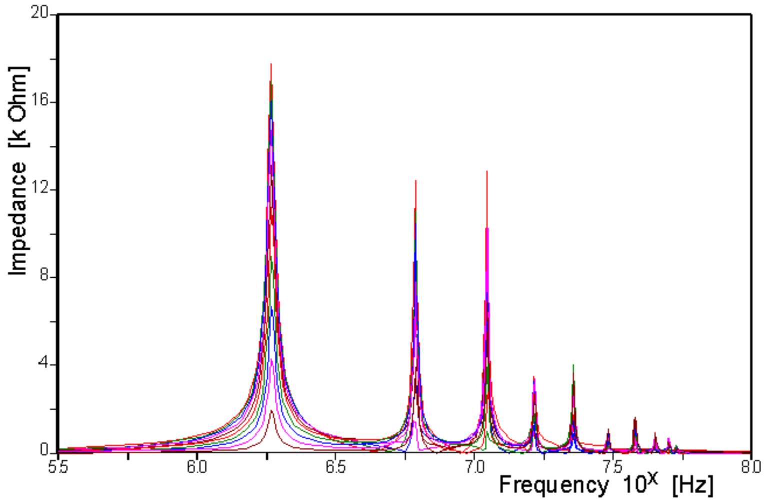

Fig. 4A.4 Voltage magnitude vs. frequency characteristic
1A of AC current applied
corresponding to Impedance (Ohm)

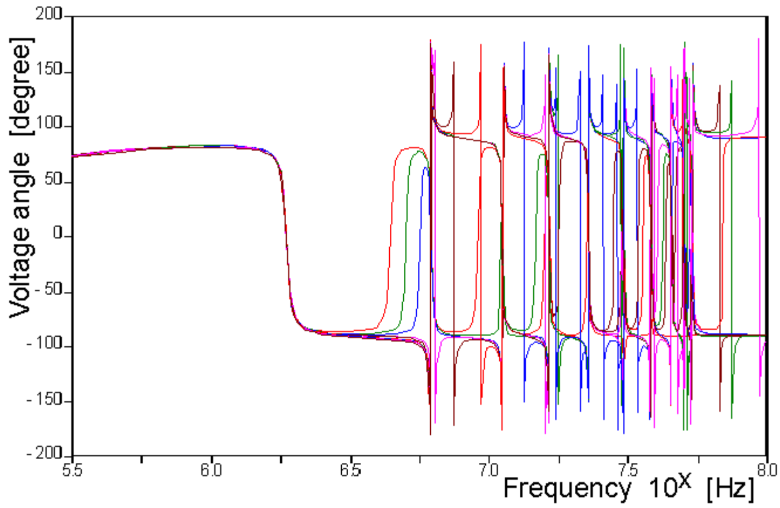

Fig. 4A.5 Voltage phase angle
corresponding to impedance phase angle