



GENERAL REPORT FOR GROUP A2 (Transformers)

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INTRODUCTION

The scope of SC A2 covers all kinds of power transformers, including industrial, DC converter transformers and reactors and transformer components, and its activities are related to design and manufacture, application of materials, utilisation, safety and environmental aspects, economic/commercial aspects and quality assurance and testing. The two key strategic directions for A2 are to provide services to customers in terms of guidance on reliability, life management, economics, etc. and to work on technology issues such as safety, new technology and concepts, electrical environment, pre-standardisation work, etc.

Approximately 300 delegates attended the 2006 SC A2 group session on Friday 1st September.

The chairman introduced briefly the activities in progress within SC A2. WG A2-23 (Fantana), A2-28 (Saravolac), A2-32 (Hoehlein), and IEC TC 14 liaison (Fyvie – Chairman of IEC TC 14), presented an overview of relevant developments in their respective working bodies. Due to the lack of time, the work in progress in WG A2-26, A2-27 and the report of the liaison officer with IEEE were not reported. All these presentations are posted on the SC website. The creation of four new working bodies was mentioned. The domains covered by these new groups are: 1) Fire safety, 2) Guide for maintenance, 3) Experience in service with new liquids and 4) Reliability aspects of transformers..

The three Preferential Subjects selected for 2006 were:

PS1: Transformers Reliability – Technical Economical and Strategic Aspects

PS2: Phase Shifter Transformers

PS3: New Developments of Electrical Transients on Transformer Performances

Twenty-seven (27) papers addressing these topics were accepted. The discussion included 57 prepared contributions. Due to the high number of prepared contributions, practically no time was left for spontaneous contributions, except for a few at the end of the session, which closed at 17h30.

1 PS1: TRANSFORMERS RELIABILITY – TECHNICAL ECONOMICAL AND STRATEGIC ASPECTS

A keynote address was presented by Arne Petersen, Powerlink (AU) on the topic ‘Reliability Drivers for Transmission System Operators - How Transformer Engineers May Respond to the Challenge’. Mr. Petersen described the practices that presently exist in the electricity supply industry in the southeast regions of Australia and Tasmania between the Transmission System Operators (TSOs) and Regulatory authorities regarding duties of electricity supply, maintenance, infrastructure replacement and associated financial issues.

Several of the system reliability issues aspects he described such as circuit availability, loss of supply consequences, forced outage durations, plant constraints and Regulatory targets are recognizable and encountered by many utilities elsewhere. At the ‘transformer level’, these issues translate into a range of practical considerations concerned with managing the condition of transformers efficiently and safely by minimizing costs, extending service life, identifying and evaluating risk, avoiding unplanned outages, especially on critical plant. Mr. Petersen believed these issues had been properly addressed by the papers received and by the Special Reporter, and fully expected the contributions at this meeting to further enhance our knowledge.

A total of 14 papers were received addressing this topic. Reliability is obviously a primary attribute expected of electricity systems and transformer reliability will have a major impact on this because of the long replacement times and costs involved. Reliability is influenced by actions taken throughout the life of a transformer, so the contributions were grouped and discussed in the following sequence of topics areas.

1.1 Specification and Manufacture

Paper A2-113 provides a retrospective review of attempts made in the UK in the 1970’s to improve the reliability of a new series of large generator transformers of 800 MVA rating following unsatisfactory experience with earlier 600 MVA units. A key decision seems to have been to specify single phase units, which itself allowed lower stress designs. Extra factory testing was also specified. Another innovation was to require inter-changeability between units produced by different manufacturers, achieved by restrictions on physical and electrical parameters. Clearly such actions were much easier to achieve with the stable commercial situation that existed then. Impressive results for reliability are claimed, together with improved availability through significant reductions in replacement time after failure.

Paper A2-101 provides a contrasting picture of difficulties experienced by a large utility in achieving good transformer reliability in the mid 1990’s during a period of increasing competition and de-regulation, with pressures to reduce equipment prices and manufacturing times. An increase in failure rates of new transformers during factory tests and in service was experienced, mainly dielectric faults in the active parts, despite the fact that dielectric test requirements had been re-enforced. A thorough investigation identified a number of inter-related causes: in particular system changes introducing the possibility of more switching transients and lower quality in manufacture under pressures to reduce manufacturing costs and time. A number of measures have been instituted in an attempt to redress the situation: increased cooperation between engineering and operational areas, and between utility and manufacturer, improved inspection during manufacture and additional monitoring systems and tests.

Question 1.1

In order to balance commercial pressures on first cost is it possible to factor into procurement decision making the cost of poor reliability ?

Is it possible to guarantee good dielectric ‘spare margin’, and therefore in service reliability, by insisting on the most exacting dielectric testing during factory acceptance, or is it still necessary to perform comprehensive inspections during manufacture ?

Is there evidence that single phase transformers are inherently more reliable than three phase ?

During the A2 group session, contributions on this question were taken together with contributions on questions about reliability surveys:

Paper A2-114 summarises the views of a Reliability Advisory Group regarding difficulties obtaining meaningful reliability statistics and proposes a way forward.

Question 1.7

Which countries, utilities or manufacturers have good information on transformer reliability which could be made available for comparative analyses ?

Is there good evidence of an increasing failure rate with age ?

Are transformers built today as reliable as older units ?

Are transformer failures due more to ageing processes than damage caused by system events ?

Mr. Caillé in his address at the CIGRE Opening Ceremony referred to the changes in business trends affecting utilities and manufacturers worldwide. The point was reinforced during the A2 Session by the first contribution, from Sweden (1.1.1). It was considered that the consequences of these changes could be far reaching and affect transformer and network reliability. Different practices in transformer design, manufacture, and quality control as well understanding specifications, standards, and the procurement risks could bear directly on reliability it was suggested. Reliability is a topic that needs a wider, structured assessment approach more than ever and purchasers should be alert to this need and the risks of doing otherwise.

A contribution from a German manufacturer (1.1.2) provided data on the in-service reliability of new transformers supplied from a number of different factories, showing that failure rates of no more than about 0.2% p.a. should be expected, with no evidence of any significant deterioration in the reliability of transformers supplied over a period of 10 years.

A contribution from Brazil (1.1.3) re-iterated factors believed to have led to the high number of failures reported in their paper A2-101. Commercial pressures such as: deregulation, energy price reductions, and competition pressure on manufacturers not only cut costs but reliability also. To improve the situation required technical co-operation with suppliers, better specifications, improved inspection during manufacture installed monitoring systems, additional tests such as ACSD test as well as ACLD induced voltage tests with measure PD’s limited to 200 pC. Core quality is verified by applying a no-load loss test for up to 24 hours at rated frequency and 1.15 x rated voltage. One general conclusion was that competent comprehensive design reviews and inspections during manufacture are still necessary despite

increased and improved factory tests. In answer to the question on whether it is possible on a first cost basis to factor the cost of poor reliability into the procurement decision making, they were concerned that this would tend to reduce the number of suppliers and increase first cost, and would not necessarily address the causes of poor reliability.

On the question of whether single phase units were inherently more reliable, a contribution from Australia (1.1.4) reported that over a 45-year period, the failure rate on 220 kV transformers excluding bushings and tap changers was 1.6% p.a. for single-phase banks and 0.18% for 3-phase transformers. At 500 kV the failure rates of the two transformer types was virtually the same and very small. However, it was recognized that whilst this data suggested there was no evidence that single-phase banks were inherently more reliable, these considerations could become dominant when transport considerations preclude 3-phase units.

By contrast, a contribution from South Africa (1.1.5) showed clearly that their single phase transmission transformers were significantly more reliable than equivalent three phase units. Their data also provided dramatic evidence of increasing failure rates with age, with average life expectancies of around 25 years.

A contribution from the Netherlands (1.1.6) reminded the audience that short circuit performance should not be forgotten when attempting to improve reliability by enhanced specifications and urged that short circuit tests should be carried out to verify performance, since experience showed that many new designs that were tested failed.

Lastly, a contribution from Canada (1.1.7) described work done to evaluate the in-service cost implications of replacing failed units with more expensive higher specification units, compared to the lower first cost option of repairing, which had been shown to result in less reliable units.

1.2 Diagnostic monitoring and assessment in service

Paper A2-106 describes work undertaken in Japan to try to distinguish between abnormalities in the winding and the core when a problem is indicated by dissolved gas analysis (DGA) results, to assess the probability of internal faults developing and triggering shutdowns, and to assess the possibility of repairs. Models of windings and cores were constructed with different types of faults. A diagnostic algorithm based on ethylene/ethane ratio and gas generation trends is proposed.

Paper A2-112 describes a methodology for ranking the risks of continued operation of power transformers used in Thailand, concern having been expressed about transformers more than 15 years old. The risk ranking is based on DGA fault interpretation using Rogers' ratios and degree of depolymerisation (DP) of paper estimated from measured furan in oil concentrations using the Chendong equation.

Paper A2-103 describes practice in the Czech Republic to assess the remanent life of transformer insulation from measurements of furan concentrations in the oil. A DP value of about 350 is taken as corresponding to end of insulation life. Ageing experiments with representative ratios of paper and oil have been used to derive furan concentrations corresponding to particular DP values.

Paper A2-109 describes experience in Russia of detecting and diagnosing winding deformation faults using low voltage impulse (LVI), frequency response analysis (FRA) and short-circuit impedance (SCI) techniques and how prognoses are qualified using computer programs to calculate short circuit strength. The axial, radial and tangential (twisting) forces on windings during short-circuits are discussed. Several case examples of estimation of mechanical condition after short-circuit tests and in-service faults are described.

Question 1.2

Diagnostic tests can only improve reliability if a fault is detected which can be repaired, or if a transformer is identified as being critically damaged and is replaced during the next planned outage to avoid a forced outage. What successes can be claimed for detecting problems before failure and avoiding a forced outage ? Is there sufficient confidence in diagnostic tests, or concern about forced outage costs, to remove expensive transformers from service when there is little or no confirmatory evidence from protection or system events ?

What other innovative techniques are used to decide from a routine DGA result that a transformer definitely has a fault and to assess the seriousness, and what successes can be claimed ?

Regarding ageing, is there consensus on what should be considered as critical values of DP and furan concentration, and have utilities established practical correlations between these from data obtained from real transformers rather than test-tube experiments, so that they are confident they can recognise when insulation is near to end of life ?

Regarding the assessment of ageing from furan measurements a contribution from the Czech Republic (1.2.1) re-iterated their reservations about determining degree of polymerization (DP) of cellulose insulation from FFA measurements, since the latter can be affected by the type of transformer and especially the type of oil preservation system e.g. hermetically sealed v. free breathing. A safe DP value was considered to be in the region of 300-200. DP values such as 200-150 indicated a transformer end-of-life condition and equipment exhibiting these values should be regarded as unsafe. It was recommended that transformers operating in the range 200 kV-400 kV should possess a DP value not less than 400 to cope with short-circuit faults.

A contribution on behalf of CIGRE D1.01 (1.2.2) listed the factors influencing the generation of 2-FAL in transformers as well as those affecting the partition of FFA between oil and paper in a transformer. The value of FFA as a diagnostic tool was not disputed but it was accepted that paper ageing could be determined with greater assurance in the laboratory than in transformers because of their more complex insulation system and internal environment. It was not considered realistic to try to correlate data from all transformers worldwide in all conditions. Data surveys within a utility that take into account transformer types and operating practices may be the most useful. The measurements that offered the greatest benefit for condition assessment were those that provided a trend. It was noted that the work by WG D.01.13 in association with A2 was at an advanced stage and a final report and Brochure are still scheduled for publication in 2007.

Regarding the successful use of diagnostics to improve in-service reliability, a contribution from France (1.2.3) presented two examples of the use of dissolved gas monitoring of 550MVA 400kV single-phase units at EDF nuclear power plants. In the first case a

continuous hydrogen monitor was fitted after a Buchholz alarm with H₂ and C₂H₂ indicated by DGA. This enabled the transformer to be operated for a further 4 years until it had to be removed when dissolved gases started to increase and give alarms. In the second case a thermal fault was diagnosed from routine DGA, so a multi-gas monitoring system was installed. Expert interpretation diagnosed a fault in the magnetic circuit, which allowed the system to be removed when gas levels started to show a falling trend, thereby avoiding the replacement of the transformer. Although such monitoring systems provide valuable information, skilled support and judgment are essential in deciding ‘what should be done’.

A contribution from Russia (1.2.4) recounted how low voltage injection (LVI) or frequency response analysis (FRA) tests had helped to assess the condition of three transformers with suspected short-circuit damage. In one case the transformer was 38-years old and was replaced directly. The transformer in the second case was younger and was successfully repaired and returned to service. Otherwise, if there are significant prospects of short-circuit events and the above measures are not instituted a serious loss could result, as the user in the reported third case apparently discovered to his cost.

A contribution from Australia (1.2.5) described how FRA and impedance tests had indicated that a key 48 year old single phase transformer bank had been damaged by a short-circuit incident and prompted a spare transformer to be moved to site, which minimised out of service time when one of the phases subsequently failed.

A contribution from the UK (1.2.6) described how innovative assessment of routine DGA results using a ‘DGA scoring algorithm’ had allowed a suspect transmission transformer to be identified despite DGA levels being well below accepted norms, and how subsequent off-line diagnostic tests (FRA and capacitance and loss angle measurements) had demonstrated beyond reasonable doubt that the transformer was seriously damaged mechanically despite there having been no adverse indications from protection. It was decided to replace the transformer to avoid any unscheduled forced outage in the future, and when the transformer was scrapped on site serious hoop buckling of the inner common winding layers was found.

The discussions on this topic concluded with a contribution from Japan (1.2.7) outlining a new technique to diagnose the condition of oil-filled transformers. Gas chromatography-mass spectrometry and purge/trap gas extraction are employed to condense and analyze very small, decomposed products in transformer oil. Approximately 130 thermal decomposition products were identified as the result of thermal decomposition of insulating materials. Their source was as diverse as thermally upgraded paper, varnish coated paper, glass epoxy and the insulating oil itself and were attributed to discharge activity and overheating. The technique, which is referred to as PTI-GCMS Analysis, has apparently been applied to transformers in service for some two years with beneficial effect.

1.3 Reliability of major components (bushings and tap-changers)

Paper A2-104 describes the application of polarisation/depolarisation current (PDC) dielectric response measurements to HV bushings in Germany, to distinguish between ageing and oil conductivity problems, and to identify defects not detected by traditional $C/\tan \delta$ measurements at ambient temperature. Experiments were carried out on laboratory samples of new Kraft paper prepared to various moisture contents and oil conductivities, and on service aged OIP bushings. It is stated that PDC analysis can be used to distinguish ageing

and enhanced water content of OIP and that severely aged OIP can be detected with PDC at ambient temperature. It is supposed that ageing mainly affects the dielectric properties of the oil component in OIP. Also considered were the effects of external influences, e.g. leakage currents from grading foils to ground, which are assumed to be responsible for 'negative dissipation factor measurements' and polarity reversals during PDC measurements. It is claimed that conductive bandages can be used to limit the effects of parasitic currents, and that PDC and power frequency measurements on severely aged bushings are not sensitive to parasitic currents.

Paper A2-102 describes the maintenance strategy adopted by a major Canadian utility for on-load tap-changers (OLTCs), which can have a serious impact on the reliability of the transformer and add very substantially to the maintenance effort required. For preventative maintenance three diagnostic tests are discussed: winding resistance measurements are performed during internal inspection outages and are effective for detecting contact problems, OLTC DGA is not currently part of the utility's routine program while a vibro-acoustic technique is being trialled for yearly on-line checks during service and before and after internal inspections, in the hope of providing an effective, on-line and low cost diagnostic for all types of faults and OLTC designs. For corrective maintenance two complementary processes are applied: a Reliability Analysis process to investigate the performance of a particular type of OLTC and optimise corrective actions and a Life Decision Making process to justify any major work on individual OLTC's. The application of these two processes is illustrated by a case example of the analysis of an old 'bolt-on' OLTC type for which improved solutions for some minor works were developed, with a retrofit solution recommended if major work is required.

Question 1.3

Bushings and tap-changers are both critical items affecting transformer reliability but pose very different maintenance challenges. Bushings are essentially simple passive insulation components with common degradation processes which unfortunately are difficult to assess, and tend to be replaced rather than monitored if problems are suspected. Tap-changers are complicated mechanical components with many different failure modes which vary from type to type.

Is there sufficient confidence in 'dielectric response' measurements for reliable assessment of the condition of HV bushings, bearing in mind the sensitivity of bushing dielectric loss measurements to external influences? Can a 'one-off' off-line assessment provide sufficient assurance that a bushing is fit for continued operation for a significant period, e.g. 5-10 years?

Can an economic solution be developed for condition based maintenance of OLTCs or is it better to rely on traditional time based maintenance, backed up by cost justified engineering modifications?

A contribution from Germany (1.3.1) clarified the means of assessing ageing in OIP bushings from PDC results described in paper A2-104, and how the effects of leakage currents could be assessed using conducting 'bandages'.

A second contribution from Germany (1.3.2) described a monitoring system to make on-line voltage measurements at an HV bushing tap using a capacitive voltage sensor. Measurements on the 275 kV bushings of a 185 MVA step-up transformer were shown, illustrating typical voltage fluctuations and phase imbalances, together with a surprising number of transient

over-voltages. In a second example, on-line measurements on a 420 kV bushing automatically generated a warning after only 18 months in service, the system having diagnosed a change in capacitance corresponding to a short between 2 grading foils. The contributor claimed a potentially hazardous problem was thus avoided.

Two contributions were presented that addressed issues related to OLTCs. The first, from the Netherlands (1.3.3), summarized up to 25 years of service department experience of in-tank tap changers. It was claimed the adoption of silver plated contacts, time based inspections of 5–6 years for tap changers at star connected winding neutral ends and 3-4 years for those connected into HV delta windings, together with monitoring diverter switching times had improved tap changer service performance to the extent that a peak failure rate of 9 per annum in 1980 was reduced to six by 1985 and steadily thereafter to 2 in 2005. The same contributor also gave details of bushing failures in the Netherlands which started increasing from 1990, mainly due to various ageing processes, e.g. corrosion leading to moisture ingress. Stringent monitoring of ageing HV bushings was recommended.

A contribution from Canada (1.3.4) reported that with an ageing population of tap changers, failure rates are consistently increasing with age for all types of tap changer although some models were significantly worse than others. Fault rates for tap changers between the ages of 20 and 40 years old were said to have more than doubled. The methodology to manage this population was to use time based maintenance (TBM) at intervals appropriate to the model, together with engineering modifications where appropriate, and to look to techniques such as acoustics to introduce condition based maintenance (CBM).

Lastly, a contribution from France (1.3.5) covering a number of topic areas described a transformer refurbishment policy being implemented to address an increasing failure rate with age. Serious failures were due mainly to problems with bushings, tap-changers and the active part, but maintenance of other auxiliary parts, e.g. coolers and oil was considered essential for long term serviceability. The policy schedules the refurbishment of accessories and oil charge where this is seen as necessary to achieve the expected remaining life of the active part, provided this is at least 15 years. There is no intervention on the active part, no moving of transformers for factory intervention and no preventative replacement of equipment which is still working properly, mainly because there have been no defects in active parts detected to date.

1.4 Repair and refurbishment options

Paper A2-304 describes the investigation and on-site repair of a number of HVDC converter transformers in India. Concerns about a possible problem were first raised by routine DGA results from one of the transformers: a rising trend in hydrogen and higher than expected furan levels for a new transformer suggested a thermal fault despite levels of diagnostic gases being within accepted norms and gas ratios being normal. An internal inspection identified severely overheated ‘T’ joints between top LV leads and LV bushings, caused by a localised lack of cooling around the joint. Inspection of other units confirmed a generic problem. After consultation with the manufacturer it was decided to carry out on-site repairs of all similar units, to minimise outage times. To facilitate the repairs additional access holes were trepanned in the top tank cover above one of the leads, and special measures were taken to protect the active part from debris and moisture during the repair work. After the repair work,

some LV tests were carried out to check the condition of the units before they were returned to service.

Paper A2-108 describes Norwegian experiences of the rehabilitation of the paper insulation in power transformers using LFH drying technology and oil reclamation. The importance of both moisture and low molecular weight acids regarding paper ageing rates is discussed. A limit of 0.1 mgKOH/g for oil acidity is suggested. Oil reclamation with reactivation of the Fullers earth reagent is recommended to allow sufficient absorbent to be used to achieve a long term stability of the reclaimed oil. Practical experience with the on-site rehabilitation of two 200 MVA network transformers is discussed.

Question 1.4

Do manufacturers or other service providers have the capability to perform on-site repairs, when these are preferred to keep forced outage costs to a minimum, and is it necessary or even possible to carry out HV testing to verify the dielectric condition prior to return to service ? What about repairs to the winding assembly itself, or on-site replacement of windings ?

Can the effectiveness of refurbishments on service aged transformers be reliably determined, and how can such work be cost justified ? Are on-line treatments as effective and are they more attractive economically than off-line procedures ?

The first contribution on this topic, from India (1.4.1) clarified that for the on-site repair of overheated LV lead insulation on a number of HVDC converter transformers, described in their paper A2.304, one of these transformers was in fact repaired at a local factory and fully tested to prove the repair methodology.

A contribution from France (1.4.2) described the site repair and subsequent testing of a single-phase 206 MVA 400 kV HVDC transformer associated with the Cross Channel DC link between France and the UK. Examinations at site had established the problem was a core fault which was repaired in-situ. The transformer was re-filled and subject to a series of 80C heating and vacuum cycles. Valve winding limitations prevented AC dielectric proving tests after the drying treatment so the unit was tested by applying a DC voltage corresponding to about 80% of the factory test voltage level to the valve windings. The transformer was successfully restored to service in October 2005.

A second contribution from France (1.4.3) described mobile workshops that had been used to carry out repairs in difficult ambient conditions, with all facilities for atmospheric control and site testing. These facilities had also been used to effect insulation upgrades, e.g. by retrofitting with high temperature insulation assemblies.

A contribution from Switzerland (1.4.4) described how 200 transformers had been repaired at site around the world in the last 15 years without any subsequent in-service failures. In most cases HV testing had been carried out. Only a few on-site repairs are made to the winding assembly itself – usually limited to repair of minor defects or connections. For more serious winding damage it is preferred to replace the whole winding assembly with a sealed replacement shipped out from a factory which has been fully processed and tested. Final drying of the repaired unit is by hot oil circulation and vacuum cycles or Low Frequency Heating.

One of the factors that sometimes justifies repairing transformers at site is the relative remoteness of suitable factory facilities. A contribution from Germany (1.4.5) described recent repairs on two HVDC transformers overseas, both involving replacement of a winding in addition to other parts. The new windings were manufactured and tested in Europe and shipped to site together with test and other equipment to complete the repair and permit dielectric proving tests at 100%AC and at least 80%DC of the original test voltage level. Both units have been successfully returned to service, one of them as recently as June 2005.

Another contribution from Germany (1.4.6) described a comprehensive commercial mobile HV test facility based on a 450 kW 3-phase static frequency converter capable of providing a voltage up to 620 V at pre-selectable frequencies between 40 and 200 Hz. It is capable of supplying AC induced and applied withstand voltages. The total harmonic distortion (THD) is of the order of 3% and the PD noise level around 30 pC. It has been used to site test transformers up to 200 MVA. An additional mobile unit is used for short-circuit loss and no-load loss measurements. Further separate mobile test voltage equipment is available to perform impulse voltage tests up to 1600 kV and is complete with computer controls and transient recorder equipment.

A contribution from the UK (1.4.7) referred to on-site repairs carried out on the external winding insulation of the series unit of a 400 kV 2,000 MVA quadrature-booster and described how the repaired phase was subsequently energised off-line on-site to above working voltage levels by supplying a relatively low voltage to one of the other phases. The point was made that the characteristics of the quadrature booster that allowed this innovative method of off-circuit testing also raise the possibility of very high voltages being generated in service in the event of particular circumstances that cause transient differences in phase voltages, in particular if a phase to earth fault occurs and the faulted phase is the last to clear (discussed further in A2.207).

A contribution from Norway (1.4.8) addressed questions about on-site insulation refurbishments. Regarding how the effectiveness of such operations should be assessed, the point was made that because of the long time constants involved it can take many months before the full picture is seen. The value of refurbishment was the extension in insulation life. On-line treatments appear effective for directly treating the oil but because they can only improve solid insulation quality by a lengthy 'dilution process', off-line processes that involve heat and vacuum directly applied to the paper, like hot oil spray or low frequency heating, provide more immediate benefits.

A contribution from France (1.4.9) provided a salutary warning that refurbishment operations do not always improve reliability. Two instances were described when partial discharge problems were encountered after oil was replaced in two different transformers. The fundamental cause has yet to be determined.

The last contribution on this topic, from Canada (1.4.10), described how the financial benefits of insulation refurbishments had been calculated, based on assumed improvements in failure rates.

1.5 New threats to reliability – corrosive sulphur

Paper A2-111 describes work undertaken by a major Swedish manufacturer to understand recent transformer failures attributed to corrosive sulphur. It is pointed out that these failures have occurred despite design, operation and materials being well within established industry practice, and the present-day sulphur content of oils being orders of magnitude lower than previously. A review of failed units points to a number of likely risk factors: transformers or reactors operating at relatively high temperatures due to loading or ambient temperature, with sealed conservators and un-enamelled windings, but perhaps most significantly the use of particular grades of oil. Examination of Cu₂S deposition in failed windings shows a strong overall correlation with temperature, but also localised variations which suggest that other environmental factors can predominate over temperature. The deposition phenomenon has been reproduced in laboratory experiments using a covered conductor deposition (CCD) setup: but only for those few oils that have been associated with failures and over a narrow range of oxygen concentrations. It is recommended that in order to make the existing ASTM D1275 test capable of identifying oils that can cause corrosive sulphur problems it is necessary to have a controlled oxygen presence.

Paper A2-105 describes laboratory investigations undertaken by an Indian manufacturer into the effect of mercaptan sulphur on the insulation performance of oil impregnated winding insulation. Experiments were conducted with a range of mercaptan concentrations up to 100 ppm achieved by two different sources. Samples were aged for up to 2,000 hours at either 105 or 140°C, with either air or continuous N₂ bubbling through the oil. After the ageing period metallurgical and chemical studies showed the presence of copper and sulphur on paper surfaces immediately in contact with the copper conductor but only very marginal degradation of electrical properties of the paper.

Question 1.5

Does the discovery that copper sulphide deposition is critically dependent on a narrow range of oxygen concentrations provide a reliable means of identifying suspect oils and units that may be at risk ? Is there any prospect of remedial action for units which are suspected to have been contaminated by corrosive sulphur ? Are there any new developments to report ?

A contribution from India (1.5.1) emphasised the roles of mercaptan sulphur in the oil and oxygen concentrations in the copper on the production of copper sulphide at low oxygen concentrations, but also pointed out that particularly for HVDC transformers unusual operating stresses, e.g. frequent line faults and commutation failures, were probably responsible for copper sulphide deposition causing winding failures. Regarding possible remedial action, passivators such as BTA were recommended to slow the formation of deposits and oil could be treated with molecular sieves to remove reactive sulphur.

A contribution from Sweden (1.5.2) emphasised the strong dependence on oxygen concentration described in their paper A2-111 and contrasted the effectiveness of their CCD test for identifying problem oils compared to the extended ASTM test: the CCD test had highlighted three oils had been shown to be responsible for failures, together with a further two oils that had been recently introduced. Having identified a current oil which passes the test, the corrosive sulphur problem is said to have been solved for new transformers.

1.6 New Technology

Paper A2-107 describes the development of a low pressure (1.2-1.4 kg/cm²) SF₆ gas insulated 20 MVA 154 kV transformer in Korea, to overcome the economic disadvantages of high pressure alternatives. Key tasks were to cope with the reduced impulse strength and heat transformer performance at the lower pressure. Electric field calculations were performed to limit the maximum electric stress in the key wedge-like gaps between turns and sections and a half scale model was built to check the impulse strength of the HV winding design. Directed forced cooled performance of the active part was verified using a 3-D computational fluid dynamics (CFD) computer program and a compatible water cooler was developed. A tank was designed capable of withstanding the gas pressures to be used and the over-pressure that would arise during an internal fault. Finally, a full scale prototype transformer was built and successfully tested.

Paper A2-110 describes the joint development of a Transformer Electronic Control (TEC) system between a Swedish utility and transformer manufacturer. The primary objective was to develop a system for monitoring thermal performance using a limited number of standard sensors which could be installed on a transformer in a short time. The system is also designed to accept and display information from other types of sensors, e.g. gas in oil and tap-changer sensors. The TEC cabinet has green, yellow and red status lights, displays all important information at the touch of a button and provides communication with a local or remote PC. It is concluded that such systems should be simple, self supporting and not require operator attention in case of normal operation.

Question 1.6

It is accepted that new technology will initially be more expensive and relatively untried. How can the costs of unreliability of conventional technology be evaluated to evaluate acceptable cost premiums for such new technology ? What reliability requirements should be imposed on new technology solutions ?

A contribution from Korea (1.6.1) emphasised that gas insulated transformers were essential for compact underground substations in city centres and re-iterated the advantages of low pressure units: both main tank and tap-changer can operate at the same pressure, with savings in manufacturing and maintenance costs.

Regarding monitoring systems, a contribution from Slovenia (1.6.2) recommended that the most cost effective approach was to make use of measurements already provided by SCADA systems, together with specialist sensors for dissolved gas or moisture, etc.

2 PS2: PHASE SHIFTER TRANSFORMERS

As there was no keynote speech for this preferential subject, the Special Reporter, Milan Saravolac, made a brief introduction of this topic.

The Special Reporter emphasized the importance of a good collaboration between the equipment manufacturers and final users throughout the project life, in order to ensure that the challenging tasks imposed by the complexity of the PST specification, design and testing requirements are adequately addressed. In addition to the requirement of achieving the

adequate short circuit withstand capability, these key challenges may include selection of a suitable OLTC, finding of an optimum compromise between the no-load phase shift and minimum impedance requirements, as well as modelling of internal voltages and fluxes for a variety of possible schematics and configurations. An effective control, protection, monitoring and maintenance strategy needs to be adopted as well in order to optimise utilisation of PSTs while preventing operation outside the safe operating envelopes. It is also possible to extend the functionality of PSTs and enhance further their performance by adding reactive elements (inductors and capacitors) in parallel or series.

Mr Saravolac concluded his introduction with a statement that Phase Shifting Transformers (PST) have been providing well-proven means for controlling the active power flow in electrical power systems for many years and that It can be expected that due to the deregulation of the electricity market the need for PSTs in conventional and/or novel applications may increase in the future.

In total, seven papers were accepted by A2 for this preferential subject. The Special Reporter arranged these papers in five categories and raised questions for discussion accordingly. Altogether, 10 prepared contributions were received in advance of the plenary session.

2.1 Quadrature Boosters, Phase Shifting Transformers and Autotransformers

There were five contributions addressing the questions raised on the papers A2-202, A2-204, A2-206 and A2-207.

Paper A2-202 reports on installing a Phase Shifting Autotransformer in the 220 kV interconnection between the Belgian and French transmission systems in order to boost the power exchange capacity. The solution involved a replacement of the existing autotransformer by a phase shifting autotransformer in a line susceptible to overload. The main operational parameters of the phase shifting autotransformer were derived from the extensive load flow studies. The innovative design features the autotransformer and booster transformer active parts in the same tank, with 6 tap changers, 3 at the 150 kV the level for the voltage regulation and 3 in the neutral of the autotransformer for the angle regulation. Some advantages and drawbacks of this concept are briefly discussed. Due to the multitude of the possible combinations of the voltage-angle regulations and associated guaranteed values the testing program of such device had to be optimized. The protection scheme provided functionality and redundancy required in accordance with the Belgian standards with two differential protections at each side of the phase shifting autotransformer. The control strategy ensured that all potential dangerous situations are prevented and some tap combinations were interlocked in order to prevent over-fluxing of the magnetic core. The authors comment that in order to adequately address all possible operational issues a close cooperation between the grid operator and manufacturer is essential.

Paper A2-204 describes French experience with the application of PSTs in the RTE network, together with some examples of design and application of Phase Shifting Autotransformers for simultaneous regulation of active and reactive power flow that were provided by French transformer manufacturers for other networks. PST technology is in general considered as proven and reliable, despite some additional complexity over the conventional and well established power transformer technology. However, it can not become an alternative to the structural development of the grid but an effective short term solution for increasing

efficiency of the existing power systems. Some specific aspects of application, specification and design are discussed in the report. The necessity of a good collaboration between users and suppliers of the equipment, spreading from the early specification to the design review and verification stage is strongly emphasized, with an example of the short circuit strength withstand capability evaluation carried out by the R&D facility of the user. The RTE specifications will impose the basic configuration of the PST including the number of cores. The maximum on load phase shift is imposed by the specification, allowing designers to come up with a value of the maximum no-load phase angle for the optimum design. In terms of the control strategy, the speed of the OLTC is seen as an essential performance parameter. A brief comment on the control strategy is provided, including curative, preventive and combined approaches. Some specific test aspects are briefly presented in the paper especially those associated with the two-core type of PST, such as the heat run and dielectric tests. Finally, two different designs of the Phase Shifting Autotransformers intended for the phase angle and voltage regulations with separate regulating windings and tap changers for the two functionalities are briefly presented.

Paper A2-205 deals with special requirements regarding the selection of OLTCs for application in phase shifting transformers. Some specific aspects of selecting OLTCs for different types of PSTs are briefly discussed, including limitations associated with the line end connection in the single core design and flexibility with choosing the insulation level for the two core PST application. A brief explanation of the phenomenon and effect on the winding design of the recovery voltage that can appear across the change-over selectors is briefly discussed. In some applications and operating conditions additional means for the fault current limitation may be required as the PST impedance may be very low. One of the most important parameters to be taken into account while selecting OLTCs for the PST applications is the breaking capacity. For such applications the breaking capacity will be a function of a maximum value of the step voltage that can appear under any specified operating and loading conditions. A procedure for dimensioning transition resistors is briefly described. Some specific aspects of selecting OLTCs for PSTs intended for parallel operation are also discussed. Unacceptably high circulating currents may appear under the “out-of-step” conditions due to the low effective short circuit impedance and high step voltages and as a result, for some types of PST like the single core design, paralleling is not possible.

Paper A2-206 presents Italian experience regarding the use of the large phase shifting (quadrature booster) transformers, with more detail on specification, design, testing, operation and maintenance aspects of two 400 kV, 1630 MVA units installed in a strategically important network node. The objective was to increase the import capacity by utilizing PSTs in order to relieve congestion and optimize power flow at interconnections. The specification left the choice of impedance to transformer designers while specifying the on load phase shift and interestingly the maximum commutation time over the full regulation range. Some specific aspects of testing, in particular the dielectric ones, are briefly commented in the paper. A summary of considerations in respect of the insulation coordination based on the system transient studies, choice of the single line diagram for maximizing operational flexibility as well as control strategies for optimizing the response time is also given. Finally, an example of the cross-border coordination of the operation of the PSTs at two ends of the system interconnection is presented, with an objective of optimizing utilization of the installed equipment at both ends while increasing the level of operational security.

Paper A2-207 summarises UK experience with resolving the key design, test and control challenges imposed by an application of large, 400 kV, 2750 MVA, quadrature booster

transformers for restricting the post-fault power flow in the lowest capacity system interconnections. The key design issues are discussed, including the selection of a suitable OLTC and modelling of the internal voltages and fluxes, especially for the “bucking” mode of operation, in order to prevent over-fluxing in the core. A model developed for determining the operational parameters is presented in the paper. The test program required testing of the shunt and series units separately or interconnected and agreed calculation methods were used for the conditions which could not be covered by the test (e.g. withstand of the load bucking condition). It also took into account the actual bypass arrangement in service and results of the system transient studies. The control system was designed with a view to achieve the most efficient and economic design while preventing at the same time the quadrature booster from operation outside the safe envelope, i.e. in the domain where an excessive over-fluxing of the magnetic circuit could occur.

Question 2.1

It is critically important that users and suppliers work together at the early specification stage in order to ensure that the system operating conditions and their implication on the equipment design are fully understood and adequately addressed. The main performance characteristics may be specified in different ways thus affecting the level of flexibility that can be given to designers in terms of design choices and optimization. One of the key design parameters is the minimum phase angle, which can be specified at the no-load condition in which case a minimum impedance requirements have to be specified as well, or at the specified load conditions, whereby the choice of the optimum compromise between a minimum short-circuit impedance and a minimum no-load phase angle is left to the designer. The choice of the approach may be influenced by various requirements, such as a need for standardizing parameters in order to enable interchangeability of the units in the system.

Are there any views and justification of preferences in this respect and/or any data resulting from the techno-economical evaluation of the two approaches that can be shared with the industry?

The system transient studies can point to some specific conditions which can cause dielectric stresses that can not be evaluated by applying the specified standard dielectric test requirements. The reports discusses some of these conditions such as the transient voltages under the single phase to earth fault following asynchronous operation of the individual phases of the associated circuit breakers or a case when one terminal of the series winding is hit by a lightning impulse while the opposite terminal is at the peak AC voltage of the opposite polarity.

Should some of these requirements, which are generally applicable, be included in specifications for PST/QB so that adequate evaluation and mitigation strategy can be adopted? Are there other operating conditions that should be taken into account?

An effective control, protection, monitoring and maintenance strategy needs to be adopted in order to optimize utilization of QBs while preventing operation outside the safe operating envelopes. Some examples were shown in the reports. Is there more experience in this respect that could be shared?

An example was shown of the successful cross-border (Italy-France) coordination of the operation of PSTs in order to optimize utilization of the system interconnections. Are there other examples of such collaboration?

Question 2.2

Some system operators will specify the preferred type of PST. Is this a common practice or a specific approach?

Both reports stress the importance of a close cooperation between the transmission system operators and equipment manufacturers throughout the duration of the project, starting at the early specification stage. An example was presented where a critical design requirement such as the short-circuit withstand capability is evaluated by the R&D facility of the equipment user. Are there other examples of users defining detailed procedures for evaluating critical performance characteristics?

A Phase Shifting Autotransformer enables control of the reactive power flow as an additional functionality to the active power flow control. In this regard it provides the same functionality as FACTS systems. Is there any information available on a technological comparison between these two concepts?

In order to enable voltage regulation by PSAs, additional regulating windings, OLTCs and internal connections are required. Furthermore, with a view to provide effective protection, a multitude of CTs needs to be “buried” inside the tank. Is the increased complexity of PSAs likely to affect reliability and maintenance requirements for this type of equipment when compared with conventional PSTs?

Question 2.3

The importance of the adequate choice of OLTC for PST application has been addressed in several contributions. In addition to the key requirements for the selection of OLTCs discussed in the report A2-205, the speed of commutation was identified as an essential parameter required to enable a quick phase shifting action that may be required in order to prevent the tripping of the system interconnections. Is the view on the importance of this requirement widely shared? What are the present technological limitations in this respect? Are there any views on the feasibility of increasing the speed of operation of OLTCs?

Contributions, from Germany, Canada, France and Japan stress the point that common understanding between equipment manufacturer and system engineering is an absolute necessity. Significant benefit can be achieved through early cooperation and several design configurations can be considered to achieve the level of phase angle control and voltage control needed. It was shown that the choice of the optimum PST concept within may result in increased ratings in terms of the throughput and phase angle regulation range while remaining within the same budget. Transportation limits and sound level requirements may raise design constraints that need to be adequately addressed.

An interesting example of a close collaboration between the equipment manufacturer and system operator was presented, whereby it became necessary to assist the PST by adding a reactor in parallel in order to share the load and increase a fairly low pre-contingency rating of PST without any risk of exceeding the transformer thermal capability under the worst post-contingency operating conditions. The value of the inductor was optimized while taking into account simultaneously, the characteristics of the system and those of PST.

For complex project, cooperation can be time consuming but much better economical solution fulfilling actual needs can be identified.

Experience reported from Japan also points in the same direction. Close cooperation between equipment manufacturer and client has resulted in a new concept replacing the two tank with one tank design featuring voltage and phase angle regulating windings wound on the same core leg. This design addressed better the system operator requirements while dispensing with a separate phase regulation unit.

The short circuit withstand capability of PST was also discussed. A specific approach to evaluating the short circuit strength was presented by the French utility. Due to the complexity of PSTs, its unique design, usual two active part configuration, the short circuit testing is not feasible. As a result, a theoretical demonstration is acceptable, either by referring to tested transformers or by calculation in accordance with the IEC 60076-5 standard. However, the equipment user may require in addition some experimental derivation of the constants for use in calculations. The models should utilize conductors of a similar type of that intended to use in the actual design. Clarification of the requirement to demonstrate the short circuit withstand capability will be wired in the specifications. Feedback on such an approach could be used for the future evolution of the relevant standards.

The same contribution also addressed the method of assessing the thermal performance of PSTs suggesting the similar approach as for the evaluation of the mechanical strength, involving calculations and experimental evaluation. It is believed that the IEC 60076-2 should contain a description of a procedure for evaluating the estimated values of the hot spot temperatures and that the opportunity of the present revision of this document should be used for effecting such modification.

2.2 Innovative concept for PST and Techno-Economic Comparison with FACTS

Paper A2-203 presents several innovative PST applications utilizing additional reactive elements connected in series or in parallel in order to extend the power flow control capability and provide additional functionality, such as fault current limitation. It has been shown that by adding PST in series with a bus tie-in reactor a concept of a fault current limiting phase shifting transformer (FCL-PST) can be realized, thus enabling cost effective substation upgrading while maintaining the fault level and providing effective means for load balancing. Further applications of FCL-PST such as those for the substation reserve sharing and network decoupling are briefly discussed. A concept of assisted phase shifting transformer (APST) which features addition of reactive elements in parallel to the series winding of PST for sharing the line current, is briefly presented. It claims that the PST installation utilizing a PST of a lower rating and a parallel reactive component may provide a more cost effective alternative to the full-rated PST, especially for the wide phase-angle regulation requirements. Some examples of application APSTs are also presented. An effective and simple analytical tool, developed for designing PSTs and APSTs while taking into account the system constraints, is briefly discussed. Finally, an application of PST for the on-load network de-icer concept (ONDI) is shown, whereby one installation of ONDI in strategic network intersections can be used for de-icing of a large number of circuits.

Report A2-208 briefly presents some key technological aspects of a Variable Frequency Transformer (VFT) which is comparable to the back-to-back HVDC schemes in its functionality. It can also be utilized as a continuously-variable phase shifting transformer with an ability to regulate the angle over the full 360° range. The device is in essence a three phase rotary transformer with the rotor and stator windings connected to two different asynchronous

power networks that require to be interconnected. The direction and magnitude of the power flow through VFT is proportional to the torque applied to the rotor. In addition to the rotary transformer, the system comprises of two fully-rated, double-wound transformers, DC motor and drive system as well as the switched shunt capacitor banks. The paper summarises experience gained with the Langlois VFT project, including both, the phase shifting and asynchronous modes of operation. The key operational, control and protection features are briefly described, together with maintenance requirements. The emphasis was placed on the performance reliability and a special approach was adopted based on the delivered versus scheduled energy. The field trial presented an opportunity to subject VFT to various system conditions which could not be covered by the factory and commissioning tests and to define in collaboration between the system user and the equipment manufacturer effective remedial actions and modifications in response to some minor protection and equipment issues. The system has been in full commercial operation since April 2005.

Question 2.4

The authors believe that these innovative applications of PSTs can enlarge their utilization in the modern power systems. Does the industry share this view? Is there any information available on a techno-economical comparison of these solutions with the FACTS applications such as the unified power flow controller (UPFC)?

Question 2.5

The authors claim additional features over the conventional PST technology such as the smooth phase regulation and extended angle range. Is there any additional information on the techno-economical-reliability comparison with the conventional PST applications in the synchronous system interconnections? Are there any new application scenarios resulting from the additional functionality that could justify the cost differential over the conventional technology?

There were four contributions addressing the questions raised on the papers A2-203 and A2-208.

In a contribution from Switzerland it was stated that the FACTS technology based on VSC (Voltage Source Converters), such as TCSC (Thyristor Controlled Series Compensation) may offer in the future a cost effective alternative to PSTs. TCSC application should be compared with PSTs rather than UPFC (Unified Power Flow Controller) as they may bring more competitive solutions.

A contribution from Germany presented a PST manufacturer's view on novel (assisted) applications. These included bus coupling with fault current limitation, decoupling interconnection, assisted PST and de-icing of lines. An interesting example of PST use for bus coupling and fault limitation was shared with the audience.

In a contribution from France it was explained how an autotransformer comprising also a phase shifting functionality can be used to control power flow between two lines of different voltage. The phase shifting autotransformer will cost approximately 7% more than the conventional autotransformer. Such an integrated solution will also enable simultaneous control of active and reactive power between two systems at different voltages.

A contribution from Canada summarised results of comparison between conversion of PST in APST and application of UPFC. It was concluded that APST conversion was more economical than UPFC addition where the speed of operation was not critical. From a speed point of view, APSTs and FACTS controllers have different fields of application.

Another innovative concept is the variable frequency transformer (VFT). In this innovation, the rotor turns to compensate the frequency difference between two asynchronous networks. A continuously variable phase-shifting transformer with the ability to regulate over a full 360 degree range is then provided. A report from Canada summarized the first few years of experience on a 100 MVA installation. In terms of a techno-economic comparison with PSTs the cost of VFT would be more comparable to a DC project of similar size.

3 PS3: NEW DEVELOPMENTS OF ELECTRICAL TRANSIENTS ON TRANSFORMER PERFORMANCES

As there was no keynote speech for this preferential subject, the Special Reporter, Milan Saravolac, made a brief introduction of the topic.

The Special Reporter summarised that understanding and adequately addressing phenomena associated with the interaction between power transformers and the system, in particular those resulting in voltage transients and consequent high dielectric stresses, has been the subject of continued CIGRE interest in the recent years.

This subject was addressed at an open workshop organized by JWG 12/13/23-21 (Electrical Environment of Transformers) for the occasion of the CIGRE 2002 Conference, at the A2 Colloquium in Moscow in 2005 and recently by the newly formed JWG C4/A2 in Brazil (Transient Interaction between Transformer and System).

The JWG 12/13/23-21 was mainly focusing on VFTOs while the Brazilian JWG C4/A2 looks more into transients related to HVDC Converter Transformers, such as those caused by the commutation of static components.

In total, six papers were accepted by A2 for this preferential subject. The Special Reporter arranged these papers in separate categories and raised questions for discussion accordingly. Altogether, 12 prepared contributions were received in advance of the plenary session.

3.1 Effect of switching voltage transients

Paper A2-301 presents a good example of a joint effort between the equipment user and manufacturer in response to a requirement to use 30 years old shunt reactors in a 525 kV network as switchable. In order to provide data required for evaluating the need for refurbishing the shunt reactor a system owner carried out extensive transient simulations and field measurements. The objective was to determine the voltage and inrush current transients associated with the switching operations of energising and de-energising shunt reactors and their effect on the dielectric and mechanical strength of the equipment. The output of this study was used as a base for defining requirements for refurbishing shunt reactors and controlled switching of circuit breakers in order to optimise the effect of the HF voltage and inrush current transients thus ensuring the adequate withstand to cumulative dielectric and mechanical stresses.

Question 3.1

Is there a proof of deterioration of the dielectric strength of insulation due to the cumulative effect of repetitive voltage transients?

Are there other examples of such collaboration between the equipment users and manufacturers in order to clearly define changes in operating environment and evaluate their effect on equipment performance and reliability?

A contribution from Brazil reported on the successful interaction with the manufacturers during the design process and the equipment operation. It describe how the transient simulations and field-test results were taken into account by the manufacturer. Transients were recorded in a wide frequency range from 200 kHz to 1.4 MHz. This collaboration was found valuable to ensure a reliable operation of equipment. The contributor, Mrs A. da C O Rocha also used this opportunity to inform briefly of the initiation of the Brazilian JWG C4/A2 on Transient Interaction between Transformer and System. Focus on System/Transformer operation reliability. The JWG was initiated in response to increasing failure rate of HVDC Transformers but the scope of the group extends beyond HVDC. It involves utilities, manufacturers and research establishments and had 5 meetings since inauguration in May 2005. The objective is to carry out various system transient studies and use the results for upgrading transformer specifications operation and planning criteria.

The critical parameters to be considered in the case of transformers energisation where reviewed in a contribution from France. Importance of the accurate knowledge of the residual fluxes and the characteristics of the circuit breaker were outlined. Energisation of no-load transformers can lead to undesirable effects and palliative solutions were presented. Some results of the on site tests conducted in order to evaluate repeatability performance of the circuit breakers were also presented. In order to reduce inrush currents controlled switching was recommended.

3.2 Modeling of Fast Transients

Paper A302 deals with high frequency (HF) modelling of transformers required for evaluation of their response to system transients. The importance of the experimental validation is emphasised so that the adopted HF model can be used for the applications where non-intrusive measurement may not be feasible. The frequency range of interest (10 Hz to 2 MHz) is divided into three main frequency bands in order to address the inductive effect of the magnetic core, winding structures and lead arrangements respectively and the associated modelling techniques are briefly commented, including the LF transformer conventional model, lumped parameter RLC network and the multiple transmission line theory approach. A 240 MVA, 275/132 kV autotransformer is used as a means for experimental verification of the computer simulation through a series of case studies.

Question 3.2

Is there any other evidence available of the successful evaluation/prediction of the effects of the fast fronted voltage transients on transformers by applying HF modelling in the range above 500 kHz, that has been experimentally confirmed?

What can be considered as the acceptable deviation between the measurement and the simulation FRA data in order to validate the HF model?

A contribution from Japan reported on a transformer connected to a GIS through a gas-insulated bus. Operations of a disconnecter switch in the GIS can generate very fast transient overvoltages with rise-time: less than 0.1 μ s an unusually high turn-to-turn voltage of a 500 kV shell-type autotransformer could be generated at resonant frequencies. Analysis of this observation with a multi-conductor transmission line model has shown good correlation with the measured wave shape.

A contribution from Switzerland reported on the development of the software package for HF simulation of electrical equipment. It is claimed that the agreement of such simulation with the measurement data is of the order of 1%. The systems operates in a way that the HF model is first developed utilizing the measurement data obtained on the actual transformer under consideration and subsequently utilized for simulation, such as for example, for FRA.

A contribution from UK on the same subject reviews the different method applicable for high frequency modeling of power transformer. Such as lumped element (RLC) network, disc by disc or layer by layer element representation for frequency up to 1 MHz , or multiple transmission line turn by turn element representation for frequency up to 500 MHz.

3.3 Application of ZnOs for over-voltage protection

Paper A2 303 summarises the long-term experience gained with using ZnO varistors for over-voltage protection of power transformer windings and on load tap changers. The authors claim a high reliability of ZnOs in service resulting from the stringent quality control of varistor elements and conservative design rules based on the long term investigations. It is stated that non-linear ZnO varistors provide more effective protection against incoming transient impulse as well as internal resonant over voltages than so called "snubber circuit" which are effective mainly for damping the resonant voltage oscillations. The operating voltage is chosen in accordance with the results of the long term ageing tests in order to ensure stabilised power consumption during the life time of varistors, which matches the life time of transformers. In case of installation of MOVs inside OLTCs, impulse current through varistors is limited to 3 kA and the residual voltage at 1 mA DC is maintained within pre-defined boundaries in order to ensure adequate thermal performance under the hot transformer oil. Compliance with the latter criterion is checked routinely during the planned maintenance work.

Question 3.3

Does the industry share this view/experience on reliability and effectiveness of internally fitted ZnO varistors? Can it be confirmed that the expected life of ZnOs is at least that of transformers/OLTCs that they are built in? Is there any negative experience with regards to the long term reliability of the internally fitted ZnOs? Would other manufacturers be prepared to share information on their design and quality approach in order to achieve required reliability in service? Is there experience of internally fitted ZnOs being ineffective in limiting incoming voltage transients?

Would the authors be willing to share any experience or information on the adopted approach to the design and quality assurance criteria defined with the objective to

ensure reliable operation of the "snubbers", especially in the large power transformer applications? Is there any other experience in this respect, including the effect on dielectric tests?

Australian experience indicates that ZnO varistors used to reduce overvoltages on the tap changer winding have an expected service life of the same order as the transformer itself. Sometimes additional impulses may be required in the range of 90% of BIL in order to indicate that the deviation between records at 75% and 100% of BIL is due to the effect of MOVs. Similar experience is reported from Japan where transformers have been delivered with ZnO varistors since 1980 without problems. Accelerated aging test under hot oil concur to expect long life duration. Japanese contribution also summarized some typical applications of ZnOs in power transformers.

3.4 Effect of remote energisation

Paper A2-305 discusses several internal unexplained dielectric failures over a period of 10 years in a population of UK power transformers that are likely attributable to the remote energisation. As these failures took place in a population of transformers which is characterized by a low failure rate compared to international norms the authors are of the opinion that the significance of this phenomenon and the effect on transformer insulation may be underestimated as well as not being fully covered by the factory tests. Part winding resonance triggered by the switching transients was suspected as the most likely cause of internal over-voltages. The authors acknowledge that a better understanding of the phenomena involved would be required before practical mitigation measures could be recommended, in addition to the actual recording of the transient waveforms appearing at the transformer terminals. Some possible mitigation measures are considered, which may include installation of surge arrestors, application of controlled switching or definition of the design specification requirements aimed to avoid winding resonance for the known system configurations.

Question 3.4

Does similar experience exist of inadequately explained internal dielectric failures (likely resulting from the remote energisation) which could support the view that the effect of such switching phenomena on transformers may be underestimated?

Is there any information available on similar phenomena with more explanation and better understanding of the failure mechanisms involved?

Does the industry share the view that the existing dielectric tests may not ensure adequate dielectric strength for such resonant scenarios/phenomena?

Is there any experience of collaboration between equipment users and suppliers at the specification stage in order to assess the risk in this respect and define design requirements with a view of avoiding the part winding resonance?

In Japan, one failure of a 500 kV transformer could be attributed to remote energisation. A step wave was transmitted via cables because the circuit breaker was closed at the remote substation. The oscillatory rectangular wave, caused by the reflection in cable, was applied to the transformer primary side. There was little attenuation in the surge propagation because of the cable system. The frequency of the oscillatory surge applied to the transformer happened to coincide with the resonant frequency determined by the secondary side cable and the

transformer impedance itself, and a switching surge overvoltage of magnitude 3.8 occurred at the secondary terminal of the transformer.

A report from France discusses the risk of overvoltage during power restoration following a blackout. In addition, sympathetic interaction between transformers is also a possibility. Simulations indicate that high voltage transformer and autotransformers could be at risk and some mitigation methods are proposed.

3.5 Effect of sympathetic interaction on inrush currents

Paper A2-306 presents an output of an analytical study that has been carried out in order to investigate interaction between generator step-up transformers of one power station connected to the same (400 kV) busbar system and associated effect on inrush current during energisation of individual units from the system side, following a repeated incidence of the spurious operation of the transformer differential protection. It showed that such interactions could have an effect on the maximum amplitude, decay time and frequency content of the inrush current. Application of the pre-insertion resistors in the 400 kV circuit breakers did show potential for significant reduction of the amplitude but not of the attenuation time of the inrush current and the associated second harmonic component. In order to prevent similar spurious operation in the future, while taking into account interaction under various system configurations, it was decided to adjust the setting of the differential protection and allow higher amplitude of the second harmonic component of the inrush current.

Question 3.5

Was this solution to the problem implemented and if so how effective it was in preventing erroneous protection operation?

Would fitting of the pre-insertion resistors to the HV CBs, in addition to reducing the maximum amplitude of the inrush current, also reduce the risk of switching voltage transients? Is there any relevant experience to report?

An interesting contribution from Venezuela reported on the sympathetic interaction between two step-up transformers of 13.2 / 400 kV. This contribution addressed questions raised on the paper A2-306 and provided some additional information to that already presented. It stated that the installation of the pre-insertion resistor provided effective mitigation technique thus preventing further spurious operation of differential protection.

3.6 HF modelling for evaluating the effect of voltage transients

Paper A2-201 presents output of an investigation into repetitive failures of generator step-up transformers in a substation located in the area subjected to frequent tropical storms and associated lightning transients. Seven transformers failed in the same mode with the HV winding insulation punctured close to the line-terminal. These failures were attributed to the high frequency voltage transients that were appearing at the transformer terminals after lightning impulses chopped close to their crest values were repeatedly reflected at the ends of the short busbar sections connecting the HV line and transformers, with a travel time matching one of the winding natural resonance frequencies. In addition, the substation overvoltage protection relying on the aged silicone-carbide lightning arresters was found to be

ineffective. A comprehensive computer simulation was supported by the experimental confirmation of the winding resonant frequencies, however the ongoing effort to record the steep-fronted, high-frequency transients at the transformer terminals has not succeeded yet in providing such information. It is expected to achieve this during the next lightning season. In addition to the installation of the metal-oxide lightning arresters close to the transformer terminals and further monitoring of the voltage transients, the authors are recommending an additional steep-front lightning impulse test for inclusion in the technical specifications for transformers intended for operation in the high keraunic level areas.

Question 3.6

Are the existing IEC 60076 dielectric tests considered to be insufficient in terms of ensuring adequate withstand capability against repetitive fast fronted transients? Is there enough evidence to justify a consideration of an additional dielectric test in this respect? Are there any views on the potential test requirements with regards to the test parameters and procedures in order to make them representative of various system specific conditions and interactions?

What are the applications that may merit such considerations more than others?

Should a proof of a capability to withstand application specific repetitive fast fronted transients be left to the user and manufacturer to address at the specification and design review level?

Was any measurement carried out in service to confirm the transient waveform at the transformer terminals?

Are there any records of the lightning-induced fast fronted transients acquired following the study that could provide experimental proof of the simulation conclusion? If so, would the authors be willing to share such information?

Starting from the specification stage, should an effort be made to predict and mitigate against the risk of a possible resonance involving transformer internals/windings and associated HV busbars, rather than introducing an additional lightning impulse test?

A contribution from Mexico reported that in high isokeraunic level regions, repeated atmospheric discharges lead to steep-front transients and result in a dielectric stress concentration in the winding. It was recommended that in the next revision of IEC standard, a steep-front overvoltage test should be considered for those applications (for areas renowned for the intense tropical storms resulting in severe lightning transients) if requested by the equipment users. Extended recording of these overvoltages to orient the transformer design and determine required characteristics of protection devices was recommended.