Chapter 14

Transformer user requirements, specifications and testing

J.A. Lapworth

14.1 Introduction

Transformers are required to transform the power output from electrical generators up to the voltages used in the transmission system (400 and 275 kV in the UK), to interconnect parts of the transmission system and to step down the voltage at bulk supply points and at various points in the distribution network before reaching the consumer. In addition, special transformers are required for AC/DC convertor stations and for transmission control devices such as quadrature boosters and static VAr compensators.

For a utility, large power transformers are major capital items, costing up to £2M, with construction lead times up to 18 months. Although generally very reliable, when problems occur they are often difficult to diagnose and expensive to correct. For example, just to handle the oil from a transformer to allow an internal inspection, which very often can be inconclusive, can cost over £10 000 for a large transformer.

A utility is therefore concerned, as a customer, to ensure that as far as possible every new transformer purchased is capable of performing to requirements and will continue to do so for a service life of at least 40 years, over the specified operating conditions and without being damaged by the inevitable occasional system abnormalities. The user requires a transformer which will be effective, efficient, reliable and also economical. Key activities in ensuring this are the specification for the transformer, quality assurance during manufacture, effective testing of the transformer before it leaves the manufacturer's works, and appropriate maintenance and diagnostic testing in service.

Several commercial and technical factors combine to colour the transformer procurement scene. First, transformers are generally not ordered in large batches, and each customer has different requirements, so there is seldom an opportunity to benefit from economies of scale. Second, it is usual for each new transformer order to go out to competitive tender, unless there are overriding reasons why a repeat order is necessary, e.g. to meet a very short delivery time. This further reduces the possibilities of extended production runs. Third, even though the basic technology of building transformers has changed little over the last 50 years, transformer manufacturers continue to refine their designs to take into account changing requirements, material advances or technical design improvements, with the result that even though a sizeable number of transformers may have been purchased to the same basic specification over a decade, there will be several different designs involved.

The overall outcome of all these factors is that transformers are effectively custom made rather than purchased off the shelf. In such situations the onus is even more than usual on the customer to ensure that his particular requirements are identified and met.

14.2 User requirements

14.2.1 Specific requirements

The fundamental specific performance parameters for transformers are:

Primary and secondary voltages and ratios	e.g. 400/132 kV
Tapping range	e.g. +15% to −5% in 14 steps
Rated power	e.g. 240 MVA
Impedance	e.g. 20%
Connection	e.g. Auto (YNaO)

The principal parameters of the main types of power transformers connected to the UK Grid system are given in Table 14.1.

14.2.1.1 Voltage ratios

The voltages specified are for the no-load condition. Voltage ratios must be met to within ± 0.5% at every tap position. This is particularly important where transformers have to operate in parallel, otherwise large circulating currents can arise.

14.2.1.2 Impedances

The magnetising flux set up in the core of a transformer (Figure 14.1) generates the voltage and current transformations. Winding currents also generate leakage fluxes which do not link both windings, and these are responsible for winding impedances.

Table 14.1 Classification of UK power transformers

Voltage ratio, kV	Rating, MVA	Type	Impedance, % on rating	Tap range
Generator transformers				
18, 22 or 23.5/300 or 432	Up to 600 or 800	Delta/star	16	+ 2 to − 18% of HV
Transmission transformers				
400/275	1000	Auto	16 or 20	–
"	750	"	12 or 20	–
"	500	"	12	–
400/132	240	"	20	+ 15 to − 5% of 132 kV
400/66	180	Star/delta	22.5	+ 5 to − 15% of 400 kV
275/132	240	Auto	20	± 15% of 132 kV
"	180	"	15	"
"	120	"	15	"
275/66	120	Star/star	20	± 15% of 275 kV
275/33	120	Star/delta	20	± 20% of 275 kV
Distribution transformers				
132/66	90	Star/star	17	+ 10 to − 20% of 132 kV
"	60	"	12.5	"
"	45	"	"	"
132/33	120	Star/delta	22.5	"
"	90	"	"	"
"	60	"	15	"
132/11/11	60	Star/star	15	"
132/11	30	"	22.5	"

The impedance of a transformer is largely reactive, the resistive components being very small. Impedance is useful in that it limits currents that will flow under short-circuit currents, thereby providing protection from short-circuit damage and enabling switchgear to operate within rating. The disadvantage of impedance is that it results in a reduction of secondary voltage with load (Figure 14.2), an effect referred to as regulation. Following standard electrical engineering practice, the impedance is expressed on a per unit basis, in terms of the percentage voltage drop caused.

During operation, depending on the loading and impedances involved, it may be necessary to change tap position to maintain the desired secondary voltage. Since impedance can vary with tap position, it is important that a change to a tap position with a higher secondary voltage does not introduce too much additional impedance, otherwise the effectiveness of the tap change can be severely reduced. Also, and perhaps of

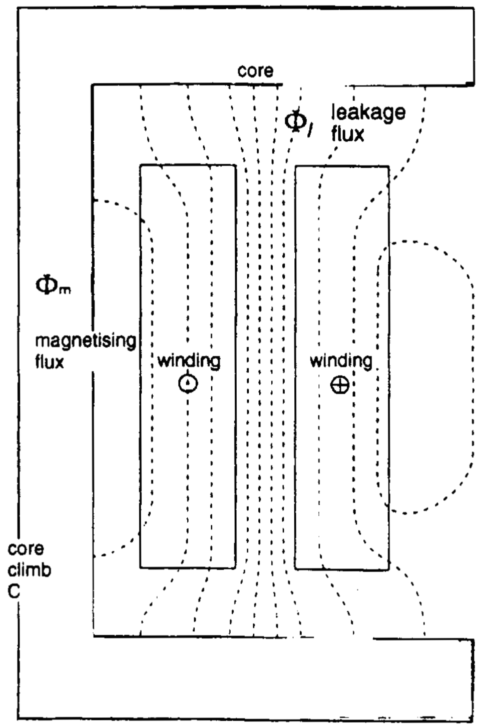

Figure 14.1 Transformer magnetic fluxes

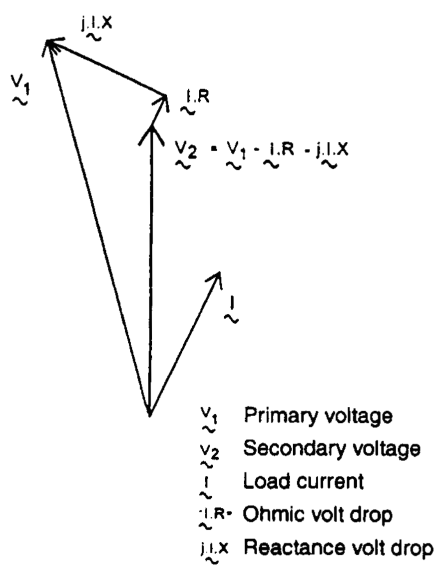

Figure 14.2 Transformer regulation phasor diagram

greater importance in practice, it is necessary to ensure that where transformers operate in parallel, their impedances have similar characteristics, to avoid unequal power sharing between them. For these reasons it is now common practice to specify impedance envelopes, i.e. minimum and maximum impedances at the extremes of the tap range. Figure 14.3 illustrates the impedance envelope currently specified for NGC 275/66 kV transformers, together with the characteristics of some new and old transformer designs.

For three-phase systems, the zero-phase sequence impedance of the transformer is also of importance, since this determines the magnitude of fault currents flowing between the neutral of a star-connected winding and earth if a single phase to earth fault occurs. Zero-phase sequence impedance depends on whether the transformer has a three- or five-limb core, and whether a delta-connected tertiary winding is fitted. The user requires to know what the zero-phase sequence of a transformer will be in order to select appropriate circuit-breakers.

14.2.1.3 Tertiary windings

It has become common practice to specify that star-auto and star-star connected transmission transformers are fitted with delta-connected tertiary windings to provide one or more of the following:

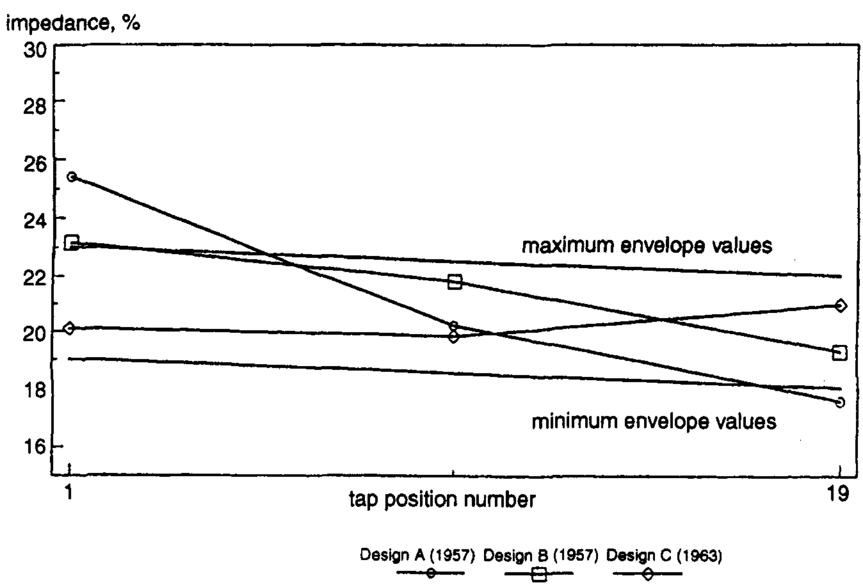

Figure 14.3 Transformer impedance characteristics

(a) stabilisation of the neutral point of unearthed transformers, or line voltages for earthed neutrals
(b) reduction of triple harmonic voltages in the lines and currents in the neutral/earth circuits
(c) reduction of zero-phase sequence impedance to a known level, to have some control of earth fault currents
(d) reduction of current imbalance in primary phases resulting from unbalanced secondary loading
(e) an auxiliary supply for loading or for reactive compensation.

Whatever the primary purpose, it has become practice to specify that all tertiary windings be capable of supplying an external load of 60 MVA at 13 kV, without detracting from the rating of the secondary winding, whatever the cooling state in operation, and of limiting the fault level at the tertiary terminals to 1250 MVA, assuming fault infeeds from the other terminals at their designed system maximum levels.

If the tertiary winding is not to be used for external loading, then only two tertiary terminals are brought out so that the delta can be closed and earthed at one corner externally to the tank.

14.2.1.4 Tap windings and tap-changers

When voltage tappings are required, there are often several possible arrangements of tap winding (e.g. line end, neutral end or linear, and reversing or coarse/fine). In the main there are no specific requirements limiting this choice. If neutral end taps are used in the design, then there may be a requirement to provide some boosting arrangement to ensure that tertiary winding voltages do not vary with tap position because of varying volts per turn on the core.

Where taps are required, a tap-changer must also be provided, and this is usually an on-load high speed device. Several designs are available to the transformer manufacturer. The utility may have a preference, based on previous experience or a need to restrict the number of different sets of spares held. One specific requirement that is common in the UK is for the tap-changer to be housed in a separate tank from the windings, or at least separated from them by an oil-tight compartment. The reason for this is that UK utilities rely heavily on dissolved gas analysis of main tank and tap selector oil for condition monitoring.

14.2.1.5 Rated power, temperatures and cooling

Load currents flowing in windings cause ohmic and stray loss heating. Maximum MVA is often determined by the necessity to limit winding temperatures to levels which will result in an acceptable insulation life. Since maximum MVA is temperature dependent, the rated power required by the user is defined for particular ambient conditions, typically 10 °C.

It is usual for the rated power to refer to steady state loading, i.e. continuous maximum rating, CMR. However, particularly for transmission and distribution transformers, the user is more concerned with variable loads. For this reason, in addition to the rated power required, a user usually specifies that the transformer also be capable of operation for specific load cycles and emergency overloads with limited periods above nameplate rating.

When the transformer is intended for operation at constant load, e.g. generator transformers, then only one cooling regime is normally required. For transmission and large distribution transformers the loading is often well below nameplate rating because of daily and seasonal variations and because more than one transformer normally operates in parallel for security of supply. In such cases, two or more cooler stages are required. It has become practice in the UK for transmission transformers to be required to have an 'uncooled' ONAN (oil natural circulation, air natural circulation) rating of 50% of their main OFAF (oil forced circulation, air forced circulation) rating. Switching between the two cooler stages is automatic.

14.2.1.6 Capitalisation of losses

Transformers are highly efficient devices, but nevertheless over the life of the unit the cost of the losses (up to 1000 kW for a 500 MVA unit) is significant. Losses can be reduced by increasing the amount of copper and iron, but this increases the capital cost of the transformer.

To arrive at the most cost-effective design, a utility calculates the sum required to pay for the expected losses over the life of the transformer, taking into account transformer loading, electricity costs, interest rates and projected movements in these quantities and derives £/kW figures for capitalising load and no-load losses which are specified in tender enquiries. Alternative designs offered by manufacturers are evaluated on the basis of a total capitalised cost.

The cost of losses can reach 30% of the total and is often a decisive factor in determining the most cost-effective design.

14.2.2 General requirements

In addition to the specific requirements of a particular installation, there will be requirements common to all installations covering the following aspects:

- transport limitations on weight and dimensions of the largest indivisible load arranged for transport
- system fault levels
- electrical and safety clearances
- maximum core flux density

- maximum sound pressure levels
- short-circuit performance
- overload performance
- protection practice and CT provision
- terminations and bushings
- cooler arrangements, oil pipework and valves
- ancillary components and fittings such as: winding temperature indicators, dehydrating breathers to limit the moisture uptake of the cooling oil, pressure relief valves, gas in oil monitors, and marshalling kiosks with control, alarm and trip facilities
- documentation.

14.3 Specification and standards

In the procurement process, the user's technical requirements are detailed in a technical specification, which with a contractual specification together form the tender and subsequent contract documentation on customer requirements. Technical specifications make reference to National, European or International Standards.

14.3.1 Standards

Two common dictionary definitions of the word *standard* are:

(i) 'a measure to which others conform or by which others are judged'
(ii) 'a degree of excellence or minimum performance required for a particular purpose'.

In this context neither definition is wholly complete, since the main purpose of transformer standards is to provide a common definition of technical terms and processes, without attempting to set acceptable or target figures for performance.

The main standards relevant to transformers and reactors are:

- IEC 60076 Power transformers
- IEC 60214 On-load tap-changers
- IEC 60289 Reactors
- IEC 60354 Loading guide for oil-immersed transformers
- IEC 60551 Determination of transformer and reactor sound levels.

14.3.2 Specifications

Most large power transformers and reactors purchased in the UK in the last 30 years have been ordered to the *British Electricity Boards Specification for Transformers and Reactors (BEBS T2): 1966*, an electrical industry specification based on the practices of the UK electricity supply and transformer industries.

As is the case for any general technical specification, the aims were:

- to ensure system needs were met
- to obtain technical uniformity
- to eliminate unsuccessful practices
- to satisfy maintenance, safety and environmental requirements
- to achieve economies.

In over 30 sections, BEBS T2, within the framework of BS 171 and other relevant standards, details general requirements – for performance, ancillary components and facilities – provides a standardised format for the user to describe his specific requirements, and specifies test requirements and acceptance criteria.

In addition to providing detailed functional requirements, BEBS T2 also specifies in many key aspects how a transformer is to be constructed. For example, Section IX *Windings, Connections and Terminal Markings* specifies in clause 3.4 that:

'No radial cooling duct shall be less than 3 mm thick and no axial duct containing strips supporting radial spacers less than 6 mm thick.'

This necessity to control manufacturing practices has now largely been obviated by improved understanding of technical issues and the introduction of quality systems such as ISO 9000/BS 5750.

In recent years BEBS T2 has not always been used, either because of greater pressure to achieve a lower initial capital cost since the privatisation of the UK Electricity Supply Industry, or because it is not entirely compatible with EC Procurement Directives.

Because of this, users have now introduced new 'functional' or 'technical' specifications which cover the requirements of their own particular company. Most companies have reinforced this approach by retaining an approval procedure which includes a design review to ensure product compatibility with the user's needs, ensures that the equipment has been fully tested and that the manufacturer can consistently meet the necessary quality assurance standards.

14.4 Testing

When all manufacturing processes have been completed, tests are performed on transformers at the manufacturer's works as part of the procurement process for one of two purposes:

(i) to prove the design meets requirements and to obtain transformer characteristics

(ii) to check that quality requirements have been met and that performance is within the tolerance guaranteed.

Tests performed for the former purpose are referred to as type tests (TT) and are performed on the first unit of a new design, and on selected repeat units where a large number of units of a given type have been ordered. Tests performed for the latter purpose are referred to as routine tests (RT) and are carried out on every unit manufactured. During works testing, special tests (ST) may also be performed to obtain information useful to the user during operation or maintenance of the transformer.

The tests to be performed on a particular transformer and the acceptance criteria are specified in the customer's purchase order and specification and in appropriate standards.

The following tests are performed at the manufacturer's works and form part of the customer's acceptance tests:

- voltage ratio and vector group (RT)
- no-load loss and magnetising current (RT)
- load losses and impedance (RT)
- zero-phase sequence impedance (TT)
- tap-changer operation (RT)
- noise levels (RT)
- winding resistance (RT)
- temperature rise (TT)
- applied and induced overvoltage (RT)
- lightning (RT) and switching (TT) impulses
- insulation resistance (RT)
- hydrostatic oil pressure (RT)
- pressure and vacuum (TT)
- ancillary components (RT and TT).

In some cases, the tests involve a simple check that the transformer has passed some criterion. In others, quantities have to be measured for information or to qualify for performance payments.

14.4.1 No-load loss and magnetisation current

The no-load losses are essentially the iron losses in the core due to hysteresis and eddy currents set up by the main core magnetising flux, and are independent of load current and dependent only on the core excitation.

No-load losses are measured by applying rated voltage at rated frequency to one of the windings, i.e. HV, LV or tertiary, with all other windings open-circuit. Measurements are made at 90, 100 and 110% of rated voltage on normal tap and, for auto transformers with neutral end taps, on maximum and minimum tap position.

14.4.2 Noise levels

The basic cause of transformer noise is the magnetostriction of the sheets of laminations forming the transformer core. The fundamental frequency is double the system frequency, 100 Hz in the UK, but there are numerous harmonics.

Noise measurements are made as specified in IEC 60551 with the transformer on open-circuit at rated voltage. Sound level measurements are made at a number of equally spaced points around the transformer, at a distance of 0.3 m away from a contour formed by a taut string around all projections on the tank at a height of 1.2 m above the ground.

Cooler noise, including fans and pumps, is a further sound source, and noise measurements are made at 2 m from the cooler, and usually at two heights.

14.4.3 Load losses and impedance

Load losses include ohmic losses in the windings, together with winding eddy losses and other stray losses (in framework, tank, etc.) induced by the transformer leakage fluxes.

Load losses are measured by short-circuiting the terminals of one winding (usually the LV) and applying sufficient voltage at rated frequency to the other winding to circulate rated current in both windings. The voltage required is a measurement of the impedance between that pair of windings. Measurements are made for HV/LV, HV/tertiary and LV/tertiary combinations, on maximum, normal, mean and minimum tapping positions, or on all tap positions for a type test. Load losses are usually measured at room temperature, and have to be corrected to the appropriate reference temperature, usually 75 °C.

14.4.4 Tap-changer operation

An on-load tap-changer is operated up and down its full range with rated voltage applied on the LV or tertiary terminals.

14.4.5 Temperature rise

To prove that temperature rises comply to limits specified in IEC 60076, and to derive thermal characteristics for the transformer, a heat run is carried out supplying full load losses for sufficient time to ensure that the temperature rises of the winding and oil reach steady-state values. The 'top oil' temperature is measured by a thermometer in a pocket at the top of the transformer tank, and this is used to verify that steady conditions have been reached. Final winding temperatures cannot be measured directly, and have to be determined by measuring winding resistances for about 15 min after excitation has been removed, and extrapolating back the cooling curves to derive the mean winding temperatures at shut-down (Figure 14.4). Standards describe how winding hotspot temperatures are to be calculated from the heat run test data.

Since with large transformers it is not practicable to supply both rated current and volts simultaneously, the accepted practice is to use the same test method as for a load loss test, but at an enhanced current, so as to supply full load losses to the windings until oil temperatures have stabilised. Once steady-state oil rises have been determined, the excitation current is reduced to the rated value and the test continued for a further hour, after which time the winding rises above oil, referred to as the 'winding gradient', will have reached their steady state.

Oil samples are taken from the main tank before and after heat runs for dissolved gas analysis (DGA) to detect whether any localised overheating has occurred.

Tank temperature rises are also measured during heat run tests, often with the aid of infra-red thermal imagers, to ensure that there are no excessive hotspots.

14.4.6 Induced and applied overvoltage

The induced overvoltage test is intended to verify the power frequency withstand strength between turns and adjacent winding parts, along the winding, between connections, between windings and between phases.

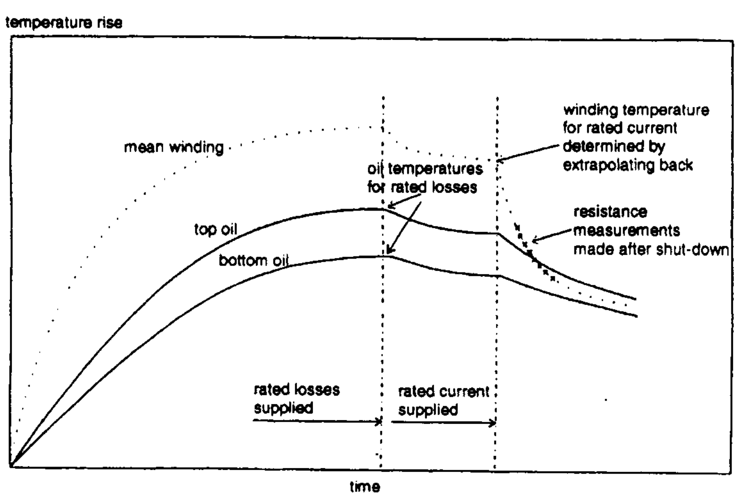

Figure 14.4 Heat run test temperatures

An alternating sinusoidal voltage is applied to the terminals of one phase winding with the other windings open-circuit (Figure 14.5) so as to achieve the test voltages specified. The test is carried out at an increased frequency (up to 400 Hz) to avoid core saturation.

IEC 60076 recognises two different methods for performing overvoltage tests. NGC adopts Method 1, in which the duration of the test is between 15 and 60s, depending on the test frequency, with test voltages as given in Table 14.2. During the induced overvoltage test, partial discharge measurements are made at the line terminals of each phase at 1.2 and 1.6 pu of the rated phase to earth voltage before reaching the full

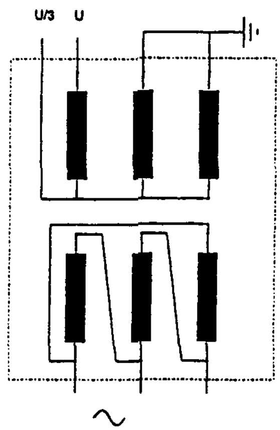

Figure 14.5 Induced overvoltage test arrangement

Table 14.2 NGC test voltages

Rated voltage between phases, kV	400	275	132	66	33	13	11
(a) Minimum lightning impulse voltage withstand (full wave), kV_{peak}	1425	1050	550	325	170	150	95
(b) Minimum induced overvoltage withstand, kV_{RMS}	630	460	230	132	66	26	22
(c) Minimum applied voltage withstand, kV_{RMS}	38	38	38	140	70	50	38
(d) Minimum switching impulse withstand, kV_{peak}	1050	850	–	–	–	–	–

over-potential voltage, at that level, and again at 1.6 and 1.2 pu while reducing the voltage. The intention of the partial discharge measurement is to ensure that the transformer is discharge free at system highest voltage. Any significant discharges detected have to be investigated to the satisfaction of the customer.

The Method 2 test involves a longer test period of about 35 min at somewhat lower test voltages.

Applied overvoltage tests are intended to verify the power frequency withstand strength of a winding under test to earth and to other windings. A sinusoidal single-phase voltage of not less than 80% rated frequency is applied to the winding for 60 s. The test is passed if no collapse of the test voltage occurs.

14.4.7 Lightning and switching impulses

Lightning and switching impulses are intended to simulate the types of high frequency transient overvoltages a transformer is expected to withstand in service. Transients such as these produce high stress concentrations at the winding ends.

Lightning impulse tests are made using a standard 1.2/50μs waveshape (Figure 14.6). which may be chopped to simulate the effect of a protective gap flashover. A switching impulse has a 175/2500 μs waveshape. Tests are made by direct application of the impulse to each line terminal in turn, with the transformer set up as in service (but without attached busbars) (Figure 14.7), on the most onerous tap position, as previously determined by RSO tests.

The test sequence required by NGC for routine tests on every unit, at the voltage level specified in Table 14.2, is:

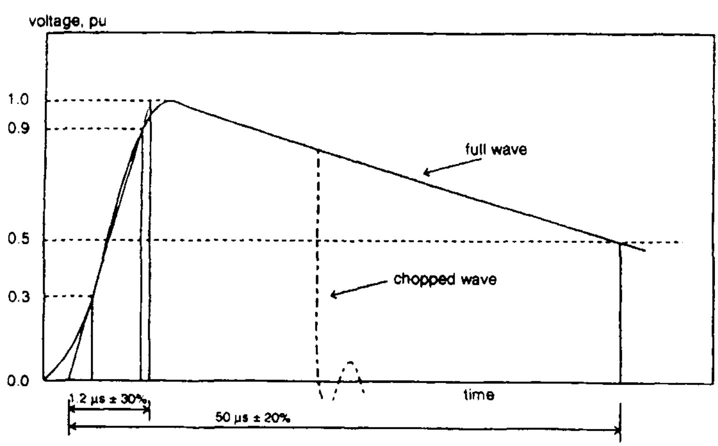

Figure 14.6 Lightning impulse wave shape

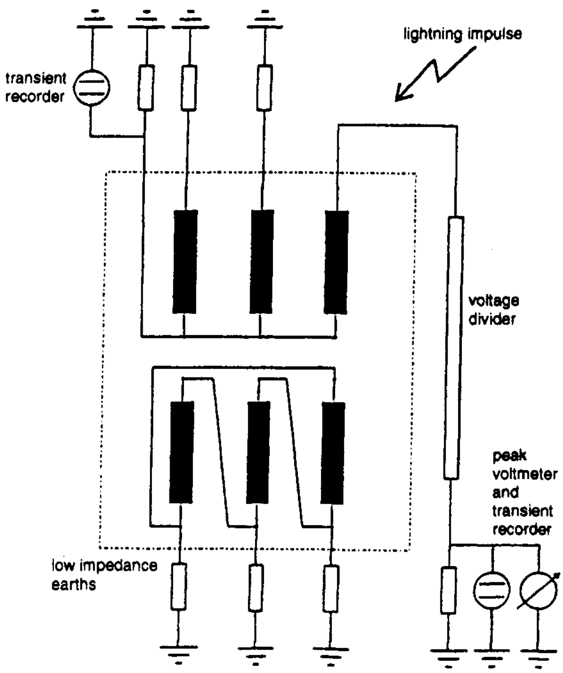

Figure 14.7 Lightning impulse test arrangement

(i) 1 reduced full wave (between 50 and 75%)
(ii) 1 full wave (100%)
(iii) 2 chopped waves (115%)
(iv) 2 full waves (100%)
(v) 1 reduced full wave (at same level as first impulse).

Transient recordings of the applied voltage and of the current at the neutral end of the winding under test are taken.

The transformer passes the test if there is no evidence of complete or incipient failure from audible indications or changes in the voltage or current records.

14.5 Concluding remarks

Current UK practice concerning specifications and testing is based on experience gained over almost 50 years on high voltage transformers of 275 kV and over. During this time there have been few major changes in the transformer procurement scene. In the main, such practice has served very well in that transformers purchased have proved to be very reliable over an extended life.

With the recent changes in the structure of the electricity supply industry, and new EC procurement directives, there are now new pressures to review current practice to achieve immediate capital savings. The challenge is to achieve this without endangering longer term benefits.

14.6 Recent developments regarding life management of transformers

As with all other power system assets, once a transformer has been manufactured to the user's specification and installed on the system, it enters the long operational phase of its life-cycle. Over 40 or so years of service, periodic monitoring and maintenance activities will be carried out to manage the life of the asset, with the twin aims of maximising useful life and determining when the asset should be replaced.

Because of their nature, transformers pose very distinctive life management challenges. As for most other electrical plant items, transformers are usually very reliable, but unfortunately when they occur, faults can develop catastrophically, resulting in the loss of what is usually the most expensive asset in the substation. Therefore life management activities have to be appropriate to the high reliability expected, but also to the serious consequences of failures. Unlike the situation for most other electrical plant items, maintenance is largely a peripheral activity for transformers affecting ancillary components such as tap-changers. Furthermore, internal inspections are rarely carried out because of the expensive oil handling required, and are often inconclusive because so little of the active part is visible. Therefore, successful life management of transformers relies heavily on noninvasive condition monitoring techniques. Fortunately, although the design of transformers has become more sophisticated over the years, the basic technology has not changed, so that design has only a secondary impact on life management activities for transformers. One consequence of this is that collaboration between utilities is perhaps more productive and active than for other asset types.

Perhaps the most important forum for international collaboration on power systems is the Paris based organisation 'CIGRE' (Conference Internationale des Grands Reseaux Electriques a Haute Tension/ International Conference on Large High Voltage Electric Systems). Within Study Committee 12 (Transformers) there are at present three Working Groups dealing with procurement issues: Specifications (12.15), Guidelines for Transformer Design Reviews (12.20) and Short Circuit Performance (12.19). [Visit http://www.cigre-sc12.org/]

Perhaps the most established technique for monitoring the condition of large power transformers and other oil filled equipment in service is dissolved gas analysis (DGA). Most types of faults in transformers cause some breakdown of the oil, generating various gases which dissolve in the oil and can be detected at very low concentrations. Whereas techniques for sampling and analysing oil samples have been standardised, there is less agreement on the interpretation of DGA results. Recently, Task Force 01 of the CIGRE Study Committee 15 Materials Working Group 01 addressing oil impregnated systems published new guidelines for the International Standard IEC 60599 [1], but this is unlikely to be the last word on the subject. One of the main difficulties in interpretation is establishing when a DGA result is indicative of an abnormal condition. Traditionally, company standards have been based on the subjective assessments of specialists based on their experience and statistical analysis of population data. A new approach has been to make use of computer based Kohonen neural networks to perform 'data-mining', to find patterns not predicted by established theory and unearth information hidden in the data [2]. Such techniques differ from so-called 'expert systems' in that, instead of trying to replicate the decision making of human experts, they are providing the human expert with a new perspective on the data which is unclouded by conventional wisdom.

Another CIGRE Working Group (12.18) is charged with the task of taking a wider view of the life management of transformers, and comprises three Task Forces attempting to integrate existing knowledge of failure processes, modern diagnostic and monitoring techniques and experience of carrying out remedial or life extension operations on transformers. Instrument transformers are covered by a separate Working Group (12.16).

A new Working Group (12.20), Economics of Transformer Management, has been charged specifically with considering how economic aspects should be incorporated into life management decision making.

Three other Working Groups are concerned with specific operational problems: Particles in oil (12.17), Static electrification (12/15.13) and Electrical environment (12/13/23.21).

Last, there has been a continued interest in reliability, despite difficulties in collecting data from utilities, attributed to the impact of deregulation. A new Joint Task Force (23/13/14/21/22.16) has been set up to prepare guidelines for the collection and handling of reliability data to a consistent methodology over a range of asset types.

14.7 References

1 CIGRE Working Group 15.01, Task Force, 01: 'New guidelines for interpretation of dissolved gas analysis in oil-filled transformers', *Electra* no. 186, October 1999

2 URWIN, R.J.: Engineering challenges in a competitive electricity market'. High Voltage Engineering Symposium, 22–27 August 1999, London, Paper 5.366 SO