IEEE Transactions on Power Delivery, Vol. 6, No. 1, January 1991

TRANSIENT SIMULATION AND ANALYSIS OF A THREE-PHASE FIVE-LIMB STEP-UP TRANSFORMER FOLLOWING AN OUT-OF-PHASE SYNCHRONIZATION

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ABSTRACT

This paper presents the theoretical and the experimental analysis of the electromagnetic transient following the out-of-phase synchronization of a three-phase five-limb step-up transformer; this means an abnormal condition where the angle between phasors representing the generated voltages and those representing the power network voltages at the instant of closure of the connecting circuit breaker is not near zero, as normal, but may be as much as 180°(phase opposition). When this happens, the peak values of the transient currents in the windings of the transformer might be sensibly higher than those of the failure currents estimated in a conventional way; in addition they correspond to unbalanced magnetomotive forces (MMF) in the primary and secondary windings of each phase of the machine.

The currents and fluxes during the transient are computed by a non-conventional circuital non-linear model of the transformer simulated by the ElectroMagnetic Transient Program (EMTP). The results of an experimental validation made on a specially built 100 kVA three-phase five-limb transformer are also reported.

Key Words: Three-phase 5-limb transformer models, Out-of-phase synchronization, Magnetic networks, Duality.

1. INTRODUCTION

The operation of generator step-up transformers following short-circuit events is, from the electromechanical stresses point of view, rather more secure than that of interconnection transformers and autotransformers. For the latter, in fact, a short circuit, whether on the high-voltage (HV) or on the medium-voltage (MV) network, is supplied from large powers and the resulting currents are very close to that determined by the only impedance of the machine. On the contrary, in step-up transformers, in the case of short circuit on the HV network, the currents are limited by the direct-axis subtransient impedance of the synchronous generator, which is relatively high, whereas a short circuit at the low voltage (LV) terminals is extremely unlikely, bearing in mind the type of the connection between synchronous generator and transformer, usually made with segregated bars.

Nevertheless it is not rare, unfortunately, that step-up transformers undergo an out-of-phase synchronization operation, that is an abnormal condition where the angle between phasors representing the generated voltages and those representing the power network voltages at the instant of closure of the connecting circuit breaker is not zero, as normal, but may be as much as 180 (phase opposition).

90 WM 225-3 PWRD A paper recommended and approved by the IEEE Transformers Committee of the IEEE Power Engineering Society for presentation at the IEEE/PES 1990 Winter Meeting, Atlanta, Georgia, February 4 - 8, 1990. Manuscript submitted July 31, 1989; made available for printing December 6, 1989.

Although there are not many papers published on the analysis and the effects of the out-of-phase synchronization operation of transformers [1-2], this problem is very important in consideration of both the high repair cost of large power transformers and synchronuos machines added to the long outage time. Therefore a model which allows the prediction of the values of the currents in the windings during an out-of-phase synchronization event with suitable accuracy is very useful. From these currents, the magnitude of the related electromechanical stresses can be determined.

The axial electromechanical stresses due to a out-of-phase synchronization transient might lead to the failure of the windings, particularly of the HV coils connected to the power network. Fig.1 shows a photograph of an HV coil of a large power three-phase five-limb transformer which has undergone a wrong parallel operation with a network the power of which was nearly 70 times greater than the rating of the transformer.

The parallel connection of a transformer, energized by a generator with the same power, to a network having a power 50-100 times greater, leads to an electromagnetic transient with different and very high saturation level of the various iron branches of the magnetic circuit, much heavier than that corresponding to the rated flux operation. In fact, if it is assumed

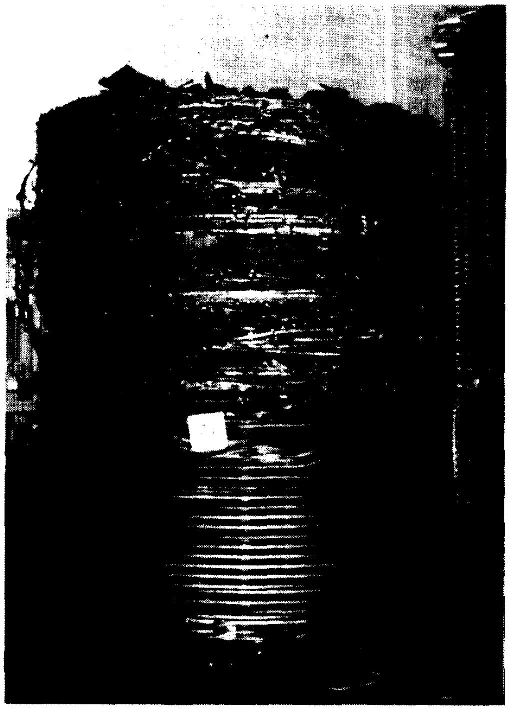

Fig.1 - HV coil of a large power step-up transformer which has undergone a failure caused by excessive axial electromechanical stresses due to an out-of-phase synchronization operation.

that one phase voltage is zero at the instant of the synchronization with 180° phase-error, the corresponding flux linkage is maximum. Further, since this voltage gets on a half wave with the same sign of that just described, the linkage flux with the HV coil goes on to increase until a peak value not much less than 3 times the rated flux is reached. Consequently, the iron branches of the magnetic circuit undergo a very high saturation, analogous to that which would happen in an inrush operation with a residual flux density equal to the rated one. It follows that the MMFs on the iron branches are by no means negligible and the corresponding magnetizing currents are of the order of the rated ones. The MMFs associated to the iron branches combine with those associated to the leakage branches and give, as a result, the MMFs of the primary and secondary windings which, because of the contribution of the iron branches, are considerably unbalanced. In other words, a short-circuit transient adds to an inrush transient with maximum initial flux.

It is clear that, for a correct analysis of the outlined phenomenon, the transformer model has to consider a subdivision of the magnetic core in more branches with non-linear characteristics. Further, it is also evident that the conventional models of the three-phase transformer, set up with the leakage inductances and one saturable element per phase, are completely inadequate for the present analysis.

Details are given below of how to obtain a circuital model of the transformer by the procedure of the duality, starting from the magnetic network associated to the real configuration of the core and the windings. The obtained model for a large power transformer (370 MVA) is simulated with different impedance of the power network. An experimental validation of the theoretical results was carried out on a specially built 100 kVA transformer.

The simulation of the model was made by the ElectroMagnetic Transient Program (EMTP)[3].

2. METHOD OF ANALYSIS

2.1- Circuital model of the three-phase five-limb transformer.

The structure of a three-phase five-limb transformer is represented in Fig.2a. The windings are assumed to be made with three couples of concentric coils: three LV internal coils and three HV external ones. The core is made up of three wound limbs of equal sections, four intermediate yokes A-C, C-E, B-D, D-F and two lateral branches, composed of the lateral limbs and the related yokes. The lateral limbs and yokes normally have a smaller section than the wound limbs. Usually the intermediate yokes and the lateral limbs may have the same cross section (about 0.57-0.58 times the cross section of the wound limbs) or the lateral yokes and limbs may be smaller (nearly 0.4) and the intermediate yokes bigger (0.7 times the cross section of the wound limbs) accordingly the required reduction of the total core height.

The adopted circuital model comes from the magnetic network associated with the real configuration of the transformer by duality [4-8]. The magnetic network is set up by the nodes and the most significant flux tubes which approximate the real map of the magnetic field. The number of the nodes and branches to consider are to be selected in order to approximate the field satisfactorily, without complicating the magnetic network excessively.

The concept of magnetic network is based on the description of the field by means of the scalar magnetic potential [9], the definition of which implies rotH=0 in the considered space. Hence it is necessary to outline an essential difference between the flux tubes of the real magnetic field and that considered to set up the magnetic network. Whereas the first can also exist in regions where rotH is not zero, i.e. where there are currents, the second ones cannot. In other words, the field is assumed to be exclusively confined into the flux tubes which form the magnetic network, and they must be totally linked with the coils. Therefore, the radial thickness of the coils has not been considered. Further, the eddy-current loss of the magnetic core is assumed to be negligible.

At first, the nodes of the magnetic network have to be outlined. It is reasonable, in the present case, to select three nodes on the upper yoke (A, C, E) and three on the lower one (B, D, F). These nodes subdivide the core into nine branches outlined by the corresponding reluctances: three for the wound limbs, two for the lateral yokes and limbs, four for the intermediate yokes - two on the top and two at the bottom - which are in series and can be reduced to two. As a consequence, the network is simplified and the previous three nodes in the lower yokes can be put together and represented by just one.

Parallel to each iron branch there is an air branch, which is not usually considered in the conventional models of transformers but is indispensable for the analysis of the heavy saturated behaviour. Finally, between each top node and the corresponding lower node there is the leakage reluctance associated with each couple of concentric coils.

The sources of the magnetic network are represented by the MMFs of the six coils. These sources have to be concentrated out of the space where the field is supposed to be confined.

The magnetic network described is reported in Fig.2b with a linear or non-linear reluctance (the non-linear ones are shown in black) for each branch and a MMF source for each coil. In conclusion, the magnetic network includes seven non-linear reluctances and as many parallel linear reluctances, three leakage reluctances and six MMFs sources.

The corresponding dual electric network can be obtained from the magnetic network, assuming a common reference number of turns N (Fig.2c). An inductance ($L=N^2/R$) corresponds to a reluctance (R), a current source ($i=F/N$) corresponds to a MMF source (F), a node corresponds to a loop, series elements correspond to dual elements in parallel and so on.

The analysis of the electric network also gives all the information concerning the magnetic network of the transformer; in fact, on the base of the duality, there is a correspondance between the voltage **v** of a branch of the electric network and the flux **Φ** of the corresponding dual branch of the magnetic network ($\Phi=(\int v\cdot dt)/N+\Phi_0$) as well as between the current i of a branch of the electric network and the MMF **F** on the terminals of the corresponding dual branch of the magnetic network ($F=N\cdot i$).

The model so obtained has to be improved with six ideal transformers, both to take into account the actual number of turns of the coils and to allow for the star or delta connection of the windings. So far, no dissipation parameters have been considered and the radial thickness of the coils has been neglected. If the resistances of the windings and both the synchronous machine and the power network models are included, the equivalent network becomes that of Fig.2d. This is, finally, the circuital model used for the simulation of the wrong synchronizing transient.

As it is the first few periods of the transient just after the starting of the wrong parallel that are of interest, it is not necessary to adopt a dynamic model for the synchronuos machine. A three-phase voltage source in series with the direct-axis subtransient impedance is deemed to be suitable. The power network model is made by a three-phase voltage source in series with the impedance of the network.

Both the HV network and the HV transformer side have earthed neutrals.

A possible further improvement of the model of the

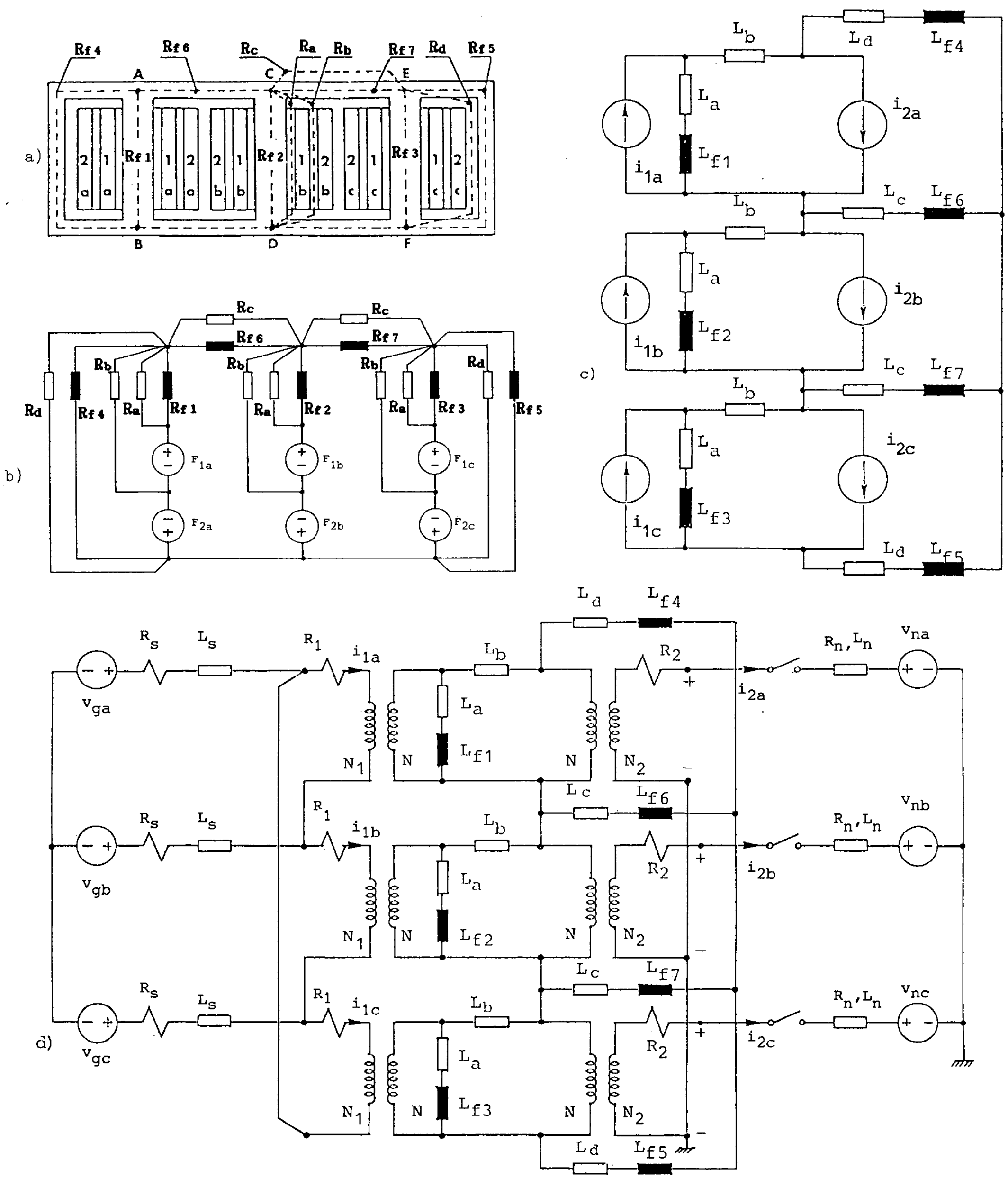

Fig.2 - Three-phase five-limb transformer: a)structure and main flux tubes; b)magnetic network; c)equivalent electric network; d) complete equivalent electric network of the transformer delta-star connected with neutral earthed, of the synchronous machine and of the power network.

transformer should consider the thickness of the coils. They could be taken into account by means of six negative inductances, each in series with the terminals of an ideal transformer. Each negative inductance corresponds to a negative air flux tube totally linked with each coil, i.e. in parallel to each MMF source, and take into account the influence of the partially linked phisical flux tubes [6].

2.2- Determination of the parameters of the equivalent network of a three-phase five-limb transformer.

The equivalent network of a three-phase five-limb transformer shown in Fig.2c has seven non linear inductances and ten linear ones.

The flux-current curve of the non-linear inductances is determined by the B(H) curve of the magnetic steel used to build the core, the section and the length of each iron branch. This is enough for computing the currents with very high saturation level but gives values which are well lower than the real ones when the flux is near to the nominal value, since the equivalent air gaps of the core have not been considered. Therefore, if the model must also be accurate for these last conditions, a linear inductance in parallel to each iron inductance is needed in the equivalent network. Such inductances are not visualized in the Fig.2c.

The linear inductances of the transformer model include three leakage inductances, which are assumed to have the same value and can be computed or determined by the short circuit test, and seven inductances associated to the air flux tubes in parallel to those in iron. Due to the symmetry, the three inductances in series with the non-linear inductances of the wound limbs are equal as well as the two inductances for the intermediate yokes and those for the lateral branches. Consequently, there are only three linear inductances to be determined: L_a, L_c and L_d (Fig.2c).

The calculation of L_a, L_c and L_d can be made by the following criterium: assuming that the equivalent network of the transformer is supplied from the terminals of a coil in order to be in a very high saturation condition, the inductance seen from those terminals is imposed to be equal to the air-core inductance of that coil. This value is a minumum physical limit which can be computed with certainty on the base of the geometrical dimensions of the coil. In this procedure, the vacuum permeability is used for computing the saturated inductances of the iron branches.

The inductance of the network as seen from three different couples of terminals, let us say, for example, those of the internal and the external coils of the central limb and those of a coil of a lateral limb, are expressed by a system of three algebraic equations which gives the three unknown inductances L_a, L_c and L_d.

The values of the air inductances are reported in App.A for the transformers analysed in this paper.

2.3 - Model simulation

The analyis of the out-of-phase synchronization operation of a three-phase five-limb transformer has been made with a phase error of 180°, that is in phase opposition.

First, the transformer is taken on no-load operation, and then the circuit breacker closes at the instant in which the voltage of the phase named 'a' is zero. The power of the network is assumed to be equal to 40 and 12.5 GVA, that is almost 108 and 34 times the rating of the transformer analysed, which is assumed equal to 370MVA.

The parameters of the equivalent network are listed in detail in App.A. The direct-axis subtransient reactance of the synchronuos machine is 22.7%; the leakage reactance of the transformer is 12.8% and the network reactance is 0.91% or 3%, respectively, for the two powers selected. The resistance is almost 1% for the generator, 0.2% for the transformer and 0.1% for the power network. The reference value is the nominal impedance of the transformer.

The results of the simulation of the transient operation of the three-phase five-limb transformer, with phase-error of 180°, are presented in Fig.3: phase voltages, flux linkages with the coils, phase currents just before and after the operation of the circuit breaker are shown. The maximum values of the various quantities, in their first peak, for both the values of the reactances of the network (0.91% and 3%), computed with the non-linear model (NLM) of Fig.2d are reported below and compared with those obtained not taking into account the magnetizing currents of the iron branches, i.e. by the corresponding linear conventional model (LM). All the computed quantities are expressed in per unit and refer to the corresponding nominal values of the transformer.

Phase currents (reference value: 755.3 A, peak value; 370MVA, 400kV, HV side):

	0.91%		3%	
phase	NLM	LM	NLM	LM
a1	-9.8	-10.5	-9.57	-9.94
a2	-11.5	-10.5	-10.59	-9.94
b1	8.0	7.9	7.51	7.52
b2	8.4	7.9	7.79	7.52
c1	8.2	8.0	7.66	7.62
c2	8.7	8.0	8.06	7.62

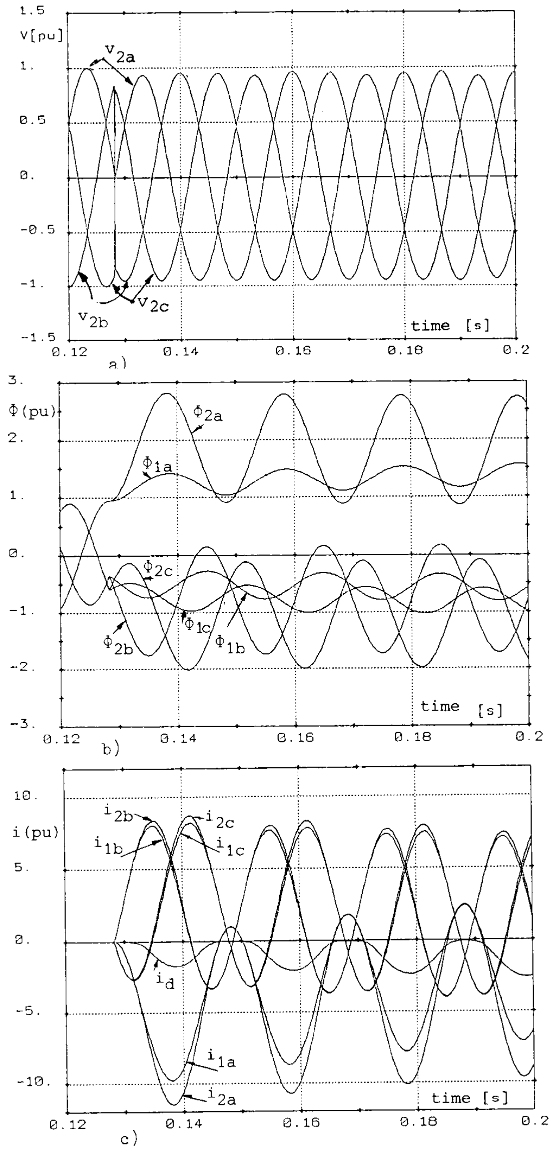

Fig.3- Computed transient of an out-of-phase synchronization operation of a three-phase 5-limb transformer with 180° phase-error: short circuit inductance 12.8%, direct-axis subtransient inductance 22.7%, power network inductance 0.91%; a) secondary phase voltages in per unit before and after the instant of the wrong parallel; b)flux linkages with the coils in per unit; reference flux linkage: 1040 Wb; c)phase currents and differential current $i_d=i_{a2}-i_{a1}$ of the most stressed phase in per unit; reference current of H.V.side: 755.3 A, peak value.

Flux linkages with the coils:

	0.91%		3%	
phase	NLM	LM	NLM	LM
a1	1.57	1.71	1.48	1.60
a2	2.83	2.83	2.61	2.63
b1	1.15	1.15	1.14	1.15
b2	1.75	1.15	1.61	1.14
c1	1.10	1.10	1.09	1.10
c2	2.00	2.00	1.85	1.87

Reference value: 1040 Wb (2.09 Wb·497 turns).

Total fluxes in the air and iron reluctances connected in parallel in the magnetic network of Fig.2b (for shortness, only the index number of the iron element is pointed out):

	0.91%	3%
branch	NLM	NLM
4 e 5	0.95	0.902
6	1.88	1.72
7	1.11	0.996

Fluxes in the iron reluctances of the magnetic network:

	0.91%	3%
branch	NLM	NLM
R_{f1}	1.41	1.36
R_{f2}	1.14	1.14
R_{f3}	1.09	1.09
R_{f4} e R_{f5}	0.707	0.702
R_{f6}	0.73	0.725
R_{f7}	0.70	0.692

Magnetizing currents of the iron branches:

	0.91%	3%
branch	NLM	NLM
R_{f1}	2.07	1.55
R_{f2}	0.044	0.045
R_{f3}	0.014	0.014
R_{f4} e R_{f5}	0.548	0.454
R_{f6}	0.998	0.851
R_{f7}	0.350	0.261

The previous results, when the reactance of the power network is 0.91%, are commented below.

The ratio between the current peak values of phase 'a', which is the most stressed one, is 11.5/9.8≐1.173. In comparison with the per unit current evaluated with the linear model (10.5), i.e. following the conventional procedure, the non-linear model gives a current 6.7% less in the internal coil and 9.5% more in the external one.

It is to be noted that the maximum value of the difference between the istantaneous value of the currents reaches the value of 3.1 p.u., which is greater than the difference between the peak values (1.7 p.u.), as shown in Fig.3c.

Still referring to phase 'a', the maximum flux linkage with the external coils reaches the value of 2.83 p.u. whereas the maximum flux linkage with the internal coil is 1.57 p.u.; the difference between them is equal to the leakage flux, as is evident from the magnetic network of Fig.2b. The flux linkage with the external coil is also equal to the sum of the total flux in the air-iron parallel of the adjacent lateral branches (0.95, with index number 4) and that of the air-iron parallel of the adjacent yoke (1.88 with index 6). In the lateral branch, 74% (0.707/0.95) of the flux goes in the iron path and gives a flux density of 2.11 T and a magnetizing current of 0.548 p.u. (it should be noted that the section of both the lateral limbs and yokes is 0.57 times that of the wound limbs and the nominal flux density is assumed to be equal to 1.7 T; therefore 0.707·1.7/0.57=2.11 T).

In the parallel of the adjacent yoke, only 39% of the flux goes in the iron path; it gives a flux density of 2.16 T and a magnetizing current of 0.998 p.u.

In the parallel of the other yoke (with index number 7), 63% of the flux goes in the iron path, i.e. more than in the yoke number 6, since the saturation level is lower. This flux gives a flux density of 2.07 T and a magnetizing current of 0.35 p.u.

In the parallel of the wound limb of phase 'a', 90% of the flux goes in the iron path; this gives a flux density of 2.41 T and a magnetizing current of 2.07 p.u., which is the greatest contribution due to the saturation of the iron branches.

It is important to compare the flux linkages with the internal and the external coils (1.57 and 2.83 p.u.) and magnetizing current associated to the respective iron branches (2.07 as compared with 0.548+0.989=1.546). It can be seen that the iron path of the wound limb has a saturation level (2.41 T) higher than that of both the iron of the lateral iron path (2.11 T) and the iron of the adjacent yoke (2.16 T) although the flux of the internal coil is nearly half the flux of the external coil. This is because the air inductance L_a, in parallel with the wound limb, is nearly 1/6th of the air inductance L_d, in parallel with the lateral limb and nearly 1/15th of of L_c, in parallel with the yoke. This clarifies the importance of the air branches in parallel with the iron branches in the magnetic network of a transformer operating with very high saturation level. On the contrary, if the model were to be used to simulate a nearly rated flux operation, the above mentioned air branches could be completely neglected.

It should be noted that the two lateral limbs have nearly the same fluxes with opposite sign because both the impedance of the power network is very small and its voltage system has a zero value resultant.

The second case, with 3% value for the power network impedance, is obviously less heavy than the previous one but substantially similar.

The maximum values of the unbalanced MMFs of the most stressed phase can be used for computing the magnetic field in the space occupied by the coils, by means of numerical methods, in order to evaluate the distribution of the axial electromechanical stress. A further study will consider this analysis.

3 - EXPERIMENTAL VERIFICATION

The experimental verification of the theoretical results was carried out on a three-phase five-limb transformer rated 100 kVA, specially built and proportioned in order to have a per unit short-circuit voltage nearly equal to that of a 370MVA power transformer, like that simulated in the previous paragraph. The characteristics of the test transformer are listed in detail in App.A. It has the same number of turns on both the primary and the secondary windings which are delta-star connected. A series of EMF search coils were mounted both on the coils and the core to measure, by integration, the corresponding fluxes.

The test circuit is schematically represented in Fig.4a and a photograph of the test equipment is shown in Fig.4b. The test circuit includes a source, represented by a synchronous machine (SM) rated 17MVA, a three-winding transformer (TWT) rated 17 MVA, the test transformer (TT), two impedances Z_a and Z_b and a synchronized circuit breaker (SW). The three-winding transformer (TWT) is connected delta-delta-star: the primary is connected to the synchronous generator, the secondary delta-connected winding supplies the primary side of the test transformer, through the Z_b impedance, and the secondary star-connected winding supplies the secondary side of the test transformer through the Z_a impedance and the synchronized circuit breaker.

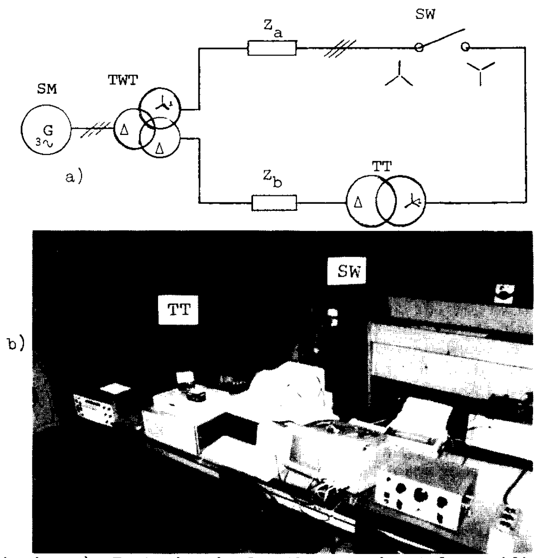

Fig.4 - a) Test circuit for the experimental verification of the out-of-phase synchronization operation of a three-phase 5-limb transformer rated 100 kVA. SM: synchronous machine rated 17 MVA; TWT: three-winding transformer rated 17 MVA; TT: test transformer rated 100 kVA; Z_a and Z_b impedances: 0.653{84.5°} Ω and 2.352{89.3°} Ω respectively; SW: synchronized circuit breaker. b) test equipment.

The connection of the two secondary windings of the TWT transformer is made in order to have phase opposition of the two voltage systems.

The synchronous machine SM and the TWT transformer are both rated 17 MVA, that is 170 times the rating of the test transformer. Therefore their impedance are very small in comparison with those that have to be included in order to simulate the per unit impedance of a real power system experimentally. Hence the need for the impedances Z_a and Z_b, the value of which are selected to represent the impedance of the power network and the direct-axis subtransient impedance of the SM, respectively.

The paralleling test with 180° of phase-error is made after the TT transformer has been supplied and is operating on no-load condition, by closing the synchronized circuit breaker at the instant when the voltage of a lateral phase, named 'a' is zero. The opening of the circuit breaker follows after nearly 0.5 s.

A multi-channel acquisition system, with sampling frequency of 33kHz (Multiprogrammer HP 6942), controlled by the computer HP 9826S, permits the acquisition and the processing of signals proportional to the quantities of interest. The sampled quantities are: phase voltage 'a', primary and secondary currents of the same phase, EMFs of the search coils mounted in order to give, by integration, the flux linkages with both coils of the examined phase or the flux in the various branches of the core.

Measured voltage of phase 'a', currents and flux linkages of both coils of the same phase are reported in Fig.5. The test transformer was supplied with the rated voltage and the power network impedance was 2.41%.

The computed quantities for phase 'a', corresponding to those of Fig.5, are reported in Fig.6. They were computed by the circuital model of Fig.2d and the parameters listed in detail in App.A.

The comparison among the computed and the measured values is reported below:

Measured		Computed		Difference	
i_{1a}	i_{2a}	i_{1a}	i_{2a}	i_{1a}	i_{2a}
[A]		[A]		%	
336.7	551.2	351.8	521.7	+4.5	-5.4
[p.u.]		[p.u.]			
7.14	11.69	7.46	11.07		

The reference current is the rated one: 47.14 A (peak value).

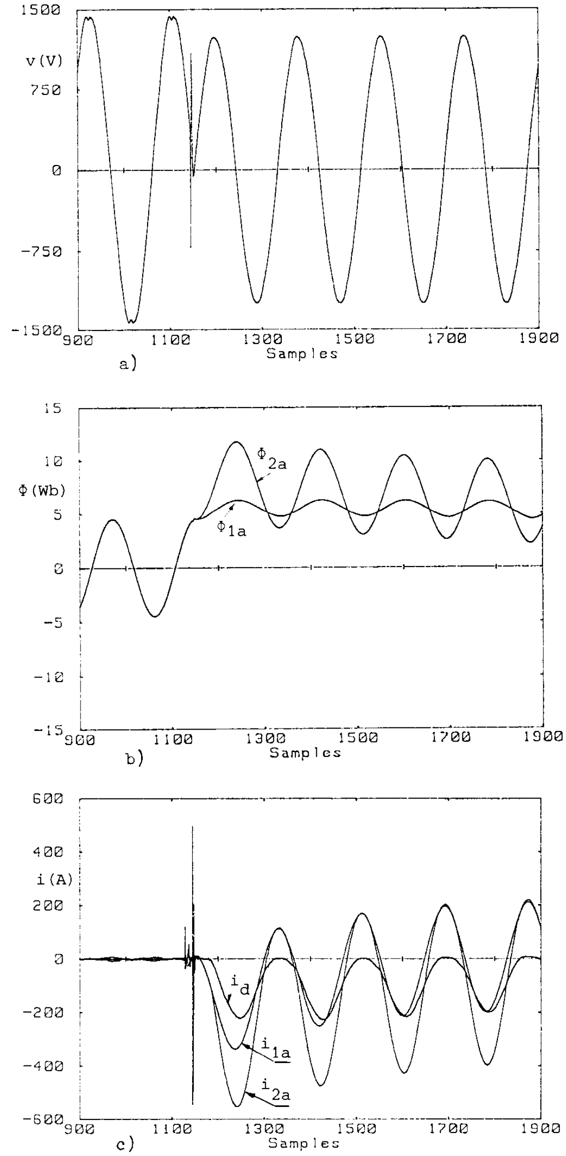

Fig.5- Measured transient of an out-of-phase synchronization of a three-phase 5-limb 100 kVA transformer with 180° phase-error: short circuit inductance 12.7%, direct-axis subtransient inductance 22.8%, power network inductance 2.41%; a) secondary line-to-neutral voltage of phase 'a'before and after the instant of the wrong parallel; b)flux linkages with the coils of phase 'a'; rated flux: 4.5 Wb; c)phase currents and differential current $i_d=i_{a2}-i_{a1}$ of the most stressed phase; rated current: 47.13A, peak value.

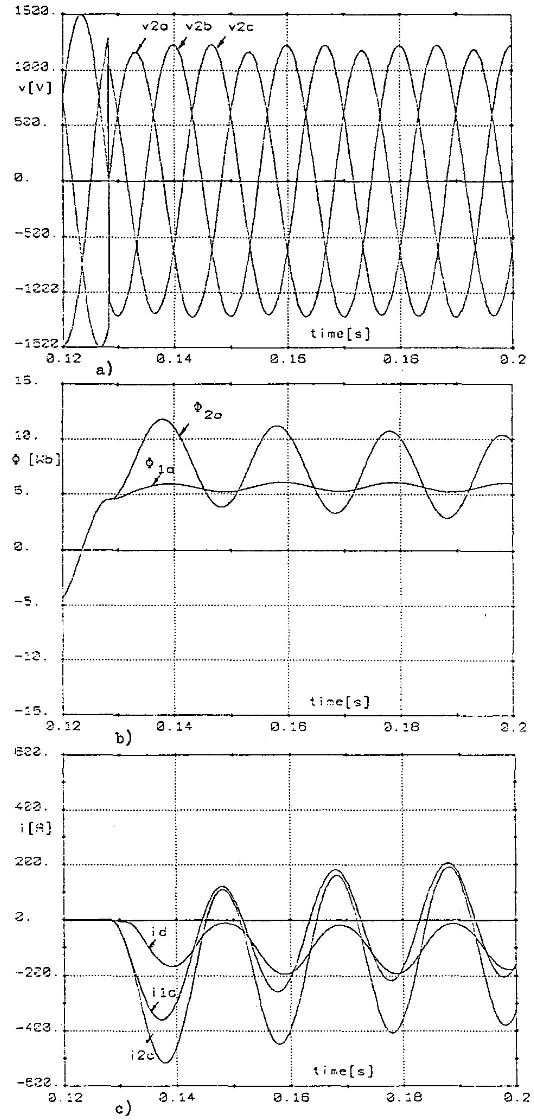

Fig.6- Computed transient of a out-of-phase synchronization of a three-phase 5-limb transformer rated 100 kVA with 180° phase-error, corresponding to the measured transient shown in Fig.5 with the same parameters.

The measured maximum unbalance between i_{2a} and i_{1a}, which is proportional to the MMFs unbalance, is of 226.9 A (i.e. 4.8 p.u.) and the computed one is 203.9A (4.3 p.u.). This maximun unbalance take place around the second peak of the currents and is greater than the difference between their peak values because the current peaks are not simultaneous.

It should be noted that the conventional evaluation of the currents, neglecting the magnetizing currents of the iron branches of the model of Fig.2d, would give a peak value $i_{a(conv)}$=415.5 A. Hence:

$$i_{1a}/i_{a(conv)} = 0.8467$$

and

$$i_{2a}/i_{a(conv)} = 1.256.$$

with the computed values.

The flux linkages with the internal coil (Φ_{1a}) and the external one (Φ_{2a}) are:

Measured		**Computed**		**Difference**	
Φ_{1a}	Φ_{2a}	Φ_{1a}	Φ_{2a}	Φ_{1a}	Φ_{2a}
[p.u.]		[p.u.]		%	
1.39	2.66	1.30	2.62	-6.5	-1.5

referred to the rated flux linkage, which is 4.5 Wb.

When the unbalance of the MMFs in the test transformer (1.48) is compared with that in the high power transformer simulated above (1.17), a remarkable differenze is evident. This is mainly because the per unit value of air inductance L_a of the 100kVA transformer is much less than that of the 370MVA transformer (0.03284 p.u. as compared with 0.4346 p.u.). This air inductance, associated to the air flux tube in parallel to the iron flux tube of the wound limbs, has the important role of limiting the corresponding magnetizing current during the operation with very high saturation level.

The agreement among the computed and the experimentally measured results is satisfactory. Consequently, the validity of both the proposed model and the methodology adopted for the analysis can be regarded as positive. Therefore, this methodology can be applied for the study of the electromagnetic behaviour of large power three-phase five-limb transformers during the out-of-phase synchronization operation.

4.- CONCLUSIONS

This paper presents the analysis of the electromagnetic transient of a large power three-phase five-limb step-up transformer, during a 180° phase-error synchronization operation. The analysis has been made by a nonconventional circuital model for the transformer, to take into account the very high saturation level of some branches of its magnetic core. The simulation of the model was carried out by the ElectroMagnetic Transient Program (EMTP).

The obtained results have shown that:

(1) the peak value of the MMF in the HV coil of the most stressed phase is 10-20% greater than that evaluated in a conventional way, that is not taking the magnetizing current of the iron branches of the magnetic network of the transformer into account;

(2) there is a notable unbalance between the primary and the secondary MMFs of the same phase, due to the demand of MMFs on the very high saturated iron branches. The unbalance depends on the geometry of both the coils and the magnetic core of the transformer. Further, it increases as the power of the network increases. With a network having a power 100 times the rating of the transformer, the unbalance of the MMFs of the same phase is of the order of 3 p.u.

The experimental check of the validity of the proposed model has been carried out on a specially built 100 kVA three-phase five-limb transformer. The agreement between computed and measured results was satisfactory.

The result of the present work is the preliminary important step for the subsequent evaluation of the axial electromechanical stresses on the coils, which are expected to be notably higher than those conventionally evaluated with balanced MMFs. This will be the object of a future study.

ACKNOWLEDGEMENTS

This research was carried out in collaboration with the Societa' Nazionale delle Officine di Savigliano of

Turin (Italy). The author wishes to express to Mr.G.Sgorbati the recognition for his intuition concerning the greater magnitude of the actual stresses, in comparison with those predictable by conventional evaluations, in step-up transformers during wrong parallel operations. Further, the author wishes to thank both Mr.M.Borsani and Mr.M.Amprimo for their technical and experimental support as well as their valuable suggestions during the development of this research.

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APPENDIX A

Values of the parameters of the circuital model of Fig.2d for both a large power plant (in first column) and the test circuit (in second column).

Five-limb transformers

The nominal characteristics are:

Rated power	370 MVA	100kVA
Nominal voltages	20 kV/400 kV	1kV/√3kV

Connection: delta on the LV side and star with neutral earthed on the HV side.

All the parameter values refer to the number of turns of the HV coils which is 497 for the 370MVA transformer and 237 for the 100 kVA transformer.

The magnetization curve B(H) of the iron branches is that of a typical cold-rolled grain-oriented steel. The length (in m) of the various iron branches of the magnetic circuit are:

	370MVA	100kVA
$l_{f1}=l_{f2}=l_{f3}$	2.790	0.462
$l_{f4}=l_{f5}$	6.030	0.954
$l_{f6}=l_{f7}$	4.690	0.830

and the corresponding cross sections (in m^2) are:

wound limbs	1.220	0.01099
yokes and lateral limbs	0.695	0.006375

Knowing the saturated inductances (in mH):

wound limbs	$L_{f1}=L_{f2}=L_{f3}$	135.9	1.679
lateral limbs	$L_{f4}=L_{f5}$	36.15	0.4717
intermediate yokes	$L_{f6}=L_{f7}$	46.48	0.5421
leakage	L_b	176.7(12.8%)	12.09(12.66%)

and the air inductances (in mH):

internal coils L_{a1}	206.2	4.533
external coils L_{a2}	314.7	13.43

the following air inductance values are obtained(in mH):

L_a	104	3.136
L_c	1602	95.26
L_d	609	32.20

The phase resistances (in Ω) are:

primary	R_1	0.3773	0.1208
secondary	R_2	0.5104	0.2104

Synchronous machines

Resistance R_s (Ω)	1.44 (.999%)	0.2946(2.95%)
Direct-axis subtransient inductance L_s(mH)	104.1 (22.69%)	7.565 (23.77%)

Power networks

Resistance R_n(Ω)	0.43 (0.1%)	0.078 (0.26%)
Inductance L_n (mH)	12.52 (0.91%) or 41.29 (3.0%)	2.301 (2.41%)

Cesare Mario Arturi (M'88)was born in Italy in 1950. He received his Electrical Engineering degree from the Politechnic of Milan (Italy) in 1975. From 1975 to 1985 he was Assistent Professor at the Electrical Department of the Politechnic of Milan for the Electric Machines course. Since 1985 he has been Associate Professor of Electrical Engineering at the Politechnic of Milan where he teaches Fundamentals of Electrical Engineering. His special fields of interest are the theory of the parametric transformer and the problems related to the thermal and electromagnetic modellization of large power transformers and reactors.

He is Member of the IEEE Power Engineering Society and Expert of the Technical Committee n.14 on Power Transformers of the Italian Electrotechical Commission.

Discussion

Adam Semlyen and Francisco de Leon (University of Toronto): We wish to congratulate Professor Arturi for his interesting and well written paper. Our discussion will focus on the derivation of the equivalent circuit, as shown in Fig.4.

While we fully agree with the final result of Fig.4d, we wonder whether the explicit representation of MMF sources in Fig.4b and of current sources in Fig.4c is necessary or useful? The reason for this question is that the symbol of a reluctance in Fig.4b could imply the existence of both a flux through it and of the related magnetic drop (negative MMF), provided that in all meshes with windings we assume the existence of the MMF excitation of the windings. Consequently, as an alternative to the author's procedure, we indicate a direct, graphical derivation of the equivalent circuit[1,2,3], based on the graph of the magnetic circuit drawn in thin lines in Fig.A. This part of Fig.A corresponds to the reluctances of Fig.4b, with two lines shown for those reluctances which are in parallel, without windings in between. The next step is to put nodes, represented by •, in all meshes with windings, and to draw inductance branches (strong lines in Fig.A) to cut all reluctance branches (the thin lines). The "external node" is represented by a dashed line. Inductance branches in parallel have been lumped together. The nodes with MMF sources (•) will be used to connect the corresponding ideal transformers (after the negative inductances have been added[3], as pointed out by Professor Arturi) and all the rest of the elements shown in Fig.4d. In Fig.A braces P_a, P_b, and P_c indicate the connection of the ideal transformers for the primary windings and S_a, S_b, and S_c for the secondary windings. Rotation by 90° of the electric part of the graph of Fig.A permits to verify that it is, in essence, identical to the central part of Fig.4d.

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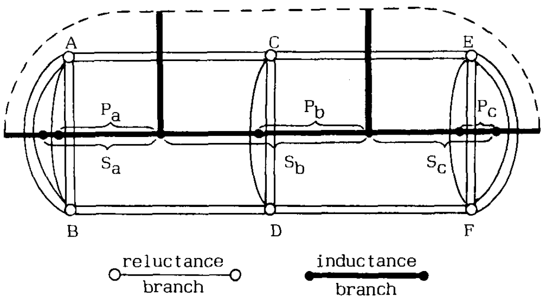

Fig.A Direct implementation of duality using the graph of the magnetic paths (thin lines) to obtain the graph of the inductances (strong lines) of the electric equivalent of the transformer. The external connections are via ideal transformers connected to P_a, P_b, P_c (primary) and S_a, S_b, S_c (secondary).

Manuscript received February 28, 1990.

Robert J. Meredith (New York Power Authority, White Plains, New York): Discusser agrees with the author on the necessity of developing saturable transformer models from physical parameters and commends him for his correct evolution of an equivalent electrical circuit from an initial magnetic circuit. However, the author's demonstration of winding currents only 10% greater than found with a linear model indicates that his test case is not very sensitive to the nonlinear and saturated linear parameters of his models. Consequently, his model for a saturated transformer cannot be validated very well, even against the physical model he developed. In the context of mechanical winding failure, discusser also believes that direct analysis of relative winding forces, being the product of current and an appropriate leakage flux density, would have provided more insight than a discussion of winding current differences, whose significance is unstated. A comparison of the test case against a design-basis transformer fault simulation would have been welcomed.

The author's iron flux path model appears appropriate, except for the omission of the steel tank. When the end limbs of the transformer saturate, flux is forced into air paths outside the core. The tank steel, being thousands of times better at conducting flux than air, cannot be ignored, except at great error to the external air-flux paths modeled. There also appear to be inconsistencies in the tabulations of iron fluxes. The smaller sized limbs all display saturated flux densities just above the 2-Tesla capability of transformer steels, but the author's identification of a 2.41-Tesla level within the wound core cannot be so reconciled. The discrepancy potentially causes large undercalculation of excitation currents, leakage fluxes and winding forces.

The use of the dimensions of core members to calculate "saturated inductances" cannot be recommended. The incremental reluctance, of what amounts to an air gap where a saturated core member exists, depends only on the geometry of adjacent unsaturated iron members or coils; it is unrelated to the cross-sectional area of the saturated limb. For wound limbs the "saturated inductance" is related to coil dimensions, rather than core dimensions. Even more to the point, the "saturated inductance" must be determined for each unique saturation condition of concern, in order to formulate an equivalent with either mutual couplings or additive terms reflecting a known sequence of limb saturation. Unlike the unsaturated iron-core counterpart, the closed loop air-flux path cannot be assumed to be composed of a summation of independent series segments whose reluctances can be individually varied without affecting the shape of the overall flux path.

Figure A displays a suggested air-flux reluctance model for the author's transformer, which would overcome many of these objections. The five iron nonlinearities at the right of the diagram are a rough attempt to model the tank as a type of nonlinear mesh. Only such a model can express the unsaturated tank's influence as a magnetic node above the core and as a shared low-reluctance path for flux in excess of fully-saturated core capacity. After tank and yoke saturation, all flux coupling between phases via air paths is assumed to disappear, approximating the very low levels which would actually exist. This is in sharp contrast to the low reluctance yoke air-path connections of the author's model. The air-flux reluctance

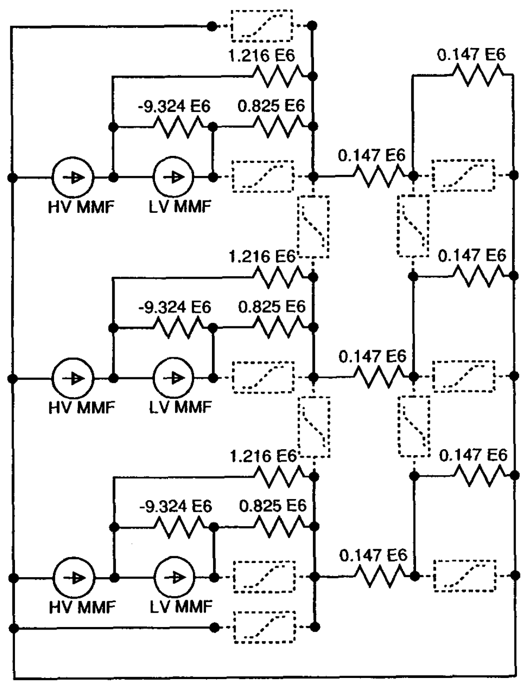

Fig. A. Suggested air-flux reluctance model for author's transformer equivalent of Figure A closely duplicates air-core coupling results for the estimated dimensions of the coils on the author's transformer (60% of HV flux coupled to open circuit LV coil; 91% of LV flux coupled to open circuit HV coil). In addition it displays: 1) appropriate leakage reluctance between HV and LV coils; 2) stated air-core reluctances of both coils; 3) upper and lower magnetic node placement closely coinciding with that of the iron flux path nodes; 4) modeling to accommodate wound-leg saturation (solenoidal reluctances) followed optionally by return path saturation. Saturation onset in the reverse order would not necessarily be modeled as accurately.

It should be noted that any one-to-one relationship between iron- and air-flux paths is only coincidental. Phase models of the same form would be used for core-form transformers having any number of legs, including single-phase designs. The model is derived from coil configuration and is independent of core design.

Manuscript received February 27, 1990.

A. Narang (Ontario Hydro Research, Toronto, Canada): The author is to be congratulated for employing a model which seems particularly appropriate for this study. A physically based electric circuit model, displaying one-to-one correspondence with flux in the non-linear magnetic circuit, seems well equipped for simulating disturbances which may produce widely differing saturation states in parts of the core. The author has clearly recognized this need and opted for an "unconventional" model. Though uncommon, similar models based on this approach have been proposed earlier/A-E/, and are completely general and rigorously valid. I would welcome the author's response to the following:

1. The author recognizes that a further improvement to the model would include negative inductances to take account of coil thickness. However, these were apparently not included in the reported study. Would their inclusion not alter calculated flux levels and MMFs, and consequently also the computed axial electromechanical stresses appreciably? Can the author give approximate values for these inductances in relation to air-inductances La1 and La2 (Appendix A), or provide winding dimensions necessary for their calculation.
2. Results are presented for a "linear conventional model" and compared with the detailed model. This may be an unfair comparison since better models can be accomodated using existing EMTP components. For example, one might use three single phase, 3-winding transformers, with the innermost winding connected in open-corner delta and a non-linear inductance connected across the open-delta to model the influence of outer limbs for zero-sequence mode. Non-linear inductors would also be connected at the innermost winding terminals to model phase magnetizing impedances. Could such models produce comparable results for this study?

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I very much appreciate the broad interest shown in this paper and I thank all the discussors for their comments and objections stimulated by the accurate evaluation of the material I have presented. Their observations point out some aspects of the analysis I have made and permit the discussion of some points which have perhaps been stated in too concise a way.

I reply to Prof.A.Semlyen and Dr.F. de Leon, as regards the method of obtaining the equivalent network of the three-phase five-limb transformer, shown in Fig.2. The field sources, either the M.M.F. sources F, associated to the coil currents (F=NI), or the flux sources Φ, associated to the voltage applied at the coil terminals ($\Phi=(\int vdt)/N$), are modelled by two-terminal sources which could reasonably be included expressly in the magnetic network. Their localization is necessary since it is not possible to state a magnetic network with only reluctances and noy sources. The analysis of the behaviour of an electromagnetic device could also be made directly in terms of magnetic network, without considering the corresponding equivalent electric network. I therefore think that it is not necessary to wait for the electric network to point out the sources. It is also evident that the current sources of the electric network are the direct consequence of the M.M.F. sources of the magnetic network.

It should be noted that any duality procedure always presents two aspects: a topological one and a physical one. The topological aspect is given by the mesh-node correspondence whereas the physical aspect, which expresses the nature of the corresponding dual circuital elements, is better expressed by the analytical procedure which transforms the magnetic equations of the independent meshes in the corresponding electric equations of the independent nodes. In other words, starting from a planar magnetic network, the behaviour of which is expressed, in matrix terms, by the magnetic equation:

$$|R|\cdot|\Phi|=|F|,$$

one gets the electric matrix equation:

$$1/(d/dt)\cdot|1/L|\cdot|v|=|i|,$$

which expresses the behaviour of the dual equivalent electric network. The magnetic network is supplied by the M.M.F. sources $|F|$ just as the dual electric network is supplied by the source currents $|i|$.

In response to Mr.A.Narang as regards the negative inductances of the equivalent electric network and their influence on the obtained results, I give here the coil dimensions of the 370MVA rated transformer examined in the paper:

	L.V.coils	H.V.coils
internal diameter[mm]	1392	1842
external diameter[mm]	1634	2192
height [mm]	1834	1914

The negative inductances L_1 and L_2, which take into account the thickness of the coils, are to be connected in series to the terminals of each ideal transformer of the equivalent network. To compute them, it is necessary to consider two fictitious coils concentric to the actual ones: one inside the L.V. coil and the other outside the H.V. one. In this way one has a 4-winding transformer for which the binary short-circuit inductances are to be computed. From the relationships between the inductances of the equivalent network of the 4-winding transformers and the short-circuit inductances, the following inductances can be obtained:

$$L_1=-11.41 \text{ mH}, \quad L_2=-27.05 \text{ mH}, \quad L_b=215.2 \text{ mH}.$$

Obviously, the value of the inductance Lb of the equivalent network now has a different value in comparison with that seen in absence of negative inductances. The sum of L_1, L_2 and L_b must in fact always be equal to the leakage inductance, which in this case is 176.7 mH. With these air-inductances and the saturated-inductances of the iron paths one has to compute the air inductances L_a, L_c and L_d, associated to the air fluxes in parallel to the iron fluxes of the wound limbs, of the intermediate yokes and the lateral limbs. The obtained values are:

$$L_a=119.8 \text{ mH}, \ L_c=1401 \text{ mH e } L_d=586.9 \text{ mH}.$$

The simulation of the improved model, including the previous inductances, gives the following results, for the most stressed phase:

$$i'_{a1}=9.69 \text{ p.u.} \quad \text{e} \quad i'_{a2}=11.65 \text{ p.u.}$$

which are to be compared with

$$i_{a1}=9.8 \text{ p.u.} \quad \text{e} \quad i_{a2}=11.5 \text{ p.u.}$$

already obtained neglecting the negative inductances. As one can see, the unbalance between the M.M.F.s increases slightly (11.65/9.69=1.20 instead of 1.17) but the conclusions already obtained by neglecting the negative inductances are substantially the same.

The second point asked by Mr. Narang refers to the use of three single-phase 3-winding transformers in order to simulate by the EMTP program the equivalent network of the three-phase 5-limb transformer. My response is that only one non-linear inductance connected across the open-delta of the innermost windings does not seem enough to me to take into account the heavy and differing saturation of yokes and lateral limbs.

One should also consider that the EMTP program permits the equivalent network of Fig.2d to be easily implemented, as it is, without forced simplification, by means of seven type-98 pseudo non-linear reactors, six ideal transformers and a number of linear inductances and resistances. Therefore, I do not see the convenience of using a network configuration different from that which has been judged suitable for modelling the physical behaviour of the device under examination. This rule is always valid, for any structure of the magnetic network or number of windings.

Finally I reply to Mr.R.J.Meredith, who raised several objections. He proposed, in turn, a magnetic network for the three-phase 5-limb transformer, which should take into account the influence of the tank when highly saturated.

The 370MVA transformer examined in this paper and the corresponding wrong parallel operation represent a real matter (no a test case) for the analysis of which a circuital model has been set up. The circuit model has been also verified experimentally on a 100kVA test-transformer and has given satisfactorily results, as reported in the paper.

The effect of saturation is more or less evident in relation to the characteristics of the considered machine. As a matter of fact, the influence of saturation on the results is more notable in the 100kVA test-transformer than in the 370MVA transformer.

As regards the suggestion of Mr.Meredith for a direct analysis of the relative winding forces by means of "an appropriate leakage flux density", it is to be noted that the radial component of the flux density in the space occupied by the windings, which is responsible for the axial mechanical stress, varies considerably. With the F.M.M. reported in the paper for the most stressed phase, it varies from about 1.0T and zero, between the end and the middle of the winding. For the calculation of the mechanical forces one has therefore to evaluate the magnetic field by a numerical method imposing the unbalanced F.M.M. computed with the proposed circuital model and then evaluate the stress tensor on the surface of the coils in the axial and radial directions.

As regards the tank, I believe we can neglect its influence in the case of a three-phase 5-limb transformer. As a matter of fact, when the lateral limbs and the yokes are in high saturation conditions, the air-inductances Lc and Ld are computed in such a way to consider that the global behaviour of the devices has to lead to the value of the air-core inductance of the supplied coils. Therefore, the inductance La, Lc, Ld are associated to equivalent flux paths which may not have simple geometrical configurations.

It should also be considered that the tank has a thickness of almost 10 mm and an apparent cross-section of some percent of the cross-section of lateral limb. Further it has a skin depth of the order of 1 mm and therefore one should not neglect eddy currents. In other words, the tank behaves more like a magnetic shield than a magnetic shunt. In any case, I believe it is not worth while to complicate the model to take the tank into account. However, even when it is necessary to take the tank into account , as in the case of three-phase 3-limb transformer without delta-connected winding, one should not model the tank by a simple network of reluctances.

Referring to the flux density values reported in the paper for the wound limb and the lateral limbs and yokes, I have to observe that there are no inconsistencies in the fact that iron reluctances with less cross-section, like the yoke and the lateral limbs, have a less flux density (almost 2T) than the wound limb (2.41T) of the most stressed phase, since neither the flux nor the magnetic potential drop have been imposed. It is to be noted, in passing, that the lateral limbs have an average length of 6.03m against an average length of the wound limbs equal to 2.78m. The intermediate yokes have a mean length of 2.345m, which, multiplied per two, gives 4.69m, considering the series between the top and lower yoke. Although the B(H) characteristic is the same for all the iron paths, the ratio cross-section/length (S/l) is considerably different. Further it is to be considered that each iron path has air permeances in parallel with different values:

	ratio S/l	permeance in parallel
· wound limb	1.2196/2.78 = 0.4387	Λ_a=0.421 μH
· intermediate yoke	0.57*1.2196/4.69 = 0.1482	Λ_c=15.4 Λ_a
· lateral limb	0.57*1.2196/6.03 = 0.1153	Λ_d=5.86 Λ_a

As regards the "saturated inductances" used for the calculation of the air-inductances L_a, L_c end L_d, they do not represent the inductance of the coils in high saturation levels, as observed by Mr.Meredith. Indeed they only model the behaviour of the iron-path in high saturation and are in parallel with air-inductances. In the case of a wound limb, for instance, the "saturated inductance" is in parallel with La, which takes the air flux of the space between the coil and the iron-core into account.

Finally, referring to the magnetic network suggested by Mr.Meredith, in addition to the comments already made about the tank, I would observe that the numerical values given for the parameters do not correspond to the 370MVA transformer of this paper, as can easily be checked by the air inductances reported in Appendix A.

Furthermore, if the negative reluctance in parallel with each L.V. M.M.F. has to model the thickness of the corresponding coil I wonder why those of the H.V. coils are not considered as well.

In conclusion I hope that the interest stimulated by this paper will encourage other experts to consider the usefulness of the physical circuital models in the analysis of transient with high saturation level of the magnetic circuit, for electromagnetic devices in which it is possible to know, with good approximation, the distribution of the most significative magnetic flux tubes. It is also to be stressed that we should not over-estimate the field of applicability of the magnetic networks method and keep in mind their limits clearly, in order to avoid an improper or arbitrary use of this wonderful method of analysis.

Manuscript received April 9, 1990.