

209

THE SHORT-CIRCUIT PERFORMANCE OF POWER TRANSFORMERS

Working Group 12.19

August 2002



THE SHORT CIRCUIT PERFORMANCE OF POWER TRANSFORMERS

Working Group 12.19

Convenor; Jim Fyvie – U.K.

Task Force Leaders;

Anders Lindroth – Sweden
Kees Spoorenberg – Netherlands
Jim Fyvie – U.K.
John Lapworth – U.K.

Working Group Members;

Serge Therry – Switzerland
Anatoly Panibratetz – Russia
Endre Matthe – Hungary
Rafael Gonzalez – Spain
Masami Ikeda – Japan
Wolfgang Knorr – Germany
Wladislaw Pewca – Poland
Horoshi Murakami – Japan
Eric Chemin – France
Hasse Nordman – Finland
Volodimir Zaitsev – Ukraine
Victor Lazarev – Ukraine

Joe Foldi – Canada
Willi Felber – Austria
Benedikt Damm – Austria
Bob Del Vecchio – USA
Gerard Robert – France
John Lapworth – U.K.
Luis Cheim – Brasil
Chen Kui – China
V Pitsuriya – Thailand
Tim Noonan – Ireland
Walter Wasinger – Australia

CONTENTS

Introduction

1. Task Force #1 - Service conditions
 - 1.1 Questionnaire
 - 1.2 Conclusions
 - 1.3 Discussion at the " SC12 " Colloquium in Budapest 1999
2. Task Force #2 - Design calculations
 - 2.1 Introduction
 - 2.2 Magnetic field and force calculations
 - 2.3 Mechanical stress calculations
3. Task Force #3 - Design review
 - 3.1 Introduction
 - 3.2 Procedure
 - 3.3 Description of radial and axial forces
 - 3.3.1 Core type
 - 3.3.2 Shell type
 - 3.3.3 Comparison of stress and strength
 - 3.4 Manufacturing issues
 - 3.5 References
4. Task Force #4 - Monitoring
 - 4.1 Introduction
 - 4.2 Winding movement detection techniques
 - 4.3 Standardisation and optimisation of techniques
 - 4.4 Problems of interpretation
 - 4.5 Winding slackness
 - 4.6 On line monitoring
 - 4.7 Conclusions
 - 4.8 Recommendations
 - 4.9 References
5. Conclusion

Enclosures

- 1 – Questionnaire
- 2 – Summary of Responses
- 3 – Detailed Information on Failures

LIST OF TABLES

- Table 1. How is the short-circuit capability secured ?
Table 2. Number of transformers in survey
Table 3. Failure frequency
Table 4. Comparison of axial pressure calculations
Table 5. Comparison of Radial Pressure Calculations
Table 6. Comparison of boundary conditions
Table 7. Comparison table for stress and strength
Table 8. Failure Criterion and Diagnostic Credibility
Table 9. The three-state 'traffic light' assessment
-

LIST OF FIGURES

- Figure 1. Comparison of calculations (Axial pressure)
Figure 2. Comparison of calculations (Radial pressure)
Figure 3. Comparison of boundary conditions
Figure 4. Example of magnetic field plots for a core type
Figure 5. Radial forces due to axial field
Figure 6. Axial forces due to radial field
Figure 7. Typical force distribution for a core type
Figure 8. Copper proof stress for various levels of 'hardness'
Figure 9. Conductors for transformer windings
Figure 10. Bending test : bare flat wire - CTC epoxy-coated
Figure 11. Example of magnetic field plots for a shell type
Figure 12. Typical Force distribution for a shell type
Figure 13. Bending stress on the copper
Figure 14. Pressure on covering areas to hold the magnetic circuit
Figure 15. Typical FRA signature

Introduction

In October 1996 the Chairman of SC 12, Dr R. Baehr gave approval to set up a working group with the following remit ;

Title of the Group : WG 12.19 Short Circuit Performance of Power Transformers

Scope : To review the short circuit duty, design and test verification and service performance of power transformers, including the following three topics.

Service conditions : Review of actual service duties and classification for specification considerations.

Design review : To consider and recommend appropriate design validation procedures taking into account anticipated service conditions. To review short circuit strength design calculations and to propose a standard calculation with performance criteria.

Mechanical Strength Assessment : To review methods of condition monitoring in respect of mechanical strength conditions following short circuit test and service utilisation. To consider and propose assessment methods with application guidelines.

Deliverables : Reports and Guidelines within 4 years.

Start-up Meeting ; The first meeting of the group was held in Edinburgh and consisted of mainly manufacturers with one user from the NGC in the UK. After some discussion it was agreed that we would set up 4 task forces to cover the three areas of the scope with two task forces allocated to the Design review section. This was agreed so that the calculations, which were seen to be more tangible, were separated from the manufacturing and quality control procedures, which would vary in accordance with the individual manufacturers.

After the WG had a few meetings, and we had discussed many aspects of all the task forces, SC 12 agreed that we should have a work shop and obtain a wider input from the whole SC 12. The working Group Task force leaders agreed to give presentations on the work of the working group to date and by combining the input from the workshop, we would produce a final report on our findings for submission to SC12.

1. Task Force #1 : Service Conditions

Leader : Anders Lindroth, ABB Transmission & Distribution - Sweden

Scope : Review of actual service duties and classification for specification considerations

1.1 QUESTIONNAIRE

Taskforce # 1 of WG 12.19 was given the task to conduct a survey to establish the position of short-circuit failures on power transformers.

The survey was conducted by means of a questionnaire according to enclosure 1, which was sent out to the utilities via the SC 12 study committee members.

The questionnaire was divided into two parts. In the first part, we asked for some general information on :

- measures to secure the short-circuit withstand capability when ordering a new transformer
- how many transformers are installed in the systems
- typical frequency of short-circuits in the systems
- overall failure frequency of transformers due to short-circuits assessment methods

In the second part we asked for specific information on failures during the last five years, that were caused by short-circuits.

After a reminder responses were received from 18 utilities in 11 countries covering a total of 24 292 transformers. The countries were Australia, Brazil, Canada, Finland, Germany, Ireland, Japan, Netherlands, New Zealand, Russia and Thailand. A summary of the responses is given in Enclosure 2.

The Respondents reported their methods to secure the short-circuit capability of their transformers (see Table 1). The transformers were divided between different system voltages as shown in the Table 2.

Select trusted supplier	11
Design review, own	7
Design review, consultant	5
Order SC-test	2
Table 1 : How is the short-circuit capability secured ?	

System voltage	No of transformers
800 kV	444
500 kV	2536
300 kV	1918
230 kV	2814
160 kV	6900
110 kV	2299
70 kV	7381
Total	24292
Table 2 : Number of transformers in survey	

In total 15 failures during the last five years were reported. The division of the failures between the system voltages are detailed in Table 3.

System voltage	No of transformer years	No of failures	Failure frequency
300-800 kV	24490	5	2,04 E-04
110-230 kV	60065	8	1,33 E-04
70 kV	36905	2	0,54 E-04
Total	121460	15	1,23 E-04

Table 3 : Failure frequency

Detailed information on the failed transformers are given in Enclosure 3. The main observations are as follows :

- the average rating of the failed transformers is 148 MVA.
- approx. equal split between units with and without regulation
- the average age is 19 years.
- in 5 cases (33 %) design reviews had been performed.
- no short-circuit tests had been made on the failed units or the same design.

The detailed descriptions on the failures supplied by the respondents, showed that the most common mode of failure (>50%) was winding failures from axial stresses. Radial buckling or spiralling was described as the failure mode in some 20 % of the failures. In the remaining cases the reports did not give sufficient information to draw conclusions regarding the primary causes.

In many of the cases it was also reported that the failed transformer had a history of previous incidents of system short circuit events, where the transformer tripped and been put back in operation after some diagnostic tests.

The failed transformers were operating in systems with the following frequency of short-circuit events :

- Daily 1 failure
- More than weekly 2 “
- Less than weekly 1 “
- More than monthly 3 “
- Yearly 1 “
- No information 7 “

Three Utilities reported that they make regular assessments of the mechanical conditions on their transformers. The methods used are FRA (2 utilities), LVI (2 utilities) and Impedance measurement (1 utility). One Utility also reported two additional transformer failures, where the damages had been identified by LVI and where the transformers were still in operation.

1.2 CONCLUSIONS

This survey has shown that the failure frequency due to external short-circuits in power transformers during the time period 1993-1997 has been 1,2 failures in 10000 transformer years based on a fairly large transformer population. Considering the focus the question on the short-circuit withstand capabilities of power transformers has been given in the discussions during the last few years, this value must be regarded as surprisingly low. However, countries like China and India, where we today hear a lot about problems with short-circuit failures have not given any contributions to the survey. Utilities in Russia and Thailand have participated in the survey and indicated very few failures during the time period of the survey but considerably higher failure rates in the time period before 1990. A utility in Russia reported a 2 % failure frequency due to short-circuits in the time period 1970-1989.

During the discussions at the SC 12 Colloquium in Budapest 1999 similar past histories of high rates of transformer short circuit failures were reported also from US, Italy and Turkey. A general pattern seems to be that many countries experience this type of problems at some time in their evolution. Given the right attention from both utilities and suppliers, the situation is then normally drastically improved.

From the survey, it has not been possible to draw any statistically proven conclusions on the best way to secure the short-circuit capability of power transformers. Failures have occurred to utilities practising all four methods in Table 1. On the other hand, there is reason to believe that the procedure adopted by most utilities participating in the survey, i.e. to choose a trusted supplier and make a design review, is contributing to the low failure rate.

1.3 DISCUSSION AT THE " SC12 " COLLOQUIUM IN BUDAPEST 1999

At the SC 12 Colloquium 1999 Mr Giorgio Bertagnolli, convenor of IEC TC 14 WG 23, presented a paper titled "Results of short-circuit tests carried out by high-power Laboratories" where a study of the failure frequency of transformers during Short Circuit test in high-power laboratories had been studied. The study indicated an overall failure rate of 23 % for a total of 3934 tests.

The apparent contradiction between the results of the short circuit tests and the situation in operation as indicated by the survey made by this WG was discussed during a workshop at the Colloquium. The following three questions were presented for discussion :

1. Due to the current short circuit performance of transformers in the field, which according to the survey is very good, is there a need to improve this performance and if so, at what price ?
2. Why is there such a high failure rate at the short circuit testing station, relative to the actual failures in service ?
3. How do the Utilities view the use of design reviews to assess the short circuit ability of transformers ?

As an answer to question 1, the general opinion among the participants in the discussion was that there is no need to improve the situation from new transformers in most countries, which have the development phase with high failure rates in operation behind them. For developing countries, which are facing the problem with high failure rates today, actions must naturally be taken. There was a general concern for old transformers on many markets due to ageing, accumulated stresses and in some cases inexperienced supplier at the time of delivery. It was recommended to use the diagnostic test methods available to access the condition of transformers in critical positions in the net works.

In the discussion on the second question, it was a clear opinion that the main reason for the difference is the severity of the short circuit test. The stresses in the tests are far above what most transformers ever are exposed to in operation. It was also pointed out, that there might be a difference between the recorded failure frequency and the actual damages that have occurred on units in service. The detailed diagnostic tests and visual inspections, which are made on units in connection with short circuit tests are normally not made in operation. The remarks from the respondents to the questionnaire regarding earlier records of short circuit events on some of the failed units also support that theory. It was noticed that suppliers are learning from the experiences gained in the short circuit tests.

The design review was regarded as a very important tool to assess the ability of a transformer to withstand short circuit stresses. However many participants expressed concerns regarding the available competence of the utilities to make a detailed review. A need for guidance was expressed and great hopes were put on the results from the work of Task Force # 3 of this WG.

Acknowledgement

Sincere thanks and gratitude to the Utilities who have participated in the survey.

2. Task Force #2 : Calculations

Leader – Kees Spoorenberg – SMIT Transformers, The Netherlands.

Scope : To consider and recommend appropriate design validation procedures taking into account anticipated service conditions. To review short circuit strength design calculations and to propose a standard calculation with performance criteria.

2.1 INTRODUCTION

The TF # 2 conducted a survey of the methods used by the following contributors to calculate the forces in transformer windings due to the passage of short circuit currents :

1. All Russian Institute - Own
2. Smit Transformers - Own
3. Smit Transformers - Anderson
4. Peebles Transformers - Own
5. Jeumont Schnieder - Own
6. Ganz Ansaldo - Own
7. VIT Ukraine - Own

A detailed design which had passed a short circuit test was offered by Russia to be used a bench mark for this exercise, each contributor fed the details of this design into their own computer programs and calculated the forces in the windings.

2.2 MAGNETIC FIELD AND FORCE CALCULATIONS

The boundary conditions for modelling are important aspects of the calculations, and account for the differences in the results, these conditions include;

- The place in the circumference of the winding where the cross sectional area is taken.
- The planes of symmetry
- The spiral of the winding
- The location of the boundaries, such as tank wall and cover.
- The sub-division in the number of parts.
- The way of presenting the data (SI-units or ‘company units’) Company units cannot simply be re-calculated to SI-units as they may have a different definition.

These parameters vary between the manufacturers, and this should be kept in mind when comparing results.

It was agreed that the smallest element required to give consistent results should be an individual conductor, or cable in the event of continuously transposed cable. **Tables 4, 5 and 6** show the forces calculated. These forces are the most onerous forces for the particular winding and may not all occur simultaneously. (At this time, no effort was made to determine the computed strength of the windings or margins of safety).

2.3 MECHANICAL STRESS CALCULATIONS

After forces are calculated one must calculate the mechanical stresses, by making a two dimensional mechanical model of a part of the construction.

The boundary conditions and the assumptions are important aspects and these include :

- Area or cross section on which the forces are applied to (for example : bare copper or insulated cable dimensions)
- Youngs modulus of material or composed material (copper, CTC cable, epoxy-bonded CTC cable)
- Is mechanical boundary clamped or layed-on.
- Static or dynamic calculation, because material parameters are different under static load than under dynamic load.
- Is the oil taken into account , yes or no
- Which force is limiting (force in a single non supported conductor or the average force of some conductors together in radial direction)
- The magnetic forces change depending on the place in the circumference, but which force does one use to calculate the stress (peak or averaged over the circumference)

To judge the capability of a design one has:

On one hand: - Material criteria (Young's modulus, 0.2% yield strength , maximum pressure and tensile strength)

On the other hand: - Mechanical stresses based on a 2-D magnetic field model (which calculates the forces) proceeded by a 2-D mechanical model (which calculates the stresses). They take into account the manufacturers experience (winding; epoxy bonding, drying, assembling procedure) and the manufacturers construction with aspects as type of core (core or shell type), spacers (axial and/or radial), clamping construction.

It is therefore very difficult to make simple rules for judging the requirement of a design without taking into account all the parameters mentioned above. As an example the detailed results of calculations from several contributors are compared and shown in **Figures 1 , 2 and 3**.

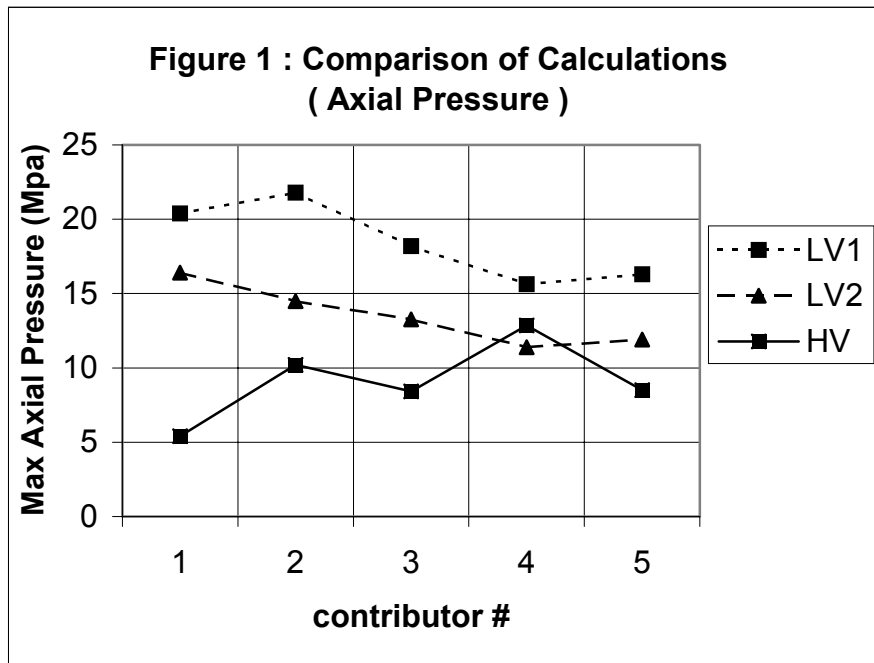
# \ Wdg:	LV1	LV2	HV	
All Russian Institute	1	20.4	16.4	5.4
Smit (own)	2	21.8	14.49	10.21
Smit (Andersen)	3	18.2	13.26	8.43
Ganz Ansaldo(1/4)	4	15.64	11.39	12.85
Peebles	5	16.3	11.9	8.5

Remark 1 : Contributors 1,3,5 have yokes and tank wall far away: outside window

Remark 2 : Contributor 2 has yokes close, tank wall far away; influence of yokes, tank wall saturated

Remark 3 : Contributor 4 has yokes and tank wall close: inside window.

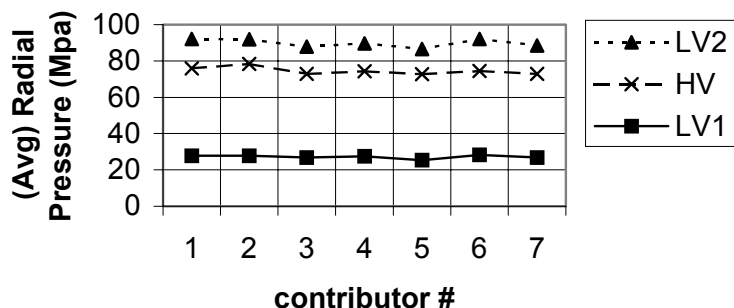
Table 4 : Comparison of axial pressure calculations



# \ Wdg:		LV1	LV2	HV
All Russian Institute	1	27.8	92.1	75.9
Smit (own)	2	27.84	91.88	78.35
Smit (Andersen)	3	26.89	87.91	72.9
Ganz Ansaldo	4	27.43	89.68	74.38
Peebles	5	25.4	86.6	72.7
Jeumont Schneider	6	28.33	92.06	74.5
VIT-Ukraine	7	26.8	88.6	72.8

Table 5 : Comparison of Radial Pressure Calculations

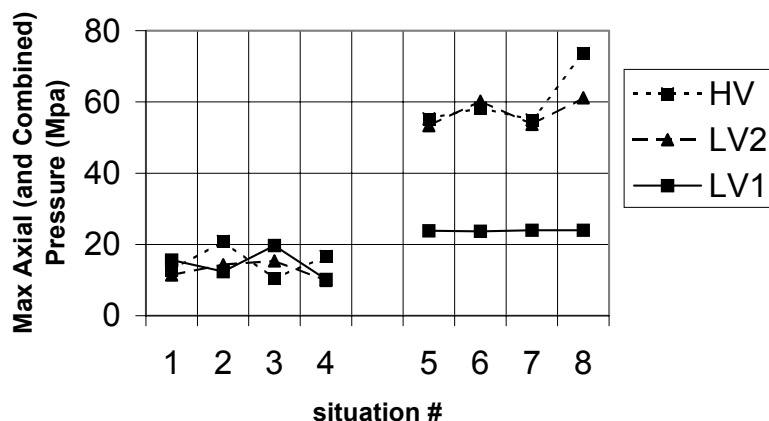
**Figure 2 : Comparison of Calculations
(Radial Pressure)**



Boundary Condition: (Axial Pressure)	# \ Wdg:	LV1	LV2	HV
Yokes +- 1000 mm; Tank 400 mm	1	15.64	11.39	12.85
Yokes +- 0 mm; Tank 50 mm	2	12.35	14.31	20.89
Yokes +- 1000 mm; Tank 400 mm; more detail	3	19.71	15.41	10.4
Yokes +- 0 mm; Tank 50 mm; more detail	4	10.17	9.85	16.68
Boundary Condition: (Combined Pressure)				
Yokes +- 1000 mm; Tank 400 mm	5	23.8	53.3	55.3
Yokes +- 0 mm; Tank 50 mm	6	23.67	60.26	58.37
Yokes +- 1000 mm; Tank 400 mm; more detail	7	24	53.68	54.97
Yokes +- 0 mm; Tank 50 mm; more detail	8	23.97	61.13	73.59

Table 6 : Comparison of boundary conditions

Figure 3 : Comparison of Boundary Conditions



3. Task Force #3 : Design Review

Leader - J.D.Fyvie, VA Tech Transformers.

Scope : To consider and recommend appropriate design validation procedures taking into account anticipated service conditions. To review short circuit strength design calculations and to propose a standard calculation with performance criteria.

3.1 INTRODUCTION

Design reviews are common place in the transformer manufacturing industry and are used as Quality Control Tools. The individual manufacturers have their own in-house procedures to specify the various types of reviews that they conduct. These reviews can look at technical issues, commercial issues, and financial issues and project management issues and are based on ISO 9001 requirements. The design review procedure described in this paper has been specifically targeted to address the ability of a transformer to withstand the dynamic forces that are generated due to through fault currents in the windings. Reference should be made to the specifications IEC 60076-5 and IEC 60076-8. These specifications advise the types, duration and magnitudes of the fault currents that should be considered. They also cover the calculations required to demonstrate the thermal ability to withstand short circuit.

It is known that the industry requires all different types and sizes of power transformers ranging from small distribution transformers < 1000 KVA with a simple two winding arrangement, to very large high voltage units in excess of 1000 MVA with very complicated winding arrangements. A variety of cores and conductors is available ranging from core type and shell type construction, foil conductors, strip conductors, and continuously transposed cable, which may include epoxy bonding. There are transformers with off-circuit taps and on-load taps utilising variable flux or constant flux regulation.... The variety of cultures is endless and who knows what next year's models will look like.

When recommending a design review procedure it is therefore advisable to take account of this 'culture', and it is necessary to modify the procedure to suit.

The industry has split transformers into three cultures, small, medium and large. Small transformers are normally classified as units that are purchased in bulk, such as pole mounted units and small distribution < 1500 KVA. The design philosophy is usually based on experience and the main parameters for the design are lowest cost and fit for purpose. The proof of short circuit ability is usually by short-circuit testing one or two of units of a bulk order. It is accepted as the quickest and cheapest way to verify conformance, since the units can be un-tanked and modified very quickly and the cost is relatively small compared to the total cost of the bulk order. IEC Category I is up to 2500 KVA.

Medium size transformers up to about 50 MVA are not normally purchased in bulk although there may be several units ordered to the same design. In this case the competitive parameters may also include performance penalties and the lowest first cost may not produce the best optimised design. The cost of short-circuit testing starts to have an influence on the total order charges. The resources required to untank and modify the design are more significant and it calls for more effort to 'get it right first time'. This demands a deeper understanding of the design parameters and the ability to predetermine the short circuit ability of the transformer to ensure that it will pass a short circuit test. IEC Category II is up to 100 MVA.

Large transformers often in excess of 500 MVA cannot normally be short circuit tested due to either the lack of test facilities or the remoteness of a suitable testing station. It is therefore essential that manufacturers of these large units can predict the short circuit ability accurately. IEC Category III is above 100 MVA.

The ability of the transformer to withstand these forces will be assessed by the manufacturer. This assessment may be followed by an internal or external design review. This section describes such a design review procedure for large power transformers.

3.2 PROCEDURE

It must be demonstrated that the design strength of the windings and the clamping structure including all external leads and accessories, with regard to the material and type of construction used, exceeds the calculated forces that will exist when the transformer is subjected to a through fault. Every precaution should be taken to ensure the integrity of the unit. It is recommended that such a procedure is adopted whether or not a short circuit test is requested.

The forces in any winding arrangement may be determined by mathematical modelling and the methods used for the calculations will vary between the manufacturers depending on the computing power available. These calculations will give the axial and radial forces in all the windings, the cumulative forces which will be used to determine the end force and the maximum compression in each winding and the inward and outward hoop stress in all the windings. The tangential winding forces on the windings and the forces on all leads and accessories will also be calculated. The transformer manufacturer must demonstrate his ability to perform these calculations to an acceptable degree of accuracy. The manufacturer must then demonstrate his ability to manufacture the transformer in such a fashion that the structure and quality control procedures ensure that the transformer as built will withstand these forces and stresses and agree on acceptable limits for these stresses and forces. These acceptable limits should be referenced back to some proven values, either by certification of material strength, research / development projects or some other historical evidence. A short circuit test on a 'similar unit' as defined in IEC 60076-5 may also be used to demonstrate the ability of the manufacturer to control the quality of the product and to meet these stress limits.

3.3 DESCRIPTION OF RADIAL AND AXIAL FORCES

For the benefit of this procedure further description of the types of radial and axial forces and stresses follows, referring to the typical field plots shown, with the corresponding force distribution. The relationships given in the equations have been assigned basic dimensions but they be represented in SI or Imperial Units requiring different factors, there will also be some correction factors involved depending on the type of material or method of manufacture used. This was a decision made by the working group to maintain some level of technical differential between manufacturers, but still give common denominator guidelines. Further, it was acknowledged by the majority of the attendees at the workshop held in Budapest that, tying things down to precise values and factors of safety would inhibit competition and healthy development.

Two types of transformer are considered, the core type using concentric windings and the shell type using sandwich windings.

3.3.1 CORE TYPE

The Figure 4 shows the stray magnetic field for a transformer which has two LV windings axially stacked and one HV winding wound in two parallel halves, also axially stacked, each half with a tap section located in the electrical and magnetic centre of the HV halves. The leakage fields shown are for four different conditions to demonstrate various effects.

A description of each condition is thus :

- (a) Both LV's are carrying currents and the magnetic centres of the windings are balanced. This shows a symmetrical field with a clear indication of how the axial flux is highest at the middle and the radial flux is highest at the ends of the windings.
- (b) This demonstrates the effect of unbalance in the magnetic centres when the windings are displaced by 20mm. The effect is to concentrate the radial field at the bottom of the windings which increases the axial force at this position.
- (c) This shows the effect of the tapping gaps when the unit is connected on minimum tap. This also indicates that there will be local axial forces in this region for this condition.
- (d) This shows the effect on the leakage field when there is only one LV winding carrying current. There is a significant change in the field pattern.

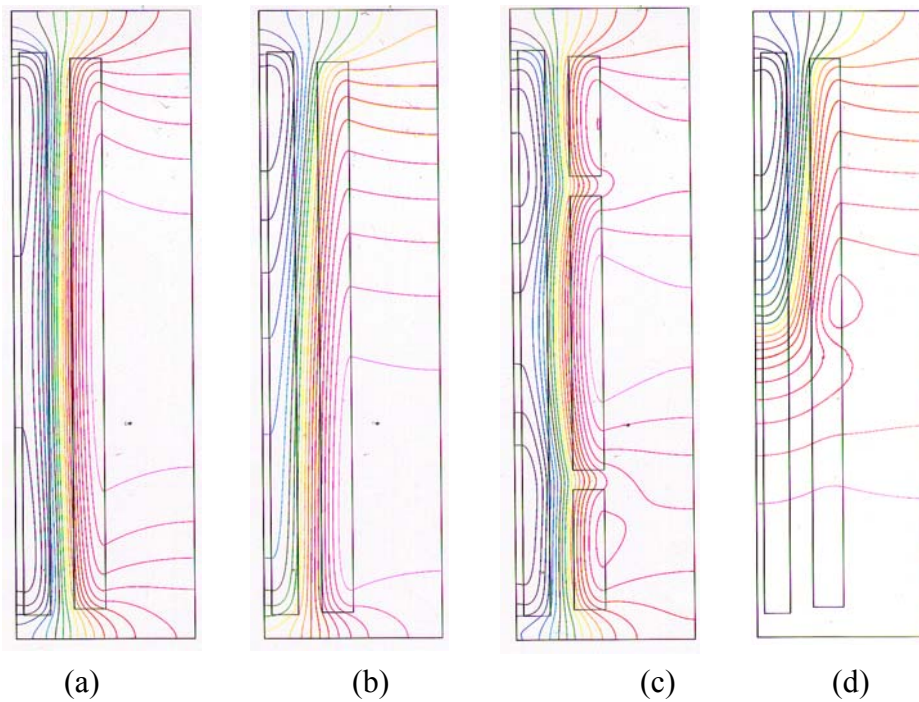


Figure 4 : Typical Magnetic Field Plots: « + » tap position :
 original arrangement
 (b) : « + » tap position : HV shifted 20mm
 (c) : « - » tap position : original arrangement
 (d) : only upper axial LV system in operation

The forces on each conductor should be calculated for each conductor position and for the most onerous field and fault current. For convenience, these forces are normally split into radial and axial components (Figures 5 and 6).

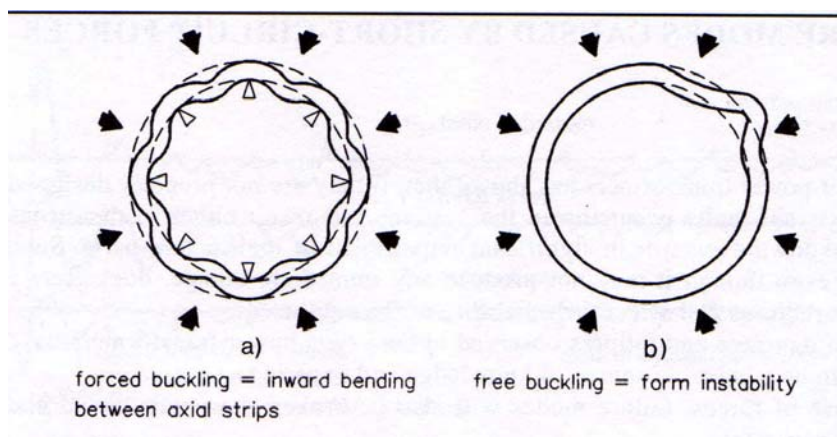


Figure 5 : Radial forces due to axial field

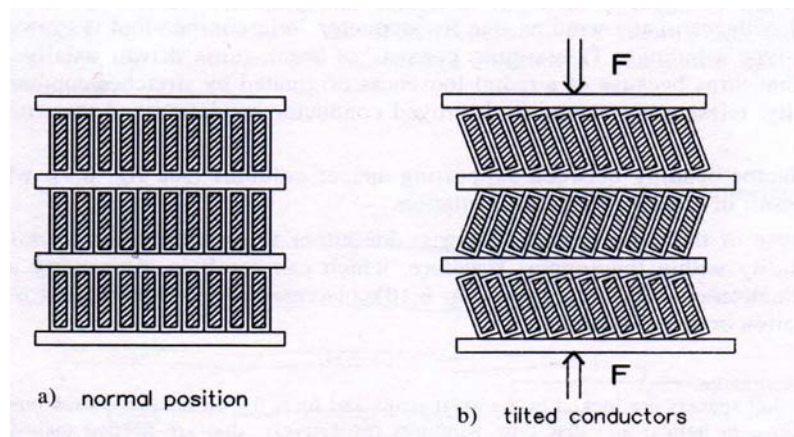
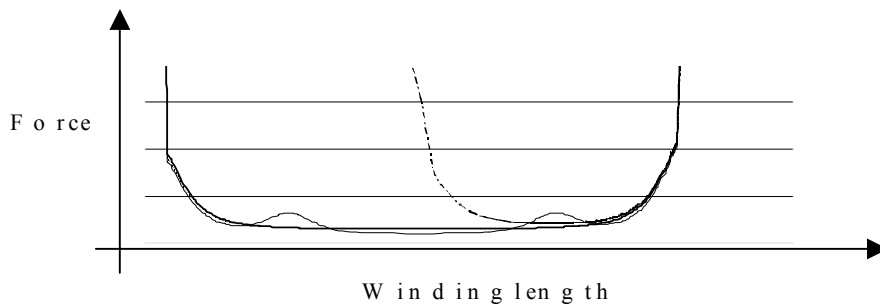


Figure 6 : Axial forces due to radial field

Figure 7 : Typical force distribution for a core type



The forces are normally considered to be cumulative within the windings and the axial forces are transmitted through the insulation structure. This will give rise to a compressive force in the axial supports or stampings and the insulation must tolerate this compression. In the case of an inner disc type winding the radial inward forces on the conductors may also be cumulative. There will be a tendency for the turns to tighten and the winding to reduce in diameter, causing a circumferential compression force on the inner conductor, which may lead to buckling, and a compression on the inner vertical sticks. A typical force distribution is shown in Figure 7 for each of the situations described in Figure 4.

The most controversial criterion is the ability of the inner winding to withstand buckling. The definition of buckling may apply to the 'free mode' where the supporting effect of any radial sticks inside the inner diameter of the winding is neglected or 'higher order' buckling where some account is taken of the inner supports. The conductor is treated as a short column with a compressive force acting on the cross sectional area of the conductor, this force being equal to the product of the distributed inward radial force and the mean diameter of the winding. The area of conductor under stress is taken as the total solid area exposed across a section taken through the diameter of the winding.

This stress may be determined by the following relationship:

$$\sigma = \frac{F_{rad} \times D}{2 \times a} \quad - \text{N/m}^2$$

where ;

F_{rad} = the distributed inward radial component of the force. – N/m
 D = the winding diameter - m
 a = the conductor cross sectional area – m²

It should also be noted that when the winding is subjected to an inward force, the diameter reduces by some increment depending on the elastic limit of the material and that this small reduction causes the winding to tighten, creating a spiralling effect. There will therefore be a force on the lead exits of the winding and the lead ends must be secured to retain this force. The force may be estimated by using the relationship:

$$F = F_{rad} \times D \quad - \text{N}$$

The critical level of buckling is a function of the cross sectional area and the type of material and the type of conductor. The critical value may be increased for a given cross sectional area by using a higher proof stress material and/or using epoxy-bonding techniques. The material manufacturers will normally provide basic critical strength values for various materials and conductor arrangements. A typical example of copper proof stress for various levels of ‘hardness’ is shown in Figure 8. The values indicated are for 0.2% Proof Stress, but it is common practice to use only 80% of this value. Some manufacturers use 85% of the 0.1% Proof Stress.

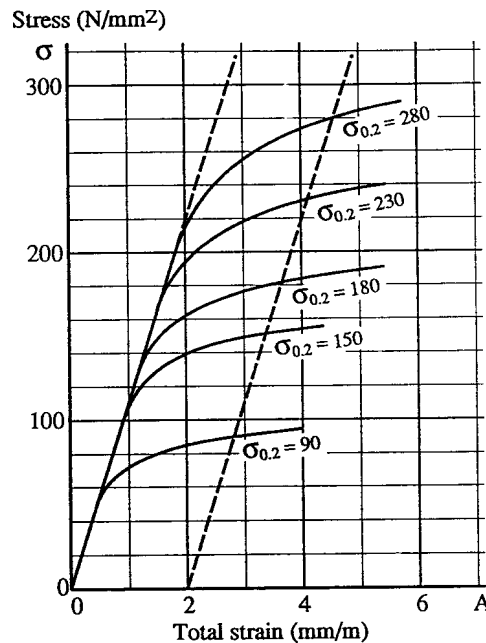


Figure 8 : Copper proof stress for various levels of ‘hardness’

Due to the many shapes and types of conductor available, the normal formulae for bending stresses may need modified to allow for these variations. An example of the types of conductor available is shown in Figure 9.

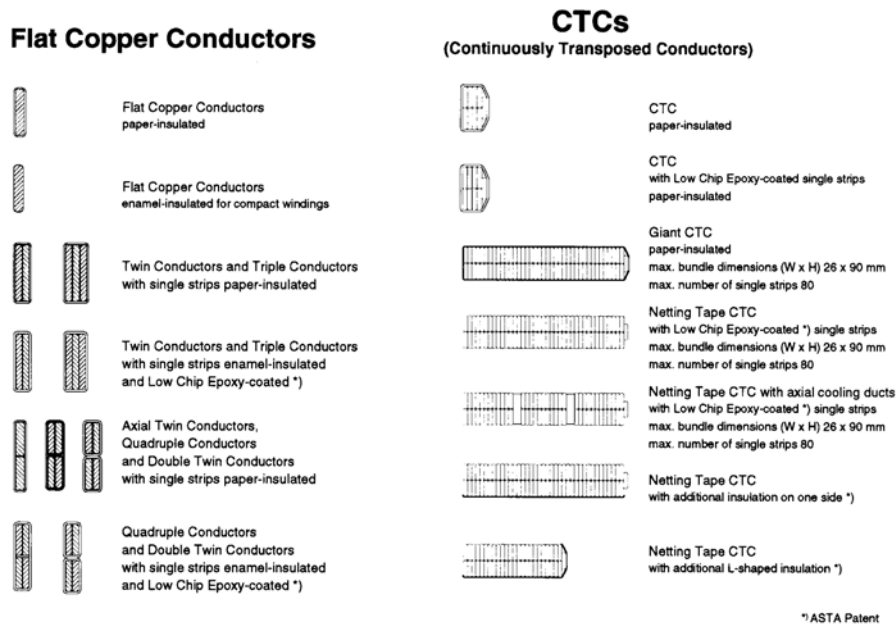


Figure 9 : Conductors for transformer windings

The allowable stress for the various conductor shapes may differ from the parent material and an example is shown in Figure 10, relating to types of Continuously Transposed Cable (CTC).

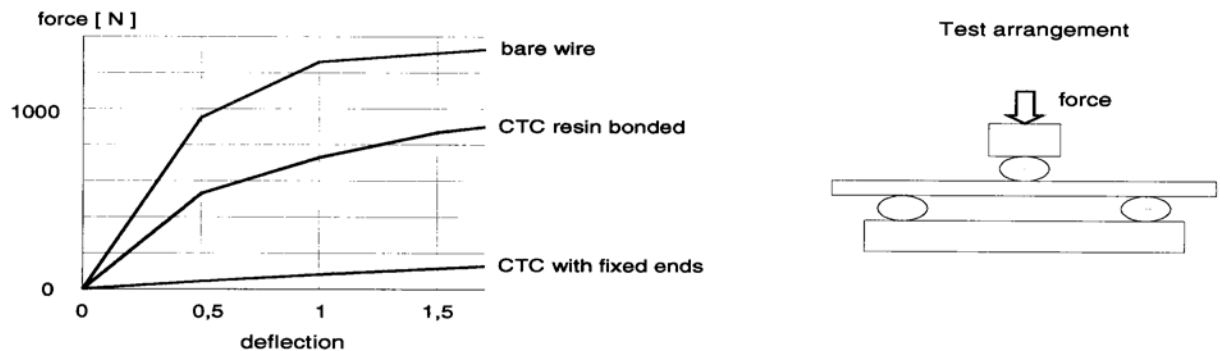


Figure 10 : Bending test : bare flat wire - CTC epoxy-coated

There are two values for the critical buckling stress depending on the construction of the winding and test evidence is required to verify which value is acceptable. These values may be calculated using the following relationships:

For oval or unsupported windings, based on a 'long column collapse'

$$\sigma_{crit} = \frac{E \times t^2}{4 \times R^2} \quad - \text{N/m}^2$$

where ;

E = Modulus of elasticity – N/m²
 t = conductor radial dimension - m
 R = the winding radius - m

For round and well supported windings, based on a 'short column collapse'

$$\sigma_{crit} = \frac{E(\delta) \times (kt)^2 \times (N)^2}{12 \times D^2} \quad \text{N/m}^2$$

where ;

E(δ) = incremental Modulus of elasticity at the critical value. - N/m²
 t = conductor radial dimension - m
 k = manufacturers constant for equivalent thickness
 D = the winding diameter - m
 N = number of radial supports per circle

The radial bending forces are created by the same distributed inward force on the winding but this time the inner supports are required to prevent any inward winding movement at these points. The material stress is calculated by using a simply supported beam structure with a distributed load between the supports. The stress is in this case a function of the distance between the supports and the dimensions of the conductor and is given by the relationship;

$$\sigma = \frac{F_{rad} \times l^2}{2 \times b \times t^2} \quad - \text{N/m}^2$$

where ;

F_{rad} = distributed radial force – N/m
 l = distance between supports - m
 b = axial height of conductor - m
 t = radial thickness of conductor - m

The radial forces and stresses in the outer windings are due to the outward distributed load and the main stress is that of tension in the conductor. This may be determined by taking the product of the distributed load and the winding mean diameter and dividing it by the total cross sectional area of the conductor taken through a section on the diameter.

$$\sigma = \frac{F_{rad} \times D}{2 \times a} \quad - \text{N/m}^2$$

where ;

F_{rad} = distributed outward radial force – N/m
 D = winding diameter - m
 a = conductor cross sectional area – m²

There will also be a bending tendency in the axial direction due to the distributed axial component of the force. The stress associated with this component may be determined by considering the following relationship:

$$\sigma = \frac{F_{ax} \times L^2}{2 \times t \times b^2} \quad - \text{N/m}^2$$

where:

F_{ax} = distributed axial force – N/m
 L = Distance between stampings - m
 t = conductor radial dimension - m
 b = conductor axial dimension - m

The tilting of conductors is caused by the axial cumulative compression applied to the conductors via any axial spacers or stampings. The critical load that the winding can tolerate is therefore not only a function of the conductor parameters but also of the winding construction including the insulation between the conductors. This critical load may be determined by the following relationship;

$$\sigma_{crit} = \frac{E \times b^2}{14 \times R^2} + \frac{m \times s \times c \times t^2}{12 \times \pi \times R \times b^2} \quad - \text{N/m}^2$$

where;

E : modulus of elasticity – N/m²
 b : axial dimension of conductor - m
 R : radius of winding - m
 m : number of stampings
 s : width of spacers - m
 c : equivalent modulus of elasticity of paper and pressboard - N/m²
 t : radial dimension of conductor – m

3.3.2 SHELL TYPE TRANSFORMER

The Figure 11 shows the typical field plot for a Shell Type Construction.

The main component of the linkage flux density of a shell type transformer is the radial component. This radial component develops axial electromagnetic forces, which tend to separate the low voltage windings from the high voltage windings. The corresponding force distribution is shown in Figure 12.

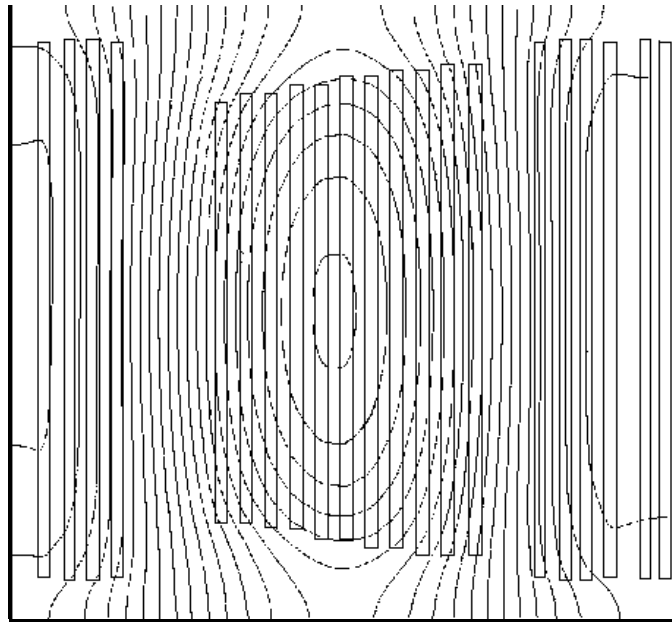


Figure 11 : Example of magnetic field plots for a shell type

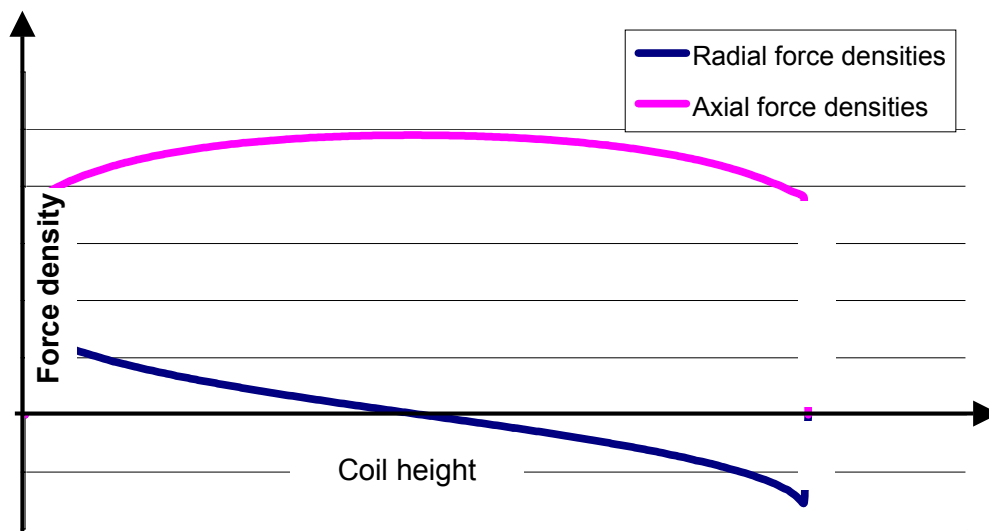


Figure 12 : Typical Force distribution for a shell type

The forces originating in a coil are exerted :

- Onto the conductor spans between spacer blocks, which results in a bending stress on the copper (see Figure 13). The stress may be calculated by determining the maximum bending moment. If the oil effect is negligible and as an example for one conductor, the equation based on the beam theory is used, as described in Figure 13. The type of material controls the critical bending stress.
- Onto the spacers which transmit them to the neighbouring coil, then to the next ones. Maximum pressures occur in parts where the leakage magnetic induction is the lowest. The type of material controls the critical pressures on the most stressed spacer.
- Onto the magnetic circuit. The pressure to apply to the covering areas, in order to hold the magnetic circuit is detailed in Figure 14.

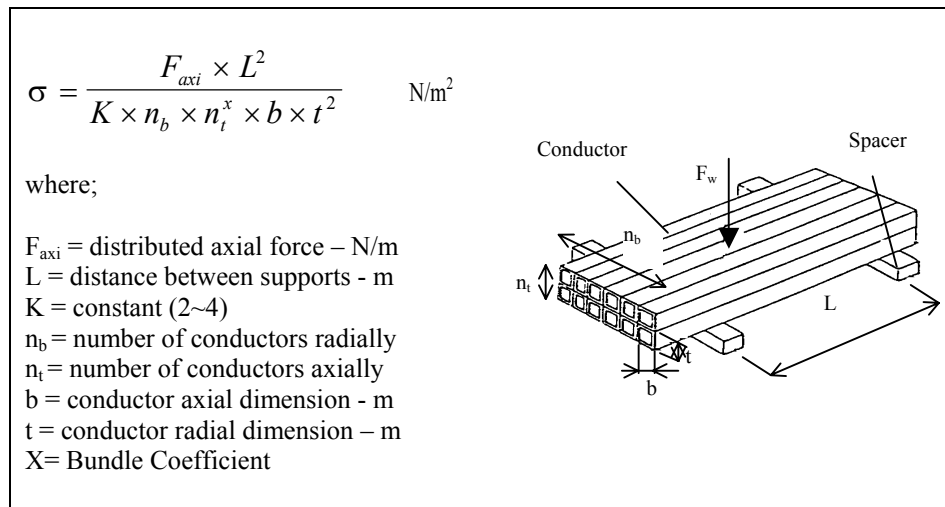


Figure 13 : Bending stress on the copper

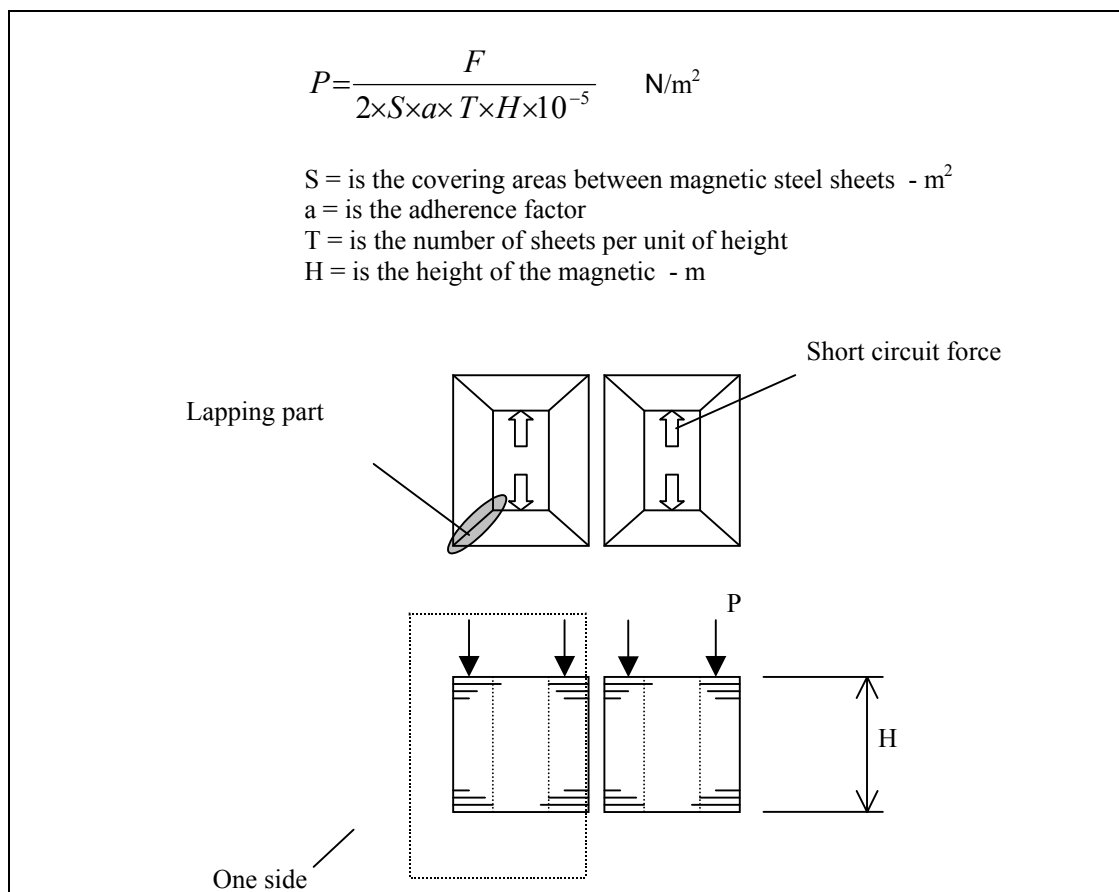


Figure 14 : Pressure on covering areas to hold the magnetic circuit

3.3.3 COMPARISON OF STRESS AND STRENGTH

Table 7 shows a typical comparison table for stress and strength. The values indicated in this table would be the most onerous values taken from different fault conditions and will not all occur at the same time.

Windings	LV		HV + Tap		Tap	
	Stress	Strength	Stress	Strength	Stress	Strength
Compressive Stress on Stampings(MPa)						
Axial Bending Stress(MPa)						
Compressive Stress on Sticks(MPa)						
Radial Buckling Stress(MPa)						
Radial Bending Stress(MPa)						
Hoop Stress(MPa)						
Tilting Force(Tonnes)						
Winding End Axial Force Top/Bottom (Tonnes)						
Force on Lead Exits (Tonnes)						
Force on Lead Runs						

Table 7 : Comparison table for stress and strength

3.4 MANUFACTURING ISSUES

The manufacturer must demonstrate his ability to :

- Wind the windings under a controlled condition with enough tension in the conductors to ensure that there are no unwanted gaps between the individual conductors.
- Properly size the windings to consolidate the radial and axial insulation to ensure that the winding turns are located as predicted by the design within the design tolerances.
- Properly process the minor and major insulation so that it is fully shrunk and oil impregnated and to demonstrate the ability to manage this process and control the quality of the insulation winding supporting structure.
- Demonstrate that the processing procedure is sufficient to provide long term integrity of the insulation, by specifying end points and methods of any pre-loading used.
- Predict final winding dimensions and relative positions within the limited tolerance used in the force calculation, and specify how these dimensions are checked at the final stage of manufacture.
- Secure any accessories, leads, crossovers and lead exits to ensure that they will not be displaced during any fault current condition.
- Ensure that the winding supporting structure and winding conductor will withstand without permanent deflection the various types of stresses and forces that will be present such as radial bending, axial bending, radial buckling, hoop stress, tilting, axial and radial compression on the insulation and tangential twisting.
- Demonstrate the philosophy of the supporting structure, i.e. tie-rods or plate clamps, the type of support back to the core for inner windings, any pre-load used and any form of transport bracing.
- Ensure that the strength of the materials used is adequate to support the predicted forces

3.5 REFERENCES

“Transformer Short-Circuit Strength”
ELEKTROTECHNIEK 68, 6 June 1990
Mevr. A.J.M. Mattheij en E. vanZanten

“Mechanical Condition Assessment of Power Transformers using Frequency Response Analysis” -
Conference Paper, 62nd. Annual International Conference of Doble Clients 1995.
John A Lapworth, Timothy J Noonan.

“Advanced Technologies for Improvement of Efficiency of Large Power Transformers”
Conference Paper, Transform 98 - Forum der Technik, Munich 21 April 1998.
Willibald Felber

“ASTA Winding Conductor Materials for Modern Power Transformers”

Conference Paper, Transfom 98 - Forum der Technik, Munich. 21 April 1998

Willibald Felber.

“Condition Assessment Techniques for Large Power Transformers”

IEEE Conference ‘The Reliability of Transmission and Distribution Equipment’, Publication No. 406.
March 1995.

J A Lapworth, P N Jarman, I R Funnell.

“Transformer Winding Movement and Fault Detection Frequency Response Analysis”

Conference Paper 7th BEAMA International Electrical Insulation Conference.

John A Lapworth, Paul N Jarman.

“Transformer Board II”

Weidmann Publication

H.P.Moser, V.Dahinden

“Short-Circuit Duty of Power Transformers”

ABB Publication

Giorgio Bertagnolli

“Power Transformer Condition Assessment and Renewal, Frequency Response Analysis Update.”

Sixty-Fourth Annual International Conference of Doble Clients

Timothy J. Noonan

“Transformer Windings Electrodynamic Stability at Short Circuit Conditions”

VIT Paper Zaporozhzhzy, Ukraine.

Dr. Victor Lazarev

“Transformer Colloquium SC12 – Budapest, Hungary 1999”

There were many papers and discussions which contributed to this report. See the separate minutes for this meeting for details of these contributions.

4. Task Force #4 : Diagnostic and Monitoring

Leader - John Lapworth – National Grid Company

This chapter summarises the present state of development of diagnostic and monitoring techniques for short circuit performance, for both short-circuit testing and also monitoring of transformers in service: in particular to determine what are the main limitations and how the various techniques used compare. The information presented is based on published papers and discussions of experts at the 1999 CIGRE SC12 Colloquium in Budapest.

4.1 INTRODUCTION

Transformers are usually very reliable items of equipment, but when faults occur, they can develop catastrophically and are usually very expensive, if not uneconomic, to repair. A typical problem encountered is that after some event a transformer is switched out of service, possibly by the operation of protection equipment, and there is an urgent need to determine whether it can be safely re-energised. Visual inspections are expensive and time consuming because of the oil handling required and are very often inconclusive because so little of the winding assembly is accessible, so effective diagnostic techniques are required.

In addition to electrical and thermal failure mechanisms, transformers can suffer mechanical damage from the very large electromagnetic forces arising during short circuits. Transformers are specified and designed to withstand the effects of limited duration short circuits at their terminals, but for large transformers short circuit performance is rarely tested. There are also some faults, which the designer cannot easily design against, e.g. tap to tap faults. The technology to ensure that transformers can withstand short circuit faults has improved in recent times, but problems still arise, particularly with older units. Another important factor with older transformers is that significant winding shrinkage can occur with age, leading to a reduction in clamping pressure and short circuit withstand strength.

Short circuit faults are potentially very destructive since if the clamping system is not capable of restraining the forces involved, substantial permanent winding deformation or even collapse can occur almost instantaneously, often accompanied by shorted turns. A common cause of such failures is a close-up phase to earth fault resulting from a lightning strike.

It is expected that a transformer will experience and survive a number of short circuits during its service life, but sooner or later one such event will cause some slight winding movement, and the ability of the transformer to survive further short circuits will then be severely reduced. It is therefore desirable to be able to check the mechanical condition of transformers periodically during their service life, particularly for older units and after significant short-circuit events, to provide an early warning of an impending failure. Such a capability is perhaps just as important as the ability to be able to diagnose suspected short-circuit failures. Conventional condition monitoring techniques such as dissolved gas analysis (DGA) are unlikely to be able to detect such damage until it develops into a dielectric or thermal fault, so a specialist technique is clearly required for the monitoring and assessment of mechanical condition.

4.2 WINDING MOVEMENT DETECTION TECHNIQUES

The main techniques used to detect winding movement in transformers are :

- winding capacitances
- magnetising (exciting currents) currents
- short-circuit impedance / leakage reactance
- low voltage impulse (LVI)
- frequency response analysis (FRA)

These techniques can be divided into two groups: the first three depend on detecting the change in a global quantity, e.g. total leakage flux, that winding movement produces, while the last two (LVI and FRA) rely on detecting the effects of the resulting local change in signal propagation characteristics produced by a fault.

Magnetising currents

This technique has the advantage of requiring only very simple equipment, essentially a voltage source and voltage and current meters. Often a three phase low voltage supply (e.g. 415 V phase to phase) is used. Alternatively, a single-phase insulation test set is used, which allows a 'mag curve' to be obtained over a range of voltages, usually 1 to 10 kV. While magnetising current measurements are usually the easiest way of detecting any shorted turns that may have arisen from winding movement, the technique is of limited sensitivity for other types of faults.

Winding capacitances

This technique requires standard test equipment, e.g. the portable 10 kV insulation test sets available from equipment manufacturers such as Doble, Tettex and Biddle, such as will be owned by almost every manufacturer and utility. This is undoubtedly the reason why this is still by far the most popular technique used by utilities to detect winding movement, along with the measurement of magnetising currents.

Measurements of winding capacitances can in principle detect winding movement if a measurable capacitance is affected. However, in practice the sensitivity of the technique depends on the type of fault involved, and there may be difficulties in interpreting measured values if reference results are not available. The technique is particularly effective in cases when it is possible to make separate measurements for each phase, when phase-by-phase comparisons of results greatly improve the chances of identifying any anomaly, particularly for inter-winding capacitances which should be very similar for each phase. However, in other cases, e.g. autotransformers, the technique is of limited use because it is not possible to measure any main inter-winding capacitances at all.

Impedance

Short-circuit impedance (often referred to as leakage reactance) measurements are probably the most widely accepted method of detecting winding movement, and are prescribed in standards for short-circuit tests. The technique is simple in principle, and requires relatively standard equipment.

During factory acceptance tests, impedances are measured using three-phase excitation at currents of at least 10% of rated value. At site, impedances may be measured using low voltage three phase supplies or using single-phase insulation test sets. If single-phase measurements are made, then separate 'per-phase' measurements may be made on each phase in an attempt to facilitate the detection of faults by phase-by-phase comparisons. When interpreting such results it should be borne in mind that a single phase measurement may not give the same value as a three phase measurement, depending on winding and core configurations. For this reason, when using single-phase measurements it is desirable to make 'three-phase equivalent' measurements by energising two phases simultaneously to obtain results which can be compared with nameplate impedance values [1].

The technique suffers the disadvantage that very small changes (of the order of 1 %) have to be detected. In order to obtain good results it is necessary to carry out the measurement at a current sufficiently high that the magnetising impedance is insignificant, and to ensure that shorting leads are of a sufficiently low impedance, particularly when testing transformers with large turns ratios.

Even so, the main difficulty in making use of the technique appears to lie not with the repeatability of the measurements, but in the natural variation of the measured quantity. Measured per-phase leakage reactances often differ significantly between phases, even for new transformers, and also between transformers of the same design. Agreement with nameplate values is also variable. Therefore, it appears that without reference results from the transformer in question it is very difficult to make a reliable interpretation of results, a far more restrictive condition for usability than for FRA techniques.

If more than two windings are involved and the impedances between them can be measured, then there is a better chance of detecting a fault without reference results by considering the ‘image of the defect’ [2], i.e. by recognising the complementary changes in the various impedances that a particular fault will introduce. However, such a degree of sophistication is only possible in a limited number of cases, e.g. autotransformers with tertiary windings which have all three phases brought out.

It is probably the case that most winding mechanical failures can be diagnosed by impedance measurements. The main limitation of the technique for operational use appears to be that in the more usual situation of a transformer that has not failed, it is not always possible to obtain a reliable indication of this from impedance measurements if no reference results are available.

Despite the above difficulties for use on transformers in service, reactance measurements are still the preferred diagnostic technique for short circuit testing because of the need for a conclusive answer to the question of whether or not the transformer has passed the tests [3].

Low Voltage Impulse

The low voltage impulse (LVI) test [4] has long been recognised as more sensitive than traditional measurements. The response, a current or voltage at the same or another terminal, to an impulse signal is recorded. Just as a dielectric breakdown during a factory lightning impulse test will produce a change in the winding response, so will any winding movement occurring as a result of a short circuit.

The disadvantage of the test, which has limited its usefulness for periodic measurements on transformers in service, is poor repeatability. One reason is that it is difficult to reproduce a standard input signal because of the complicated and varied impedance characteristics of transformers. Also, the disposition of test leads has a significant influence on results, to such an extent that it has been necessary to use the same leads in exactly the same position to obtain acceptable results. Nevertheless, the technique is still used with success, being effective for fault diagnosis and short-circuit testing where changes to the test set-up are not required, although increasingly frequency response analysis techniques are used to analyse the results [5].

Frequency Response Analysis - Variations on a theme

The repeatability problems of LVI have been solved by **frequency response analysis** (FRA) techniques [6,7]. If both the applied impulse signal and the corresponding response are recorded using a high performance digitiser and the results transformed into the frequency domain by a Fast Fourier Transform calculation, a response function is obtained which is dependent almost entirely on the test object and independent of applied signal and test circuit. In this way, changes in the test object can be more clearly and consistently identified, which greatly simplifies the interpretation of the results. The so-called ‘transfer function method’ has become a powerful tool for analysing factory HV impulse tests [8]. Recently, relatively inexpensive packaged portable systems for carrying out FRA tests by the **impulse method** have become available.

In a further development, the transfer function method has been implemented as an **on-line technique** making use of system voltage transients caused by switching operations to provide the excitation impulses [9].

In parallel to the above, Ontario Hydro pioneered an alternative FRA technique based on frequency domain measurements [10]. Instead of an applied impulse signal, a sinusoidal voltage is applied to one terminal and the response of the winding is determined directly by measuring the amplitude change and phase shift of the response voltage at another terminal over a range of frequencies. A comprehensive description of the successful application of such a **swept frequency method** using a commercially available network/spectrum analyser has been given recently [11]. This technique is now being used by many utilities in Europe and Australia (Figure 15).

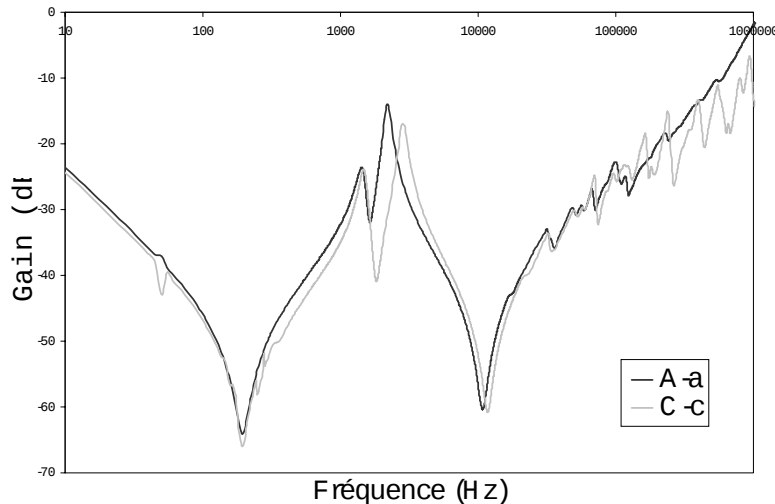


Figure 15 : Typical FRA signature

The C phase winding was damaged [paper 12-111 Cigre 2002 Paris Session]

The effects of test leads have been all but eliminated in most FRA techniques by the use of wide bandwidth leads whose characteristic impedance is matched to the input impedance of the measuring equipment so that reflections do not occur at the instrument end, with separate leads to apply and measure the signal at the input terminal. This has greatly improved the repeatability, sensitivity and reliability of the detection of winding movement, although it has to be said that users of some FRA techniques still report problems with the disposition of leads affecting results.

In principle it should be possible to obtain the same results by either **impulse or swept frequency method**, although it has been suggested that the swept frequency method is more suited to site use and has a superior signal to noise performance at the high frequencies (up to 2 MHz) considered to be important for the detection of winding movement.

Further to the two different methods of making a measurement, a **variety of measurements** can be made, principally :

- input impedance/admittance
- voltage transfer from one winding to another
- attenuation across a winding

A **further variation in test method** that can be introduced concerns the way in which tested and untested windings are terminated. Whatever choice is made, it is essential that the same procedure is followed on subsequent tests on the same or similar transformers, to ensure that measurements are entirely repeatable. Ideally, windings should also be tested in such a way that differences between the responses of the three phases are not introduced, so that comparisons between the responses of the three phases can be used as part of the assessment and interpretation process.

In an attempt to introduce some **standardisation of test methods**, European users of the swept frequency technique have come together under the auspices of the Doble Annual European ('EuroDoble') Colloquium to agree a **test specification**. The immediate objective is to enable results obtained by different parties to be compared. The long-term aim is to collate results from failed transformers so that a **guide to the interpretation of results** can be produced. Already, a number of examples have been collected involving a range of failure modes including hoop buckling, axial collapse and clamping structure collapse.

Interpretation of FRA test results is based on a subjective comparison of equivalent responses. The appearance of new features or major frequency shifts is cause for concern.

Measured responses are analysed for :

- changes in the response of a particular transformer over time
- differences between the responses of transformers of the same design
- differences between the responses of the three phases of the same transformer

With the excellent repeatability of FRA techniques, the first comparison can be made with confidence if reference results are available. However, the big advantage of the FRA technique over alternatives is that in most cases the other two comparisons are almost as effective, which greatly increases the power of the technique and usually allows winding failures to be diagnosed with confidence even if reference results are not available.

4.3 STANDARDISATION AND OPTIMISATION OF TECHNIQUES

With so many techniques available, there is a need to assess that is best so that resources can be applied where they will be most productive.

For instance, in an attempt to improve the prospects of detecting winding movement faults, utilities are increasingly asking manufacturers to provide 'benchmark' results. The problem for the manufacturer is knowing which technique should be used, and precisely how the measurement is to be made.

Against this, there is the possibility that the use of complementary tests may provide more information and increase confidence in a diagnosis by providing mutually confirmatory indications. However, if ineffective techniques are used there is obviously a danger that such a multi-track approach will lead to confusion.

Since LVI and FRA by the impulse method are essentially the same technique, and impulse and swept frequency techniques can give the same results, the leading contenders for complementary tests are FRA and impedance measurements.

In view of the variety of FRA techniques being practised, there is clearly a need to establish, compare and optimise the sensitivities of these techniques, with a view to focussing on one. Some work has already been carried out in this area by producing 'staged faults' on redundant units [12,13]. For instance, it has been shown that for the impulse method, transferred voltage measurements are more sensitive than admittance measurements for detecting simulated faults [12].

For newcomers to the field, what is still lacking is a definitive comparison of the effectiveness of the leading impulse and swept frequency FRA techniques, although a start has been made on this [14]. At the end of the day, it may well be that it does not matter **how** the measurement is made, but only **what** measurement is made.

4.4 PROBLEMS OF INTERPRETATION

Quite obviously, the degree of confidence that can be placed on the interpretations of diagnostic results is central to the usefulness of a technique: a technique that raises more questions than it answers is of little use.

A common problem when interpreting the results of any diagnostic test is knowing where the boundary between a ‘good’ and ‘bad’ result lies. This **difficulty of setting a failure criterion** often impacts on the credibility of a technique as illustrated in the Table 8.

DIAGNOSTIC CREDIBILITY			
Diagnostic Indicates	BAD	FALSE POSITIVE YYYY Unfortunate result, Rarely forgiven. Safe but expensive.	TRUE POSITIVE UUU Excellent result: Diagnostic shows promise
	GOOD	TRUE NEGATIVE Y Good result, but expected.	FALSE NEGATIVE YY Poor result, but often forgiven. Incurs unknown risks.
		GOOD	BAD
Reality is			
Table 8 : Failure Criterion and Diagnostic Credibility			

In reality, the situation is not as simple as this. Although in many cases it may be very obvious that a transformer has failed, it is still surprisingly difficult to set a failure criterion. Something that has to be taken into account is that a transformer can be ‘broken’, i.e. with serious winding movement, e.g. with broken winding clamping, but may still be serviceable, i.e. not yet failed in the usual operational sense of the term. In fact, most failures during short-circuit tests are probably ‘technical failures’ judged according to the applied failure criterion, but would probably be capable of being put into service, although the risk of ‘actual failure’ would be very high at the next short circuit.

Furthermore, evidence from short circuit testing indicates that failure normally requires a number of short circuits, involving some initial ‘settling’ followed by some progressive deterioration before the fault deteriorates rapidly to failure. This being the case, as recommended by CIGRE Working Group 12.18, a three-state ‘traffic light’ type of assessment is more appropriate (Table 9), although some utilities have expressed uncertainties about how to react to the intermediate assessment.

(GREEN) ‘GOOD’ NORMAL No winding movement ACCEPTABLE	(AMBER) ‘POOR’ DEFECTIVE / NOT SERIOUS Some movement ACCEPTABLE	(RED) ‘BAD’ FAILED / SERIOUS Too much movement UNACCEPTABLE
<i>transition levels</i>	CAUTION (GOOD to POOR)	CRITICAL (POOR to BAD)
Table 9 : The three-state ‘traffic light’ assessment		

Fortunately there is evidence that the transition from 'normal' to 'defective' may be the easier to recognise, particularly with the advent of FRA techniques. The subsequent progress from 'defective' to 'failed' state is then the key issue. Usually further deterioration of a winding movement fault would be expected to require further short circuits. This being the case, it would seem appropriate that such events be recorded by some monitoring equipment.

When setting a criterion for assessing the degree of winding damage sustained, it is desirable to be quantitative. The quantitative interpretation of an FRA picture is clearly not as easy as a single measured numerical value, and some work in this area is required to produce robust and objective criteria.

The other main issue in interpreting results is the desirability of being able to identify where a **fault is located**. The location could help in the assessment of the seriousness of a fault, but how much detail is required? Most techniques allow the faulty phase to be identified. When the faulty winding can also be diagnosed, as is the case with the swept frequency FRA method, then more confidence in the diagnosis is obtained. It is doubtful whether any greater degree of resolution would offer any further operational advantage.

4.5 WINDING SLACKNESS

The emphasis of much development work on the FRA impulse method in the US is to detect loss of clamping rather than winding movement. It has been claimed that changes in the measured responses can be detected after clamping operations, specifically an amplitude change in the main resonance peak at MHz frequencies [15,16]. However, there is some uncertainty as to what is actually being detected: movement of the windings resulting from the clamping or a change in clamping pressure itself. Also, it is not clear what reference results are required to provide sufficient confidence that it is necessary to re-clamp a transformer in the first place.

Furthermore, users of the swept frequency FRA method have reported detecting loss of clamping pressure faults at much lower frequencies [11,13,17]. Clearly, some resolution of these differences is required.

An alternative technique for monitoring winding slackness on-line has been developed in the form of a galvanically isolated displacement transducer [18], although service experience is still limited. As with all such systems, even when the technology is perfected there are still difficult decisions to be made about when it is appropriate to take action.

4.6 ON-LINE MONITORING

Several systems for on-line monitoring of winding movement have been either proposed or developed [9, 18,19,20], but service experience is still limited. As for all such on-line systems there are still questions to be answered about the economic justification of dedicating such monitoring to a specific transformer and how the information from such systems are to be interpreted and acted upon.

What perhaps has not been pursued enough is the development of systems for monitoring and recording abnormal conditions experienced in service by transformers, e.g. through faults, tap-changer faults.

4.7 CONCLUSIONS

A wide variety of techniques are being used to detect winding movement in transformers. The two most likely reasons for this are inadequate information in the public domain about the effectiveness of alternatives and economic constraints preventing the use of the expensive test equipment required for the newer techniques.

There is clearly a need to clarify and confirm the relationships between the various techniques used and consider the benefits of promoting one as a CIGRE method. Having selected one, the method then needs to be optimised and the effects of all other factors, e.g. test leads and terminations, clarified. Finally, the sensitivity of the chosen technique needs to be determined for typical geometry's and relevant failure modes.

The most promising technique appears to be frequency response analysis (FRA), a development of the low voltage impulse (LVI) test, with many recent reports of successful applications. Unfortunately, several different variations of FRA are currently being used. There are presently two main camps: impulse and swept frequency methods. It should be possible to obtain the same result by either method and test leads should not have any significant effect on the measurements, provided care has been taken with the implementation, but unfortunately this has not always been the case. Perhaps of greater importance is the need to determine which of the different measurements made (e.g. input admittance, voltage transfer between windings or attenuation across windings) gives the best detection sensitivity.

The perceived difficulties of interpreting FRA responses has been a deterrent up to now. However, these concerns have been eased recently by an ever-increasing number of documented examples of the detection of a variety of winding movement faults. The prospects of producing a reasonably comprehensive guide to the interpretation of FRA results are now good.

FRA techniques offer the prospect of not only being able to diagnose winding failures, but also of being able to detect minor winding movement prior to failure. Furthermore, experience shows that windings can be 'broken' by short circuit events, but may not fail until a further short circuit event occurs. Therefore a three state (green / amber / red 'traffic light') type of condition assessment scheme appears to be the most appropriate. The main difficulties in applying such a scheme will be in agreeing the 'critical' transition from a 'defective' (amber) to a 'failed' (red) condition, and deciding what appropriate action is to be taken if minor winding movement is suspected.

There are arguments for continuing to carry out more traditional measurements to complement FRA testing, at least until the latter technique is fully accepted. Although measurements of interwinding capacitances may be more sensitive in some instances, only leakage reactance / short circuit impedance measurements can be recommended for universal application. However, the limitations of this technique (small changes to be detected, uncertain failure criteria and the need for reference results from the transformer in question) need to be appreciated.

Various on-line techniques for detecting winding movement are being developed, but there is not sufficient operating experience to be able to recommend any particular one at the moment.

4.8 RECOMMENDATIONS

Further development work should concentrate on FRA techniques.

A priority is to compare the various FRA variants currently being used to determine the best technique for detecting typical winding failure modes.

The use of mathematical modelling to help in the interpretation of FRA results should be investigated.

A guide to the interpretation of FRA results should be prepared.

Traditional leakage reactance / short circuit impedance measurements should still be carried out, at least until the FRA technique is fully established and particularly in the case of winding failures.

Utilities need to develop strategies for dealing with situations where winding movement is diagnosed, but the transformer has not yet failed.

4.9 REFERENCES

1. Lachman, M.F., 'Low-voltage single-phase leakage reactance measurement on transformers - Significance and Application Part 1', DOBLE Client Conference Paper 6-5, 1994.
2. Sokolov, V. V., 'Consideration in Power Transformers Condition Based Maintenance', EPRI Substation Equipment Diagnostics Conference VIII, New Orleans, February 2000.
3. Janssen, A. L. J. and te Paske, L. H., 'Short-Circuit Testing Experience with Large Power Transformers', KEMA High Power Laboratory, Arnhem, the Netherlands.
4. Lech, W. and Tyminski, L., 'Detecting transformer winding damage by the Low Voltage Impulse method', Electrical Review, No. 21, Vol 179, November 1966, pp 768-772, (ERA Translation).
5. Khrennikov, A. Yu., 'Short-Circuit Performance of Power Transformers: Test Experience at Samaraenergo Co and at Power Testing Centre in Togliatti, Russia, including Fault Diagnostic', CIGRE Transformer Colloquium 1999, Budapest.
6. Richenbacher, A. G., 'Frequency domain analysis of responses from LVI testing of power transformers', DOBLE Client Conference Paper 6-201, 1976.
7. Vaessen, P.T.M. and Hanique, E., 'A new frequency response analysis method for power transformers', IEEE Winter Meeting 1991.
8. Malewski, R. and Poulin, B., 'Impulse testing of power transformers using the transfer function method', IEEE Transactions on Power Delivery, Vol. 3, No. 2, April 1988.
9. Liebfried, T. and Feser, K., 'Monitoring of Power Transformers using the Transfer Function Method', Siemens AG
10. Dick, E.P. and Erven, C.C., 'Transformer diagnostic testing by frequency response analysis', IEEE Trans PAS-97, No. 6, pp 2144-2153, 1978.
11. Lapworth, J. A. and McGrail, A. J., 'Transformer Winding Movement Detection by Frequency Response Analysis (FRA)', Sixty-Sixth Annual International Conference of Doble Clients, April 1999.
12. Christian, J., Feser, K. and Kachler, A., 'The Transfer Function Analysis: A Method to Detect Mechanical Changes in Transformer Windings', CIGRE Transformer Colloquium 1999, Budapest.
13. Noonan, T. J., 'Off-line Electromagnetic-Mechanical Condition Assessment of Power Transformers, ESBI Experience', CIGRE Transformer Colloquium 1999, Budapest.
14. Denis, R. J., An, S. K., Vandermaar, J. and Wang, M., 'Comparison of Two FRA Methods to Detect Transformer Winding Movement', EPRI Substation Equipment Diagnostics Conference VIII, New Orleans, February 2000.
15. Vandermaar, A. J., Wang, M., Stefanski, C. and Ward, B., 'Frequency Response Analysis using the Impulse Test Method as a Transformer Diagnostic Technique', Sixty-Sixth Annual International Conference of Doble Clients, April 1999.
16. Ozaki, E. and Soyama, S., 'An Application of FRA to Fault Location on Transformer', CIGRE Transformer Colloquium 1999, Budapest.

17. Islam, S. M., 'Detection of Shorted Turns and Winding Movements in Large Power Transformers using Frequency Response Analysis', IEEE Symposium Singapore, 2000.
18. de Klerk, P. J. and Reynders, J. P., 'Winding Slackness Monitoring as a Diagnostic for Insulation Ageing in Oil-Paper Insulated Power Transformers', International High Voltage Engineering Symposium (ISH), August 1999, IEE, London.
19. Birlasekaran, S. and Fetherston, F., 'Off/On-Line FRA Condition Monitoring Technique for Power Transformer', IEEE Power Engineering Review, August 1999, Vol. 19, No. 8, pp. 54-56.
20. McDowell, G. W. A. and Lockwood, M. L., "Real Time Monitoring Of Movement Of Transformer Winding," *Science, Education and Technology Division Colloquium on Condition Monitoring and Remanent Life Assessment in Power Transformers*, IEE Colloquium (Digest) No. 075, 22 March 1994, Published by IEE, Michael Faraday House, Stevenage, Engl. p 6/1-6/6

5. Conclusion

As WG convenor I must thank the members of the working group for their efforts and the energy that they put in to this group, without their enthusiasm, it would have been a much greater task. In particular I must thank the Task Force Leaders who gave that little extra and added their own personality and experience to the document.

As previously stated, we decided to tackle the work in four tasks, firstly to identify the magnitude of the problem. It had been reported that the short circuit performance of transformers was very poor and units were failing all over the place. We initiated a survey to put some numbers on this and we were very surprised at the result. From the manufacturers point of view the result was very encouraging, at one point we were tempted to abandon the WG since the evidence indicated that the problem was minimum and the industry could live with it. We decided however that if we could improve the current design review techniques, we would in turn improve the long term integrity of the transformers in general and provide an even better product.

It was agreed at this time that we would not repeat the earlier work of Cigre which had produced the fundamental calculations, but we would consider how these had been developed practically. The second task considered the different developments of the original mathematical solutions, such as Rabins, and compared the results from various models.. It was noted that the main differences were due to the interpretation of the initial boundary conditions. The rotational symmetry technique used to convert a three dimensional problem into a two dimensional problem considers the iron circuit in different positions. This led to further discussions on which were the best assumptions. The results indicated that the biggest differences were in the axial forces, the results of the radial forces being very close.

The many discussions held soon indicated that the working group would not reach a simple quick fit for the initial brief given. It soon became apparent that the transformer industry is multicultural and covers an enormous range of products, each product requiring a separate approach and each manufacturer having a different building. There was a lot of discussion on which calculating approach we should use. At one point we became very close to removing all the formulae and simply addressing the problem with long-winded discussion. Hasse Nordman came to the rescue at this point and many formulas are detailed in the Brochure.

The third task was to combine the proposed calculation with a design review procedure that would allow individual manufacturers to defend their reasons for doing things differently. It would also encourage an open rapport with their customers and allow the manufacturers to develop technical differentials and retain some form of competition. This philosophy was also supported by the members attending the Budapest workshop. This section linked in with the work carried out by WG12.22 on Design Reviews.

The forth task was to review the methods that were or could be used to monitor the short circuit health of a transformer during its life. This turned out to be one of the largest sections in the report and covered a wide range of monitoring, linking in with the work carried out by WG12.18 on life management.

Future work to improve the calculating techniques will no doubt involve three dimensional calculations which will eliminate the need to model synthetic boundary conditions and will allow the designer to take account of correctly position tanks and clamps, but this will not be widely available for some time.

The improvement in FRA is something that is worth developing as it can give a non-destructive indication of winding movement, and an early indication of a developing problem.

The short circuit testing stations are at present making an effort to measure the forces on structures and windings and this should be encouraged in order to collect more information on actual forces. It must be stated that a simple pass/fail test is extremely risky for very large expensive transformers, particularly in the present situation where initial cost for a large unit is of prime importance.

ENCLOSURES

- 1 – Questionnaire
- 2 – Summary of Responses
- 3 – Detailed Information on Failures

Enclosure – 1 - Questionnaire on Short-Circuit Failures of Power Transformers

Company..... Country.....

Part 1: General information

How do you normally secure the short-circuit withstand capability when you buy a new transformer?

- ☐ Select a supplier we trust
- ☐ Perform design review with own staff
- ☐ Perform design review assisted by consultant
- ☐ Order a short-circuit test

How many transformers are connected to your different transmission systems > 50 kV?

..... units to the-kV system
 units to the-kV system
 units to the-kV system
 units to the-kV system
 units to the-kV system

What is the typical frequency of short-circuits in the systems?

- ☐ Daily in the-kV system(s)
- ☐ Weekly in the-kV system(s)
- ☐ Monthly in the-kV system(s)
- ☐ Yearly in the-kV system(s)
- ☐ More seldom in the-kV system(s)

What is the overall transformer failure frequency due to short-circuits expressed in failures per transformer year of operation?.....

Do you perform regular checks on your transformers to assess their mechanical condition by e.g. Frequency Response Analysis or Low Voltage Impulse Tests?

- ☐ Yes
- ☐ No

If yes, which method and how frequent?

.....

Part 2: Information on failures

We ask you to fill in one set of this part 2 for each transformer short-circuit failure you have experienced during the last 5 years.

Failure No.....

Transformer Data

Type	☐ Generation	☐ Transmission
Rating.....		MVA
Ratio...../...../.....		kV
Voltage regulation		☐ in Phase
		☐ in Neutral
		☐ with OLTC
		☐ with DETC
Impedance.....		%
Connection.....		
Year of manufacture.....		
Year of failure.....		

Network short-circuit power specified for the transformer

HV.....	GVA
MV.....	GVA
LV.....	GVA
Ratio zero/positive sequence impedance.....	

Was the fault current recorded at the failure event?

If yes, what was the recorded value?	Amps
If no, what was the estimated value?	Amps

How was the short-circuit capability of the transformer verified at the time of delivery?

	Short-circuit test on actual unit
☐	Short-circuit test on an other unit of the same design
☐	Design review
☐	No special action

Description of the short-circuit event

.....

.....

.....

.....

.....

Did the protection equipment function properly ?

☐ Yes

☐ No

Type of short-circuit

☐ Single-phase

☐ Two-phase

☐ Three-phase

☐ To ground

Description of the transformer damages

.....

.....

.....

.....

.....

.....

.....

Report prepared by

Name.....

Company.....

Address.....

.....

.....

Telephone.....Fax.....

Enclosure – 2 - Summary of Responses

	H.Q.	B.C.H.	K.E.P.	E.P.D.	C.E.P.	G.P.U.P.N.	V.E.W.E.	Badenwer k	U.N.	Finland	E.S.B.	N.U.O.N.	P.N.E.M.	C.E.P.E.L.	Dr. Baehr	Transpower	TransGri d	E.G.A.T.	Sep & others	Summary
	Canada	Canada	Japan	Japan	Japan	Australia	Germany	Germany	Russia	Finland	Ireland	Netherland s	Netherlands	Brasil	Germany	New Zealand	Australia	Thailand	Netherland s	18 Utilities
How secure SC capability																				
Select trusted supplier	x				x	partly	x	x		x	x	x		x		x	x		x	11+
Design review, own		x	x	x		limited		x						x			x	x		7+
Design review, consultant					x				x				x	x		x			x	5
Order SC-test					x				<16 MVA			x(new supplier)						x		2+
No. of trans' in system																				
800 kV	309								45					90						444
500 kV		140	40	8	25	27			560	50	7			1658			9	12		2536
300 kV	286	16	129	67	130	15	22	13	100					989			115		36	1918
230 kV	188	180	4	32		168	53	34		50	28	6		1557		257	2	225	30	2814
160 kV	98	170	118		222					1600	130	150	97	4315						6900
110 kV	854			28			260	154				30				607	23	343		2299
70 kV		175	2395	23	1978	8								2645		154	3			7381
SC frequency/year																				
800 kV	>monthly													<yearly						
500 kV		>weekly	monthly	<yearly	<yearly	yearly								yearly						
300 kV	weekly		monthly	<yearly	<yearly	yearly	monthly	<yearly						yearly			weekly		<yearly	
230 kV	<weekly	weekly		<yearly		>weekly	monthly	<yearly				<yearly		yearly		yearly			<yearly	
160 kV	>monthly	>weekly	weekly		<yearly		<yearly					<yearly	<yearly	monthly		<monthly				
110 kV	>weekly			<yearly				<yearly				<yearly				<monthly	weekly			
70 kV		>>weekly	daily	<yearly	<yearly	>weekly								yearly				monthly	monthly	
Failure frequency	0.0006		0.00002			0.0002	0		0.001	0.0002	0	<0.01	0			0.0002	0		0.0009	
Condition assessment	No	No	No	No	No	Some	No	No	Yes	No	Yes	No	No	No		No	No	Yes	No	
How						FRA			LVI,Imp		FRA		FRA					FRA, LVI		

Enclosure – 3 - Detailed Information on Failures

Information of failures																		
	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	Ave/Sum	Units	Frequency
Transformer data																		
Rating MVA	550	1.5	190	111	10	15	30	400	200	30	15	520	50	50	50	148		
HV kV	735	120	735	735	77	210	66	220	330	110	110	420	130	220	115			
300-800	x		x	x					x			x				5	4898	2.0E-04
110-230		x				x		x		x	x		x	x	x	8	12013	1.3E-04
70					x		x									2	7381	5.4E-05
Regulation																		
No	x		x	x	x	x		x						x		7		
OLTC		x					x		x	x		x	x		x	7		
DETC											x					1		
in phase																		
in neutral									x						x			
Impedance %	19.5	9	19.4	14.5	7.5	8.25	10	11	11	10.7	10.5	16	10	9.55	12.7			
Age	8	3	19	5	29	36		24	12	28	32	20	17	31	3	18		
Verification																		
SC test on unit																		
SC test on same design																		
Design review					x				x			x	x		x	5		
No special action	x	x	x	x		x	x	x		x	x			x		10		

Le CIGRÉ a apporté le plus grand soin à la réalisation de cette brochure thématique numérique afin de vous fournir une information complète et fiable.

Cependant, le CIGRÉ ne pourra en aucun cas être tenu responsable des préjudices ou dommages de quelque nature que ce soit pouvant résulter d'une mauvaise utilisation des informations contenues dans cette brochure.

Publié par le CIGRÉ
21, rue d'Artois
FR-75 008 PARIS
Tél. : +33 1 53 89 12 90
Fax : +33 1 53 89 12 99

Copyright © 2002

Tous droits de diffusion, de traduction et de reproduction réservés pour tous pays.

Toute reproduction, même partielle, par quelque procédé que ce soit, est interdite sans autorisation préalable. Cette interdiction ne peut s'appliquer à l'utilisateur personne physique ayant acheté ce document pour l'impression dudit document à des fins strictement personnelles.

Pour toute utilisation collective, prière de nous contacter à sales-meetings@cigre.org

The greatest care has been taken by CIGRE to produce this digital technical brochure so as to provide you with full and reliable information.

However, CIGRE could in any case be held responsible for any damage resulting from any misuse of the information contained therein.

*Published by CIGRE
21, rue d'Artois
FR-75 008 PARIS
Tel : +33 1 53 89 12 90
Fax : +33 1 53 89 12 99*

Copyright © 2002

All rights of circulation, translation and reproduction reserved for all countries.

No part of this publication may be produced or transmitted, in any form or by any means, without prior permission of the publisher. This measure will not apply in the case of printing off of this document by any individual having purchased it for personal purposes.

For any collective use, please contact us at sales-meetings@cigre.org