Influence of the representation of the distribution transformer core configuration on voltages developed during unbalanced operations

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Abstract - **The object of this paper is to emphasize the importance of the representation of the core configuration when seeking transients developed in a distribution transformer under an unbalanced situation.**

Digital time-domain simulations are performed with the Alternative Transients Program (ATP) for the case of a distribution three-phase transformer using the following two core configuration representations available in the ATP: three-legged core form and five-legged core.

Severe overvoltages and high saturated currents would not be evidenced if the wrong core configuration representation was used during simulations.

Keywords: Transient Analysis, Transformer, ATP.

I. INTRODUCTION

Transformer core configuration representation becomes important especially in cases of unbalanced conditions in which zero sequence parameters are excited.

In a three-legged core type transformer zero sequence fluxes cannot circulate exclusively in the core. They are forced to do it outside the windings through the air gap, structural steel and the tank. As a consequence a higher reluctance is seen by this flux, and the resulting zero sequence magnetising inductance will be less than that for the positive sequence. An appropriate representation of such behaviour should be required.

On the contrary, a five-legged core type transformer provides an iron-core path where the homopolar flux can close. Therefore, for such configuration it is reasonable to assume the zero sequence parameters equal to the positive sequence ones.

II. DESCRIPTION

The case under study consists of an unloaded distribution transformer fed through an underground cable, and under unbalanced excitation conditions.

The transformer considered is a two winding, **three-legged core type**, three-phase, 40 MVA, 132 kV/13.8 kV transformer one. With both windings WYE-connected, and with both STAR points grounded.

In order to reveal the influence of the core configuration representation in the resulting voltage and current waveforms, some simulations were performed with the Alternative Transients Program (ATP) using either the three-legged core type or the five-legged core type available models.

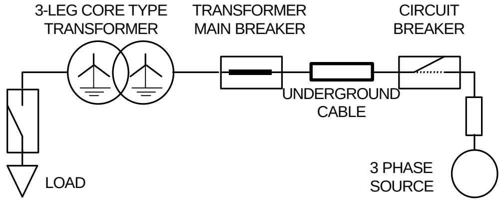

Fig. 1 - Simplified circuit representation.

The event performed during the simulations consisted of opening two poles of the circuit breaker located at the opposite end of the cable, as depicted in the simplified circuit of Fig.1.

Transformer load was considered disconnected. Table 1 shows the transformer specifications data, and Table 2 shows the positive sequence saturation curve obtained from the excitation test (LV side).

Table 1. Transformer specification data.

HV: High Voltage
LV: Low Voltage
Voltages Rating (V_{HV}/V_{LV}): 132 kV/13.86 kV
Power Rating = 40 MVA
Winding connection (HV/LV): YNyn0 grounded-grounded
Positive sequence parameters:
Excitation losses = 24 kW
Excitation current = 0.15 %
Short-circuit losses = 176 kW
Short-circuit impedance = 13.3 %
Zero sequence parameters:
Excitation losses (at excitation voltage)= 2.1 kW
Excitation current LV side ($3\ I_0$)= 77 A
Excitation voltage LV side = 140 V

Table 2. Positive sequence saturation curve.

U (p.u.)	U_{LINE} rms (kV)	I rms (A)
0.96	13.30	1.80
0.97	13.48	2.00
1.00	13.86	2.50
1.02	14.20	3.20
1.05	14.60	4.30
1.08	15.00	6.45
1.09	15.10	7.40
1.10	15.25	9.55
1.158	16.05	22.53

A 13.5 km in length underground cable, with a positive sequence capacitance of 0.404 μF/km, and a three phase equivalent source with its inductance, represent the rest of the 132 kV system.

III. TRANSFORMER REPRESENTATION

The transformer was modelled with the SATURABLE TRANSFORMER component, which consists of a three-single phase units bank. Magnetic circuit saturation effect is represented with a non-linear magnetising inductance connected phase to ground on the LV windings of each phase. Magnetic coupling between phases is not represented.

CASE A. Five-legged core type

For the five-legged core type configuration the zero sequence parameters are supposed to be the same as the positive sequence ones. The model represents the non-linear positive sequence magnetising inductance as connected phase to ground on the LV windings of each phase. At the linear region its value is $L_m = 1{,}242$ H seen from HV side. Excitation losses are represented internally through a linear resistance parallel to the magnetising reactance in each phase.

CASE B. Three-legged core type

Since the homopolar reluctance is very high because of the air gap where the flux is forced to close, the zero sequence magnetising curve is nearly linear, and a totally different model is needed. The ATP library offers a model which represents the equivalent circuit depicted in Fig. 2, where the zero sequence magnetising curve is represented through the linear magnetising inductance L_0 (1.483 H from HV side). The non-linear positive sequence magnetising inductance, the same represented in *CASE A*, is indicated as SATURA in Fig. 2, and it is connected through the LV side winding in each phase.

Besides, the zero sequence excitation losses are very different from those for the positive sequence. As a consequence the selected model uses three linear mutually coupled resistances (R_{MAG}), externally connected in parallel with the non-linear magnetising inductance, as indicated in Fig. 2, to represent positive and zero sequence losses.

IV. SIMULATIONS

Simulations have been performed for the two analyzed cases. Circuit breaker opens poles B and C at t = 0.1 sec., while phase A remains energized.

The response of the cable-transformer system to de-energising two phases can be determined by observing the voltage waveform at the open phases.

CASE A: Results

Since the model does not represent magnetic coupling among phases, after the poles of the circuit breaker (Fig.1) are opened the cable becomes isolated from the excitation source in these two phases. As a consequence the trapped charge in the cable starts to decay through the transformer oscillating at a frequency that it is influenced by the saturation characteristic of the magnetizing inductance.

Fig. 3 shows phases B and C currents flowing from the cable to the transformer. As the core reaches its saturation condition, magnetizing current climbs up to several times the transformer rated excitation current (110 A peak value). Anyway the current peak values are lower than the transformer rated peak current (247 A).

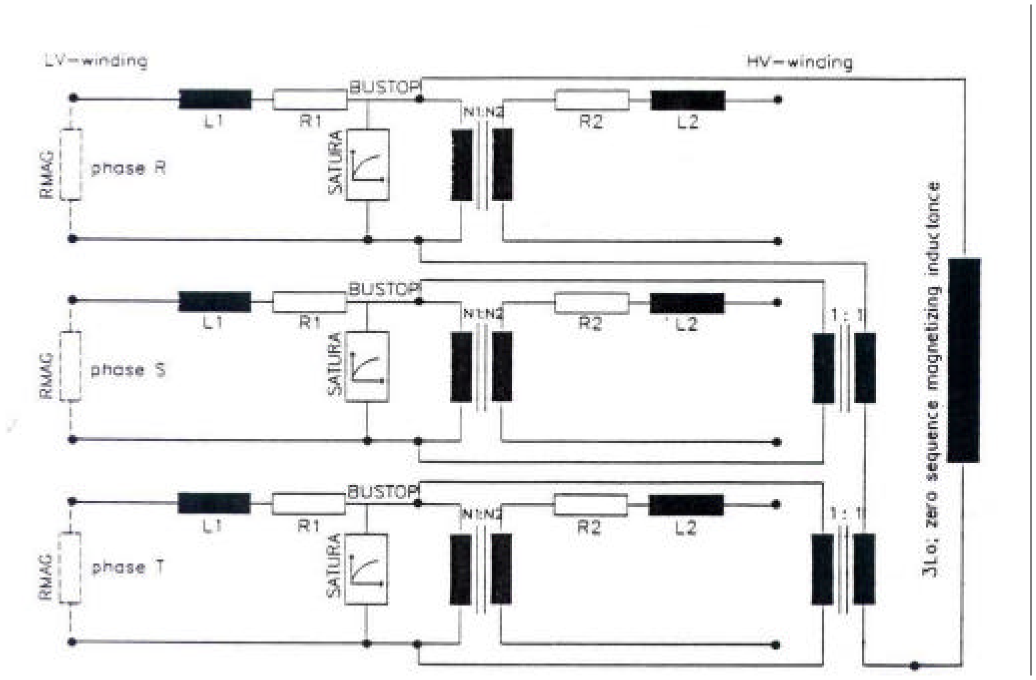

Fig. 2 - Equivalent circuit representing a two-winding, 3-leg core-type, three-phase transformer.

Fig. 4 shows line-to-ground voltage waveforms in phases B and C, which always remain below rated voltage, and decrease as the trapped charge decays.

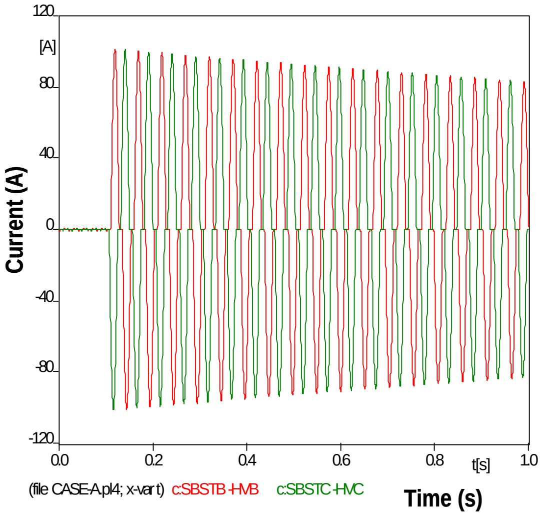

Fig. 3 - CASE A - Phases B and C currents.

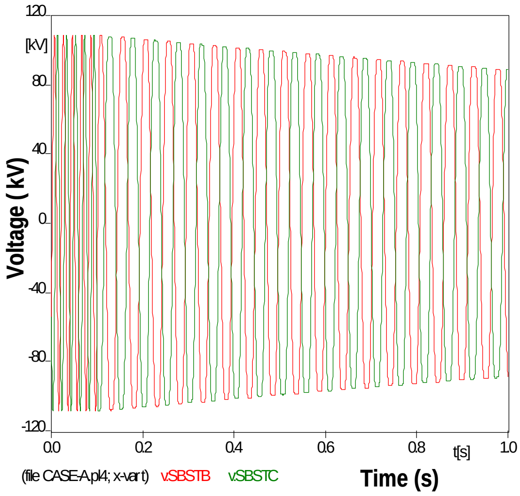

Fig. 4 - CASE A - Phases B and C line-to-ground voltage waveforms.

The current flowing to earth from the neutral point of the transformer HV side can be seen in Fig. 5.

Current and voltage waveforms show how the core gets in and out from the saturation region.

CASE B: Results

Although the model is not intended to represent the existing magnetic coupling among phases the equivalent electric circuit depicted in Fig. 6 provides a path for the zero sequence current that, in some way, reproduces the coupling among phases.

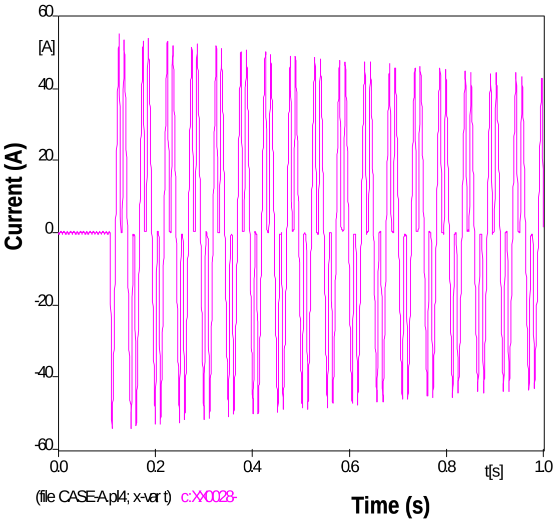

Fig. 5 - CASE A - Earth current from the transformer HV side.

Hence after opening the two poles of the circuit breaker, voltage applied to phase A results in magnetically induced voltages in the two apparently de-energised phases B and C.

The magnitudes of the line-to-ground voltages induced in phases B and C depend on the circuit parameters, i.e. the zero sequence transformer magnetising inductance, the underground cable capacitance, the transformer losses and the load.

Line-to-ground voltage waveforms in phases B and C reach values that exceed the rated voltage for more than four times (440 kV peak value > 4 p.u. value), as depicted in Fig. 7. It can also be observed that the voltage waveforms are modulated by a low frequency.

Fig. 8 shows phases A, B and C current waveforms in the transformer. As the core reaches its saturation condition magnetizing currents climb up to several times transformer rated excitation current, moreover they exceed for more than two and a half times the transformer rated peak current (650 A peak value for phases B against 247 A transformer rated peak current).

Fig. 9 shows phases B and C magnetizing current waveform, and Fig. 10 shows the current flowing to earth from the neutral point, all of them considered on the HV side of the transformer.

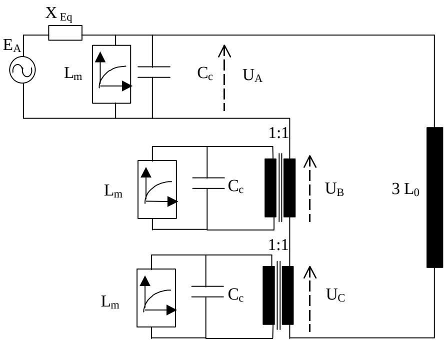

Fig. 6 - CASE B - Simplified equivalent circuit.

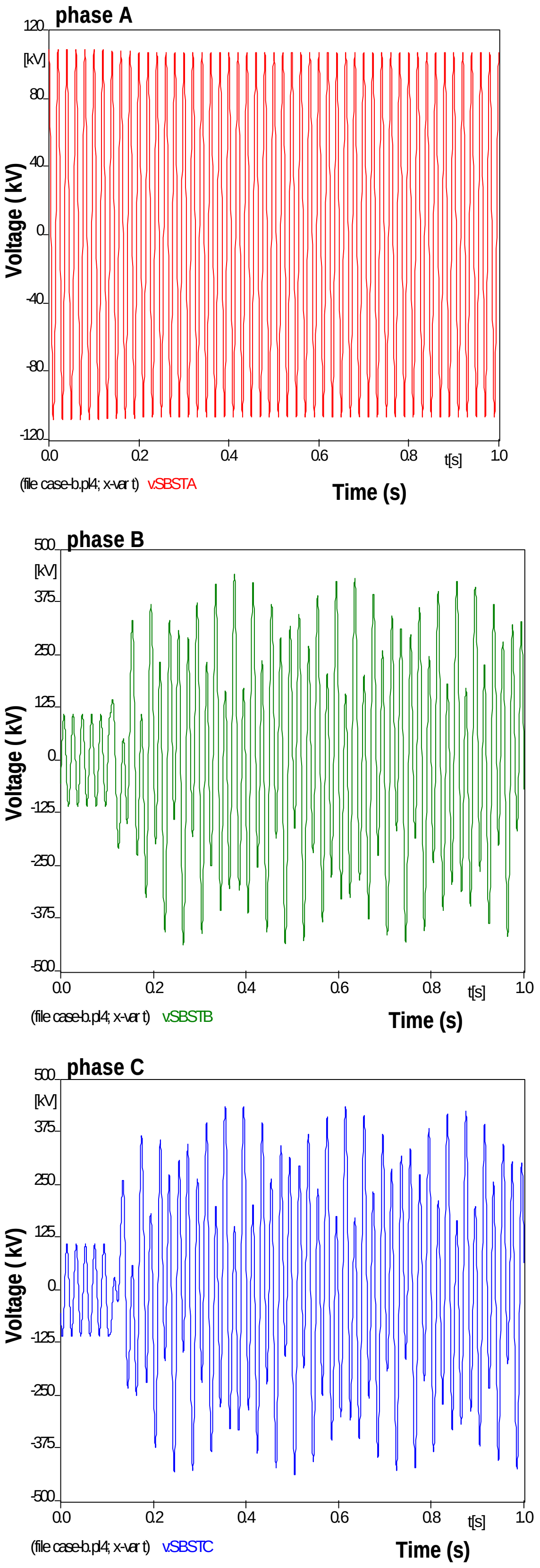

Fig. 7 - CASE B - Phases A, B and C line-to-ground voltage waveforms.

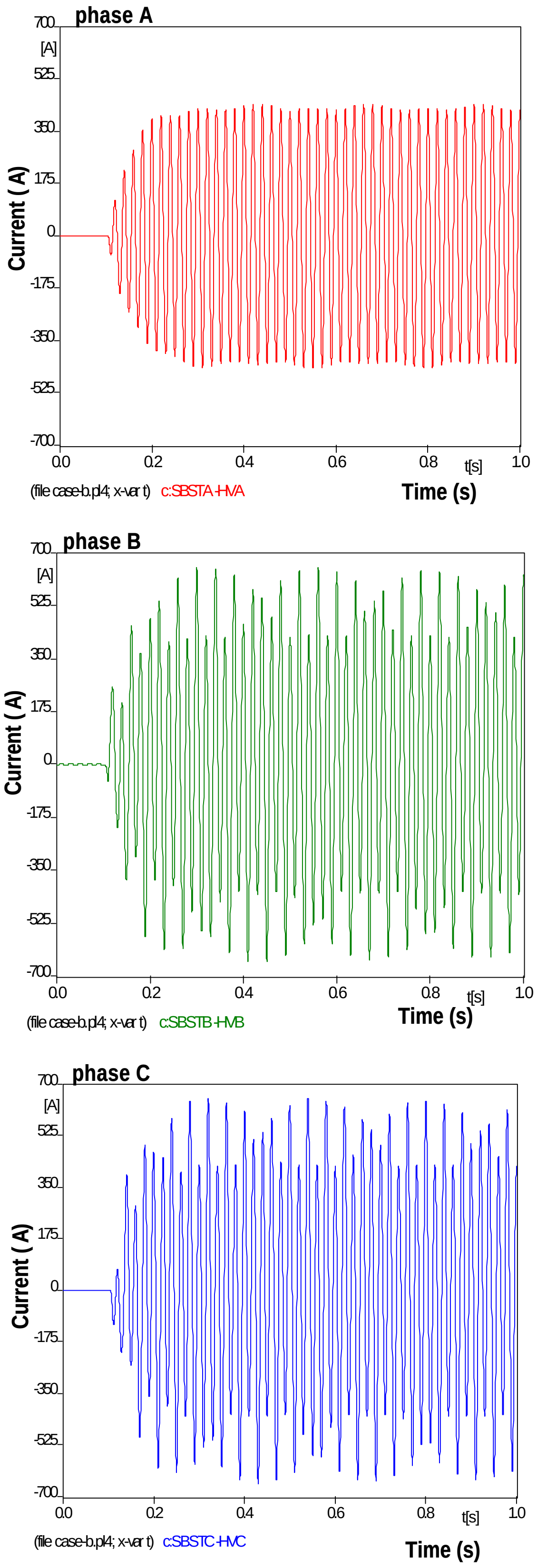

Fig. 8 - CASE B - Phases A, B and C current waveforms.

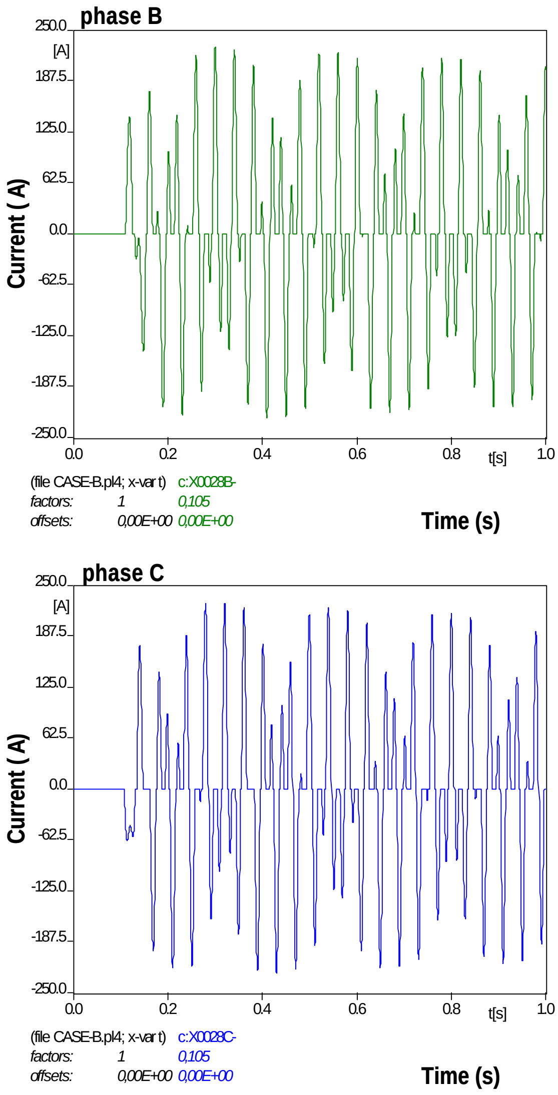

Fig. 9 - CASE B - Phases B and C magnetising current waveforms reflected on HV side.

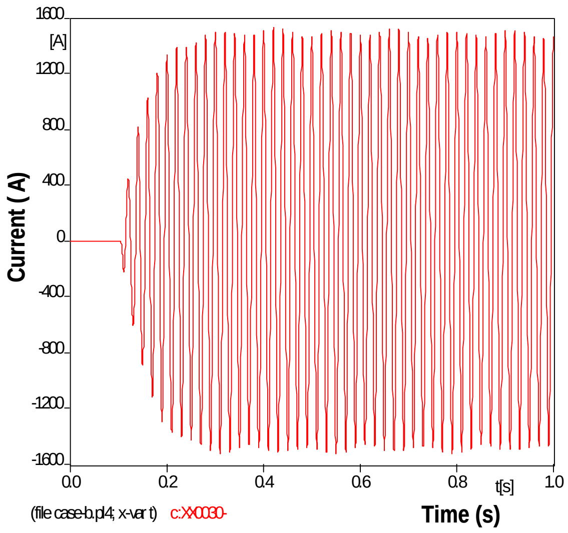

Fig. 10 - CASE B - Earth current from the transformer HV side.

To understand the cause of such high voltages and the presence of the low frequency modulation the equivalent circuit shown in Fig. 6 will be analyzed. Transformer losses and transformer leakage inductance have not been depicted in the figure, in order to make it simpler.

While the voltage drop across the phase A equivalent impedance X_{Eq} is negligible, the excitation voltage E_A can be considered as directly applied to the direct sequence transformer phase A non-linear magnetising inductance (L_m) in parallel with the phase A cable capacitance (C_c), and in parallel to a series-circuit which includes three times the zero sequence transformer magnetising inductance ($3L_0$), as well as the two other phases shunt circuits.

The two shunt circuits, phases B and C, constituted by the direct sequence magnetising inductance and the cable capacitance, have a resonance frequency at 1.94 Hz. This frequency is responsible for the low frequency modulation seen in voltages and current waveforms of Fig. 7 and 8.

Under the excitation frequency (50 Hz) and at the linear region the dominant characteristic of the equivalent shunt circuit is the cable capacitance. Consequently, under such conditions the equivalent circuit of Fig. 6 can be reduced to a series circuit constituted by the two capacitance (phases B and C), three times the zero sequence transformer magnetising inductance and the excitation voltage, considering the following fasorial relation (1).

$$\boldsymbol{E_A = U_{3L0} - U_B - U_C} \tag{1}$$

where E_A is the equivalent source terminal excitation voltage on phase A, U_{3L0} is the voltage drop across the three-time zero sequence transformer magnetising inductance, U_B and U_C are the line-to-ground voltages at the HV transformer phase B and C terminals, respectively.

This series circuit has a resonance frequency near 45 Hz, which can be determined using (2) and available data.

$$f = \frac{1}{2p\sqrt{3L_0 \cdot \left(\frac{C_c}{2}\right)}} \tag{2}$$

where f is the resonance frequency of the series equivalent circuit.

Since at the excitation frequency, 50 Hz, this circuit is close to its oscillation frequency it could be expected important overvoltages in the middle points of the series LC circuit. Furthermore, these line-to ground overvoltages $\mathbf{U_B}$ and $\mathbf{U_C}$, applied to the non-linear magnetizing inductance (L_m) in phases B and C cause core saturation, and consequently increase the overvoltages even more.

The core saturation condition can be observed through the current waveforms of phases B and C magnetizing current, shown in Fig. 9.

V. CONCLUSIONS

When the distribution transformer core configuration influence is underestimated, choosing a five legged core configuration representation instead of a three legged one, could lead to overlook overvoltages and saturation conditions that in a real distribution transformer with a three-legged core type may occur under unbalanced excitation.

Although neither the five-legged nor the three-legged core type configuration selected models represent magnetic coupling among phases properly, the equivalent electric circuit employed by the second one reproduces, in some way, through the zero sequence magnetising inductance the magnetic coupling among phases. Therefore this model is more appropriate to make evident the overvoltages that could occur on the other two phases involving the cable capacitance and the non-linear behaviour of the core.

The five-legged core type available model definitely fails to reproduce voltages induced over the two other phases as well as the non-linear phenomena developed on such phases.

In the case under study several different circumstances appeared and were responsible for the overvoltages developed over the two apparently de-energised transformer phases. First of all it is worth to be mentioned the unbalance condition that excites the low zero sequence magnetising inductance that this kind of core configuration presents. Then it is also important to mention the series LC circuit near resonant conditions which result in high voltages exciting the non-linear behaviour of the transformer core. Finally the lack of damping, cause of long permanence of high voltages that, without any additional protective action, may affect the transformer insulation.

A real case confirms the overvoltages predicted considering that serious damage were registered in a lightly loaded three-phase three-legged core form distribution transformer when one pole remained closed after an anomalous three-phase circuit breaker opening operation.

To sum up, the representation of the special behaviour of the three-legged core configuration under zero sequence excitation conditions becomes essential for the system being analysed. The three-legged representation available from the ATP seems to show, in this case, a better performance to reveal the abnormal conditions that stress the transformer, than the five-legged representation also available in the ATP.

VI. REFERENCES

[1] R. Iravani et al., “Modelling Guidelines for Low Frequency Transients”, *IEEE PES Special Publication “Modelling and Analysis of System Transients” 99TP133-0,* 1998, pp.3-1/3-29.

[2] Phillipe Ferracci, “Ferrorresonance”, *Cahier Technique Schneider n°190*, March 1998.

[3] Bonneville Power Administration, *Electromagnetic Transients Program Rule Book*, Portland, Oregon, April 1982.